DEVELOPMENT AND USE
OF COMPOSITE FIBROUS MATERIALS
IN THE U.K. CONSTRUCTION INDUSTRY

VOLUME 1

A thesis submitted in partial fulfilment of the requirements for the degree of Ph.D. of the University of Surrey.

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1977
I am greatly indebted to my wife who has given me every encouragement and assistance throughout this study.

I am also greatly indebted to Dr. H.L. Burstall and Dr. I. Hollaway under whose supervision this project has been completed. I have received many valuable suggestions, much advice and constructive criticism from my supervisors and also from Professor C. Robinson, Dr. I.F. Haber, Dr. H. Mooshin, Mr. J.J. Zonsveld, and many other academic members of the University of Surrey.

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SUMMARY

The work described in this thesis is the result of a series of technological and economic studies carried out in 1974-76 on the development and use of new composite fibrous materials in the construction industry. The research embraces all technical, economic and managerial aspects of the design and development of building panels, units and systems made wholly or partly from composite fibrous materials, whether manufactured on site or off site.

The main objective of the research has been to discover the significance and relative importance of factors affecting acceptance by, and use of new materials in, the construction industry using glass fibre reinforced plastics (G.R.P.) as a model material and generalizing the findings as far as possible.

It has been found that, although the relative importance of technical and architectural factors varies considerably from one material to another, the average cost of a product made from a given material relative to those of alternatives determines the extent of utilization of that product (or material).

The studies covered by this thesis are as follows:

(1) A review of the organization and management of building projects including the influences exerted by various parties on the final form of a building and its constituent materials. It is concluded that despite the large output of the construction industry, and unlike oligopolistic industries, the control over the design of projects and use of materials is neither centralized nor systematic. There is a strong inclination amongst designers to treat each project as unique and to design and develop its components independently. The construction companies have generally little influence on the design of buildings except in the case of package deals, speculative development and system building.

(2) A review of the science and technology of composite fibrous materials, including comparisons between mechanical, physical and fire-resistant properties of various composite materials with each other and with those of other relevant structural materials. The economic prospects of these composites have also been considered.
(3) Properties of glassfibre, plastic resins and G.R.P. composites are discussed in detail and compared with those of other relevant materials. Manufacturing and constructional techniques used for producing G.R.P. panels and structures are outlined. Installed cost comparison between G.R.P. panels and typical constructions based on traditional materials have been carried out. It has been shown that the unit cost of G.R.P. panels, which is dependent on the method of manufacture, tooling costs, the design of panels, etc., could compare favourably with those of natural stone and metal curtain-walling.

(4) Investigations have been conducted on the service performance requirements of load-bearing and infill panels, design criteria and procedure, analytical methods for the structural analysis and design of both single plate and structural sandwich construction in G.R.P. composites. It is shown that with the amount of design data available on G.R.P., it is likely that designers would face various problems when undertaking the structural analysis and design of panels and structures in G.R.P. To approach the design problem in a systematic manner, a design routine, incorporating a suggested method of accounting for the visco-elastic nature of G.R.P. composites and for fluctuations in loading, has been developed.

(5) Statistics on the use of G.R.P. in the construction industry are given. The characteristics of past trends within the G.R.P. industry are discussed in detail.

(6) The attitudes of the practising architects and engineers and those of local authority designers towards the service performance, advantages, disadvantages and potential of G.R.P. panels have been collected in a comprehensive postal survey and analysed. The results are reported in detail and indicate that despite the potential of G.R.P. for producing novel and exciting architectural solutions, the use of this material has remained sporadic and insignificant relative to the use of traditional materials. The reasons responsible for this trend are discussed. However, despite numerous technical, economic, constructional and contractual problems, architects appeared to be enthusiastic about G.R.P.

(7) Influences of architectural fashion and statutory planning/aesthetic approval on the design of buildings in general, and
G.R.P. panels in particular, have been investigated. One conclusion has been that unorthodox structural shapes such as shells and composite folded-plates are generally incompatible with the functional design requirements in buildings; moreover, they do not easily blend in with the surrounding environments. Their uses are essentially associated with one-off projects such as recreational buildings.

(8) The attitudes of clients and insurance companies on the use of new materials have been collected and analysed. The results show that whereas clients are mostly influenced by professional designers, insurance companies exhibit, through the Fire Officers' Committee (F.O.C.), a conservative and 'ad-hoc' approach to the use of new materials penalizing the use of materials containing combustible matter.

(9) A review has been carried out of the developments in the field of industrialized building. It has been shown that in comparison with concrete, G.R.P. appears to be capable of enhancing the appearance and reducing the weight of industrialized systems. However, G.R.P. has not been used to any significant scale in conjunction with these systems, the reasons responsible for this trend are discussed.

(10) Future prospects for basic engineering materials have been reviewed; in particular, it has been shown that availability and costs of many materials are dependent on the availability and cost of energy.

(11) The properties, applications and post-war progress of aluminium alloys have been reviewed. Mathematical formulae relating the consumption of aluminium products in the construction industry to the construction output and to an 'aluminium/wood' price ratio, have been developed. It is concluded that the market for standardized products in the construction industry is highly price-sensitive.

The apparent disagreement between the progress of G.R.P. composites and aluminium alloys is explained and a tentative forecast made for the future progress of G.R.P. in the construction industry.

(12) The need for basic and applied research in the field of composite materials is discussed and a survey has been carried out on the future likely developments in this field. It has
been shown that current developments of new generation of polymeric fibres (high strength/high modulus fibres) could pave the way for large scale future use of composite materials in the construction industry.

(13) Finally, the relative importance of factors affecting acceptance and use of new materials in the construction industry are discussed and related to the experience of G.R.P. and aluminium alloys.

Attempts have been made to see if a reliable estimate could be made of the time-scale required for a new material to reach the traditional status; it has been shown that there is no single reliable method which can be used to arrive at the required estimate. However, from the available data, it has been estimated that the above time-scale is at least of the order of two decades.

Methods for systematic development and marketing of new materials and products into the construction industry are given; these are based on the experience of reinforced plastics and aluminium alloys.
1.1 Introduction:

As will be seen from the statistics presented in Chapter 2, the construction market is a large and complex market which, in recent times, has attracted an increasing number of entrepreneurs and innovators, especially producers of new materials. However, only a limited number of these entrepreneurs and innovators have successfully managed to sell their products and services to the construction industry. The remaining have found it difficult to establish themselves in this complex and fragmented market. This has meant that many potentially useful innovations may have received little or no attention, with the effect that their potential benefits have not been realized resulting in a net loss to the industry and the nation as a whole.

The plan for this study was formulated against this background, and it was decided to investigate the process of introduction into, and acceptance of new materials by, the construction industry. Further, it was decided to select composite fibrous materials in general and reinforced plastics in particular for detailed scrutiny, and compare their stages of development and marketing with similar or alternative materials. The objective of this study may therefore be described as the development of a model which conceptually explains the stages involved in development, marketing and selling of new materials and products in the construction industry. However, as may be seen, the actual research work has necessarily been extended to include detailed technological studies in the field of composite fibrous materials and the structural analysis and design of structures which resist the applied loads, mainly by developing 'in-plane' forces and stresses. Moreover, a review of the 'fire-resisting' properties of materials was also carried out and incorporated into the study.

1.2 Structure and Layout:

The main part of this thesis is divided into 14 chapters: Chapter 2 reviews the industrial structure of the construction industry; Chapter 3 reviews the division of responsibilities
within the construction industry; Chapter 4 reviews the technology of composite fibrous materials; Chapters 5 to 11 deal with the various aspects of the development and use of glass reinforced plastics products in the construction industry; Chapter 12 reviews the future prospects for all constructional materials; Chapter 13 reviews the development and use of aluminium products and various forecasting models for both aluminium and G.R.P. are discussed; Chapter 14 contains suggestions for further research and development in the field of composites; and finally Chapter 15 contains generalized findings as related to the experiences of G.R.P. and aluminium products in the construction industry.

For ease of reference, references are given at the end of each chapter. Each chapter is further divided into sections.
2.1 Nature and Importance in relation to the U.K. Economy

The construction industry with a gross output of around £9000 million in 1973, constitutes a vital section of the modern economy; yet it is strikingly different in nature from other industries.

In terms of percentage, the construction industry's contribution to the gross domestic product in 1973 was 6.9 percent, compared with 29 percent which was the share of the manufacturing industry (2).

The composition of the construction output in 1973 was as follows:

a - New public and private housing 28.2 percent.
b - Private industrial and commercial works 21.6 percent.
c - Public buildings other than housing 21.7 percent.
d - Total repairs and maintenance works 28.5 percent.

The construction industry has been affected by successive government policies and its output has been subject to fluctuation (see Fig. 2.1). However, from Fig. 2.1, it can be seen that between 1963-73(1), the construction output showed a positive general trend; this trend has been persistent since the last war.

The construction industry with a grand total employment of 1,875,000 in October 1973(3), employed one in every fourteen of the total working population in the U.K. The breakdown of the employment is shown in Table 2.1.

These data do not include the designers and quantity surveyors in private practice whose services are employed by clients, also the staff engaged by private sector clients (other than those engaged by contractors).
FIG. 2.1. INDEX OF THE CONSTRUCTION OUTPUT (1963 = 100). BASED ON TABLE II OF HOUSING & CONSTRUCTION STATISTICS No. 10.
Table 2.1 Composition of Employment in the Construction Industry (Ref. 3)

<table>
<thead>
<tr>
<th>Classification</th>
<th>1973⁹</th>
<th>1973ᵇ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number (Thous)</td>
<td>% of Total</td>
</tr>
<tr>
<td>Operatives:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Private contractors</td>
<td>863</td>
<td>46</td>
</tr>
<tr>
<td>2. Public authorities</td>
<td>242</td>
<td>12.9</td>
</tr>
<tr>
<td>Administrative, Professional, Technical and Clerical:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Private contractors</td>
<td>241</td>
<td>12.9</td>
</tr>
<tr>
<td>2. Public authorities</td>
<td>116</td>
<td>6.2</td>
</tr>
<tr>
<td>Working Principals:</td>
<td>36</td>
<td>4.6</td>
</tr>
<tr>
<td>Total</td>
<td>1875ᵇ</td>
<td>100ᵇ</td>
</tr>
</tbody>
</table>

a - based on the D.O.E.'s main list
b - based on the combined list which includes 25,000 mainly very small firms
Table 2.2 shows the distribution of employment of professional designers and quantity surveyors as well as the professional members of the Institute of Building (I.O.B.); it can be seen that the employment of professionals (excluding supporting technical and clerical staff) varies considerably, depending mainly on the type of profession, e.g. the proportions of architects and quantity surveyors in private practice are 50 and 63 percent respectively (i.e. entries under 'principals' and 'employees' in Table 2.2). The corresponding figures for civil engineers and building services engineers are 26 and 20 percent respectively.

The reasons for the above differences will be considered in a more appropriate place; however, it can be seen that the total number of professionals engaged in the construction industry is not high in relation to the total employment of operatives, etc. in the industry already noted in Table 2.1.

The interdependence of the construction industry and the rest of industries can be examined by reference to the national input - output table; the latest reliable table at the time of writing is the 1968 Input - Output Table, part of which has been reproduced in Table 2.3.

The figures in the row indicate those parts of the construction output used up in the production of other goods and services, i.e. mainly repair and maintenance works for building and other facilities used by various industries. (The row in Table 2.3 is in fact shorter than the corresponding row in the national table because only the important items have been included; this should be sufficient for the purpose of illustration. Note that the same applies to the data in the column, Table 2.3).

Agriculture and coal mining have traditionally required a large amount of repair and maintenance works, because they have in addition to buildings of all sorts, a large network of roads, etc. to maintain; this is reflected in their share of the total intermediate output of the construction industry.

(There is an apparently large sum of the output consumed by 'Industrial Steelwork and Plants' i.e. £73.2 million, see Table 2.3. This is an artefact of the industrial classification, as prior to 1968, the classification was such that the above
Table 2.2 Distribution of professionals by type of employment (Ref 4)

<table>
<thead>
<tr>
<th>Type of Employment</th>
<th>Architects (RIBA) (%)</th>
<th>Civil Engineers (IOB) (%)</th>
<th>Quantity Surveyors (RICS) (%)</th>
<th>Structural Engineers (I of Struct. E) (%)</th>
<th>Building Services Engineers (IHVE) (%)</th>
<th>Builders (IOB) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Private Sector:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 - Principals</td>
<td>30</td>
<td>5</td>
<td>30</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 - Employees</td>
<td>20</td>
<td>21</td>
<td>33</td>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 - Contractors and other commercial/industrial companies</td>
<td>5</td>
<td>19</td>
<td>8</td>
<td>21</td>
<td>45</td>
<td>65</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td>55</td>
<td>45</td>
<td>71</td>
<td>66</td>
<td>65</td>
<td>73</td>
</tr>
<tr>
<td><strong>Public Sector:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 - Local authorities</td>
<td>32</td>
<td>37</td>
<td>16</td>
<td>19</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>2 - Central government and public corporations</td>
<td>9</td>
<td>12</td>
<td>11</td>
<td>9</td>
<td>18</td>
<td>5</td>
</tr>
<tr>
<td>3 - Education</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>13</td>
</tr>
<tr>
<td><strong>Sub-total</strong></td>
<td>44</td>
<td>52</td>
<td>29</td>
<td>31</td>
<td>32</td>
<td>26</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td>1</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>Corporate membership</strong></td>
<td>22600</td>
<td>34000</td>
<td>10100</td>
<td>10500</td>
<td>4500</td>
<td>7200</td>
</tr>
</tbody>
</table>

Notes: Overlapping membership is possible; e.g. architects and quantity surveyors or civil and structural engineers, etc.

OEI Survey of professional engineers, 1973
RICS Membership records, April, 1972.
TABLE 2.3 PART OF THE INPUT-OUTPUT TABLE FOR THE U.K. - 1968 (£m)

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone, slate, chalk, sand etc. (extraction)</td>
<td>94.8</td>
</tr>
<tr>
<td>Mineral refining, lubricating greases etc.</td>
<td>28.5</td>
</tr>
<tr>
<td>Paint</td>
<td>50.2</td>
</tr>
<tr>
<td>Iron casting etc.</td>
<td>35.4</td>
</tr>
<tr>
<td>Other iron &amp; steel</td>
<td>122.0</td>
</tr>
<tr>
<td>Other non-ferrous metals</td>
<td>36.3</td>
</tr>
<tr>
<td>Pumps, valves, compressors</td>
<td>9.8</td>
</tr>
<tr>
<td>Construction &amp; mechanical handling equipment</td>
<td>29.7</td>
</tr>
<tr>
<td>Other mechanical machinery</td>
<td>107.7</td>
</tr>
<tr>
<td>Industrial plant &amp; steelwork</td>
<td>183.1</td>
</tr>
<tr>
<td>Other mechanical engineering</td>
<td>17.1</td>
</tr>
<tr>
<td>Insulated wires &amp; cables</td>
<td>26.5</td>
</tr>
<tr>
<td>Other electrical goods</td>
<td>34.2</td>
</tr>
<tr>
<td>Motor vehicles</td>
<td>11.5</td>
</tr>
<tr>
<td>Wire &amp; wire manufacturers</td>
<td>12.6</td>
</tr>
<tr>
<td>Other metal goods</td>
<td>55.1</td>
</tr>
<tr>
<td>Bricks, fireclay &amp; refactory goods</td>
<td>103.5</td>
</tr>
<tr>
<td>Pottery &amp; glass</td>
<td>51.5</td>
</tr>
<tr>
<td>Cement</td>
<td>57.8</td>
</tr>
<tr>
<td>Other building materials etc.</td>
<td>309.5</td>
</tr>
<tr>
<td>Timber &amp; miscellaneous wood products</td>
<td>264.7</td>
</tr>
<tr>
<td>Other paper &amp; board products</td>
<td>13.9</td>
</tr>
<tr>
<td>Electricity</td>
<td>37.0</td>
</tr>
<tr>
<td>Plastic products n.e.s.</td>
<td>57.2</td>
</tr>
<tr>
<td>Road transport</td>
<td>16.7</td>
</tr>
<tr>
<td>Communication</td>
<td>32.5</td>
</tr>
<tr>
<td>Distributive trades</td>
<td>151.7</td>
</tr>
<tr>
<td>Miscellaneous services</td>
<td>123.3</td>
</tr>
<tr>
<td>Imports of goods &amp; services</td>
<td>14.8</td>
</tr>
<tr>
<td>Sales by final buyers</td>
<td>238.2</td>
</tr>
<tr>
<td>Taxes on expenditure, less subsidies</td>
<td></td>
</tr>
<tr>
<td>Income from employment</td>
<td>1795.0</td>
</tr>
<tr>
<td>Gross profit &amp; other trading income</td>
<td>733.0</td>
</tr>
<tr>
<td>TOTAL INPUT</td>
<td>4954.3</td>
</tr>
</tbody>
</table>

NOTE: Input column excludes the entries with values less than £9.0m. Output column excludes entries with values less than £5.0m. For full details see the Input-Output Table for the U.K. 1968.
sum formed part of the transactions within the construction industry itself - in other words, this was added to £951.1 m.)

As has already been noted, about 70 percent of the construction output is in the form of new buildings and other construction facilities such as roads, railways, etc.; these constitute up to 50 per cent of the U.K.'s new investment in fixed assets(5). (The new investment in fixed assets is termed fixed capital formation in Table 2.3).

An examination of the input data reveals that the industry in 1968 purchased some £1200 m worth of principle building and construction materials from other industries; stone, slate, sand, chalk, paint, brick, pottery and glass, cement, timber and board products together accounted for £636.4 million; cast iron and steel for £157.4 m and the non-ferrous metals for £37m (see Table 2.3).

The above figures do not give a full picture of the importance of the construction materials and components producers, because they do not include semi and fully finished products sold exclusively to the construction industry; these have been entered as manufactured goods in the input data.

The input data clearly show that the wages' bill is the highest single input, e.g. in 1968, total income from employment was £1795m.(2). The ratio of wages and salaries to the net output in the construction industry in 1968 was about 0.65, compared to a ratio of 0.5 in the case of manufacturing industries; this is not surprising in view of the fact that the construction industry has traditionally relied on labour-intensive production techniques.

Although the turnover of the construction industry is high, the capital investment by the industry is low. The industry in 1973 undertook an investment of about £58m, or 0.85 percent of output; this is substantially lower than that of the manufacturing industry which was £318m or 13.3 percent of output. The imports bill of the construction industry in 1968 was £123.3m or about 10 percent of the value of all construction materials used in the construction industry (excluding semi and fully finished products); this is relatively low. The reason for this is the fact that the majority of construction materials are bulky and dense; thus, they incur high transportation costs relative to their value.
2.2 Economic Trends in the Construction Industry.

2.2.1 Construction activity.

The output of the construction industry has been fluctuating since 1963 in response to the general economic activities and the successive government policies. As can be seen by reference to Table 2.4 and Fig. 2.2, the extent of fluctuation is relatively more pronounced in 'total housing starts' and 'new orders' than 'construction output'. This is because the repair and maintenance works have a smoothing effect. In addition, large projects are usually spread over a few years which again smoothes the total output of the industry.

It may be noted from Figs. 2.2 and 2.3 that 'cement deliveries' is a good measure of the construction output whereas 'brick deliveries' is related to the housing starts. This is not unexpected since brick is mainly used in the housing market.

2.2.2 Production of principle materials:

Table 2.5 and Fig. 2.4 show the trends in production of principle construction materials. It can be seen that with the exception of wood based boards and bricks, the production of all materials has been expanded, though to different levels, e.g. production of plasterboard in 1973 was nearly 2.45 times that of 1954; production of cement was 1.65 times that of 1954; and production of asbestos-cement corrugated sheet was 1.46 times that of 1954.

How far the demand for these materials can be attributed to the price levels as distinct from other external factors is difficult to determine, e.g. in the case of brick, the demand is mainly controlled by demand for housing. However, no doubt the relative cheapness of plasterboard coupled with the rising cost of labour must have expanded the demand for this material (see below).

2.2.3 Materials' price movements:

Table 2.6 and Fig. 2.5 show the rise in 'construction materials' and 'House Building Materials' indices in 1954-74. It can be seen that after the freeing of the construction
## Table 2.4 The Construction Activity Indices
(Source: Housing & Construction Statistics)

<table>
<thead>
<tr>
<th>Year</th>
<th>Construction output, all works (index)</th>
<th>Construction output, all new works (index)</th>
<th>Operatives employed by contractors (index)</th>
<th>Total housing starts (index)</th>
<th>Cement deliveries (index)</th>
<th>Brick deliveries (index)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>99.7</td>
<td>89.9</td>
<td>101.8</td>
<td>84.9</td>
<td>100.8</td>
<td>100.1</td>
</tr>
<tr>
<td>1962</td>
<td>100.0</td>
<td>81.4</td>
<td>102.6</td>
<td>88.0</td>
<td>101.1</td>
<td>97.0</td>
</tr>
<tr>
<td>1963</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>1964</td>
<td>111.2</td>
<td>114.6</td>
<td>104.9</td>
<td>115.8</td>
<td>122.5</td>
<td>111.9</td>
</tr>
<tr>
<td>1965</td>
<td>113.9</td>
<td>108.4</td>
<td>103.3</td>
<td>106.7</td>
<td>122.5</td>
<td>102.3</td>
</tr>
<tr>
<td>1966</td>
<td>114.7</td>
<td>103.2</td>
<td>100.9</td>
<td>103.1</td>
<td>121.8</td>
<td>92.1</td>
</tr>
<tr>
<td>1967</td>
<td>119.2</td>
<td>119.4</td>
<td>97.0</td>
<td>121.6</td>
<td>127.9</td>
<td>105.6</td>
</tr>
<tr>
<td>1968</td>
<td>121.7</td>
<td>107.4</td>
<td>94.0</td>
<td>107.2</td>
<td>130.5</td>
<td>99.2</td>
</tr>
<tr>
<td>1969</td>
<td>118.8</td>
<td>102.3</td>
<td>88.4</td>
<td>93.3</td>
<td>127.1</td>
<td>90.3</td>
</tr>
<tr>
<td>1970</td>
<td>115.0</td>
<td>101.9</td>
<td>80.8</td>
<td>86.7</td>
<td>124.4</td>
<td>87.1</td>
</tr>
<tr>
<td>1971</td>
<td>117.1</td>
<td>111.3</td>
<td>75.6</td>
<td>93.5</td>
<td>127.1</td>
<td>93.4</td>
</tr>
<tr>
<td>1972</td>
<td>120.0</td>
<td>115.9</td>
<td>76.2</td>
<td>95.0</td>
<td>130.8</td>
<td>96.3</td>
</tr>
<tr>
<td>1973</td>
<td>123.7</td>
<td>111.0</td>
<td>80.2</td>
<td>89.0</td>
<td>145.0</td>
<td>96.0</td>
</tr>
<tr>
<td>1974</td>
<td>114.0</td>
<td>83.2</td>
<td>[76.5]</td>
<td>68.4</td>
<td>[127.1]</td>
<td>68.6</td>
</tr>
</tbody>
</table>

* Quite apart from the effects of increase in productivity per operative employed, this index does not reflect the true level of labour employment owing to the use of self-employed labourers, etc. by the contractors, especially on private housing sites and smaller remote projects.
FIG. 2.2 INDICES OF CONSTRUCTION OUTPUT, NEW ORDERS AND TOTAL HOUSING STARTS

FIG. 2.3 INDICES OF CEMENT AND BRICK DELIVERIES
<table>
<thead>
<tr>
<th>Year</th>
<th>G.B. Bricks excluding refractory &amp; glazed ((X10^6n)) index</th>
<th>U.K. Cement production ((X10^3T)) index</th>
<th>Plasterboard production (approx.) ((X10^3m^2)) index</th>
<th>Insulation board, laminated wall board production ((52\text{ weeks})) ((X10^3T)) index</th>
<th>Asbestos-cement sheet production ((X10^3T)) index</th>
<th>Asbestos cement consumption ((X10^3T)) index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1954</td>
<td>7247 99.9</td>
<td>12140 100</td>
<td>46500 100</td>
<td>49.9 100</td>
<td>n.a.</td>
<td>-</td>
</tr>
<tr>
<td>1955</td>
<td>7163 99.9</td>
<td>12725 105</td>
<td>45650 98.2</td>
<td>50.8 101.8</td>
<td>n.a.</td>
<td>-</td>
</tr>
<tr>
<td>1956</td>
<td>7131 98.5</td>
<td>12980 106.7</td>
<td>44100 95</td>
<td>53.1 106.2</td>
<td>n.a.</td>
<td>-</td>
</tr>
<tr>
<td>1957</td>
<td>6914 95.5</td>
<td>12140 100</td>
<td>44100 95</td>
<td>60.7 121.7</td>
<td>296.3 100</td>
<td>-</td>
</tr>
<tr>
<td>1958</td>
<td>6440 89</td>
<td>11850 97.6</td>
<td>40700 87.5</td>
<td>67.2 134.6</td>
<td>300 101</td>
<td>-</td>
</tr>
<tr>
<td>1959</td>
<td>6967 96.2</td>
<td>12800 105.2</td>
<td>43800 92</td>
<td>66.6 133.7</td>
<td>375 126.7</td>
<td>-</td>
</tr>
<tr>
<td>1960</td>
<td>7283 100.2</td>
<td>13500 111</td>
<td>48000 103</td>
<td>75.1 150.5</td>
<td>418.0 141</td>
<td>-</td>
</tr>
<tr>
<td>1961</td>
<td>7414 102.3</td>
<td>14390 118.5</td>
<td>50600 109</td>
<td>70.3 141.0</td>
<td>412.0 139</td>
<td>-</td>
</tr>
<tr>
<td>1962</td>
<td>7289 100.3</td>
<td>14290 117.6</td>
<td>53100 114</td>
<td>61.3 123</td>
<td>389.0 131</td>
<td>-</td>
</tr>
<tr>
<td>1963</td>
<td>7139 98.5</td>
<td>14061 115.8</td>
<td>55750 120</td>
<td>54.4 109</td>
<td>347.4 117</td>
<td>341 100</td>
</tr>
<tr>
<td>1964</td>
<td>7954 110</td>
<td>16972 139.5</td>
<td>64950 139.5</td>
<td>73.5 147</td>
<td>414.8 140</td>
<td>383 112.3</td>
</tr>
</tbody>
</table>

* Messrs Cape Universal Ltd.*

contd over
<table>
<thead>
<tr>
<th>Year</th>
<th>G.B. Bricks excluding refractory &amp; glazed $(X10^6\text{n})$ index</th>
<th>U.K. Cement production $(X10^3\text{T})$ index</th>
<th>Plasterboard production (approx.) $(X10^3\text{m}^2)$ index</th>
<th>Insulation board, laminated wall board production (52 weeks) $(X10^3\text{T})$ index</th>
<th>Asbestos-cement sheet production $(X10^3\text{T})$ index</th>
<th>Asbestos-cement sheet consumption $(X10^3\text{T})$ index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965</td>
<td>7868 108.5</td>
<td>16977 140</td>
<td>62800 135</td>
<td>77.0 154.3</td>
<td>380.0 128.3</td>
<td>372 109</td>
</tr>
<tr>
<td>1966</td>
<td>7072 97.7</td>
<td>16792 138.1</td>
<td>64700 139</td>
<td>58.7 117.7</td>
<td>369 124.5</td>
<td>367 107.5</td>
</tr>
<tr>
<td>1967</td>
<td>7208 99.5</td>
<td>17617 145.1</td>
<td>76059 163.5</td>
<td>36.4 73</td>
<td>373.1 126</td>
<td>358 105</td>
</tr>
<tr>
<td>1968</td>
<td>7465 103</td>
<td>17940 147.8</td>
<td>85285 183.2</td>
<td>37.4 75</td>
<td>394.3 133</td>
<td>367 107.5</td>
</tr>
<tr>
<td>1969</td>
<td>6734 93</td>
<td>17460 143.6</td>
<td>82824 178</td>
<td>38.6 77.4</td>
<td>352.6 119</td>
<td>358 105</td>
</tr>
<tr>
<td>1970</td>
<td>6062 83.7</td>
<td>17171 141.1</td>
<td>82118 176.6</td>
<td>38.0 76.2</td>
<td>353.5 120</td>
<td>342 100</td>
</tr>
<tr>
<td>1971</td>
<td>6541 90.2</td>
<td>17697 145.8</td>
<td>95401 205</td>
<td>31.9 64</td>
<td>380.2 128.4</td>
<td>345 99</td>
</tr>
<tr>
<td>1972</td>
<td>6938 95.8</td>
<td>18048 148.5</td>
<td>103241 222</td>
<td>36.4 73</td>
<td>395.7 133.5</td>
<td>391 115</td>
</tr>
<tr>
<td>1973</td>
<td>7183 99.2</td>
<td>19986 164.5</td>
<td>112801 242.5</td>
<td>35.3 70.8</td>
<td>433.9 146.5</td>
<td>429 126</td>
</tr>
<tr>
<td>1974</td>
<td>5575 75</td>
<td>17781 146.5</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
<td>395 116</td>
</tr>
</tbody>
</table>

* - Messrs. Cape Universal Ltd.
KEY:

- Insulation board, laminated wall board and hardboard.
- Plasterboard
- Cement
- Corrugated asbestos-cement sheet
- Bricks

FIG. 2.4 PRODUCTION INDICES 1954 = 100
(ASEBESTOS-CEMENT SHEET; 1957 = 100)
### Table 2.6 Construction Materials' and House Building Materials' Price Indices (Source D.O.E.)

<table>
<thead>
<tr>
<th>Year</th>
<th>Construction Materials (index)</th>
<th>House Building Materials (index)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1954</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1955</td>
<td>105</td>
<td>105</td>
</tr>
<tr>
<td>1956</td>
<td>110</td>
<td>109</td>
</tr>
<tr>
<td>1957</td>
<td>114</td>
<td>112</td>
</tr>
<tr>
<td>1958</td>
<td>114</td>
<td>112</td>
</tr>
<tr>
<td>1959</td>
<td>113</td>
<td>111</td>
</tr>
<tr>
<td>1960</td>
<td>115</td>
<td>114</td>
</tr>
<tr>
<td>1961</td>
<td>118</td>
<td>118</td>
</tr>
<tr>
<td>1962</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>1963</td>
<td>122</td>
<td>122</td>
</tr>
<tr>
<td>1964</td>
<td>126</td>
<td>126</td>
</tr>
<tr>
<td>1965</td>
<td>130</td>
<td>131</td>
</tr>
<tr>
<td>1966</td>
<td>134</td>
<td>135</td>
</tr>
<tr>
<td>1967</td>
<td>135</td>
<td>136</td>
</tr>
<tr>
<td>1968</td>
<td>140</td>
<td>143</td>
</tr>
<tr>
<td>1969</td>
<td>145</td>
<td>148</td>
</tr>
<tr>
<td>1970*</td>
<td>157(100)</td>
<td>160(100)</td>
</tr>
<tr>
<td>1971</td>
<td>173(110)</td>
<td>176(110)</td>
</tr>
<tr>
<td>1972</td>
<td>182(116)</td>
<td>189(118)</td>
</tr>
<tr>
<td>1973</td>
<td>214(136)</td>
<td>226(141)</td>
</tr>
<tr>
<td>1974</td>
<td>275(175)</td>
<td>284(177)</td>
</tr>
</tbody>
</table>

FIG. 2.5 INDEX OF CONSTRUCTION AND HOUSE BUILDING MATERIALS PRICES (1954 = 100)
market in 1953 and the complete removal of all forms of
government control in 1954, materials' prices have risen
steadily throughout the 1960's. However, the rapid inflation
of the 1970's has pushed up the price indices to unprecedented
levels. The price movements in 1954-74 of individual
materials are shown in Table 2.7 and Fig. 2.6; it can be
seen that timber and copper have recorded the highest price
rises, followed in a descending order by brick, steel,
aluminium, cement and plasterboard. (See also Chapter 12
for a more detailed discussion).

Whatever the cause, the present price structure of
materials may have produced conditions favourable to
innovation; an example of such innovation will be noted in
Chapter 13. It will also generally be shown in Chapters 4
to 11 that expensive metals are being replaced by cheaper
materials, and in many ways, more efficient materials, e.g.
cast iron pipes have been replaced by P.V.C., or copper/bronze
decorative and cladding panels by reinforced plastics, etc.

2.2.4 Movements in capital and labour costs:

Tables 2.8 and 2.9 and Fig. 2.7 indicate movements in
capital and labour costs. It can be seen that capital costs
fluctuated about a rising trend; labour costs have increased
steadily in both construction and all manufacturing
industries.

Observations on costs of industrialised buildings,
which by definition use more capital than labour compared
with traditional buildings, can yield useful indications
on the economics of substitution of capital for labour; a
study of this has been included in Chapter 11. The data
included in this chapter show that in 1973, industrialized
buildings were significantly cheaper than traditional
buildings. Taken from 1967, the rate of increase in the
the average cost of industrialized buildings was slower
than the corresponding average in traditional buildings.
(For detailed discussion on this subject see Chapter 11).

2.2.5 Summary:

Apart from shortages of steel for reinforcement and
other applications which occurred from time to time, the
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium plates, sheets and strips</td>
<td>123</td>
<td>127.8</td>
<td>129.9</td>
<td>113</td>
<td>110.5</td>
<td>120.4</td>
<td>124</td>
<td>128.75</td>
<td>131.5</td>
<td>146.4</td>
<td>154.5</td>
<td>163.7</td>
<td>170.5</td>
<td>177</td>
<td>191.5</td>
<td>239</td>
</tr>
<tr>
<td>Copper sheet and strip</td>
<td>102.5</td>
<td>104</td>
<td>100.1</td>
<td>101.9</td>
<td>103.3</td>
<td>112.7</td>
<td>133.7</td>
<td>190.2</td>
<td>167.7</td>
<td>202.5</td>
<td>250</td>
<td>251</td>
<td>222</td>
<td>222</td>
<td>316</td>
<td>382</td>
</tr>
<tr>
<td>Steel sheets</td>
<td>126</td>
<td>126</td>
<td>126.6</td>
<td>132.9</td>
<td>132.9</td>
<td>133.4</td>
<td>135</td>
<td>136.8</td>
<td>137.6</td>
<td>137</td>
<td>142.5</td>
<td>165.8</td>
<td>180</td>
<td>190</td>
<td>211.8</td>
<td>289.5</td>
</tr>
<tr>
<td>Imported hardwood</td>
<td>105.3</td>
<td>109.3</td>
<td>112.3</td>
<td>109.8</td>
<td>110.1</td>
<td>112.9</td>
<td>115.6</td>
<td>117.4</td>
<td>120.9</td>
<td>138</td>
<td>146</td>
<td>152.3</td>
<td>163</td>
<td>187.3</td>
<td>301.5</td>
<td>370</td>
</tr>
<tr>
<td>Imported softwood</td>
<td>96.8</td>
<td>105.1</td>
<td>107.3</td>
<td>104.2</td>
<td>104.8</td>
<td>113.2</td>
<td>118.3</td>
<td>118.6</td>
<td>118.6</td>
<td>131.1</td>
<td>137.3</td>
<td>144.8</td>
<td>150.4</td>
<td>162</td>
<td>167.3</td>
<td>245</td>
</tr>
<tr>
<td>Imported plywood</td>
<td>94</td>
<td>97.3</td>
<td>99.2</td>
<td>98.7</td>
<td>99.8</td>
<td>104.4</td>
<td>116.9</td>
<td>116.4</td>
<td>112.8</td>
<td>125.2</td>
<td>135.1</td>
<td>143.2</td>
<td>147.3</td>
<td>167.3</td>
<td>245</td>
<td>331</td>
</tr>
<tr>
<td>Asbestos-cement goods</td>
<td>124</td>
<td>124</td>
<td>124.5</td>
<td>130.4</td>
<td>134.7</td>
<td>137</td>
<td>137</td>
<td>145.1</td>
<td>148.8</td>
<td>158.5</td>
<td>(Index discontinued)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bricks</td>
<td>111</td>
<td>115</td>
<td>123</td>
<td>124</td>
<td>126.5</td>
<td>132.6</td>
<td>138</td>
<td>141.4</td>
<td>143.7</td>
<td>151.3</td>
<td>152.7</td>
<td>167.2</td>
<td>192.3</td>
<td>221</td>
<td>248</td>
<td>300</td>
</tr>
<tr>
<td>Cement</td>
<td>115</td>
<td>113.2</td>
<td>118.2</td>
<td>120</td>
<td>122</td>
<td>125</td>
<td>127.9</td>
<td>128</td>
<td>129.5</td>
<td>132</td>
<td>134.3</td>
<td>155</td>
<td>186</td>
<td>197</td>
<td>197</td>
<td>225</td>
</tr>
<tr>
<td>Plaster</td>
<td>114</td>
<td>114</td>
<td>114</td>
<td>114</td>
<td>114</td>
<td>114</td>
<td>114</td>
<td>116.7</td>
<td>118</td>
<td>118.5</td>
<td>121</td>
<td>123</td>
<td>128.3</td>
<td>134.1</td>
<td>138</td>
<td>180</td>
</tr>
<tr>
<td>Paint</td>
<td>109</td>
<td>108.2</td>
<td>110.5</td>
<td>113</td>
<td>113.8</td>
<td>115.5</td>
<td>116</td>
<td>116.8</td>
<td>117</td>
<td>119</td>
<td>120.2</td>
<td>127</td>
<td>142.3</td>
<td>153.8</td>
<td>162.9</td>
<td>204.8</td>
</tr>
</tbody>
</table>

Table 2.7 Materials' Prices Indices (1954 = 100, 1963 = 100, 1970 = 100) (Source: Data supplied by the D.O.E., and Housing and Construction Statistics)
Table 2.8 Bank Rate of Interest since the Second World War

<table>
<thead>
<tr>
<th>Year</th>
<th>Rate (%)</th>
<th>Year</th>
<th>Rate (%)</th>
<th>Year</th>
<th>Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1945</td>
<td>2.00 (50)</td>
<td>1955</td>
<td>4.31 (107.5)</td>
<td>1965</td>
<td>6.42 (160)</td>
</tr>
<tr>
<td>1946</td>
<td>2.00 (50)</td>
<td>1956</td>
<td>5.37 (134)</td>
<td>1966</td>
<td>6.46 (161.5)</td>
</tr>
<tr>
<td>1947</td>
<td>2.00 (50)</td>
<td>1957</td>
<td>5.71 (142.5)</td>
<td>1967</td>
<td>6.17 (154)</td>
</tr>
<tr>
<td>1948</td>
<td>2.00 (50)</td>
<td>1958</td>
<td>5.37 (134)</td>
<td>1968</td>
<td>7.50 (187.5)</td>
</tr>
<tr>
<td>1949</td>
<td>2.00 (50)</td>
<td>1959</td>
<td>4.00 (100)</td>
<td>1969</td>
<td>7.83 (195.5)</td>
</tr>
<tr>
<td>1950</td>
<td>2.00 (50)</td>
<td>1960</td>
<td>5.29 (132)</td>
<td>1970</td>
<td>7.20 (180)</td>
</tr>
<tr>
<td>1951</td>
<td>2.07 (51.8)</td>
<td>1961</td>
<td>5.79 (145)</td>
<td>1971</td>
<td>6.00 (150)</td>
</tr>
<tr>
<td>1952</td>
<td>3.71 (92.8)</td>
<td>1962</td>
<td>4.79 (120)</td>
<td>1972</td>
<td>6.25 (156)</td>
</tr>
<tr>
<td>1953</td>
<td>3.81 (95.5)</td>
<td>1963</td>
<td>4.00 (100)</td>
<td>1973</td>
<td>10.01 (252.5)</td>
</tr>
<tr>
<td>1954</td>
<td>3.81 (95.5)</td>
<td>1964</td>
<td>5.20 (130)</td>
<td>1974</td>
<td>11.99 (280)</td>
</tr>
</tbody>
</table>

* Average figures published in H. & C. St.s - For 1945-69 inclusive data are from reference 6.
Table 2.9 Average Earnings' Indices (Source: Dept. of Employ't)

<table>
<thead>
<tr>
<th>Year</th>
<th>Construction (index)</th>
<th>Manufacturing (index)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1963</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>1964</td>
<td>108.3</td>
<td>107.3</td>
</tr>
<tr>
<td>1965</td>
<td>116.8</td>
<td>115.0</td>
</tr>
<tr>
<td>1966</td>
<td>125.2</td>
<td>122.8</td>
</tr>
<tr>
<td>1967</td>
<td>130.0</td>
<td>126.8</td>
</tr>
<tr>
<td>1968</td>
<td>141.4</td>
<td>137.0</td>
</tr>
<tr>
<td>1969</td>
<td>150.0</td>
<td>147.5</td>
</tr>
<tr>
<td>1970</td>
<td>164.0</td>
<td>164.8</td>
</tr>
<tr>
<td>1971</td>
<td>181.0</td>
<td>183.5</td>
</tr>
<tr>
<td>1972</td>
<td>202.0</td>
<td>203.7</td>
</tr>
<tr>
<td>1973</td>
<td>240.0</td>
<td>233.8</td>
</tr>
<tr>
<td>1974</td>
<td>277.0</td>
<td>273.5</td>
</tr>
</tbody>
</table>

Table 2.10 Materials Cost Analysis for External Walls (Source: Ref. 7)

<table>
<thead>
<tr>
<th>Method of construction</th>
<th>Total Material cost (£)</th>
<th>Energy (£)</th>
<th>Other than energy (£)</th>
<th>Total import cost of material (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick/block</td>
<td>280</td>
<td>53</td>
<td>14</td>
<td>67</td>
</tr>
<tr>
<td>Timber frame*</td>
<td>430</td>
<td>9</td>
<td>140</td>
<td>149</td>
</tr>
</tbody>
</table>

* Includes the cost of 25mm mineral insulation blanket and polythene vapour barrier.
FIG. 2.7 INDICES OF AVERAGE EARNINGS AND BANK RATE OF INTEREST
construction market in the period 1963-74 operated without any government restriction on the supply of construction materials. However, steel prices were often lower due to the government control of prices and subsidy for national industries.

The general increases in the costs of traditional materials since 1969 particularly timber, have stimulated a search for cheaper construction materials and construction methods. Higher costs of fuels have also favoured use of construction systems which are more economical on consumption of fuels for heating purposes. These conditions are very favourable to innovation in materials from an economic point of view. However, other factors including technical, statutory, social and political influences often play major roles in the choice of materials and construction systems; these will be considered in more detail in the succeeding chapters.

To illustrate the extent of national concern (particularly due to the increased imports' burden), the findings of a study carried out at the Princes Risborough Laboratory in 1974 and reported by Banks(7) are considered. The results of this study showed that on a total-cost basis, timber-based roofs and upper floors were still the most economic option open to designers and builders (see Table 2.13).

In the case of timber-framed wall vis-à-vis traditional brick/block cavity wall, it was found that there was very little to choose between these (see Table 2.13; in fact timber-framed walls were marginally cheaper, though, the margin of error in the above study has not been calculated).

Other findings of this study included considerations of the imports' bill; although timber is wholly imported, the study showed that timber structure pitched roofs are less import costly than the available alternatives. The situation was however different in the case of walling, where traditional masonry material showed a saving of 50 percent in import costs over the timber-framed structures (see Tables 2.10 to 2.12).
### Table 2.11 Materials Cost Analysis for Pitched Roof Structure (Ref. 7)

<table>
<thead>
<tr>
<th>Structural Material</th>
<th>Total Material cost (£)</th>
<th>Import content</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Energy (£)</td>
<td>Other than energy (£)</td>
<td>Total import cost of material (£)</td>
<td></td>
</tr>
<tr>
<td>Softwood</td>
<td>184</td>
<td>2</td>
<td>60</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>502</td>
<td>77</td>
<td>41</td>
<td>118</td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>575</td>
<td>40</td>
<td>166</td>
<td>206</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2.12 Material Cost Analysis for Upper Floor Structures (Ref. 7)

<table>
<thead>
<tr>
<th>Structural Material</th>
<th>Total Material cost (£)</th>
<th>Import content</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Energy (£)</td>
<td>Other than energy (£)</td>
<td>Total import cost of material (£)</td>
<td></td>
</tr>
<tr>
<td>Timber</td>
<td>167</td>
<td>2</td>
<td>53</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>154</td>
<td>23</td>
<td>12</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td>527</td>
<td>37</td>
<td>153</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>Concrete Joists*</td>
<td>343</td>
<td>72</td>
<td>14</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>Concrete Slab*</td>
<td>468</td>
<td>98</td>
<td>19</td>
<td>117</td>
<td></td>
</tr>
</tbody>
</table>

* Average cost for pre-cast and insitu construction.

### Table 2.13 Total Cost Analysis of Structure using Various Materials - 1974 prices (Ref. 7)

<table>
<thead>
<tr>
<th>Structural Material</th>
<th>Cost of Erected Structure (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wall</td>
</tr>
<tr>
<td>Timber</td>
<td>1200*</td>
</tr>
<tr>
<td>Steel</td>
<td>1090</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1290</td>
</tr>
<tr>
<td>Brick/block Concrete</td>
<td>1240</td>
</tr>
<tr>
<td>Concrete</td>
<td>7501</td>
</tr>
</tbody>
</table>

* Estimated - Softwood cladding not included in walls.
I Cheapest of 3 concrete systems investigated (i.e. concrete joists, insitu slab and pre-cast slabs).
This example illustrates the fact that in spite of the relatively substantial increases in the costs of factors of production, the relative positions of some materials have not changed. In times of economic difficulties, any new material besides being satisfactory from technical and aesthetic points of view, must at least offer a potential for cost-savings in order to stimulate its development and use; the issues involved in this statement are complex and are subject of detailed consideration in the case of glassfibre reinforced plastics and to a lesser extent aluminium alloys (see also Chapter 12).

2.3 Size and Nature of Contractors in the Construction Industry.

2.3.1 Main-contractors:

Main-contractors or general contractors are construction companies who undertake the construction of projected schemes. They usually tender for a project and, if successful, enter into a contract for the execution of the projected works under the supervision of the client's representative, who is usually the designer or his representative. The works are required to be constructed in accordance with the design drawings, specifications, bill of quantities and other relevant documents supplied by the designer at the time of contract (see Chapter 3).

The conditions of contracts are usually those of standard conditions prepared by the professional institutions in consultation with the contractors' representatives and other relevant bodies (see Chapter 3). The public clients often use a different set of conditions; however, in general, most of the conditions are similar. The contract requires the contractor to complete the projected works on or before the completion date which is specified at the time of tendering and subsequently written into the contract.
There are three types of main-contractors, viz:

a - Builders (or general builders)
b - Building and civil engineering contractors
c - Civil engineering contractors.

Builders are generally engaged on the construction of houses, small to medium-sized commercial projects and similar jobs including extension, conversion and sub-contracting of brick and block works on major sites.

There were, in October 1973, according to the official data(3), 39,659 general builders. The average total employment of these was approximately 10. Their average output was approximately £64,000 per annum. Thus, they are dominated by small firms. Nevertheless, since their number was high (41.2 percent of all contractors, see Table 2.15), their shares of both total employment and output were approximately 32 percent which were the highest amongst all other contractors (see Table 2.15).

Building and civil engineering contractors are those companies who undertake both building and civil engineering works; however, they often function as separate divisions which specialize either in building or civil engineering works. In some cases, other divisions are also added, e.g. speculative housing, system building, general works which is concerned with extension, conversion and renovation contracts, etc.

The number of building and civil engineering firms in October 1973(3) stood at 2,364 or approximately 2.5 percent of the total number of contractors. Their average total employment was approximately 125, and their average output was approximately £810,000; thus, their average output per employee is approximately 6 to 7 percent higher than that of the general builders.

Although they constitute a low percentage of the total number of contractors, their shares of the total employment and output in October 1973(3) were 23 and 25 percent respectively. They therefore constitute the second highest shares of the total market.

Civil engineering constructors, as their name implies, are active only in the field of civil engineering, i.e. construction of roads, harbours, sewerage, etc; they often
specialize in one or two branches of civil engineering; they generally use more capital-intensive construction equipment compared with general builders.

The number of civil engineering contractors in October 1973(3) was 2114 or 2.2 percent of all contractors. The average total employment and annual output of these firms were 50 persons and £372,000 respectively; thus, their output per employee is approximately 19 and 27 percent greater than the building & civil engineering and general builders respectively. This indicates the greater degree of mechanized construction methods generally employed in the civil engineering industry (as has been stated in the NEDO report(4), there has been a greater degree of standardisation of specification, especially for roads and motorways which have enabled the civil engineering firms to invest in heavy construction machinery).

Official statistics incorporate both main- and sub-contractors; the latest available at the time of writing(3) indicate that in October 1973 there was a total of 96576 contractors of which only 80 had a total employment greater than 1200. Table 2.14 shows the distribution of number, employment and output of contractors by their size; these are plotted in Figs. 2.8, 2.9 and 2.10 respectively. These data show clearly the scattered nature of the structure of the construction industry, in particular, the rapid decrease in the number of contractors with increase in size.

If small firms (i.e. those with a total employment less than 60) are excluded, the resulting distribution still shows a rapid fall in the number of firms with increase in size (see Fig. 2.8, top diagram).

Of particular interest is the fact that unlike many industries (e.g. chemical and allied), the construction industry is not dominated by a few major companies accounting for a substantial proportion of the total output. (In the chemical and allied industries, companies with an employment greater than 1000 constituted 3 percent of the total firms but accounted for approximately 80 percent of the output(8)).

Locations of construction works are scattered throughout the country. Fig 2.11 shows the regional distribution of output in the third quarter of 1973(3). It can be seen
Table 2.14 Number, employment and output distribution by size of all contractors (Ref. 4)

<table>
<thead>
<tr>
<th>Size by total employment</th>
<th>No of firms (Number)</th>
<th>% of total</th>
<th>Employ't of operatives (Thous)</th>
<th>% of total</th>
<th>Total employment (Thous), % of total</th>
<th>Value of output (£ x 10⁶), % of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1</td>
<td>29563</td>
<td>33.0</td>
<td>-</td>
<td>-</td>
<td>29.0</td>
<td>2.28</td>
</tr>
<tr>
<td>2 - 7</td>
<td>43962</td>
<td>45.55</td>
<td>79.9</td>
<td>8.82</td>
<td>157.4</td>
<td>12.32</td>
</tr>
<tr>
<td>8 - 13</td>
<td>9311</td>
<td>9.65</td>
<td>67.9</td>
<td>7.50</td>
<td>94.1</td>
<td>7.37</td>
</tr>
<tr>
<td>14 - 24</td>
<td>6315</td>
<td>6.55</td>
<td>87.4</td>
<td>9.64</td>
<td>113.6</td>
<td>8.90</td>
</tr>
<tr>
<td>25 - 34</td>
<td>2364</td>
<td>2.45</td>
<td>53.8</td>
<td>5.94</td>
<td>68.3</td>
<td>5.35</td>
</tr>
<tr>
<td>35 - 59</td>
<td>2298</td>
<td>2.38</td>
<td>81.6</td>
<td>9.00</td>
<td>102.1</td>
<td>8.00</td>
</tr>
<tr>
<td>60 - 79</td>
<td>743</td>
<td>.77</td>
<td>40.3</td>
<td>4.45</td>
<td>50.7</td>
<td>3.98</td>
</tr>
<tr>
<td>80 - 114</td>
<td>697</td>
<td>.72</td>
<td>51.9</td>
<td>5.73</td>
<td>65.6</td>
<td>5.13</td>
</tr>
<tr>
<td>115 - 299</td>
<td>872</td>
<td>.905</td>
<td>118.4</td>
<td>13.8</td>
<td>151.8</td>
<td>11.90</td>
</tr>
<tr>
<td>300 - 599</td>
<td>242</td>
<td>.25</td>
<td>80.0</td>
<td>8.83</td>
<td>103.7</td>
<td>8.12</td>
</tr>
<tr>
<td>600 - 1199</td>
<td>125</td>
<td>.13</td>
<td>74.6</td>
<td>8.24</td>
<td>102.4</td>
<td>8.04</td>
</tr>
<tr>
<td>≥ 1200</td>
<td>80</td>
<td>.083</td>
<td>171.7</td>
<td>19.55</td>
<td>236.2</td>
<td>18.52</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>96576</td>
<td>100</td>
<td>907.4</td>
<td>100</td>
<td>1274.9</td>
<td>100</td>
</tr>
</tbody>
</table>

1973
FIG. 2.9 TOTAL EMPLOYMENT DISTRIBUTION OF CONTRACTORS BY SIZE

Total employment (x1000)

- Size 0-1 2-7 8-13 14-24 25-34 35-59 60-79 80-114 115-299 300-599 600-1199 >1,200
- 2.28% 12.32% 7.37% 8.9% 8.5% 3.99% 5.3% 11.1% 8.1% 8.0% 18.52%
- 29 94.1 113.6 68.3 102.1 50.7 65.6 151.8 103.7 102.4 236
FIG. 2.10 VALUE OF WORK BY GROUPS (£m)

3rd. QUARTER
1973
<table>
<thead>
<tr>
<th>Region</th>
<th>Value (£)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>NORTHERN</td>
<td>87.5</td>
<td>4.66%</td>
</tr>
<tr>
<td>YORKS. &amp; HUMBERSIDE</td>
<td>141.9</td>
<td>7.56%</td>
</tr>
<tr>
<td>EAST MIDLANDS</td>
<td>113.5</td>
<td>6.05%</td>
</tr>
<tr>
<td>EAST ANGLIA</td>
<td>61.4</td>
<td>3.27%</td>
</tr>
<tr>
<td>BEDS. ESSEX HERTS.</td>
<td>104.8</td>
<td>5.58%</td>
</tr>
<tr>
<td>GREATER LONDON</td>
<td>105.7</td>
<td>5.64%</td>
</tr>
<tr>
<td>S. EASTERN COUNTIES</td>
<td>117.0</td>
<td>6.24%</td>
</tr>
<tr>
<td>SOUTHERN COUNTIES</td>
<td>117.9</td>
<td>6.27%</td>
</tr>
<tr>
<td>SOUTH WEST</td>
<td>190.0</td>
<td>10.12%</td>
</tr>
<tr>
<td>WEST MIDLANDS</td>
<td>185.9</td>
<td>9.92%</td>
</tr>
<tr>
<td>N. WEST</td>
<td>141.6</td>
<td>7.54%</td>
</tr>
<tr>
<td>WALES</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCOTLAND</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total = £1,877.8m

3rd Quarter 1973
that variations are to some extent related to the regional population distribution: the tendency in the past has been for densely populated areas to retain proportionately bigger slices of the total output of the construction industry.

The variations in demand for buildings of different design constructed on different locations has generally shaped the existing structure of the construction industry. The major main-contractors tend to operate nationally and a few internationally; however, they tend to concentrate in the major cities, leaving towns and smaller areas to smaller companies. In addition, the major main contractors tend to operate under regional organizations.

The efficiency or the economic competitiveness of a contractor varies considerably with the size of the firm, the location and size of the project, the contractor's other commitments (workload), the supply of resources, especially skilled labour.

Generally speaking, large contractors have greater overhead charges compared with small to medium contractors; to compensate for this economic disadvantage, they have to make greater use of mechanical equipment on site, e.g. use of automatic concrete mixing plants with large outputs, etc. Thus they usually concentrate on larger projects which are amenable to greater productivity by greater use of machines; the accessibility of site plays a major part in this, since transport of heavy equipment may be restricted; also a major firm in a remote town may experience problems of finding skilled labour or it may incur additional expenses to import skilled men from other areas. To offset these disadvantages, major contractors have decentralized to a large extent, allowing a greater degree of flexibility and maneuverability; they have even been active in speculative housing, general works, etc. through such flexible structures.

The employment by all contractors of administrative, professional, technical and clerical (APTC) staff in October 1973 was 251,000 compared with 907,000 which was the number of their operatives (Table 2.1). As far as the building industry is concerned, their employment of professional staff is generally limited to members of the
Institute of Building (IOB); thus, as seen from Table 2.2, they employ the greater number of IOB members.

However, the total number of IOB membership at 7,200 is very low compared with the size of the industry. Furthermore, IOB members in the building industry tend to be involved in running building contracts (10).

The situation is different in the civil engineering part of the industry; this section employs proportionally a greater number of the professional staff, especially civil engineers (10).

The greater number of APTC staff in the main-contracting business are engaged on the administrative, clerical and technical aspects of current contracts, especially on matters of materials' purchases, job planning, day to day running and finally measurement of executed works for submission of claims etc. This is especially true with the building contracts which are of particular interest to this study. There are only a few really large contractors such as George Wimpeys, Laings and Costains (the latter is mainly engaged on civil engineering contracts) who have facilities for research and development (R & D). However, most of their laboratory staff are generally engaged on routine materials' testing, especially in relation to their civil engineering contracts.

Traditionally, the industry is accustomed to working under the direction of clients' appointed architects or civil engineers who have been responsible for the design of projects. This has had a serious effect on the capability of the construction contractors in that they do not generally feel the need for R & D. This is in direct contrast to manufacturing companies who are able to use R&D to develop new products or new production techniques etc. and therefore improve their competitiveness.

One other feature in the industry is the fact that contractors generally sell their services; whereas the manufacturing companies sell their finished products. System building, package deals and other more recent developments are exceptions; these have been considered in Chapter 3; however, these developments in the construction
process are as yet generally insignificant compared to the size of the industry.

Fig. 2.12 illustrates diagrammatically the structure of a typical regional contractor; it must be noted that there are many variations as regards separation and vertical integration of responsibilities. However, the broad pattern remains the same.

In the case of medium-sized companies, some of these responsibilities are grouped together, e.g. the planning and design are amalgamated and called: "Planning Department" whose chief engineer is normally directly responsible to the managing director. This is because there is hardly any sizeable design work, as these firms tend to avoid 'design and construct' (or as commonly known 'package deal' contracts.)

As Fig 2.12 shows, there are often no R & D sections in contracting organizations; this explains the reason for the government's initiative some fifty years ago to establish the Building Research Station and other similar research institutions to carry out R & D, etc. for the benefit of all, especially the public sector (see section 2.7).

It must be remembered that the danger in the lack of research and development is not that no new materials or construction techniques are discovered, but is failure to apply those methods already known(11).

This means that potential benefits of applied research are frequently overlooked; also, the application of scientific methods in decision making and control through 'operational research' is largely ignored, particularly in the case of small to medium-sized firms who tend to rely solely on the experience of their foremen for management of their contracts.

Many problems in the construction process can be studied using 'operational research' techniques, especially those arising because of the following:

(a) - allocation or resource problems;
(b) - sequencing or priority problems; and
(c) - queueing problems.
FIG. 2.12 A TYPICAL ORGANIZATIONAL CHART OF A REGIONAL HEAD OFFICE OF A MAJOR CONTRACTOR (BUILDING).
A Civil Engineering Company is usually an independent company or is under a director who operates fairly independently.
The reason for failure of the industry to make better use of known scientific control methods is attributable to the technical shortcomings of the majority of these firms; the attitude of the top management in the building industry is stated to be that of ignorance and prejudice, as they tend to consider that site supervisors ought to be practical men, e.g. ex-carpenters. This was probably valid in the nineteenth century, but today's buildings are technically complex products, requiring managerial skills which are necessary in all industries.

2.3.2 Sub-contractors:

These are firms of specialists who undertake work on a sub-contracting basis, i.e. they are responsible to, and their works are co-ordinated by, the main contractor on each site.

There are essentially two types of sub-contractors, viz. (a) ordinary; and (b) nominated sub-contractors.

Ordinary sub-contractors are employed directly by the main-contractor in agreement with the clients representative (i.e. architect or engineer). They are paid directly by the main-contractor and there are no special provisions for their dues in the case of failure on the part of the main-contractor.

Nominated sub-contractors are those firms who are selected by designers (architects or other consultants) usually in advance of the construction stage; they are required to carry out specialist works, such as mechanical and electrical services. They are also required to prepare detailed designs from the consultant services' engineers general design drawing, and to supply the materials and components involved in their designs.

Nominated sub-contractors and/or suppliers are employed because of the following:

(a) The dependency of architects and/or their consultants on the expertise of certain sub-contractors, e.g. in conjunction with the design of heating, ventilation and air-conditioning systems.

(b) The need for architects and their consultants (or their clients) to ensure that the most competent firm is
selected for the given purpose.

Under standard conditions, when a sub-contractor is nominated in advance of the main-contractor, and is required to undertake a certain amount of design work, his services are payable by the client even though the client may cancel the whole project before it goes to tender. An ordinary sub-contractor has no such protection. Moreover, should the main-contractor go bankrupt, the nominated sub-contractor is able to claim his costs from the client through the architect; this does not apply to an ordinary sub-contractor.

Although, the tendency in the past has been for complicated parts of a contract (such as provision of mechanical and electrical services) to go to specialist nominated sub-contractors, it is not possible to generalize on the trade since, the type and amount of work entrusted to nominated sub-contractors varies considerably from one contract to another. However, the amount of work given to nominated sub-contractors has been growing since the turn of this century; in some projects, the value of works involved may be as high as 50 percent.

There is evidence that the practice of nominating sub-contractors is considered as an important means of ensuring that the most competent firm has been appointed for the job under consideration, as most main contractors do not have the technical know-how in order to compare the technical qualities of competing alternative designs; they may therefore be making a wrong choice based on the lowest price.

As was noted in 2.3.1, all contractors are combined in the official statistical enquiries. The number, employment and output distribution of contractors by trade are shown in Table 2.15 and in Figs 2.13, 2.14 and 2.15 respectively. It can be seen that 'electrical contractors' and 'heating and ventilation engineers' accounted for approximately 9 and 11.2 percent of the total output respectively. The structure of these firms is varied as some are subsidiaries of major electrical and mechanical engineering firms. Fig. 2.16 shows a tentative organizational chart for these firms. The importance of the design and R & D section of these firms is conspicuously shown on the chart.

Another point of interest concerning heating and
Table 2.15 Distribution of number, employment and output of contractors by trade (Source: Ref. 3)

<table>
<thead>
<tr>
<th>Type of trade</th>
<th>Number of firms</th>
<th>Empl. of operatives Oct. 73</th>
<th>Total employment Oct. 73</th>
<th>Value of output (3rd. qtr. 1973)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(number)</td>
<td>(Thousand)</td>
<td>(Thousand)</td>
<td>(£ x 10⁶)</td>
</tr>
<tr>
<td>General builders</td>
<td>39659</td>
<td>41.2</td>
<td>287.8</td>
<td>616.3</td>
</tr>
<tr>
<td>Bldg. &amp; civil eng. cont'ors</td>
<td>2364</td>
<td>2.45</td>
<td>218.6</td>
<td>480.5</td>
</tr>
<tr>
<td>Civil engineering</td>
<td>2114</td>
<td>2.2</td>
<td>79.1</td>
<td>199.0</td>
</tr>
<tr>
<td>Plumbers</td>
<td>8432</td>
<td>8.72</td>
<td>23.1</td>
<td>42.8</td>
</tr>
<tr>
<td>Joiners &amp; carpenters</td>
<td>6533</td>
<td>6.75</td>
<td>17.3</td>
<td>25.8</td>
</tr>
<tr>
<td>Painters</td>
<td>15375</td>
<td>15.9</td>
<td>44.9</td>
<td>53.3</td>
</tr>
<tr>
<td>Roofers</td>
<td>1974</td>
<td>20.45</td>
<td>13.8</td>
<td>33.5</td>
</tr>
<tr>
<td>Plasterers</td>
<td>3480</td>
<td>3.6</td>
<td>15.1</td>
<td>21.3</td>
</tr>
<tr>
<td>Glaziers</td>
<td>494</td>
<td>.51</td>
<td>4.3</td>
<td>8.0</td>
</tr>
<tr>
<td>Demolition cont'ors</td>
<td>474</td>
<td>.49</td>
<td>3.8</td>
<td>5.4</td>
</tr>
<tr>
<td>Scaffolding specialists</td>
<td>212</td>
<td>.22</td>
<td>8.7</td>
<td>13.7</td>
</tr>
<tr>
<td>Reinf'd con'te specialists</td>
<td>347</td>
<td>.36</td>
<td>8.6</td>
<td>17.6</td>
</tr>
<tr>
<td>Heating &amp; ven'tion engs.</td>
<td>3284</td>
<td>3.40</td>
<td>45.7</td>
<td>92.9</td>
</tr>
<tr>
<td>Electrical cont'ors</td>
<td>6550</td>
<td>6.78</td>
<td>54.3</td>
<td>76.2</td>
</tr>
</tbody>
</table>
Table 2.15 Distribution of number, employment and output of contractors by trade (Source: Ref. 3) cont.

<table>
<thead>
<tr>
<th>Type of trade</th>
<th>Number of firms</th>
<th>Empl. of operatives Oct. 73</th>
<th>Total employment Oct. 73</th>
<th>Value of output (3rd. qtr. 1973)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(number) % of total</td>
<td>(Thousand)</td>
<td>(Thousand) % of total</td>
<td>(£ x 10^6) % of total</td>
</tr>
<tr>
<td>Asphalt &amp; tar sprayers</td>
<td>430 0.45</td>
<td>12.3</td>
<td>15.4</td>
<td>1.19</td>
</tr>
<tr>
<td>Plant hirers</td>
<td>2017 2.09</td>
<td>28.5</td>
<td>38.4</td>
<td>3.01</td>
</tr>
<tr>
<td>Flooring contractors</td>
<td>743 0.77</td>
<td>5.4</td>
<td>8.6</td>
<td>0.68</td>
</tr>
<tr>
<td>Constructional engs.</td>
<td>520 0.54</td>
<td>18.6</td>
<td>27.9</td>
<td>2.19</td>
</tr>
<tr>
<td>Insulating specialists</td>
<td>192 0.20</td>
<td>5.9</td>
<td>7.6</td>
<td>0.60</td>
</tr>
<tr>
<td>Suspended ceiling specialists</td>
<td>184 0.19</td>
<td>1.8</td>
<td>2.8</td>
<td>0.22</td>
</tr>
<tr>
<td>Floor &amp; wall specialists</td>
<td>485 0.50</td>
<td>2.6</td>
<td>3.9</td>
<td>0.30</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>713 0.74</td>
<td>7.2</td>
<td>11.0</td>
<td>0.87</td>
</tr>
<tr>
<td>Total</td>
<td>96576 100%</td>
<td>907.4</td>
<td>1274.9</td>
<td>100%</td>
</tr>
</tbody>
</table>
FIG. 2.13 NUMBER OF FIRMS BY TRADE

GENERAL BUILDERS
B & C.E. CONTRACTORS
CIVIL ENGINEERS
PLUMBERS
JOINERS & CARPENTERS
PAINTERS
ROOFERS
PLASTERERS
GLAZIERS
DEMOLITION CONTRACTORS
SCAFFOLDING SPECIALISTS
R. CONCRETE SPECIALISTS
H & V ENGINEERS
ELECTRICAL ENGINEERS
ASPHALT & TAR SPECIALISTS
PLANT HIRERS
FLOORING CONTRACTORS
CONSTRUCTIONAL ENGINEERS
INSULATING SPECIALISTS
SUSPENDED CEILING SPECIALISTS
FLOOR & WALLING SPECIALISTS
MISCELLANEOUS

39,659
2364
2114
8432
6,553
15,375
1974
3,480
494
474
212
347
3,284
6,550
413
2,017
743
520
192
184
485
713
FIG. 2.14 TOTAL EMPLOYMENT (OCT. 1973)

<table>
<thead>
<tr>
<th>Category</th>
<th>Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENERAL BUILDERS</td>
<td>404.8</td>
<td>31.79%</td>
</tr>
<tr>
<td>B &amp; C.E. CONTRACTORS</td>
<td>296.4</td>
<td>23.25%</td>
</tr>
<tr>
<td>CIVIL ENGINEERS</td>
<td>104.4</td>
<td>8.2%</td>
</tr>
<tr>
<td>PLUMBERS</td>
<td>37.9</td>
<td>2.98%</td>
</tr>
<tr>
<td>JOINERS &amp; CARPENTERS</td>
<td>27.7</td>
<td>2.17%</td>
</tr>
<tr>
<td>PAINTERS</td>
<td>68.5</td>
<td>5.44%</td>
</tr>
<tr>
<td>ROOFERS</td>
<td>20.5</td>
<td>1.61%</td>
</tr>
<tr>
<td>PLASTERERS</td>
<td>21.4</td>
<td>1.68%</td>
</tr>
<tr>
<td>GLAZIERS</td>
<td>6.6</td>
<td>0.52%</td>
</tr>
<tr>
<td>DEMOLITION CONTRACTORS</td>
<td>5.2</td>
<td>0.41%</td>
</tr>
<tr>
<td>SCAFFOLDING SPECIALISTS</td>
<td>12.6</td>
<td>0.99%</td>
</tr>
<tr>
<td>R.C. SPECIALISTS</td>
<td>11.4</td>
<td>0.90%</td>
</tr>
<tr>
<td>H.V. ENGINEERS</td>
<td>67.8</td>
<td>5.32%</td>
</tr>
<tr>
<td>ELECTRICAL ENGINEERS</td>
<td>74.1</td>
<td>5.82%</td>
</tr>
<tr>
<td>ASPHALT &amp; TAR SPRAYERS</td>
<td>15.4</td>
<td>1.20%</td>
</tr>
<tr>
<td>PLANT HIRERS</td>
<td>38.4</td>
<td>3.01%</td>
</tr>
<tr>
<td>FLOORING CONTRACTORS</td>
<td>8.6</td>
<td>0.68%</td>
</tr>
<tr>
<td>CONSTRUCTIONAL ENGINEERS</td>
<td>27.9</td>
<td>2.19%</td>
</tr>
<tr>
<td>INSULATING SPECIALISTS</td>
<td>7.6</td>
<td>0.60%</td>
</tr>
<tr>
<td>SUSPENDED CEILING SPECIALISTS</td>
<td>2.8</td>
<td>0.22%</td>
</tr>
<tr>
<td>FLOOR &amp; WALLING SPECIALISTS</td>
<td>3.9</td>
<td>0.30%</td>
</tr>
<tr>
<td>MISCELLANEOUS</td>
<td>11.0</td>
<td>0.87%</td>
</tr>
</tbody>
</table>
**Fig. 2.15 Value of Work (£m.)**

<table>
<thead>
<tr>
<th>Trade</th>
<th>1972-3 (£m.)</th>
<th>1973-4 (£m.)</th>
<th>1974-5 (£m.)</th>
<th>Total 1973-5 (£m.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Builders</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B &amp; C.E. Contractors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Civil Engineers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plumbers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joiners &amp; Carpenters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Painters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roofers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plasterers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glaziers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demolition Contractors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scaffolding Specialists</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R.C. Specialists</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H &amp; V. Engineers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical Engineers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asphalt &amp; Tar Spraying</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant Hires</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flooring Contractors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constructional Engineers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation Specialists</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suspended Ceiling Specialists</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Floor &amp; Walling Specialists</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miscellaneous</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Total                        | 616.3 (52.79%) | 480.5 (35.59%) | 199.0 (15.72%) | 601.3 (49.10%) |
FIG: 2.16 A TYPICAL ORGANIZATIONAL CHART FOR A MEDIUM-TO-LARGE-SIZED FIRM ENGAGED ON HEATING, VENTILATION AND AIR-CONDITIONING CONTRACTS.
ventilation engineering sub-contractors emerges from data in Table 2.2: up to 45 percent of the Institution of Heating and Ventilation Engineers' members are employed either by these companies or by their manufacturing divisions. This confirms the dependency of these firms on continuous research and development in order to improve the quality and efficiency of their products and to increase the economic competitiveness.

The variety of specialist sub-contractors and their numbers confirm the fact that the main-contractors have found it increasingly more economic to employ the services of these firms compared with employment of direct labour on site. This practice allows them more flexibility in terms of allocation of resources between various construction sites. It also enables them to concentrate on the planning, co-ordination and supervisory aspects of their contracts.

2.4 The Professions in the Construction Industry:

2.4.1 The need for professionals in the construction industry:

Although tradition has played a major role in shaping the present division of responsibilities within the construction industry (see reference 14 for a detailed account of the development of the professions in the construction industry), there are many reasons for the continued existence of this system; some of these reasons are as follows:

1. Clients rely on the advice and assistance of professional designers, whether employed as 'in-house' staff or appointed from private practices, in order to develop their briefs and promote these into sound designs. Clients often lack the required technical and economic expertise and therefore need the assistance of a person who has no commercial interest in the contract and who has sufficient technical expertise.

2. Clients usually take a short term view and are unable to judge the public interest involved in construction projects, i.e. a construction project has, apart from its commercial value, a purpose in relation to society as a whole (impact upon the environment, public amenity, etc) and in relation to individual users.

The professionals normally involved in the design and supervision of building projects are architects (or occasionally
civil engineers), structural engineers, quantity surveyors and services engineers (see Table 2.2); they are generally corporate (full) members of the appropriate professional body; they, as has already been noted, either function in private practice (or consultancy) or are employed directly by clients; in both forms they have an overriding influence on the social and economic 'well-being' of the construction industry, because of the following:

(a) They influence all stages of the construction process, i.e. in formulation of briefs, by development of designs, by control and supervision of construction of their projects (see Chapter 3).
(b) By so doing they directly influence the quality of the environment.
(c) The efficiency with which they discharge their duties affects the total costs of projects.
(d) Their designs largely influence the methods of construction employed by contractors, and hence their efficiency.
(e) They greatly influence the state of innovation in construction materials.
(f) By exporting their services, they are capable of contributing considerable sums to the balance of payment.

Because of the complexity of construction works and the dependency on many intangible and subjective qualities, it is not possible to make professionals financially and legally responsible for all aspects of their works. Thus the competence of an individual professional and his integrity must be controlled in order that the society and users' interests are safeguarded. Professional institutions exist to do this, i.e. to ensure that individual professionals possess the above qualities.

2.4.2 Architects:

In the U.K., the title 'architect' may be used only by persons who have been registered by the Architectural Registration Council of the U.K. (ARCUK); the usual entry qualification is full membership of the Royal Institute of British Architects (RIBA).

The RIBA requires successive stages of academic and practical examination, including a minimum length of design
experience to be undertaken, before full qualifications can be obtained. Syllabuses for the architectural courses at universities and polytechnics are approved by them. Therefore, they have a strong influence on the education of architects.

Data on the RIBA's membership and employment are given in Table 2.2; it can be seen that the number of qualified architects in 1973 stood at 22,600. About half the number of architects are employed in private practice; one third are employed by local authorities; one tenth by the central government and public corporations; three percent by the Education Authorities (Consortia + DES) and 5 percent by contractors and other commercial/industrial companies (mostly the latter; see Chapter 10).

Thus, they are generally absent from contractors' organizations.

In the building industry, the role of an architect is to develop the client's brief into a design concept and subsequently, with the help of engineering consultants and quantity surveyors, into a practical proposition. The architect is responsible for the technical co-ordination of the works of these consultants and those of nominated sub-contractors. He assumes the leadership of the design team as well as supervising the construction works.

The qualities stated(10) to be required from the architect are numerous. In the words of a NEDO study(10) as: "He should be a good designer, sensitive to the intangible human and environmental factors which partly determine the quality of the finished project, and should have the ability to lead and be numerate and articulate. He should be aware of the technical aspects of all disciplines on the team, so that he can make informed decisions; and in addition to practical experience, a qualification or endorsement in management subjects would be an advantage". (See also 10.1.10 and Tables 10.5 and 10.6).

In the U.K., there were in 1971(16), about 3,600 private practices offering clients architectural services. More than half of these firms had a total of 5 or less qualified architects(16). Many of them were one-man firms. Only a few had more than 50-100 architects including the principals (16). The average number of architects including the principals
engaged in the average private practice may be calculated from the data in Table 2.2. Assuming that in 1973 there were about 3,600 private practices, the average works out at 3.14. Architectural firms are thus generally small, having less than ten qualified professional architects.

The tendency is(16) for major architectural firms to act in consortia with other professional practices, especially quantity surveyors. They tend(16) to concentrate on bigger projects leaving small projects to smaller and less-organized firms. Thus, it appears the variations in the structure of the construction industry is reflected in the structure of the architectural profession (see also references 14 and 17).

The structure of the profession has not changed very much during the last 10-15 years. This is seen in the findings of the survey undertaken by the RIBA of the private practices in 1960-61(17), e.g. it was found that 87 percent of all the firms had less than 11 qualified architects or other professional staff; 61 percent had less than 5 professional staff; none of these small firms had access to technical library services or specialist technical staff, such as quantity surveyors, engineers, etc.

The firms having between 11 and 30 qualified architects had some technical staff but no structural engineer. These firms seldom handled contracts valued at over £1m (1960 prices) but contracts valued up to £2m were frequent. Nevertheless, not all of these firms had systematic information and library services.

The large firms, those with 30 or more qualified architects, had technical staff including quantity surveyors, but again no engineers, though they normally had a library service and access to expert knowledge.

The lack of systematically organized expert knowledge in the majority of the above firms means that effective use is not always made of the improved materials, components and construction techniques.

The RIBA's study(17) shed light on many other equally important aspects of the profession; some of which are outlined below:

(1) - Quality of design: Not all the designed schemes in the study could be classed as consistent. For example, it was found that only some firms had approached the design problems in a systematic manner and had analysed the possible
alternatives; the remainder concerned themselves with an
as aesthetic solution to the problem. Maintenance and
running costs were not often taken into consideration; little
had been comprehended of the principles of standardization
and variety reduction. Using the RIBA's rating, 43 percent
of the firms had produced 'good' designs, 37 percent 'adequate'
and 20 percent 'poor'.

(2) - Aesthetics: Aesthetic qualities were not generally
considered as satisfactory; some architects had been prejudiced
and had taken little time to really understand and translate
their clients' requirements into the designs.

The report states that: "some of these offices took the
view that the less their clients saw of the projected design,
the better, particularly if committees were involved. Others
made a point of showing the plans but never the elevations
or perspectives. Some regarded the whole problem of clients'
relations as an unavoidable nuisance."

(3) - Job management: Job management was often poor. The
office management was such that wasteful use was made of the
skilled personnel and clerical staff.

(4) - Site supervision: Site supervision and the contract
management were generally unsatisfactory; the supervision
was inadequate and ineffective; the pattern of supply, and
flow of information were unorganized and inefficient.

(5) - The design offices of the local authorities: Although
only a limited amount of information on the local authorities'
architects was collected, it revealed that the local authority
design offices appeared to be better organized.

There are, according to the NKDO study(18), arguments
for and against 'in-house' design offices (i.e. both within
the public and private clients' organizations). The arguments
for strong 'in-house' design offices are:

(a) - That, the designers have to live with the consequences
of their works, therefore they feel more responsibility and
are well-motivated.

(b) - That, being closer to the client, they understand
the needs and are more cost-effective in comparison with
outside consultants.

(c) - That, it would protect the interest of the client
against probable lack of capacity, especially in times of
Arguments against the use of 'in-house' design offices are:
(a) That, these offices tend to grow too large in relation to the work available; this results in inefficient use of professional and technical staff, low performance and low motivation. The expenses of running these offices are not realistically estimated.
(b) That, the experience of the engaged professionals can become limited, because of the lack of opportunities to learn from a broader spectrum of projects, for a variety of clients.
(c) That, they may be given the task of designing projects for which their expertise is inadequate.
(d) That, by being directly employed by the clients, they may fail to hold an impartial role between the client and the contractor.
(e) That, because of the bureaucratic hierarchy, designers can become loyal to their single-profession department rather than to the project.

Architects are not allowed to advertise or solicit work. Their business activities are covered by a 'Code of Professional Conduct' administered by the RIBA. There are three methods open to architects for obtaining work, viz:
(1) Reputation, i.e. the quality of their previous works plus the efficiency of their service including their expertise in particular fields (such as design of educational establishments, etc.) which may attract the attention of clients who may contact them directly.
(2) The RIBA's Clients' Bureau: A prospective client may go to this bureau and give a brief description of his requirements. The Clients' Bureau advises him with a short list of addresses of appropriate practices.
(3) Architectural Competition: Architectural competitions are governed by the RIBA's regulations.

A panel of assessors (who may include laymen as well as architects) are nominated by the RIBA in conjunction with the President. This panel must subsequently be approved by the client.
The services of architects employed by clients are subject to payment of a minimum fee as laid down by the RIBA in the 'Conditions of Engagement'; the fee for very simple or repetitive designs is lower than normal; is higher for alterations or extensions of existing buildings.

The basic philosophy behind the approach by the RIBA to the business practices of architects is largely influenced by the need for professional independence and competition on quality. (Note that the RIBA competition is not based on costs). Thus, architects are barred from becoming directors or shareholders in contractors' organizations or other businesses directly associated with the construction industry, furthermore, as was stated before, the quality of architects works are not always quantifiable; this is because the quality in buildings is influenced by the following factors:

1. Standards of environment, i.e. the extent of environmental modification for creating beneficial influence on the basic biological and psychological interactions between man and his surroundings.
2. Compatibility of building spaces with the pattern of activities housed by them.
3. Aesthetics: The degree of enhancement achieved on the economic value of land by use of material resources on the development.

Thus, control of professional competence is generally the only effective way of ensuring that no aspect of architectural designs are neglected; this is the responsibility of the RIBA and is no easy task.

However, architects are also liable for professional negligence for up to 6 to 12 years after completion of a building; thus, all architects in private practice have insurance coverage which gives their clients some degree of protection against negligence on the part of architects.

In short, the above discussion shows that the most important way by which a client may influence the quality and efficiency of a building is by his choice of an architect at the outset; the professional competence and integrity of the architect determines to a large extent, the subsequent success or failure of the proposed building.
2.4.3 Consulting engineers:

Consulting engineers are specialist professionals who undertake the design of various parts of building projects on a fee basis; the parts usually entrusted to them are structural and foundation engineering and services engineering; the latter may comprise electrical, heating and ventilation, and public health engineering.

In the U.K., the consulting engineers are members of the Association of Consulting Engineers (ACE), a body founded in 1913.

The ACE is an extension of the various chartered institutions representing civil, structural, mechanical, electrical, mining, etc. engineers (excluding the Institution of Heating and Ventilation Engineers's members).

The main function of the ACE is to separate the consultants from other engineers who may be in charge of construction or other companies involved in the construction market; the existence of the ACE has enabled chartered members of various engineering institutions to move jobs freely from industry to consultancy and vice versa without losing their professional status or being barred from accepting top management jobs in the industry.

There are about 1000 consulting engineering practices (i.e. members of the ACE, reference 20). However, about 215-220 of these are involved in the structural and foundation designs for building projects. The remainder are engaged on other branches of engineering such as civil, heavy electrical, mechanical, engineering, the engineering of electrical, mechanical, heating, lighting and ventilation systems in buildings, also mining, metallurgy, chemical engineering and testing, etc.

There are many large firms of consulting engineers who are capable of undertaking a variety of engineering projects as they usually employ professional engineers from various engineering fields; however, most of these firms operate under separate divisions, e.g. structural design of buildings (including the design of foundations), transportation studies and traffic engineering; public health engineering, coastal
Many of the ACE's members are based overseas; these are mainly branches of the U.K. firms (20).

The traditional practice in the U.K. has been for the architect to produce a design arrangement, often in the absence of advice from the consulting engineers concerned. The design is then passed on to a structural or civil engineer to design a structure to suit the initial arrangement. The results are then passed on to a services' engineer to design the relevant part (see Chapter 3).

In recent years, there has been a number of multi-disciplinary practices (18) aiming to give the client a comprehensive service under one roof including quantity surveying. Small multi-discipline practices have faced difficulties in achieving a balanced workload to keep all members continuously occupied (18).

Some services consulting engineers are members of the Institution of Mechanical or Electrical Engineers; however, a large proportion of the services engineers belong to the Institute of Heating and Ventilation Engineers (18).

The services' engineering consultants are reported to have a problem of staffing (10), because many professional services engineers prefer to work for sub-contractors where they have better career prospects. (Table 2.2 shows that up to 45 percent of IHVE's members are employed by specialist sub-contractors, compared with about 20 percent working as consultants).

2.4.5 Quantity surveyors:

The functions of a practising quantity surveyor are as follows: (21)

(1) - Costing of designed schemes.
(2) - Determination of the probable size and type of buildings for a given amount of capital.
(3) - Financial and economic analysis of construction projects including capital budgeting.
(4) - Co-operation with the designers at the inception stage of the design to ensure proper investigation of the possible alternative solutions; also, back-up advice at the time of preparation of detailed drawings.
(5) - Advice on the type of contract and preparation of the contract documents, especially the bill of quantities. Also
obtaining a tender and subsequent checking of the successful tender.

(6) - Co-operation with the architect or engineer to ensure proper interpretation of the financial provisions of the contract in order to safeguard the clients' interest and at the same time to treat the contractor with fairness.

(7) - Checking and control of the actual expenditure to ensure that it does not exceed the approved budget without the necessary authority.

However, in practice the services of a quantity surveyor are commonly employed for the following:

(a) - To prepare the contract documents when the design is completed (especially the bill of quantities).

(b) - To check the contractors' submitted tenders and advise architects (or clients).

(c) - To control the actual expenditure and claims.

(d) - To prepare interim certificates for payments (jointly with the contractors' surveyor).

The NEDO report indicates that whereas the quantity surveyors are generally involved in the above functions for buildings they are not generally employed in civil engineering projects, because the engineers do their own cost-analysis; they hold the view that their own cost-analysis and cost-planning give the designer a higher degree of cost-awareness at the design stage.

Table 2.2 shows that approximately two-thirds of the Royal Institute of Chartered Surveyors' (RICS) members are engaged in private practices and only 8 percent are employed by commercial industrial companies.

The RICS Code of Professional Conduct bars the quantity surveyors from being in any way connected with the contractors' organizations, even as employees. The contractors' surveyors are in fact mostly members of a separate qualifying body known as the Institute of Quantity Surveyors (IQS) whose present membership stands at about 5000.

(In May 1976, a vote was held amongst members of the RICS and IQS for amalgamation of the two; this idea was approved by the RICS members. However, it just failed to reach the 75 percent majority vote required by the IQS.)
though, the IQS's council has decided to take another vote). The NEDO survey amongst other things revealed that the cost-planning part of the profession is growing. However, some participants in this survey stated that further training of quantity surveyors was necessary before their traditional role in measurement can be extended to a full building economist(10). This would allow senior men to act as cost-planning consultants leaving the measurement tasks to junior staff.

2.4.6 Other consultants:

With the rapid development and transfer of technologies across industries new and improved materials and/or new construction techniques are occasionally introduced into the industry through various marketing channels. In some cases, the use of such novel materials and/or techniques may be technically desirable and economically advantageous; in these cases architects may find it necessary to employ the services of other consultants (e.g. plastics consultants, etc), to advise them on the relevant aspects of the contract.

However, in the case of proprietary products, the producers or appointed firms are in the majority of cases, prepared to handle the design when they are appointed as nominated sub-contractors, thus, the need for a separate consultant seldom arises (see 2.3.2).

2.5 Clients:

Contrary to the common assumption, clients are not necessarily occupiers and users of buildings. They may act as intermediaries undertaking functions of clients for various reasons such as property developers.

Clients may be divided into two categories: private and public.

2.5.1 Private clients:

Private clients comprise individual patrons and commercial and industrial firms who between them sponsor roughly one half of the construction output (see Table 2.16). Clients in the private housing sector are normally
general builders and estate developers who undertake the whole development including finance and subsequent selling of the houses; they often obtain a short term bank loan which is repaid in line with the selling of the completed houses.

In order to increase their profits, they are prepared to incorporate cost-reducing innovations. Examples of these are the acceptance of timber-framed walls clad with a single leaf of brick wall or the use of various weather boarding materials such as aluminium and plastics or, the use of plastics rainwater and services pipes, etc. However, most of these innovations have not had any major impact upon the shape, appearance or internal spaces of houses; nearly all of them have been of a pure component substitution nature.

The private housing market is generally influenced by public tastes and is dominated by symbols of tradition and social status. It is also a highly competitive market dominated by economic considerations. Thus, it is generally difficult to introduce buildings of different shape and appearance other than existing norms.

In some cases, the builders may approach an architect for preparation of the general layout of proposed housing estates or design of a few basic units which would be repeated in many locations, in rows, or in other arrangements; the architects' involvement generally ends at this stage.

As will be noted later, all building and civil engineering projects are subject to planning and other statutory control; however, a residential unit which has been designed in accordance with the minimum planning standards recommended by Parker-Morris(23) is generally acceptable to the planning authorities and builders are therefore able to obtain approval for houses using standardized designs.

Industrial clients (see Table 2.16) generally have more complicated and varied requirements. The sponsors' motivations are normally different, since they usually require the new facility to extend their industrial activities or to accommodate their administrative and managerial staff. Thus, the demand from this sector is of a 'derived' nature, depending mainly on the state of the economy.

It must be noted that the design of factories and similar industrial buildings is generally more functionally and
economically orientated than buildings such as offices, houses, etc. In some cases, the design is entrusted to civil engineers rather than to architects, especially when the whole facility including the machinery, is designed by a firm of consulting engineers.

Table 2.16 The value of new work by sector and type of market in 1973 at 1970 prices (Source Ref. 3)

<table>
<thead>
<tr>
<th>Type of market</th>
<th>Private-sector (£m)</th>
<th>% of total</th>
<th>Public-sector (£m)</th>
<th>% of total</th>
<th>Total (£m)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>New housing</td>
<td>1030</td>
<td>63.5</td>
<td>591</td>
<td>36.5</td>
<td>1621</td>
<td>100</td>
</tr>
<tr>
<td>Industrial</td>
<td>608</td>
<td>37.5</td>
<td>343</td>
<td>20.5</td>
<td>951</td>
<td>100</td>
</tr>
<tr>
<td>Commercial</td>
<td>715</td>
<td>49.8</td>
<td>1329</td>
<td>50.2</td>
<td>2044</td>
<td>100</td>
</tr>
<tr>
<td>Other (public)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2651</td>
<td>100</td>
</tr>
<tr>
<td>Total new works</td>
<td>2353</td>
<td>55</td>
<td>1920</td>
<td>45</td>
<td>4273</td>
<td>100</td>
</tr>
</tbody>
</table>

Commercial clients comprise banks, insurance companies, property companies, hotels and restaurant chains, departmental stores, chain stores, etc. Although, they are profit-motivated organisations, they are nevertheless concerned with the aesthetic standards and other aspects of their projects. Some information on these clients' reasons for employing practising architects is reported in Chapter 10 (see 10.1.10); it may be observed that visual and other qualities constitute an important part of the requirements of this group of clients (see Tables 10.5 and 10.6).

The existence and growth of 'in-house' professional designers in the big clients' organizations has already been noted; it can also be seen from Section 10.1 that many clients do not generally employ the services of practising architects.

2.5.2 Public clients:

Comprise local, regional and national authorities, government departments, nationalized industries and other public bodies whose finance comes mainly from the public
funds. They account for approximately one half of the construction output in the U.K. The public sector has a major influence on the construction industry, e.g. its share of employment of professionals now stands at roughly 50 percent (see Table 2.2).

In 1970, as a result of a reorganization of government departments, three Ministries, known previously as Public Building and Works, Housing and Local Government and Transport were merged into the newly established Department of the Environment (D.O.E.); more recently, Transport has been separated and promoted into the newly established Department of Transport.

Within D.O.E., an organization has been formed called Property Services Agency (PSA) whose functions are mainly, to provide buildings for government departments, the armed forces, etc. PSA employs its own architects, engineers and quantity surveyors.

The local authority housing schemes are required to be approved by the D.O.E. in England and Wales, and by the Scottish Office in Scotland. Standards of design and costs are subject to both control and approval; otherwise the Treasury would not sanction any loan.

Provision and construction of schools and other educational facilities (excluding universities and polytechnics), is the responsibility of the County Councils. (In the Outer London Area, it is the responsibility of the Outer London Boroughs and in Inner London Area, the Inner London Education Authority). All educational buildings proposed by these authorities are subject to control and approval by the Department of Education and Science.

Responsibility for the construction of hospitals falls on the newly re-organized Regional Health Authorities. There are Area Health Authorities in each district dealing with many other parts of public health, etc. The National Health Service is a part of the Department of Health and Social Security (DHSS). The construction programmes undertaken by the Health Authorities are subject to control and approval by the DHSS.

Nationalized industries generally control their own building programmes within overall budget limitations.
approved by the Ministers concerned.

The achievement of the public sector client in many fields is noteworthy, e.g. the rationalized approach to the design and construction of roads by D.O.E. led to investment by civil engineering contractors and materials' producers in the development of construction machinery, etc (24).

Another positive approach, which will be studied in more detail in Chapter 11, is the central government's direct involvement in the standardization of components for public buildings, etc. both through education consortia and by bringing together teams of architects, engineers and quantity surveyors, in order to design standardized components for maximum economy and quality (24). (See Chapter 11).

Public clients face difficulties because of the complicated nature of approval and problems stemming from administrative and communication difficulties (25). These problems also exist in the case of very large private clients such as ICI. However, the public sector client is also subject to political pressures of the government of the day (25).

This was borne out by the study carried out by the Tavistock Institute between 1963 and 1965 (26) of the whole system under which design and construction of buildings are carried out. Their report stated (26): "The client is a complex system of differing interest, and clients' relationship is seldom with a single member of the industry. Even if initiated through individuals, the relationship rapidly becomes a conference between groups of both sides. The client system may be an industrial or commercial organization, a hospital management committee, an education committee or one of many forms of organizational system. These client systems, as within the system of the building industry, are made up of both congruent and competing sets of understandings, values and objectives. Much design and building work has proved to be abortive, because unresolved or unrecognized conflicts of interests or objectives within the client system have only come to light after the building process has been initiated". (See also reference 25 for a detailed report of a case study on the problems encountered in the process of design and development of a local authority
2.6 Statutory Approvals:

There are two principle ways in which the statutory regulations can affect the design and construction of all buildings and to a lesser extent civil engineering facilities, viz:

(1) - Planning restrictions.
(2) - Application of the building regulations.

2.6.1 Planning restrictions:

The purpose of planning control is to provide for the appropriate location of residential, industrial, community etc. buildings and also for the future provision for land use in a beneficial way.

As with the building regulations, the powers for control given to the local authorities are established in various Acts of Parliament. Different departments within these authorities deal with the planning and building regulation aspects of each planning application. The planning department advises the planning committee of the council of its recommendation on the case under consideration; the committee and/or the full council approves or rejects the planning application (see 2.6.2 for the approval procedure under the building regulations).

The latest Town and Country Planning Act which superseded all the previous acts came into force in 1972. A main feature of this act was provision for 'structure' plans co-ordinating local planning with regional and national planning.

The local authorities have power to serve a 'stop-notice' requiring prompt stopping of all works which are subject to enforcement-notice (i.e. those buildings erected without the full consent of the council or the Secretary of State for the Environment).

The 1972 Act sets out a time limit for local authorities to accept or reject planning applications. If rejected, the applicant (usually architects handle planning and building regulations approval on behalf of their clients) has a right to appeal to the Secretary of State for the Environment, who has the final decision.

The controlling power of local authorities extends to
all aspects of architectural designs, i.e. standards of planning and layout, matters of daylighting, openings, elevational treatment, scale of building in relation to the surroundings, geometrical factors, etc. Sometimes use of materials are also controlled; see Chapter 9 for more details.

The industrial and commercial development are subject to additional controls to ensure proper distribution of these developments throughout the country.

The influence of the planning approval procedure was considered in the NEDO survey (12). Some respondents in this survey considered that: "the U.K. statutory approval system causes excessive penalties in terms of time, design costs and abortive work, and ties up too many professional resources in checking other people's designs". In addition, the report states (12): "statutory approval required for planning, concerned with the effect of construction work on quality of the environment, were said to greatly extend total project time and to affect the nature of the design".

2.6.2 Application of the building regulations:

The building regulations exist to ensure the safety and health of building occupants/users and the public; they also lay down minimum design and construction standards, and with the latest amendments they ensure that matters of national importance such as heat and energy conservation are not overlooked at the design stage. The Building Regulations are generally in the form of performance requirements and do not specify the materials or construction details. This point which is of paramount importance in relation to this study is considered in more detail in Chapters 5, 6 and 9.

In Britain there are three sets of regulations, viz:

1. The England and Wales Building Regulations.
2. The Scottish Building Regulations.
3. The London Building Bye Laws (applicable in the area originally designated as London County Council).

The national regulations (i.e. England and Wales and Scottish) are introduced by the Secretary of the State for the Environment under the 1961 Public Health Act; they are first laid before Parliament and when approved issued to local authorities who are required to administer the approved
regulations in their own areas.

Under this Act, the Secretary of State is also authorized to delegate his power to local authorities to relax or dispense with the Building Regulation; however, the delegation for those regulations relating to structural stability and structural fire precautions is not permitted. Furthermore, a local authority cannot relax or dispense with the Regulation in relation to its own buildings.

Under the London Government Act, 1963, which replaced some parts of the London Building Acts (Amendment) Act, 1939 and introduced new provisions, the G.L.C. is responsible for building and planning control.

The G.L.C. appoints a "Superintending Architect of Metropolitan Buildings" aided by a number of "District Surveyors" who are debarred from practising in private capacity. The District Surveyors are required to supervise the building works in their area to ensure that the requirements of the above Acts are fulfilled. Almost every part of the layout is subject to control and approval by the District Surveyors.

The local authorities within the G.L.C. area are responsible for matters of public health concern under the 1936 Act; they are also responsible for provisions under the Water Acts, the Clean Air Act and the Noise Abatement Act.

In the area designated as "the City of London" the "Common Council" controls the safety of the structures within the City boundaries.

In the newly established "Districts", the councils must appoint "Surveyors" or "Building Surveyors" whose duty is to supervise the application of the relevant regulations in their own area. Titles normally used are: Borough (or City) Engineer and Surveyor.

It must be noted that buildings erected by the government departments are not controlled under the building regulations. They are also generally exempt from the planning control, though the past tendency has been for them to obtain planning permission in order to keep in harmony with the surrounding environment. The design of schools, hospitals, and similar
buildings is subject to the regulations of the relevant Ministry, especially as far as aspects of technical soundness are concerned.

The importance of the building regulations and their overriding influence on the design of buildings was illustrated by Binns (B.R.E., 1976, reference 27). This study was basically aimed at identifying the length of notice required by designers for revising a part of the building regulations and the amount of redesign stemming from the new requirements; however, the survey was broadened to include many other useful aspects. Some of their findings (27) which are of direct interest to this study are reported below.

1 - Use of regulations: Approximately 85 percent of respondent designers (i.e. including those in local authority offices) used the Building Regulations either daily or weekly; the remainder used these monthly or at longer intervals.

2 - Sources of information: Approximately three-quarters of respondents learnt of the proposal for amendment of Part F 7 months after its publication. The proposal for amendment of Part F: Thermal Insulation was first published in the form of a consultative document in January 1974 by the D.O.E. and circulated to various government departments and some 200 other interested bodies. The amendment was enforced on 31st January 1975. 70 percent of the respondents first learnt of the proposal through articles or correspondence in the trade press; 15 percent learnt of it through discussion or lecture (27). About one-third of all respondents first learnt about the proposal from the government announcement; three-quarters of these were in local government.

3 - Preference for using 'deemed-to-satisfy' schedules: The survey confirmed (27) that the majority of users showed preference for the use of 'deemed-to-satisfy' constructions contained in Schedule 11, often accompanied by the designer's own details. Binns (27) concludes that this tendency amongst designers is a method of avoiding difficulties in obtaining approval under the Building Regulations. Moreover, about 40 percent of respondents preferred the use of Table 7 in the Regulation F for estimates of U-value (i.e. a measure of thermal insulation performance for a given construction), as compared with approximately 50 percent who undertook calculations of U-value. It is reported (27) that the latter group were
those who also referred to the regulation daily, and whose volume of work was also greater. Thus, performing the calculations, though difficult, was considered as worthwhile by the latter group.

2.6.3 Other statutory provisions:

These are due to the following Acts of Parliament:

2.6.3.1 The Fire Precaution Act 1971:

This Act is enforced by the Fire Authorities and requires that a 'Fire Certificate' must be obtained for buildings put to the following designated uses:

1. - Sleeping accommodation.
2. - Medical and care institutions.
3. - Recreational and entertaining, clubs, etc.
4. - Teaching, training and research works.
5. - Other buildings to which members of the public have access by payment or otherwise.

The object of the above Act is to protect the public by providing adequate fire-safety provisions of buildings during occupancy. However, its provisions equally apply to new buildings although certain types of buildings such as small dwelling houses are exempted.

2.6.3.2 The Factories Act 1961:

This Act deals with the safety, welfare and health of employees; some of its provisions also apply to construction sites.

Factory Inspectors are appointed by the Secretary of the State for Employment. They have wide powers to inspect any industrial premises to ensure that the provisions of the Act are complied with both at the time of construction and during occupancy. Their advice on the safety aspects of lifts, hoists etc. should be sought before design proposals are finalized.

2.6.3.3 The Thermal Insulation Act, 1957:

This Act applies to industrial buildings or extensions except 'unheated' buildings, boiler houses and those buildings or extensions where heat is released due to the manufacturing process. Local authorities have been given power to approve
or reject submitted designs under this Act.

2.6.3.4 Clean Air Act, 1956:
As it implies, the Act makes it illegal to emit thick and dark smoke from chimneys in a designated area; the 'Smoke Control Areas' are introduced by the local authorities with the D.O.E.'s approval.

2.6.3.5 The Control of Office and Industrial Act, 1965:
This Act controls the erection or extension of office buildings in the densely populated areas covered by the Order; the Act requires that an 'Office Development Permit' must be obtained and submitted with the planning application.

2.6.3.6 The Building Control Act, 1966:
The purpose of this Act is to enable the government to control the start of work on major projects with the aim of regulating the level of demand relative to the industry's resources and also to establish priority for socially important projects.

The Minister of Public Building and Works (Now D.O.E.) subsequently made an order suspending the building licensing from 20th November 1968. However, the government under the Act retain the power of re-imposing the licensing and control at 'short notice.'

This Act does not apply to the following categories of buildings:
(1) - Private dwellings.
(2) - Repairs and maintenance.
(3) - Industrial buildings as defined by Section 21 of the Local Employment Act, 1960.
(4) - Buildings used for scientific research in the course of a trade or business.
(5) - Projects costing less than 'Cost Exemption Limit' (excludes the cost of land and professional fees).
(6) - Public works carried out for local authorities, new towns and development corporations, universities, health authorities and many other bodies whose finance source is mainly the public fund.

The licence issued is subject to a time limit, i.e.
work must not start before, and not more than 6 months after, the approved starting date.

2.6.3.7 Offices, Shops and Railway Premises Act, 1963:

The purpose of this act is to ensure the safety, health and welfare of people employed in these places which are to be registered with the authorities responsible for enforcement of the Act's provisions.

This Act is designed to secure minimum standards of space, temperature, lighting, ventilation, sanitary conveniences, and safety aspects of the structure and fire precautions.

As has already been stated, it is the duty of the client's appointed architect to obtain all the necessary statutory approvals for a proposed scheme; furthermore, the architect should be fully conversant with the practical implications of the above acts and other relevant legislations. The architect and/or his consultants are also liable for negligence under these statutory regulations.

2.7 Influence of the British Standards Institution and the Agrément Board:

2.7.1 The British Standards Institution (BSI):

The BSI is the recognised body for the provision and publication of national standards and codes of practice. Standards for 70 major industries are prepared and promulgated by technical committees representative of manufacturers, users, the government and other interested parties.

As was noted earlier, the publicly financed research institutions such as the Building Research Station (BRS), the Prince's Risborough Laboratory (PRL), and the Fire Research Station (FRS) are charged with the task of performing the essential research, both in relation to the technical and economic needs of the nation as a whole and those of the public sector client.

Of particular importance to the building industry are BRS, PRL and FRS who are under an umbrella organization known as the Building Research Establishment (BRE). They carry out most of the scientific research required for preparation of the standards and codes of practice for the building industry
thus, they have an overriding influence on the development of building and construction technologies and related economics. The limited scope of this study does not permit a review of the research and development works carried out by these institutions; it is sufficient to mention that most of the research needed for the development of suitable tests (including performance tests) specified in numerous British Standards for the building industry has been carried out by the BAE.

The importance of the B.S tests and codes of practice lie in their use in compliance tests in the Building Regulations; as will be noted in various parts of succeeding chapters (see for example sections 5.4, 6.1 and 9.1), the changing of the B.S. tests to performance tests and their use for compliance with the Building Regulations has made it easier to introduce new materials and/or construction techniques compared with the old regulations such as the Building Model Bye-Laws which used to specify the construction materials and designs down to the minute details (c.f. 10.2).

In 2.6.2, it was noted that designers used 'deemed-to-satisfy' schedules frequently. These are in fact types of constructions which are considered to have performances greater or equal to the minima specified by the Building Regulations. Very often, these schedules are compiled by the BRE; any material or construction arrangement included in these schedules would constitute an accepted practice in the construction industry. (Note that by using 'deemed-to-satisfy' schedules, a designer effectively reduces his legal liabilities; also, he reduces the degree of risk associated with his decisions since, these schedules represent well-tried and proven materials and constructional techniques; another added advantage is the ease of obtaining approval under the Building Regulations).

If a material is not included in the 'deemed-to-satisfy' schedules, its use may be greatly facilitated by the publications of the relevant B.S. code of practice. A code of practice contains guidance on methods of meeting the requirements of the Building Regulations. It also incorporates the latest scientific, technological and economic developments in the related field, and brings together in an integrated document all essential practical, constructional and design information
accumulated from experience; trials, etc. (c.f. 9.1).

2.7.2 The Agrement Board:

The need for assessing the ever-increasing number of new products or new uses of established products was examined by a committee appointed in 1964 by the Minister of Public Building and Works. Their report was published a year later, in the form of a White Paper entitled: "The Assessment of New Building Products". It made a strong recommendation to the minister for the establishment of an organization similar to the French body known as Service de l'Agrément. The report stated: "A central, independent authority should be set up for the prime purpose of facilitating the acceptance of innovations in the building field by all interested parties including local authorities. The authority should be concerned with only new products, systems and techniques, and new uses of established ones. Submission by manufacturers for appraisal should be entirely voluntary and no publicity should be given to any innovations failing to match up to the required standards."

Careful consideration should be given as to what extent manufacturing details should be revealed to the authority and subsequently published. Certificates should be issued only for satisfactory innovations and for a limited period, giving factual and technical details, clearly identifying the use and properties.

The authority should work closely with the BSI with a view to the eventual inclusion of certified innovations in British Standards and Codes of Practice.

Certificates should aim to provide appropriate information to facilitate acceptance by local authorities under Building Regulations.

The authority should endeavour to promote the acceptance of its work abroad and at the same time encourage the introduction of good ideas from the continent.

It was suggested that the BRS should act as Technical Agent and be given the responsibility for the development, execution and assessment of suitable tests.

The government accepted the above recommendations and as a result in 1966 the Agrément Board was set up. The
success of the Agreement Board during its first decade of existence may be judged from the number of certificates issued: some 400, a quarter of which were issued in 1975(28).

The Board is controlled by a council whose members are appointed by the D.O.E. from members of the construction industry (including the professionals in the private practice); it is however independent of the government's control as is the BSI.

Part of the success achieved to date by the Agreement Board is due to the backing given to it by the government. The Ministry of Housing and Local Government undertook to notify local authorities of each new certificate published by the Board. In addition, the Ministry was prepared for consultation on the standing of innovations in relation to the requirements of the Building Regulations.

The Agreement Board joined the European Union at an early stage of its development. This enabled the Board to draw on the available information from the continent, i.e. mostly a number of Methods of Assessment and Testing (MOAT). The European Union is developing a number of common methods of assessment and standards of performance and testing. These documents are acceptable by all member countries; also, Agreement certificates are automatically interchangeable between member countries of the European Union.

It must be noted that an Agreement Certificate is issued for a particular product for closely defined applications under specified conditions; it is also valid for a limited period depending on the product. In assessing the performance of a product, the samples are chosen to represent the lowest level of quality, accuracy or dimension of the product; this ensures that the quality of the product is assured to be at least as good as the tested sample. Although, certificates have no statutory standing, the Environment Secretary has power to issue an order for their acceptance.

Initially, the Board considered(28) using the 'deemed-to-satisfy' schedules as means of statutory approval for Certificates; however, it was found that under the existing legislations, it was difficult to do this. Instead, an alternative system known as 'type-relaxations' was successfully introduced(28); 'type-relaxations' must not be confused with
the power to relax, or dispense with, the Building Regulations in relation to a specific project. 'Type-relaxations' are general relaxations for a defined class of products under defined general circumstances, e.g. in October 1975, the D.O.E. sent a circular to the local authorities giving blanket approval to those cavity wall insulation methods which obtain the Agrément Certificate provided the use of these methods in practice did not deviate from the conditions of use and exposure defined in the Certificate for the relevant method. Thus, with the 'type-relaxations' established as a powerful alternative to the 'deemed-to-satisfy' schedules, the viability and importance of the Agrément Board became indispensable.

The current cost of assessment of a product and issue of a certificate is in the range of £1500 to £3000(28); this has apparently put off many U.K. manufacturers from using the Agrément service. However, it is reported(28) that many component manufacturers now see the Agrément Certificates as selling aids (see also Chapter 9).
CHAPTER 2: References

3. Housing and Construction Statistics No. 10 (p.78-84).
5. I bid (p.1).
9. Housing and Construction Statistics No.6 (p.77).
15. See pages 4 and 5 of reference 4.
22. See New Civil Engineer, 15th July 1976.
23. Parker-Morris recommendations for residential units, HMSO.

28. See pages 24-25 of the New Civil Engineer, 26th August 1976.
3.1 General Consideration:

The purpose of this chapter is to examine briefly the mechanics of the traditional process of design and construction. A brief examination of other processes alternative to the traditional process has also been included.

The traditional process of design is referred to as the method by which the architect (whether employed as 'in-house' staff by the client or working in private practice and his services are employed by the client in connection with a particular project) controls the whole process of the design, and also subsequently supervises the construction of the project in accordance with his design and those of other consultants approved and authorised by him. This process is applicable to the design of buildings and is still in general use.

Various alternatives (see 3.10) have come into existence because of the following reasons:

1. Attempts to integrate the design and construction of buildings, and improve the productivity and speed of construction by unifying the control and improving the process of communication etc.

2. Increase in the size of projects or the number of projects handled by individual clients; also growth in the size of contractors' organizations and resources, and their desire for greater control and management of the industry.

3. Increased pressure on the construction industry for greater productivity, higher standards of quality and greater capability to handle complex projects and/or avoid treating basically similar building projects as idiosyncratic products.

3.2 Client's Brief:

A brief is a summary of information prepared by the client (sometimes with the help of the architect) and given to the architect for the design of the proposed building; a brief generally contains information on the following aspects:

3.2.1 Site:

Nature of site (acquired or considered); whether it is necessary for the architect to inspect and report on alternatives legal restrictions, etc.
3.2.2 Construction programme:
Date of completion; whether it is to be completed and occupied in phases; possible time extension, etc.

3.2.3 Capital, running and maintenance cost considerations:
The amount of capital available; whether more than one source of finance exists; professional fees, etc.

3.2.4 Schedules of accommodation required or activities to be housed:
Number of future occupants and their sex; life of the project; internal and external finishes; areas of units and their relation to each other; number of floors and basements; whether any part is, or is likely, to be put to a different use and when; future extension; night uses, etc.

3.2.5 Functional and operational considerations:
Type of lighting preferred in each unit and the amount of natural lighting desired; heating, air-conditioning (if any) and/or ventilation requirements; preference for any type of fuel; acoustic requirements, etc.

3.2.6 Services:
Lifts, stairs and hoists (if any); staff restaurant; refrigeration and hot water requirements; refuse disposal; storage spaces; peak periods for services; any other special provision.

3.3 Outline Design:
The outline design is begun with the analysis of the users' requirements in terms of allocation of spaces which can be calculated by applying known planning standards and criteria. Other items are also considered and analysed, e.g. the ground conditions, local authority planning restrictions, etc. The results of the above analysis should identify those design
parameters which have significant influence on the nature of the end result.

The design synthesis starts with careful combination or balancing of the design parameters. Many sketches are drawn and studied until a number of feasible solutions emerge. These are further analysed by evaluating each of these possibilities and improving or adjusting until the designer is satisfied that an optimum solution has been obtained. This optimum solution is not necessarily a solution based on the client's purposes since other purposes in relation to the user and society will influence the conception of the design. Thus, it is a process which aims at fulfilling a high degree of attainment of all the purposes for which the building is being designed and striking a fair balance between those purposes which are in conflict.

A careful examination of this process will reveal that for the conception of the design to be satisfactory, the designer must fully appreciate the following:

(a) The capabilities of the materials.
(b) The interdependency of aesthetic, structural, fire-resisting, environmental, etc. aspects of the design.
(c) The relation between these parameters and the construction methods.
(d) The cost implications of each of the above aspects.
(e) The effects of constraints imposed through the statutory regulations, clients' budgetary limitations, etc.

Furthermore, it requires that the designer is capable of carrying out a rigorous and sophisticated search for alternative means to satisfy the design requirements.

In practice, architects tend to arrive at some sort of solution which is not necessarily the optimum, since their speciality and experience is not necessarily consistent with all the design aspects.

Although the design at this stage is no more than a concept it must be an approximate solution to the problem; it involves making decisions of fundamental importance in relation to the project.

There are many ways through which designers normally exercise considerable freedom, viz:

(1) In transforming the users' and clients' requirements into building units by adopting a set of planning, structural
and aesthetic values and standards.

(2) In investigating possible alternatives to satisfy the given requirements.

(3) In attaching more weight to a selected number of design parameters, either due to the nature of the proposed building or purely from personal preferences.

In the traditional practice, the outline design is usually carried out by the architect; however, in the process of analysis and synthesis, he may ask advice on various aspects of the design from a variety of sources. This must not be confused with the multi-disciplinary design concept which is a relatively new process and calls for the architect, structural engineer, services engineer, quantity surveyor, builder, etc. to produce a design solution collectively.

On completion of the outline design an architect may consult a quantity surveyor to ensure that his approximate estimate of costs is reasonable. This service is normally free of charge to architects.

3.4 Client's Approval:

The client may be presented with one or a number of alternatives outline designs, each with its own estimate of costs and accompanying characteristics; the client may be asked to choose one of these whilst being fully aware of the implications of his choice. However, in the majority of cases, architects tend to present one outline design only and persuade their clients as to its viability.

In the case of public clients, in addition to the above points, there may be other aspects worthy of attention, e.g. there could be a national policy for the use of a particular material or construction technique on economic social or political grounds, the use of timber may be required to be kept as low as possible to reduce the imports' bill (90 per cent of the timber consumption is currently imported), or the use of approved insulation products encouraged in order to conserve energy. These are ideally included in the brief; however, it is possible that at the time of submission of the outline design new policies will have been introduced.
3.5 Preliminary Design:

This is the next stage of the design process which follows after the client's approval is obtained and also after an outline planning permission is obtained from the local authority concerned.

As was noted before, the usual hierarchy is for the architect to produce his own preliminary drawings i.e. general arrangement, dimensioned plans, elevations, sections, etc., using 1:100 or 1:200 scales and showing approximate dimensions for the structural members, lift shafts, service ducts, etc. These drawings are sent to the structural engineer for the design of the foundation and the structure.

After the preliminary structural design is completed, the appropriate drawings are sent to the services' engineer. The design of services in the preliminary stage is often generalized showing routes of services, approximate dimensions of the ducts, location of boilers, etc. Full details of these are often produced by relevant nominated sub-contractors.

It may be noted that the more detailed the preliminary design, the higher is the likelihood of avoiding last minute variations and design improvisations at the time of construction. It is especially important that drawings produced by different specialists are properly coordinated and cross-checked in order to ensure that gross errors are avoided.

Nevertheless, it is not always possible to prepare all the construction and shop details in advance of the construction stage because of the length of time these take. Furthermore, the construction details of some parts (e.g. upper floors, roof, etc) of a major project may not be required immediately on commencement of work by the contractor on site, so it may seem desirable to invite tenders on an approximate bill of quantities prepared by the quantity surveyor using the preliminary drawings.

The current practice is to advance the design to an appropriate stage and then invite tenders for an early start. However, as has repeatedly been warned (2,4,5) an early start does not necessarily mean an early completion; and a thorough examination of the preliminary design is essential if subsequent delays and design alterations are to be avoided.

In any case, the architect, upon completion of the
preliminary design, proceeds to preparation of schedules of finishes and specifications with the help of the quantity surveyor if necessary. The supply of the specification is mandatory with government contracts.

The specification is in fact an extension of the drawings. It gives a full description of the quality of materials to be used (sometimes names of acceptable suppliers are also specified), and also gives methods of testing and compliance, dimensional accuracy and tolerances, etc. for materials, components, finishes, etc., incorporated into the project. It therefore follows, that the published information, B.S. specifications, tests, codes of practice, etc., and the architect's own experience must be used to produce a specification for the work under consideration.

A recent development has been the publication of a comprehensive specification (i.e. the National Building Specification, 1973, R.I.B.A.) with the aim of providing a library of standard clauses covering aspects of quality, methods of testing, etc., for constructional materials, components, etc. The first attempt has not produced the desired effects; however, the efforts on this work are continuing with promising results. Many contractors blame the minor variations of the building specifications as an unnecessary and costly practice.

In addition to the specification, a bill of quantities is normally required (see 3.6). As the name implies, the bill of quantities lists, in a systematic and standardized manner, the quantities of materials, components, etc. proposed in the project; this task is commonly performed by the quantity surveyor. Ideally, he should prepare the bill of quantities simultaneous with the compilation of the specification, schedules of finishes, etc. in co-operation with the architect.

A recent development in this field has been the use of 'operational bill of quantities': the operational bill lists, in addition to the quantities of materials, the time requirements for manpower and construction plant.

The sequence of listing the above items is mostly in accordance with the sequence in which operations are expected to take place on site.
The advantage of the above bill over the former type is that when items are priced individually by contractors, it provides a better measure of the actual costs than the former; also, it may be used to study the relationship between site productivity and the design.

3.6 Invitation to Tender and Choice of a Contractor:

The invitation can take the form of a letter sent to a selected number of contractors or, in the case of 'open' tendering, it can be an advertisement placed in the national press or the relevant trade press.

A contractor applying to be included in the list of tenderers is normally supplied with the following documents:

(a) A set of drawings.
(b) A tendering form.
(c) A copy of the bill of quantities.
(d) A copy of the specification (not mandatory with non-government contracts). If there is no bill of quantities - as is the case in small projects - a specification together with the complete set of drawings are required by contractors in order to quantify the material and work content involved in the project.
(e) A copy of conditions of contract.
(f) A covering letter giving full details of such matters as the proposed completion date, etc.

It is worth noting that there is a code of procedure for the above purpose.

The choice of contractor is not necessarily based on the lowest bid. Matters such as the nature of works, the financial capacity, past experience, speciality, technical ability, etc. are all considered carefully by the architect in consultation with the quantity surveyor.

In the 'open' tendering, the bidders are generally required to provide a guarantee bond to cover any deficiency which may arise as a result of his failure to comply with his undertakings. This is generally indespensible in the case of local authority and many other public contracts.

In the case of public contracts, the architect in consultation with the Clerk to the authority concerned examines the submitted tenders and makes a recommendation to the client.
In both cases (i.e. public and private sector clients) the client studies the architect's recommendations together with the submitted tenders (including the priced copies of the bill of quantities returned by contractors). He then chooses the appropriate tender and the quantity surveyor checks the details of this tender in order to ensure that no gross mistakes have been made by the contractor concerned. In the event of gross mistakes, the contractor is notified to determine whether he wishes to withdraw his tender.

If tender prices are found to be generally higher than the client's budget a schedule of 'reduction' may be required by the client; to do this the architect must examine the project to determine where possible reductions can be made. The architect and the quantity surveyor prepare a bill of omissions from which tender prices can be adjusted; this problem can only be avoided if a sound cost planning procedure is employed before tendering.

3.7 Site Supervision:

Under the architect's terms of engagement and his obligation under the R.I.B.A.'s professional code of conduct, he is required to supervise the construction of his design in a positive manner, i.e. by acting on behalf of his client to ensure that the terms of the contract between his client and the contractor are fulfilled. He is also required to help the contractor in interpreting his design and judging the standards of works in comparison with the agreed samples and the specification.

One of the architect's obligations is in fact to protect the contractor from an unreasonable client.

The architect is not required to supervise the construction of his design full time on site. He may ensure adequate supervision by means of regular site visits and study of reports prepared by the clerks of works (see below). However, in many complex projects, architects maintain a site office operating under the direction of a senior representative architect who has often full authority through delegation.

Clerks of works are employed by clients on the architect's recommendation. A clerk of works, though employed by the client, takes his instructions from the architect.
Clerks of works share some technical background and experience (building technician level); their duties on site are as follows:

(a) To ensure that the contractor carries out the works in conformity with the latest revised drawings and architect's instructions.

(b) To keep record of any work likely to be covered by other works (e.g., in the foundation).

(c) To prepare reports for the architect, on the progress of works, extras, etc.

In most contracts, due to the importance of the engineering aspects, it is necessary for the client to employ the services of resident engineers on site in order to maintain a constant supervision over these aspects. A resident engineer is normally a chartered engineer employed by the client through the consulting engineers.

The authority of a resident engineer on a building project is limited and is controlled by the architect.

In complex building projects, several resident engineers—each qualified in a particular field—may be required, headed by a senior resident engineer. Resident engineers act in collaboration with the relevant consulting engineers.

3.8 Nature of Site Problems and the Contractor's Influence on the Design and Choice of Materials:

As has already been noted, traditionally, the design and construction processes are divorced from each other; indeed, under the standard contracts, the contractor has no influence on the design. Furthermore, he has normally no incentive to suggest any design improvisation.

A reputable contractor tries to create and maintain a good public image in the business world in order to ensure the continuity of business. In addition, there are several clauses in the contract which require the contractor to advise the architect of any design inconsistency or of suspect performance of a specified material/component/system.

Another aspect is that the contractors are liable for any defects in materials or poor construction works, etc.
A conclusion to be drawn is that contractors will avoid taking higher degrees of risks, e.g. in conjunction with new materials, etc.

A problem arises when a particular material or component is not commercially available; in such cases close substitutes are often suggested, by the contractors, to the architect.

As has already been noted, tendering may be carried out in two stages: preliminary and final. In the preliminary stage, upon receiving the documents listed in 3.6, a contractor may ask for further information and/or clarification of the projected proposals. The contractor may also put forward suggestions such as whether or not the consulting structural engineer should re-design the proposed in-situ reinforced concrete beams to be pre-cast. These suggestions do not generally involve use of innovations; they are intended to facilitate the construction of the project and are usually put forward subject to the designer's risk.

The majority of site problems stem from the wrong interpretation of, or discrepancies in, the construction documents. Problems may also arise due to the architect's instructions for variations which would either affect the parts constructed or those planned for construction; such alterations can seriously hamper the contractor's efficiency and disrupt the planned sequence of site operations, etc.

Thus, the contractors do not favour these and try to claim extra money and time; the contractors' tendency to forward costly claims has made it necessary for the establishment of a 'claim-organization' within the clients' organizations.

In short, under the standard contract the contractors' influence on the design and use of materials, etc. is limited; the contractors appear to be traditionally accustomed to their role as executors of the wishes of the designers. However, there are many post-war alternative processes which are significant; these are discussed below.

3.9 Alternative Processes for the Design and Construction of Building Projects:

Reasons for existence and growth of the organizations offering different services (compared with the traditional process) have already been noted in 3.1; these developments
have been of the following types:
1. Modified forms of the existing process.
2. Totally different processes.

3.9.1 Modified forms of the existing process:
The most commonly known forms are considered below:

3.9.1.1 Appointment of a 'project manager' by the client:
The duty of a client's project manager is to supervise both
the architect's and the contractor's contributions and at the
same time control the overall project planning and co-ordination
including monitoring the progress of all the parties involved
in both the design and construction stages of the project.

In effect, the service of project management is sometimes
provided by the 'in-house' staff in many clients' organizations,
especially when the professional in-house staff are also
charged with operating approval procedures on behalf of their
employers.

However, the need for a project manager other than the
design team leader who has adequate authority plus adequate
experience of the design and construction processes and an
ability to lead has been emphasized by several participants in
the N.E.D.C. survey.

3.9.1.2 Negotiated contract:
Instead of going to 'open' or 'selected' tendering, the
client (or his appointed quantity surveyor) may negotiate a
price with one contractor for execution of the design;
alternatively the contractor may be selected by initial tendering
based on a 'notional' bill of quantities; the final price is
calculated on the rates submitted by the contractor in the first
tender.

3.9.1.3 Costs plus fee:
In this form of contract, the contractor is paid (by the
client) his costs plus a percentage (or otherwise) fee for
his management.

3.9.1.4 Target incentives:
At the time of negotiation between the client and the
contractor, a target cost is jointly agreed; any saving from
this figure is shared between the client and the contractor.
3.9.1.5 Serial tender:

As the name implies in this form of contract, the contractor tenders for several repetitive projects, thus he is ensured of the continuity of the work.

3.9.2 Totally different processes:

These are considered below:

3.9.2.1 Design and construct:

This is commonly known as 'package-deal' or 'all-in-contract'. In this type of contract, the contractor is responsible for all aspects of design, planning and construction of the project to the client's brief; it is one of the most controversial developments in the construction industry in recent years(1).

The H.E.D.O. survey(1) amongst other things, clearly illustrated the division of opinions on advantages and disadvantages of the above practice; those in favour stated that it:

"1. Clearly allocates total responsibility and is often cheaper.
2. Can significantly shorten project time by overlapping the design and construction stages.
3. Provides incentives for ingenuity in design and construction methods.
4. Gives the contractor a larger lead time to his construction order book.
5. Can offer improved service through co-ordinated management and through commercial motivation and discipline."

However, there was repeated emphasis(1) by those favouring this practice on the need for the client to retain services of professional consultants for the following:

(a) to evaluate the design; and
(b) to check the project under construction to ensure a high degree of quality control.

Those respondents critical of the 'design and construct' practice stated(1) that it:

"1. Subordinates the subjective aspects of quality in favour of quantified objectives;
2. Can restrict creative design and results in stereotyped solutions.
3. Produces products which do not meet users' requirements, because managers are not so tolerant of design problems as they should be."
4. Can result in dissatisfaction regarding content and quality of the finished works."

A number of respondent professionals, both in the private practice and the public sector, in the above study(1) saw a problem of conflict between the professional standards and the commercial objectives; this, they stated, was the greatest weakness of the 'design and construct' practice.

It must be noted that only large contractor organizations who can afford to employ professional staff on a continuous basis are able to undertake package-deal contracts. However, it is sometimes possible for these contractors to employ the services of practising consultants, especially in relation to structural and foundation engineering and also design of services required in the project.

3.9.2.2 Develop and construct (or two-step design):

In this process the conceptual (or outline) design and the overall project control are separated from detailed design and subsequent construction.

The client's requirements and other aspects are analysed by an experienced professional designer and an outline design produced.

This outline design together with a performance specification incorporating users' requirements, etc. are used by the contractor to produce detailed design; he subsequently undertakes the construction under the overall supervision of the original designer.

The advocates of this(1) organizational arrangement claim(1) that it can result in both higher quality and improved efficiency because, the highly experienced professional consultants are able to allocate much of their efforts to establishing the brief and producing the basic design. The tasks of developing the basic design into detailed design may then be performed by those highly experienced in the detailed design. An added advantage is that the contractor will have a vested interest in ensuring compatibility of the design details with the construction operations. Moreover, the contractor has an incentive to search for indigenous design and construction methods, materials, etc.
The critics of the 'two-step' design and construct considered(1) that the idea was unsound except in the case of simple repetitive buildings; they claimed(1) that their experience is that the above organizational arrangements leads to unsatisfactory relationship and poor results.

3.9.2.3 Multi-discipline design:

A team of designers of the required disciplines may work together to analyse the client's brief and prepare the outline design collectively. This practice takes into account the interdependency of the architectural, structural and services aspects of most building projects. An extended version is to include the contractor at an early stage so that the design decisions are taken with constructional and cost implications fully in mind.

The N.E.D.O. study showed(9) the practical and organizational difficulties which are associated with this practice; in particular due to domination of one profession(10) and/or too much democracy(9) both of which can result in dull buildings.

There have been relatively few multi-discipline design practices(10); one reason for this has been(10) that due to expectations of limited job experience in their own specialized fields and restricted career advancement, top talents are not always attracted by these practices.

3.10 Summary of the Main Points:

1. Traditionally designs of building projects are carried out in the absence of contractors by professional designers (or specifiers). The common practice is for the architect to initiate the outline design and to pass it on to a structural engineer for the design of an appropriate structure. This stage is followed by the design of services, etc.; the latter designs are usually completed by the relevant nominated sub-contractors.

2. Professional designers have no responsibility in connection with the constructional aspects of their designed schemes. Furthermore, building and civil engineering facilities should fulfill the purposes for which they are constructed. These purposes are not always quantifiable; it follows that a solution arrived at by a designer is not
necessarily the minimum-cost one, the final design is in fact achieved when a fair degree of balance is attained between the conflicting purposes.

3. Under the standard contracts, contractors are neither required nor encouraged to initiate substantial changes in the designed projects; there is no incentive for them to undertake a search for cost-reducing of potentially superior innovations relevant to both materials and construction methods.

In the event of the inavailability of a specified product, the contractors tend to suggest a close substitute.

Other suggestions by contractors are usually associated with matters of pure convenience to themselves, i.e. to suit their pattern of work force, plant and equipment, etc.

4. The design process can be unduly lengthy and uneconomic. The system of control is extremely complicated and may be ineffective, because a considerable length of time may be wasted in the decision making and approval procedures. Conflicts of interests can further cripple the flow of communication and progress of work.

5. Not all design data are firmly known before a contract is signed. Tender prices do not necessarily reflect the true building costs, since subsequent design improvisation, variations, etc. can increase the costs significantly.

6. The nature of the organizations in the construction industry is such that it generates a high degree of uncertainty, because a designer's approach to building projects is controlled by a number of factors such as the needs of individual clients, the needs of users, the need to blend with the surroundings, etc. These in turn encourage individualistic solutions to the design of building projects. Furthermore, the volume of orders for construction (demand) fluctuates with time. Moreover, there is no way by which an individual contractor is able to know whether any or all of his tenders have been successful until shortly before he is required to start work.

7. Utilization of many potentially useful innovations requires firm commitment of resources to their development. The economic survival of the investors will depend on the continued use of their wares and services. The tendency to treat the construction projects in an idiosyncratic manner deters contractors and material producers from committing their resources to potential innovations; as a result, the building industry has remained highly labour-intensive compared with the manufacturing industries.
7. Ibid, pages 21-23

Other references used in this chapter:

13. Standard J.C.T. Schedule of Conditions of Contracts, revised annually (Published by R.I.B.A.)
14. General Conditions of Government Contracts for Building and Civil Engineering Works, H.M.S.O.
4.1 Definition and Types:

A fibre/matrix composite may be defined as a low modulus matrix which is generally reinforced with a high modulus fibre. The fibres normally used are glass, asbestos, carbon and steel wire. Polypropylene and nylon fibres are classed as low modulus fibres. However, these may be added to a brittle matrix to increase its impact resistance (see subsection 4.5.2).

Matrix types include plastics, cement paste, gypsum, plaster, mortar and concrete.

Table 4.1 contains properties and typical unit prices of the fibres more commonly used in constructional applications.

Stiff fibres are normally used to reinforce a low modulus matrix. The addition of such fibres to a low modulus phase increases the strength of the composite and reduces the plastic deformation. When an uncracked fibre/matrix composite of this type is stressed, and provided the fibre lengths are greater than the critical length and have complete bond, true composite action occurs, i.e. at a particular section, the matrix and fibres undergo the same strain and carry load in proportion to their stiffness. Stiffness of such composites is directly proportional to the quantity of fibre. Since the matrix is more extensible than the fibres, the stiffness is normally maintained at high stress levels. This is a desirable property in many practical applications.

A brittle and stiff matrix (e.g. hardened cement paste), reinforced by addition of fibres, cracks at a fairly low stress level and the true composite action is soon lost. Consequently, the main reason for the addition of the fibres in this case is to support the cracked matrix. This action can improve the performance of the composite in the following ways:

(a) Increase in the strength compared with the matrix: A brittle matrix is normally weak in carrying tensile and flexural loads and cracks at low stress/strain levels. Strong fibres dispersed evenly in the matrix can retard the onset of cracking by the action of stress transfer. Once the matrix is cracked the fibres are able to sustain the stress across the cracks and thus increase the ultimate strength of the composite.

(b) Extensibility: The cracked composite may extend a great deal more than the matrix before rupture.
<table>
<thead>
<tr>
<th>Type</th>
<th>Specific Gravity (µm)</th>
<th>Diameter (µm)</th>
<th>Ult. Tens. Strength (MN/m²)</th>
<th>Ultimate Elongation (%)</th>
<th>Young's Modulus (GN/m²)</th>
<th>Unit Price (£/kg)</th>
<th>Unit Price (£/m³)</th>
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<td>0.02 - 20</td>
<td>3000</td>
<td>2 - 3</td>
<td>200</td>
<td>0.1</td>
<td>260</td>
</tr>
<tr>
<td>E-glass</td>
<td>2.55</td>
<td>9 - 15</td>
<td>2 - 3000</td>
<td>2 - 3.5</td>
<td>69</td>
<td>0.5</td>
<td>1300</td>
</tr>
<tr>
<td>'Cem-Fil' glass</td>
<td>2.78</td>
<td>9 - 15</td>
<td>2500</td>
<td>2 - 3</td>
<td>70</td>
<td>1.0</td>
<td>2700</td>
</tr>
<tr>
<td>Steel</td>
<td>7.8</td>
<td>5 - 500</td>
<td>I - 3000</td>
<td>3 - 4</td>
<td>200</td>
<td>0.3</td>
<td>2150</td>
</tr>
<tr>
<td>Carbon H.S.</td>
<td>1.74</td>
<td>7.5</td>
<td>2 - 3000</td>
<td>I</td>
<td>280</td>
<td>60.0</td>
<td>10600</td>
</tr>
<tr>
<td>Carbon H.M.</td>
<td>1.86</td>
<td>7.5</td>
<td>2000</td>
<td>0.4</td>
<td>400</td>
<td>60.0</td>
<td>10600</td>
</tr>
<tr>
<td><strong>Low E-Value:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polypropylene</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monofilament</td>
<td>0.9</td>
<td>200</td>
<td>400</td>
<td>-</td>
<td>5</td>
<td>0.6</td>
<td>550</td>
</tr>
<tr>
<td>Fibrillated</td>
<td>0.9</td>
<td>-</td>
<td>400</td>
<td>-</td>
<td>8</td>
<td>0.6</td>
<td>550</td>
</tr>
<tr>
<td>Nylon</td>
<td>1.14</td>
<td>4.7</td>
<td>900</td>
<td>-</td>
<td>4</td>
<td>1.20</td>
<td>1370</td>
</tr>
</tbody>
</table>

* - 1975 typical prices
(c) Impact resistance: The cracked composite may exhibit a high impact strength because the fibres rapidly dissipate the impact energy.

The more commonly known composite materials are fibre reinforced thermoplastic and thermosetting resins, glass fibre reinforced cement (G.R.C.), glass fibre reinforced gypsum plaster (G.R.G.) and fibre reinforced concrete.

4.2 Reinforced Thermoplastic and Thermosetting Resins:

4.2.1 Nature of plastics materials:

Plastics are a group of polymeric materials. Polymers consist of long chains or structures of repeating single molecules or modified molecules termed monomers. Molecular weights of polymers normally range between 10,000 to 200,000.\(^{(1)}\). Linear polymers are formed by bifunctional monomers and have structures similar to \((-A-)_n\) or they may consist of copolymers. A polymer formed by two copolymers \(A\) and \(B\) may have the following random structure: \(-A-A-B-B-A-A-A-A-B-\). The linking of copolymers may be of a repeating structure (e.g. ethylene glycol). Cross-linked polymers contain some trifunctional units.

Polymers are divided into three groups, viz: (a) elastomers (very low modulus, e.g. 0.001 GN/m\(^2\)); (b) plastics (low modulus e.g. 0.9 - 1.38 GN/m\(^2\) for polypropylene); and (c) fibres (with modulus between 1 - 10 GN/m\(^2\)). Plastics are further divided into thermoplastics and thermosets. Thermoplastics are normally linear polymers which soften and melt on heating but do not decompose. Thermosets are cross-linkable polymers which, once cross-linked, (a process known as curing), will not soften but only degrade on heating.

Table 4.2 shows properties of some of the commonly known thermoplastics and thermosets. As can be seen, properties of unreinforced plastics are generally low compared with mild steel or aluminium alloys. Thermoplastics soften at fairly low temperatures and have very high linear coefficients of expansion.
Table 4.2 Typical Properties of Common Plastics in comparison with Traditional Materials

<table>
<thead>
<tr>
<th>Material name or abbreviation</th>
<th>Optical property</th>
<th>Compressive strength (MN/m²)</th>
<th>Tensile strength in Tension (MN/m²)</th>
<th>Modulus (0°C) (GN/m²)</th>
<th>Softening point (°C)</th>
<th>Linear thermal coeff. m/m per °C x 10⁻⁶</th>
<th>Water absorption (% 24 hrs)</th>
<th>Burning rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thermoplastics:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyethylene (H.D.)</td>
<td>cloudy/TL</td>
<td>16.5</td>
<td>21.4 - 38</td>
<td>0.55 - 1.03</td>
<td>120 - 130</td>
<td>II0 - I30</td>
<td>0.01</td>
<td>very slow</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>TP - TL</td>
<td>58.5 - 69</td>
<td>28 - 38</td>
<td>0.9 - 1.38</td>
<td>150</td>
<td>60 - 85</td>
<td>0.01</td>
<td>slow</td>
</tr>
<tr>
<td>Rigid PVC</td>
<td>clear</td>
<td>55</td>
<td>58.5</td>
<td>2.4 - 2.8</td>
<td>82</td>
<td>50</td>
<td>0.05</td>
<td>S.E.</td>
</tr>
<tr>
<td>ABS</td>
<td>TL</td>
<td>17 - 76</td>
<td>17 - 68</td>
<td>0.69 - 2.62</td>
<td>62</td>
<td>85</td>
<td>60 - 90</td>
<td>0.1 - 0.3</td>
</tr>
<tr>
<td>Nylon</td>
<td>cloudy/TP</td>
<td>48 - 96</td>
<td>48 - 83</td>
<td>1.03 - 2.76</td>
<td>melt 220</td>
<td>80 - 150</td>
<td>0.4 - 3.3</td>
<td>S.E.</td>
</tr>
<tr>
<td><strong>Thermosets:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenolic resins:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PF without fillers</td>
<td>TP</td>
<td>69 - 90</td>
<td>48 - 55</td>
<td>5.16 - 6.9</td>
<td>-</td>
<td>25 - 60</td>
<td>0.1 - 0.2</td>
<td>very slow</td>
</tr>
<tr>
<td>PF with fillers</td>
<td>opaque</td>
<td>I32 - 276</td>
<td>45 - 53.5</td>
<td>5.5 - 8.3</td>
<td>-</td>
<td>30 - 45</td>
<td>0.3 - 1.0</td>
<td>very slow</td>
</tr>
<tr>
<td>Urea resins (UP)</td>
<td>TP</td>
<td>I72 - 240</td>
<td>41.5 - 90</td>
<td>10.3</td>
<td>-</td>
<td>22 - 36</td>
<td>0.4 - 0.8</td>
<td>S.E.</td>
</tr>
<tr>
<td>Melamine resins (M/F)</td>
<td>TP</td>
<td>276 - 310</td>
<td>-</td>
<td>-</td>
<td>40</td>
<td>140</td>
<td>0.1 - 0.6</td>
<td>S.E.</td>
</tr>
<tr>
<td>Unsaturated polyesters</td>
<td>TL</td>
<td>I40</td>
<td>55</td>
<td>3.50</td>
<td>-</td>
<td>70 - 90</td>
<td>0.15</td>
<td>slow</td>
</tr>
<tr>
<td>Epoxyide resins (EP)</td>
<td>amber TP</td>
<td>I03 - 206</td>
<td>34.5 - 83</td>
<td>1.38 - 4.14</td>
<td>-</td>
<td>45 - 65</td>
<td>0.05 - 0.1</td>
<td>varies</td>
</tr>
<tr>
<td>Polyurethane (PU)</td>
<td>clear</td>
<td>varies</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>slow</td>
</tr>
<tr>
<td>UP/55 wt. % glass cloth</td>
<td>opaque TL</td>
<td>250</td>
<td>300</td>
<td>15</td>
<td>-</td>
<td>II2</td>
<td>0.2</td>
<td>slow</td>
</tr>
<tr>
<td>UP/30 wt. % glass mat</td>
<td>opaque TL</td>
<td>150</td>
<td>100</td>
<td>7</td>
<td>-</td>
<td>30</td>
<td>0.15</td>
<td>slow</td>
</tr>
<tr>
<td><strong>Other Materials:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mild Steel</td>
<td>opaque</td>
<td>486</td>
<td>860</td>
<td>200</td>
<td>-</td>
<td>II.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aluminium</td>
<td>opaque</td>
<td>83</td>
<td>450</td>
<td>70</td>
<td>-</td>
<td>23</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Timber (Douglas Fir)</td>
<td>opaque</td>
<td>60</td>
<td>69</td>
<td>9.65</td>
<td>-</td>
<td>5/4 to 0.2</td>
<td>very slow</td>
<td></td>
</tr>
<tr>
<td>Timber (Hickory)</td>
<td>opaque</td>
<td>I30</td>
<td>I38</td>
<td>15.9</td>
<td>-</td>
<td>5/4 to 0.2</td>
<td>0.3</td>
<td>slow</td>
</tr>
</tbody>
</table>

Notes:  TP = Transparent   TL = Translucent   S.E. = Self-extinguishing
They are rigid; their moduli range from 0.5 to 2.9 GN/m² in normal conditions. Their strength also varies considerably (c.f. Table 4.2).

Thermosets possess improved mechanical and thermal properties compared with thermoplastics, e.g. they are generally stronger and stiffer, do not soften at low temperatures and have lower thermal coefficients on average. Nevertheless, their capabilities do not match those of common traditional structural materials (see Table 4.2). Furthermore, plastics are sensitive to environmental changes, especially temperature. Their mechanical properties are also time-dependent. To improve properties of plastics, stiff fibres are used as very efficient reinforcements in the majority of cases (see below).

4.2.2 Mechanism of reinforcement in reinforced plastics:

It is proposed to consider, for simplicity, the case of continuous fibres aligned in the direction of the load; the creep of the matrix has been ignored. Denoting the total load by \( F \), composite, fibre and matrix by subscripts \( c, f \) and \( m \) respectively, the following relationship may be written:

\[
P_c = P_f + P_m \quad \text{(1)}
\]

or

\[
\sigma_c \times A_c = \sigma_f \times A_f + \sigma_m \times A_m \quad \text{(2)}
\]

or

\[
\sigma_c \times V = \sigma_f \times V_f + \sigma_m \times V_m \quad \text{(3)}
\]

where \( \sigma \) is stress, \( A \) is area and \( V \) is volume fraction (\( V_f + V_m = 1 \)).

Assuming perfect interfacial bond, the matrix and fibres suffer the same strain, so that

\[
\varepsilon_c = \varepsilon_f = \varepsilon_m = \frac{\sigma_c}{E_c} = \frac{\sigma_f}{E_f} = \frac{\sigma_m}{E_m} \quad \text{(4)}
\]

where \( \varepsilon \) is strain. Substitution of equation 4 in equation 3 results:

\[
\sigma_c = \varepsilon_c \times E_f \times V_f + \varepsilon_c \times E_m \times (1-V_f) \quad \text{(5)}
\]

From equation 5, the ratio of fibre load to composite load may be calculated:

\[
\frac{\text{Fibre load}}{\text{Composite load}} = \frac{\varepsilon_c \times E_f \times V_f}{\varepsilon_c \times E_f \times V_f + \varepsilon_c \times E_m \times (1-V_f)}
\]
For a given value of $V_f$ and by varying the elastic moduli ratio $E_f/E_m$, the above load ratio can be plotted (Fig. 4.1).

Fig 4.1 ELASTIC MODULI RATIO vs PERCENTAGE LOAD CARRIED BY THE FIBRES FOR VARIOUS FIBRE VOLUME FRACTIONS (After Broutman, Ref 2)

\[ V_f \times \frac{E_f}{E_m} \times \frac{1}{1 + V_f \left( \frac{E_f}{E_m} - 1 \right)} \]  
____________________(6)

$E_f/E_m$ for glass reinforced polyester resin is typically 72.5/3.42 or approximately 21. It can be seen from Fig. 4.1 that for a glass content corresponding to $V_f = 0.1$, the load carried by the fibres constitutes over 60 per cent of the total load. With $V_f$ greater than 0.3, the fibre load is in excess of 90 per cent of the total load.

It will be realised from the above that reinforcing plastics by relatively high modulus fibres is highly efficient.
4.2.3 Time-dependency of plastics properties:

As reinforced plastics may be described as visco-elastic, their deformational behaviour is different to that of metals. Reinforced plastics creep under a constant applied load; their rate of creep is dependent on the stress level, the duration of loading and the environmental conditions. To use a single value for the modulus of elasticity based on constant rate of elongation can therefore be misleading. Instead, creep characteristics of plastics must be taken into consideration. B.S. 4618 (3) contains recommendations for creep tests which adequately cover the above effects. Thus constant load tests are defined under controlled conditions for the following durations: 60S, 100S, 1h, 24h, 100h, 10 year, 10 years and 50 years. For each material a family of creep curves may be obtained by varying the stress as shown in Fig. 4.2. From these curves isochronous stress-strain curves may be drawn, each corresponding to a specific duration, e.g. a 100S isochronous stress-strain curve implies that the total strain (or creep) at the end of 100S has been plotted against the corresponding stress level. The slope of this curve is not constant. It is therefore necessary to specify at which point on the curve the slope has been determined, e.g. the value of the slope may be required at a point corresponding to 0.2 per cent strain. This is conveniently termed 'creep modulus' and has to have two prefixes denoting the loading duration and the corresponding strain value, e.g. 100S, 0.2 per cent tensile creep modulus.

From the above discussion it can be seen that for the design of a plastic article subjected to a known loading in a known duration, it is necessary to use the appropriate creep modulus to characterize the deformational behaviour of this article. Ogorkiewicz (4) has shown that under long term loading conditions, creep modulus of a plastic material may be significantly lower than the corresponding instantaneous modulus derived in a constant rate of elongation test.
Isochronous stress-log time for a strain value of $\varepsilon$.

The ISOCHRONOUS STRESS/STRAIN LOG TIME CURVES (BS 4618)

FIG. 4.2 CREEP CURVES,
ISOCHRONOUS STRESS/
STRAIN LOG TIME
CURVES (BS 4618)

The 100S-isochronous stress-strain curve.
Reinforced plastics also creep, but to a much lesser extent compared to the continuous phase; it is generally assumed that the glass fibre phase does not creep. Extrapolation of creep data is possible. However, in addition to temperature-based phenomena such as transitional regions, incipient ductile failure and brittle-type failure must also be taken into account.

4.2.4 Strain recovery:

In contrast to metals, the creep of plastics is recoverable. Thus, in cases where loading is essentially of an intermittent nature, the cumulative effects of creep may safely be ignored.

The rate of strain recovery may be determined in creep tests previously explained. However, the amount of experimental work can be reduced by plotting 'fractional recovery' against 'reduced time', each as defined below: (3)

\[
\text{fractional recovery} = \frac{\text{strain recovered}}{\text{creep strain immediately before load removal}}
\]

\[
\text{reduced time} = \frac{\text{recovery time}}{\text{duration of preceding creep period}}
\]

4.2.5 Effects of fibre length and orientation:

Stress distribution along a fibre of finite length \( l \), is shown in Fig. 4.3 below:

![Stress Distribution in Discontinuous Fibres](image)

**FIG. 4.3** STRESS DISTRIBUTION IN DISCONTINUOUS FIBRES FOR VARIOUS FIBRE LENGTHS (Ref. 2)
It can be seen that when the fibre length $l$ is shorter than a critical fibre length $l_c$, the stress in the fibre is lower than the stress in the continuous fibre. When the fibre length exceeds $l_c$, the stress distribution is trapezoidal, indicating that at each end of the fibre is ineffectively stressed. These ends are called critical fibre transfer lengths. For an ideal plastic material with a yield stress $\sigma_{y}$, the fibre stress increases in a linear manner from 0 to $\sigma_{f_{\text{max}}}$. It has been shown (5) that the critical fibre length $l_c$ for such a material may be calculated from the following equation:

$$l_c/d_f = \sigma_{f_{\text{max}}}/2\sigma_{y} \quad (7)$$

where $\sigma_{f_{\text{max}}}$ is the maximum fibre stress and $d_f$ is the fibre diameter. If interfacial failure occurs first, then $\sigma_{y}$ will be the average interfacial bond strength. In the above equation the ratio $l_c/d_f$ is conveniently defined as the critical aspect ratio.

For the ultimate strength of a composite containing discontinuous fibres aligned in the load direction, Broutman (2) has derived the following relationship:

$$\left(\frac{\sigma_{\text{cu}}^{\text{disc}}}{\sigma_{\text{cu}}^{\text{cont}}}\right) = 1 - \frac{1}{2\alpha} \left[1 + (\sigma_{m}/\sigma_{f_{\text{u}}})\epsilon_{f_{\text{u}}}\sigma_{f_{\text{u}}-1}\epsilon_{f_{\text{u}}}^{-1}\right] \quad (8)$$

In equation 8, subscript (cu) denotes ultimate strength of the composite, $\sigma_{\text{cu}}^{\text{disc}}$ is the matrix stress at a strain corresponding to the ultimate fibre strain, $\epsilon_{f_{\text{u}}}$, $\sigma_{f_{\text{u}}}$ is the breaking stress of the fibre and $\alpha$ is $1/l_c$.

The above relation can be plotted (2) assuming a hypothetical value of $\nu_f = 1$ (For any given $\alpha$, the ratio $\left(\frac{\sigma_{\text{cu}}^{\text{disc}}}{\sigma_{\text{cu}}^{\text{cont}}}\right)$ with $\nu_f = 1$ is less than with $\nu_f < 1$). With the fibre length $l_f$ greater than 10 $l_c$, the average stress in the discontinuous fibre calculated from equation 8 is greater than 95 per cent of the maximum stress. For a fibre length shorter than 5 $l_c$, the average stress begins to fall significantly (see Fig. 4.4).
In the case of chopped E-glass fibres in a plastic matrix, $l$ is normally greater than $100l_c$ and the average fibre stress is in excess of 99.5 per cent of the maximum stress. However, not all of the fibres are normally aligned in the direction of the load. When fibres are randomly distributed in a plane, the strength in any direction in that plane may be found by assuming that $3/8$ all the fibres are aligned in that direction. In a random volume distribution, the strength along any direction may be assumed (25) as $1/5$ of that obtained when all the fibres are assumed to align in that direction.

The strength and stiffness of a laminate reinforced by a system of reinforcement as shown in Fig. 4.5 are dependent on the direction of the testing.
It is often desirable to know the shear modulus of rigidity $G_{lt} = G_{tl}$, which is the shear modulus of the material. The ultimate stress in any direction $\sigma_\theta$ is related to the longitudinal and transverse stresses by:

$$\sigma_\theta = \sigma_l \cos^2 \theta + \sigma_t \sin^2 \theta$$

$$\sigma_\theta = \sigma_l \sin^2 \theta + \sigma_t \cos^2 \theta$$

where $\sigma_l$ is the ultimate stress in the longitudinal direction, $\sigma_t$ is the ultimate stress in the transverse direction, and $\theta$ is the angle of inclination.

The modulus at $\theta^\circ$, $E_\theta$, and the Poisson's ratio at $\theta^\circ$, $\nu_{lt}$, can be calculated from the following equations:

$$E_\theta = E_l \cos^2 \theta + E_t \sin^2 \theta$$

$$\nu_{lt} = \frac{E_l \sin^2 \theta - E_t \cos^2 \theta}{E_l \cos^2 \theta + E_t \sin^2 \theta}$$

These equations are valid for corresponding creep data (e.g., 100S, 0.2 per cent). The tensile creep modulus may be calculated from equation 10 using 100S, 0.2 per cent strain data in the longitudinal and transverse directions.

---

**Fig. 4.5 Orthotropic Laminates**

$G_{lt} = G_{tl}$ = shear modulus of rigidity

$\sigma_\theta$ = ultimate stress in direction $\theta$ to the longitudinal

$\sigma_l$ = ultimate stress, longitudinal

$\sigma_t$ = ultimate stress, transverse

$E_\theta$ = modulus at $\theta^\circ$

$E_l$ = modulus at $\theta^\circ = 0^\circ$

$E_t$ = modulus at $\theta^\circ = 90^\circ$

$\nu_{lt}$ = Poisson's ratio along $0^\circ$

$\sigma_s$ = shear stress along $0^\circ$ and $90^\circ$

$E_\theta$ and $\sigma_\theta$ may be calculated from the following equation:

$$\frac{1}{E_\theta} = \frac{\cos^2 \theta}{E_l} + \frac{\sin^2 \theta}{E_t}$$

$$\frac{1}{E_\theta} = \frac{\cos^2 \theta}{E_l} + \frac{\sin^2 \theta}{E_t} + \left(\frac{1}{G_{lt}} - 2\frac{lt/E_l}{E_t}\right)\cos^2 \theta \sin^2 \theta$$
4.2.6 Impact behaviour:

A simple impact test on a specimen cut from a plastic article is not sufficient to characterize the impact performance of that article. This is due to interaction of a number of variables including article design, method of fabrication, conditions of use and basic properties of the materials. B.S. 4618 (6) recommends a range of tests covering impact testing of plastics at various temperatures as well as practical tests on finished products.

Tests commonly employed for measuring materials' 'impact strength' (more accurately defined as the absorption of impact energy to failure), are of the flexural type, especially that of Charpy, which enables a range of notch geometries, including un-notched or bluntly notched specimens, to be tested. These tests are aimed at determining the two different components of the impact energy, viz: crack initiation energy, which is determined by testing un-notched or bluntly notched specimens and is a measure of resistance of the specimen to damage by a blow; and (b) crack propagation energy, which is determined by testing notched specimens and is a measure of the material's resistance to shattering through crack propagation.

Factors influencing the impact energy of plastics are temperature, speed of impact, stress concentration effects, anisotropy and the effects of thickness.

Reinforced plastics show improved resistance to impact blows. As an illustration, a glass fibre reinforced polyester laminate containing 30 per cent by weight of chopped strand glass may possess an un-notched strength of 14.8 J (20lbf\·ft). This is higher than an un-notched strength of cured polyester resin by a factor of approximately 50. (7)

G.R.P. is, however, found to be relatively notch-sensitive. It follows that performance of a G.R.P. article in service depends on the presence of cracks, notches, stress-whitening and other local stress raisers. (8)

4.2.7 Long term durability of plastics:

Polymer degradation occurs on the exposed surfaces of a plastic article. The energy for breakdown of polymers bonds is mainly provided by the ultra-violet radiation of the sun. Other factors influencing this degradation are temperature, wetness and the permeability of the exposed surface. This
last factor controls penetration of oxygen and escape of degradative products. (9)

Appearance of the exposed surface of a plastic article may change significantly on weathering and this in some cases may be sufficient to render that article aesthetically unacceptable. Mechanical properties of plastics may also decline on weathering, especially tensile strength and impact strength, which are sensitive to surface deteriorations. In extreme cases, bulk properties may also be affected.

Changes in optical, mechanical and surface appearance properties are not interrelated (9), so that observation of a single property is not an adequate measure of the weathering performance of a plastic material. The phenomena which lead to failure of plastics on weathering are complex and are different with different materials, i.e. some plastics deteriorate more than others. The degradation of plastics normally starts through the polymer chain irregularities, so any theoretical assessment of the stability of polymer chain structure may be irrelevant.

Fillers and pigments have a major effect on appearance and durability of plastics. Use of flame-retardant additives leads to gradual yellowing of the exposed surfaces of plastics.

Reproduction or simulation of natural weathering conditions on an accelerator basis in the laboratory has so far been unsuccessful. This has been partly due to difficulties of correlating the results of the accelerated laboratory tests with natural weathering conditions and partly due to lack of interrelationship amongst various optical, mechanical and surface appearance properties of a plastic material. (9)

B.S. 4618 (10) recommends natural weathering trials for the following exposure durations: 3 months, 6 months, 1 year, 2 years, 4 years, 6 years, 8 years, 10 years or such longer periods as necessary. Climates are also broadly classified into five different types: (i) hot and dry; (ii) hot and wet; (iii) mesothermal; (iv) temperate; and (v) cold. Industrial and marine conditions are also distinguished.

Trial conditions are generally recommended to be simulative of the normal service. However, effects of periodical cleaning are separately catered for by a second series of specimens subjected to the proposed cleaning treatment.
Weathered specimens are assessed against control specimens under closely defined conditions and the following are observed: (a) changes in dimensions; (b) changes in visual appearance; (c) changes in mechanical properties; and (d) biological attacks.

4.2.7.1 Changes in dimensions:
These are measured in standard conditions and are expressed in proportion to the original values.

4.2.7.2 Changes in appearance:
These are recorded using the following scale: 0 (none), S (slight), M (moderate), L (large). The visual properties examined include the following: (i) colour change and its pattern; (ii) opacity; (iii) gloss or roughness of surfaces; and (iv) occurrence of crazing, blistering, pitting, chalking, warping and delamination.

4.2.7.3 Mechanical properties:
These may be selected from the following:
(1) Tensile strength, elongation at break and tensile elongation.
(2) Flexural strength, deflection at break and elongation modulus.
(3) Shear strength.
(4) Impact strength.
(5) Other properties if considered appropriate.

4.2.7.4 Biological attacks:
Exposed surfaces of naturally weathered specimens must also be studied under low power magnification to detect presence of any organic growths. These surfaces must then be washed and re-examined to determine the nature, location and extent of any damage due to the organic growths (e.g. pitting).

Ultra-violet stabilizers may be used in plastics. These will absorb the greater part of the ultra-violet energy and will therefore extend the useful life of plastics in exposed conditions.

4.2.8 Cyclic loading and dynamic fatigue:
Behaviour of a plastic material under cyclic loading or dynamic fatigue (static fatigue is normally used to define failure through creep rupture), is governed by the following
factors: (a) its visco-elasticity; (b) heat generation due to its low thermal conductivity; and (c) its high mechanical hysteresis. Thus the frequency of the loading and testing mode affect the fatigue behaviour of a plastic material; to avoid thermal softening, frequencies as low as 0.1 - 10 Hz have been recommended (8). Also, the square load wave has been recommended in preference to the sine load wave, because it makes comparison with static loading possible.

The fatigue phenomenon can affect the mode of failure of plastics, i.e. beyond a small number of cycles, a potentially ductile plastic material may fail by brittle fracture (4).

In the case of G.R.P., the evidence available indicates that its fatigue strength is considerably lower than its static strength under constant continuous loading. (4) Better adhesion of glass fibre to matrix has been found to improve the fatigue strength of G.R.P. Thus, glass fibre reinforced epoxide resins show the highest fatigue strength (2).

4.2.9 Choice of reinforced plastics for constructional applications:

Table 4.3 summarizes the fabrication modes of those reinforced plastics which are commonly used in building applications; decorative laminates, glass reinforced polystyrene and nylon have also been included for comparison (11). From this Table it is evident that polyester resins reinforced with glass fibre are by far the most common type of plastics employed for structural and cladding purposes in the construction industry. This is due to the following reasons:
(a) relative cheapness of polyester resins (c.f. Table 4.4);
(b) high strength to weight ratio of G.R.P. (c.f. Table 4.6);
(c) wetting properties and versatility in respect of moulding processes of polyesters, particularly their suitability for contact pressure moulding, which permits large and often complex mouldings to be produced at relatively low capital costs; (d) versatility of polyesters in respect of resin formulations and qualities, especially regarding fire retardancy treatments; (e) good heat-resisting and dimensional stability of G.R.P. mouldings; and (f) translucent potentiality of G.R.P. (see Chapter 5 for details of G.R.P.).

Epoxide resins are also available in liquid form which
Table 4.3 Fabrication Modes of Reinforced Plastics

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Plastics Material</th>
<th>Moulding Method</th>
<th>Uses and Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>Phenolic</td>
<td>Compression moulded into sheet form</td>
<td>Used for flat sheets as back-up for decorative or as industrial laminated sheet. Moulded by batch process in multi-daylight high pressure presses.</td>
</tr>
<tr>
<td>Paper</td>
<td>Polyester</td>
<td>Compression moulded into sheet form</td>
<td>Used for flat sheets as decorative laminate. Can be continuously produced on heated drums, at little more than atmospheric pressures. Printed surfacing paper is used to obtain decorative effects.</td>
</tr>
<tr>
<td>Paper</td>
<td>Epoxide</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Cotton (cloth or loose fibres)</td>
<td>Phenolic</td>
<td>Compression moulded into a finished shape</td>
<td>Formed and used exactly as conventional phenolic mouldings, but the cotton fibres (or fabric) help to stabilise the material and reduce brittleness, thermal movement.</td>
</tr>
<tr>
<td>Sisal</td>
<td>Polyester</td>
<td>Compression moulded into a finished shape</td>
<td>Moulded with matched polyester tools under a low pressure or normal matched metal tools in a compression moulding press. Some tendency towards water sensitivity. Lower cost, higher bulk factor than glass fibres. Much lower tensile strength. Therefore of interest for non-stressed mouldings for interior use where polyester techniques are being utilized.</td>
</tr>
<tr>
<td>Jute</td>
<td>Polyester</td>
<td>Compression or hand lay moulded into a finished shape</td>
<td>As woven cloth, can be moulded into large radius mouldings, by hand lay process, as bulking medium, provided interlaminar air and tendency to delaminate under stress as a result are taken into account. Also compression moulded at low or high</td>
</tr>
</tbody>
</table>
Table 4.3 Fabrication Modes of Reinforced Plastics (Continued)

<table>
<thead>
<tr>
<th>Reinforcement</th>
<th>Plastics Material</th>
<th>Moulding Method</th>
<th>Uses and Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jute</td>
<td>Polyester</td>
<td></td>
<td>pressures. Useful as a cheaper reinforcement for thickening up (and therefore stiffening) machine guards and similar non-stressed parts.</td>
</tr>
<tr>
<td>Asbestos paper</td>
<td>Phenolic</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Asbestos felt</td>
<td>Phenolic</td>
<td>Compression moulded into a finished shape</td>
<td>Pre-impregnated material which can be high pressure moulded into a fairly complex shape with excellent high temperature performance characteristics, good thermal stability and great resistance to abrasion and wear. Aircraft heater ducting, fan blades, electrical parts are examples of typical use.</td>
</tr>
<tr>
<td>Asbestos flock</td>
<td>Phenolic</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Asbestos fibre</td>
<td>PVC</td>
<td>Compression moulded into sheet form</td>
<td>Supplied as semi-prepared material; for medium-pressure compression moulding into sheets in flat-bed presses or a finished compressed material for vacuum forming, and for rubber-bed pressing, also available with a coloured surfacing film to give good weathering and attractive surface gloss. Having higher impact strength, greater stability across a wide temperature range and greater stiffness than conventional PVC, the material can perform many of the functions of unreinforced PVC at up to 40 per cent cost savings. This material has great potential in building industry applications.</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>Plastics</td>
<td>Moulding Method</td>
<td>Uses and Characteristics</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------</td>
<td>-----------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Asbestos fibre</td>
<td>Polyester</td>
<td>Compression moulded into sheet and finished shapes</td>
<td>High stiffness factor with consequent savings on thickness, i.e. materials content. Improved fire performance, and therefore of strong interest in building.</td>
</tr>
<tr>
<td>Glass fibres</td>
<td>Polyester</td>
<td>Compression, hand lay or otherwise moulded into a finished shape</td>
<td>The widest used reinforced material, moulded by hand lay methods; matched polyester tools; rubber bag and vacuum; autoclave; continuous low pressure laminating; by using matched metal tools at medium pressure on a compression moulding press; by &quot;pultrusion&quot;; or by filament winding. Highest tensile strength of any plastics material known weight for weight. Can be translucent. Very versatile in respect of raw material forms and qualities, moulding methods, and finished article complexity.</td>
</tr>
<tr>
<td>Glass fibres</td>
<td>Epoxide</td>
<td>Compression or hand lay moulded into a finished shape</td>
<td>Hand lay moulded or compression moulded, mainly for high level chemical resistance.</td>
</tr>
<tr>
<td>Glass fibres</td>
<td>Phenolic</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>Glass fibres</td>
<td>Polystyrene</td>
<td>Injection moulded into a finished shape</td>
<td>An injection moulding material combining the cheapness and transparency of polystyrene with the moulding and tensile properties of glass to give a much improved dimensional stability, moderate heat distortion point (220°F), good stiffness and impact strength. Used for very large injection moulded parts, automotive applications, fan blades, etc.</td>
</tr>
<tr>
<td>Reinforcement</td>
<td>Plastics Material</td>
<td>Moulding Method</td>
<td>Uses and Characteristics</td>
</tr>
<tr>
<td>---------------</td>
<td>------------------</td>
<td>-----------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>Glass fibres</td>
<td>Nylon</td>
<td>Injection moulded into a finished shape</td>
<td>Like glass/polystyrene, an injection moulding material of improved heat distortion point (500°C), lower water absorption; lower elongation, higher tensile and flexural strength than unreinforced nylon, e.g. thermal coefficient of expansion improves from about 60 to about 10; tensile strength from about 11.5 to about 20; compressive strength from about 10 to about 20; and flexural strength from about 10 to about 30.</td>
</tr>
<tr>
<td>Glass fibres</td>
<td>Melamine</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Glass fibres</td>
<td>Silicone</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
can be reinforced in a manner similar to polyester resins. Reinforced epoxide resins show greater strength and higher heat-resistance compared with polyesters; however, they are not generally used owing to the high cost of the resin.

Phenolic resins are used extensively as mouldings powders, often filled with a filler such as wood flour, asbestos, glass fibre, mica, etc., each to improve a particular property. Phenolic resins are also used in the compression mouldings for industrial and decorative laminates. The reinforcement chosen for a laminate of this type depends on the application; paper, fabrics, glass fibre and asbestos are commonly employed.

Phenolic laminates are limited in application because of their dark colours. However, the new phenolic/melamine combinations improve this considerably.

Laminates based on urea, melamine and phenol formaldehyde in the form of rigid sheets suitable for exterior and interior claddings have been manufactured since the Second World War. However, externally, G.R.P., P.V.C.-coated aluminium and steel sheets and asbestos reinforced P.V.C. are more competitive in price and are generally preferred.

Phenolic resins and polyurethanes are foamed and used as core materials for the structural sandwich panels faced with a variety of materials. These applications will be considered in a more appropriate place.

Thermoplastics can be reinforced using a variety of fibres and fillers such as glass, asbestos, powdered metal, whiskers and carbon fibres. The use of these can improve properties of thermoplastics considerably and narrow the gap between these and reinforced thermosets or metals. Glass fibre is generally used; however, high amounts (i.e. greater than 50 per cent by weight) must be included to bring the specific stiffness of thermoplastics nearer to metals. Whiskers (i.e. single crystals with high stiffness) offer substantial improvements as reinforcement, but they are difficult to produce and are prohibitively expensive. Carbon fibres may be used, but the present price level of this material is high and the colour is a restriction, especially on building applications.

The technology for incorporation of fibres into thermoplastics is different from thermosets, as no chemical curing takes place during the moulding process. The technique normally used for inclusion of glass fibres involves impregnating
continuous rovings or strands with the hot molten resin. On cooling, they are chopped into small cylindrical pellets which may be used in normal thermoplastics' moulding processes, e.g. in injection moulding.

The fibres used are short in length, typically 7 to 12mm, although shorter fibres have been used. The composite properties will depend on the following factors: (a) fibre volume fraction; (b) glass fibre surface treatment (for good bonding); (c) fibre dispersion; and (d) fabrication process employed.

Table 4.5 includes typical values for some reinforced thermoplastics. Reinforced nylon shows the greatest improvement in tensile strength, tensile modulus, creep and elongation. However, both nylon and polycarbons are very expensive plastics (see Table 4.4), and when reinforced they are not as strong as glass reinforced polyesters (c.f. Table 4.6). Other limiting factors include high capital costs for mouldings, limitation on complexity and size of mouldings, low heat distortion temperatures and, finally, the difficulty of processing highly fibre (or filler) filled thermoplastics.

Of particular interest to the building industry is asbestos reinforced P.V.C. which can be coated using attractive and durable resins. The composite is prepared in a factory and processed using a variety of moulding techniques, viz: (a) vacuum-forming; (b) compression moulding; (c) thermoforming, etc.

The technology of reinforcing and processing thermoplastics is relatively new, and further developments are expected in this field, especially processing techniques such as injection moulding sandwich panels.

4.2.10 Fire behaviour of plastics:

Plastics are generally combustible materials and burn or decompose when in contact with fire or subjected to intense heat.

Full understanding of fire behaviour of the main plastics used in building applications is the subject of current research at the Fire Research Station (F.R.S.).

Constructional applications of plastics have been growing at a steady rate and are expected to continue to grow, as can
### Table 4.4 Plastic Material Prices (as on 5th September, 1975)
Source: Rubber and Plastics Weekly

<table>
<thead>
<tr>
<th>Materials</th>
<th>Price per 1 tonne-lots (pence/kg)</th>
<th>Price per 20 tonne-lots (pence/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoplastics:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>390</td>
<td>340</td>
</tr>
<tr>
<td>High Density Polyethylene</td>
<td>361</td>
<td>320</td>
</tr>
<tr>
<td>PVC (unplastic'd comp'd natural)</td>
<td>385</td>
<td>375</td>
</tr>
<tr>
<td>ABS</td>
<td>710</td>
<td>650</td>
</tr>
<tr>
<td>Nylon 6.6</td>
<td>1060</td>
<td>1042</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>1310</td>
<td>1160</td>
</tr>
<tr>
<td>Thermosets:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenol Formaldehyde</td>
<td>325</td>
<td>-</td>
</tr>
<tr>
<td>Urea Formaldehyde</td>
<td>416</td>
<td>-</td>
</tr>
<tr>
<td>Melamine Formaldehyde</td>
<td>610</td>
<td>-</td>
</tr>
<tr>
<td>Polyester*</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Polyester (D.M.C.)</td>
<td>525</td>
<td>-</td>
</tr>
</tbody>
</table>

* Source: Reinforced Plastics (monthly)

### Table 4.5 Properties of Reinforced Thermoplastics (Reference 2)

<table>
<thead>
<tr>
<th>Property</th>
<th>Nylon 6.6</th>
<th>Polycarbonate</th>
<th>Polystyrene</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0% 20%* 40%* 70%*</td>
<td>0% 20%* 40%*</td>
<td>0% 30%</td>
</tr>
<tr>
<td>S.G.</td>
<td>1.14 1.31 1.41  -</td>
<td>1.2 1.31 1.44</td>
<td>1.05 1.28</td>
</tr>
<tr>
<td>Ten. strength (MN/m²)</td>
<td>96 152 200 207</td>
<td>65.5 107 131</td>
<td>45 96.5</td>
</tr>
<tr>
<td>Ten. modulus (MN/m²)</td>
<td>2.76 7.7 11 21.4</td>
<td>2.2 6 10.3</td>
<td>2.76 8.3</td>
</tr>
<tr>
<td>Elong. (%)</td>
<td>60 5 5 4</td>
<td>100 7 2</td>
<td>2 1.1</td>
</tr>
<tr>
<td>Heat dist. T (18 MN/m²)</td>
<td>65 &gt;240 &gt;240 &gt;240</td>
<td>139 150 153</td>
<td>84 105</td>
</tr>
</tbody>
</table>

* - 6.3mm long fibres    " - 0.76mm long fibres
Table 4.6  Typical Physical Properties of Reinforced Plastics and some Traditional Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Spec. Grav. $\gamma$ (MN/m$^2$)</th>
<th>T. st. $E$ (GN/m$^2$)</th>
<th>T. mod. $E'$ (GN/m$^2$)</th>
<th>Spec. st. $\varepsilon_\text{st}$ (MN/m$^2$)</th>
<th>Spec. mod. $\varepsilon_\text{mod}$ (GN/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester 55 wt. % glass cloth</td>
<td>1.7</td>
<td>300</td>
<td>15</td>
<td>180</td>
<td>9</td>
</tr>
<tr>
<td>Polyester 30 wt. % glass mat</td>
<td>1.4</td>
<td>100</td>
<td>7</td>
<td>70</td>
<td>5</td>
</tr>
<tr>
<td>Nylon 6.6 40 wt. % glass</td>
<td>1.41</td>
<td>200</td>
<td>11</td>
<td>142</td>
<td>7.8</td>
</tr>
<tr>
<td>Polycarbonate 40 wt. % glass</td>
<td>1.44</td>
<td>131</td>
<td>10.3</td>
<td>91</td>
<td>7.15</td>
</tr>
<tr>
<td>Polystyrene 30 wt. % glass</td>
<td>1.28</td>
<td>96.5</td>
<td>8.3</td>
<td>75.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Rigid PVC (General Purpose)</td>
<td>1.4</td>
<td>58.5</td>
<td>2.6</td>
<td>41.8</td>
<td>1.86</td>
</tr>
<tr>
<td>Mild Steel</td>
<td>7.8</td>
<td>400</td>
<td>200</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Aluminium (Duralumin)</td>
<td>2.8</td>
<td>450</td>
<td>70</td>
<td>150</td>
<td>25</td>
</tr>
<tr>
<td>Softwood timber (Douglas Fir)</td>
<td>0.5</td>
<td>75</td>
<td>10</td>
<td>150</td>
<td>20</td>
</tr>
<tr>
<td>Hardwood (Hickory)</td>
<td>0.8</td>
<td>150</td>
<td>15</td>
<td>200</td>
<td>19</td>
</tr>
</tbody>
</table>
be seen from the data in Tables 4.7 and 4.8 (12). The increased utilization of plastics in the construction industry must be considered in the light of the fire statistics. For example, in about 1 per cent of all fires occurring in buildings in 1971, plastics were first to ignite. The proportion of all casualties due to toxicity and effects of gases increased by a factor of 3 in the period 1955 - 1971.

Factual data relating the increased number of injuries due to smoke to that of greater use of plastics materials in buildings are not available. However, it has been established that plastics generally produce greater amounts of smoke compared with traditional materials (12).

Products of pyrolysis of certain plastics have been investigated. P.V.C. has been found to produce hydrogen chloride in addition to carbon monoxide, which is present in the pyrolysis of all combustible materials, and polyurethane emits hydrogen cyanide. Laminated boards produce slight quantities of formaldehyde, phenol and cresols, wood produces only carbon monoxide, and wool produces hydrogen cyanide in addition to carbon monoxide.

The smoke density of polyurethanes in full scale fire tests have been observed to be higher than that due to wood by up to 100 per cent. Generally, P.V.C. creates more smoke than wood, but may - if the state of ventilation, temperature and rate of fire growth are correct - produce less. Emission of hydrogen chloride from P.V.C. and hydrogen cyanide from polyurethane have been found to be higher in a freer state of burning. Wood produces more carbon monoxide in a more restricted form of combustion (12).

Unfilled polyester resins burn with considerable ease. Nitric acid resins (those which have in-built chlorine or bromine in their molecules) show improved resistance to molecular decomposition, but, like antimony trioxide/chlorinated-wax filled resins, produce more smoke, especially in restricted forms of combustion (13). (See subsection 5.4.3).

A fire usually develops through three stages, viz: (a) fire growth. This stage includes ignition, flammability, spread of flame, heat release and production of smoke and toxic gases; (b) steady combustion. In this stage fire continues in a rather steady regime; and (c) fire decay. The decay stage in a fire is not normally attained until virtually
Table 4.7 Main Applications of Plastics in Building - Approximate Estimates

<table>
<thead>
<tr>
<th>Application</th>
<th>U.K. (a) Consumption 1966 (x 1000 tons)</th>
<th>U.K. (b) Consumption 1968 (x 1000 tons)</th>
<th>U.K (c) Consumption 1972 (x 1000 tons)</th>
<th>Estimate of Annual Growth Rate - 1980 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipework,</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plumbing</td>
<td>35</td>
<td>74.8</td>
<td>86.2</td>
<td>II</td>
</tr>
<tr>
<td>Floor covering</td>
<td>30</td>
<td>32.5</td>
<td>28.5</td>
<td>I</td>
</tr>
<tr>
<td>Daylighting</td>
<td>10</td>
<td>15.6</td>
<td>9.6</td>
<td>7</td>
</tr>
<tr>
<td>Insulation</td>
<td>7</td>
<td>11.8</td>
<td>12.5</td>
<td>15</td>
</tr>
<tr>
<td>Waterproofing</td>
<td>-</td>
<td>16.6</td>
<td>18.3</td>
<td>9</td>
</tr>
<tr>
<td>Decorative uses</td>
<td>)</td>
<td>)</td>
<td>)</td>
<td>II</td>
</tr>
<tr>
<td>Structural uses</td>
<td>8</td>
<td>23.4</td>
<td>1.5</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>)</td>
<td>)</td>
<td>)</td>
<td></td>
</tr>
</tbody>
</table>

(b) Source: The Plastics Industry and its Prospects, NEDO, I972
(c) Source: Reference I2
(d) Source: Reference I2, based on the oil supply prior to I973
Table 4.8 U.K. Consumption of Plastics in Building

<table>
<thead>
<tr>
<th>Material Type</th>
<th>U.K. (a) Consumption 1966 (x 1000 tons)</th>
<th>U.K. (b) Consumption 1968 (x 1000 tons)</th>
<th>U.K. (c) Consumption 1972 (x 1000 tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC</td>
<td>94</td>
<td>114.2</td>
<td>112.5</td>
</tr>
<tr>
<td>UF and PF</td>
<td>-</td>
<td>55.8&quot;</td>
<td>50&quot;</td>
</tr>
<tr>
<td>PE and PP</td>
<td>15</td>
<td>26.3</td>
<td>33.2</td>
</tr>
<tr>
<td>PS</td>
<td>12</td>
<td>II.4</td>
<td>16.9</td>
</tr>
<tr>
<td>UP</td>
<td>5.5+</td>
<td>7.8+</td>
<td>9.2</td>
</tr>
<tr>
<td>PU</td>
<td>-</td>
<td>2.4</td>
<td>8.0</td>
</tr>
</tbody>
</table>

For (a), (b) and (c) refer notes under Table 4.7
" - includes furniture uses as well
+ - Source: British Plastics (now: European Plastics News)

Table 4.9 Total import-content as percentages of final output of selected materials' industries - 1968 (Reference I9)

<table>
<thead>
<tr>
<th>Material industry</th>
<th>Direct import-content</th>
<th>Indirect import-content</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plastics</td>
<td>II.9</td>
<td>II.4</td>
<td>23.3</td>
</tr>
<tr>
<td>Non-ferrous metals</td>
<td>42.9</td>
<td>5.4</td>
<td>48.3</td>
</tr>
<tr>
<td>Cans and metal boxes</td>
<td>4.2</td>
<td>II.2</td>
<td>15.4</td>
</tr>
<tr>
<td>Pottery and glass</td>
<td>3.1</td>
<td>7.0</td>
<td>10.1</td>
</tr>
<tr>
<td>Timber and wood manufacture</td>
<td>29.9</td>
<td>5.5</td>
<td>35.4</td>
</tr>
<tr>
<td>Paper and board</td>
<td>29.0</td>
<td>6.4</td>
<td>35.4</td>
</tr>
<tr>
<td>Paper products</td>
<td>I6.9</td>
<td>IO.6</td>
<td>27.5</td>
</tr>
</tbody>
</table>
all the available combustible materials have been used up.

The behaviour of materials in the first stage is termed 'reaction-to-fire', which includes such aspects as ignitability, flammability, spread of flame, rate of heat release and emission of toxic gases and smoke. The fire-resistance of a building concerns the ability of that building to confine the fire within each of its compartments and to remain stable throughout the fire. Fire-resisting requirements of different elements of a building are therefore related to the amount of combustible materials present in the compartment. Other factors which affect the fire-resisting requirements are the functions of that compartment and its position relative to the building boundary lines.

Building Regulations require performance levels for building elements, panels and boards which are to be assessed in accordance with the following scale tests:

I - Reaction to fire:
(a) B.S. 476: part 3. External fire exposure roof test.
(b) B.S. 476: part 4. Non-combustibility tests for materials.
(c) B.S. 476: part 6. Fire propagation tests for materials.
(d) B.S. 476: part 7. Surface spread of flame test for materials.

II - Fire-resistance:
B.S. 476: part 8. Test methods and criteria for fire resistance of elements of building construction.

Plastics are generally classed as combustible materials when tested to the B.S. 476: part 4. Materials used as lining on walls and ceilings are mostly required to achieve a performance index of 12 or below when tested to the B.S. 476: part 6. (A low index of performance indicates a low potential for heat contribution and is therefore desirable; see also 5.4.3 for details.). The maximum specified index for cladding materials is 20. By the use of both organic and inorganic fillers in plastics various performance levels may be obtained; however, a very low index can only be achieved if the amount of organic material present in the specimen is reduced substantially (14).

Four classes of spread of flame are distinguished in accordance with the B.S. 476: part 7. Class 1 shows that a
material does not support spread of flame. Classes 2 and 3 indicate lower levels of performance respectively. Class 4 is in excess of Class 3. Achievement of Class 1 is possible with plastics but not recommended, owing to poor weathering performance associated with the highly filled plastics (15).

With reference to 'fire-resisting' performance, no plastic material has, to date, achieved any measurable performance when tested to the B.S. 476: part 8.

4.2.11 Prospects for plastics in the construction industry:

To a large extent, supply of oil controls the availability and prices of plastics, e.g. in 1973, the delivery of petroleum products to the petrochemical industry was 7082 thousand tons or about 6.8 per cent of the total deliveries (16). This was approximately 42.5 per cent of the total deliveries of petroleum for use as motor spirits (16).

In response to the recent increases in the price of oil, prices of plastics have risen, though to varying levels. The effect of these price increases on the competitiveness of plastics against other materials has been considered in Chapter 12 (see sections 12.5 and 12.6 in particular). One of the main conclusions reached in the above study is that traditional materials (with the exception of wood) are not spared from the effects of high costs of energy: this applies particularly to aluminium, brick, concrete and steel. In fact, from the standpoint of the total energy-input per unit area (or unit length or unit volume, whichever the case may be), plastics-based products are less energy-intensive compared with other products of equivalent performance made from metals and/or traditional masonry materials. However, plastics products are considerably more energy-intensive compared with the corresponding wood-based products.

The above findings are confirmed by ICI (Petrochemicals Division) in a recent study (17); however, the weakness of this study lies in its method of energy accounting, as no account has been taken of the considerable quantities of energy lost due to extraction, processing, transmission and/or transportation of fuels. These losses can be very significant e.g. of the order of 17 per cent for oil (see 12.5); as has been illustrated in Chapter 12, if these losses are also
taken into consideration, the energy gaps between plastics products and iron and steel products will be narrower than those given by ICI (17).

A separate study by HEDO (18) aims at identifying the prospects for the plastics industry, i.e. partly due to the reduced demand for plastics products stemming from the general economic recession, and partly as a result of continued rising costs of feedstocks. This study predicts (18) some setback for the plastics industry; however, it also points out the high degree of uncertainty associated with the supply and prices of basic chemicals and feedstocks (see also 12.6).

The dependence of plastics on oil-based chemicals may lead to a false impression that plastics are import-intensive and are therefore undesirable in terms of the country's external trade. In 1968, the Plastics Working Party of the Chemicals E.D.C. attempted (19) to analyse the situation. In their report, they stated (19) that in 1968 imports of oil amounted to only one per cent of the value of final output of the plastics industry. Table 4.9 sets out the total import-contents for materials' industries in 1968.

As can be seen, plastics contain very much less 'import-content' than non-ferrous metals or timber and allied products. The import-content of plastics could be further reduced if foreign purchases of materials which could be produced in the U.K. were avoided. If all such purchases were produced in the U.K., the total import-content would have been of the order of 13.2 per cent, or less than all other materials except pottery and glass (see Table 4.9).

It is obvious that, owing to the fourfold rise in the cost of imported oil, the above analysis is not a clear indication of the picture today; a more accurate analysis must be based on an up-to-date national 'Input-Output' table.

However, allowing for a fourfold increase in the cost of raw materials, the import-content of plastics will still be generally less than either non-ferrous metals or timber (see also sections 2.2, 12.1, 12.3, and 12.4).
4.5 General Considerations concerning Composite Fibrous Materials with a Brittle-Type Matrix:

4.5.1 Introduction:

Reinforcement of brittle-type matrix materials, especially cement and concrete, by addition of short discrete fibres has been the subject of continuous research and activity in recent years. This is reflected in the rapid development of theory and also the recent surveys published by the Concrete Society (CS) (20) and the American Concrete Institute (ACI), on the potential of fibre reinforced concrete (F.R.C.) in the construction industry (21). The CS report deals with all composites, with no limitation on fibre type and reinforcing arrangements. In contrast, the ACI report deals with steel fibre reinforced concrete only. The CS report states a number of interesting findings, viz: (a) the elastic moduli of most economically viable fibres are not high relative to the matrix; (b) because of the very low ultimate strain of the matrix in tension, cracking takes place at an early stage of stressing and fibres do not sustain any significant load until the matrix has cracked heavily; (c) the nature of the fresh mixes is such that only a limited amount of fibres can be included; (d) the interfacial bond between the fibre and the matrix is not continuous; and (e) the hydraulic phase of the composite remains highly alkaline for a long period of time, which has deleterious effects on some types of fibres.

The CS report takes the view that cement and fibres are not therefore ideal partners. It is pointed out in this report that the fibre to matrix stiffness ratio has to exceed a minimum value if the composite elastic modulus is to be higher than the matrix. This minimum value is 12 when fibres are randomly distributed in a volume and 5 when fibres are randomly distributed in a plane. Composite materials of importance to this study are glass fibre reinforced cement and gypsum plaster (G.R.C. and G.R.G.), steel fibre reinforced concrete (S.R.C.) and Polypropylene Concrete (P.P.C.). The first group is discussed separately in section 4.4 and others are combined and discussed in section 4.5 below.

4.3.2 Theoretical considerations:

Fig. 4.6 indicates a schematic curve of load vs deflection appropriate to composites formed by incorporation of stiff
fibres into a brittle-type matrix.

FIG. 4.6 SCHEMATIC LOAD vs DEFLECTION CURVE

Up to point 1 on the above curve the composite behaves elastically. The stress corresponding to this point is termed 'first cracking strength' or 'elastic limit'. The first cracking strength is generally significantly higher than the corresponding matrix strength, and can be predicted theoretically, either using composite mixture rules or by applying fracture mechanics.

The stress corresponding to point 2 is defined as 'ultimate strength'. The composite ultimate strength depends on the type and volume fraction of fibres and the interfacial bond between the fibre and matrix (22).

Romualdi and Batson (23) have proposed that the increase in the first cracking strength of the composite relative to the matrix is due to the fact that the stress intensity factor is reduced by closely spaced fibres which act as crack arrestors. The average fibre spacing is calculated from expression:

\[ s = 13.8d \times \sqrt{1/P} \]

Where \( s \) is the average fibre spacing, \( d \) is the fibre diameter.
and \( p \) is the volume percentage of fibres. In accordance with Romualdi et al. (23), the shorter the average spacing, the higher the tensile strength of the composite.

By application of the lower bound of the Voight estimate (22), the composite elastic stiffness and tensile strength can be related to the elastic properties of the fibre and matrix and also to their volume fractions:

\[
E_c = \eta_0 x E_f x V_f + E_m(1-V_f) \tag{12}
\]

\[
\sigma_c = \eta_0 x \sigma_f x V_f + \sigma_m(1-V_f) \tag{13}
\]

The definitions of the terms used in equations 12 and 13 are as given in 4.2.2 (\( \eta_0 \) and \( \eta_1 \) are defined below).

For the above equations to apply, perfect interfacial bonds must exist and the matrix and fibre Poisson's ratios must be identical.

\( \eta_0 \) is the efficiency factor for fibre orientation. Krenchel (25) shows that \( \eta_0 = 1 \) when fibres are aligned in the load direction, 3/8 and 1/5 for fibres randomly distributed in a plane and in a volume respectively.

Krenchel (25) has derived \( \eta_1 \), the length efficiency factor: \( \eta_1 = 1 - l_c/2l \); where \( l \) is the fibre length and \( l_c \) is the critical fibre length (c.f. subsection 4.2.5);

The CS report (16) includes a range of theoretically derived expressions taking into account the effects of different Poisson's ratios of the composite constituents.

The ultimate strength of a composite made of steel fibre concrete, \( S_c \), may be determined from the following empirically derived expression(21):

\[
S_c = A x S_m(1-V_f) + B x V_f x 1/d \tag{14}
\]

where \( l \) and \( d \) are fibre length and diameter respectively. \( A \) and \( B \) are constants determined from graphs of the composite strength vs \( V_f x l/d \).

For other composites with brittle matrix materials, no expressions have been developed.

The ACI (21) defines composite toughness as the total energy absorbed before complete separation of the specimen ends. Toughness of fibre reinforced materials has been reported to be substantially higher than those of the
unreinforced matrix. However, no quantitative relationship has been reported.

4.4 Glass fibre Reinforced Cement (G.R.C.) and Glass Fibre Reinforced Gypsum plaster (G.R.G.):

4.4.1 Methods of fabrication:

There are two basic requirements in choosing the correct method for inclusion of short glass fibres into these matrix materials, viz: (a) fibres must be uniformly dispersed without adversely affecting the matrix density; and (b) damaging of fibres must be avoided as far as possible during the mixing processes or fabrication operations.

There are two successful methods: (1) The direct mixing of short fibres into the slurry of cement or plaster. The excess water has to be removed by application of pressure and suction through the perforated mould surface. The drawbacks of this process are the limitations on the amount of glass fibre which can be included (i.e. up to a maximum of 6 per cent by weight) and the random distribution of fibres which results in reduced flexural strength in the plane of moulding. (2) The spray suction process. This process involves mixing streams of chopped glass rovings and cement or plaster slurry. The mixture is sprayed onto the surface of a perforated metal mould. The excess water is extracted by application of a negative pressure. The tendency is for fibres to orientate randomly in the plane of moulding, resulting in a higher planar strength. The method lends itself to mechanization and is more efficient than the direct mixing process since higher amounts of glass fibre can be incorporated (approximately 10 per cent by weight).

4.4.2 The factors affecting properties of G.R.C. and G.R.G. are:

(a) Water/solid ratio which controls the density and strength of the composite. In the case of cement, the strength is also time-dependent.

(b) Wetting properties of the fresh mix. Because of the particulate nature of the cement and plaster slurry, fibres are not uniformly wetted by the matrix. Beyond a certain fibre volume fraction, the density and strength of the composite decreases by addition of more fibres.
(c) The interfacial fibre/matrix bond is discontinuous. In the case of cement, there is an interaction between the fibre and the matrix; and

(d) The modulus of elasticity of fibres is 4 to 5 times that of the matrix (see Table 4.10). The ultimate tensile strain of the matrix is very low, around 0.04 to 0.06 per cent, compared with that of fibres, around 2 to 3 per cent. In addition, the tensile strength of the matrix is low (1.4 to 6.9 N/mm²). Thus the combination of the above factors results in a heavily cracked matrix by the time the fibres develop a significant stress.

4.4.3 Durability of G.R.C.:

Before embarking on any discussion on the short-term mechanical properties of G.R.C., it is essential to discuss the uncertainty about the durability of this composite. Because of the severe attack by the alkali present in the cement matrix on normal E or A glass fibres, these fibres cannot be used for long-term reinforcing purposes. Attempts have recently been made by Pilkingtons in association with the Building Research Station (B.R.S.) to develop alkali-resistant glass compositions (26, 27, 28, 29 and 30). The Na₂O - SiO₂ - ZrO₂ composition was found to show improved resistance to the attack of alkali. Table 4.11 shows the chemical composition of this glass compared with E and A glasses.

Fig. 4.7, which has been reproduced from reference 27, indicates the extent of damage in terms of reduction in tensile strength, sustained by alkali-resistant glass fibre in a solution simulating hydrating Portland cement at 80°C. It can be seen that this type of glass fibre is not substantially immune from the alkali effect. This is confirmed by reference to Figures 4.8 and 4.9 which show distinct deterioration with age, in mechanical properties of G.R.C. composites containing alkali-resistant glass fibre (26). Prediction of the long-term behaviour of G.R.C. in various environments is not possible, and any extrapolation of the short term trends can be misleading. The dotted line in Figures 4.8 and 4.9, as drawn by Steele (26), can give the false impression that the long term properties of G.R.C. can be obtained by extrapolating the short term trends. The plotting of the data on a
Table 4.10  Properties of Basic Materials used in G.R.C. and G.R.G. composites (Reference 28)

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Elastic Mod. (GN/m²)</th>
<th>Comp. Strength (N/mm²)</th>
<th>Ten. Strength (N/mm²)</th>
<th>Mod. of Rupture (N/mm²)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardened cement paste</td>
<td>7 - 28</td>
<td>14 - 140</td>
<td>1.4 - 7</td>
<td>2.8 - 14</td>
<td>1.7 - 2.2</td>
</tr>
<tr>
<td>Set gypsum plaster</td>
<td>14 - 20</td>
<td>7 - 50</td>
<td>1 - 7</td>
<td>2.8 - 20</td>
<td>1.1 - 2.1</td>
</tr>
<tr>
<td>E-glass fibre</td>
<td>70 - 75</td>
<td>-</td>
<td>1750 - 2100</td>
<td>-</td>
<td>2.5 - 2.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Ten. Fract. Strain (%)</th>
<th>Linear Therm. Exp. (10⁻⁶ x K⁰)</th>
<th>Shrinkage on drying (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardened cement paste</td>
<td>0.02 - 0.06</td>
<td>12 - 20</td>
<td>0.2 - 0.3</td>
</tr>
<tr>
<td>Set gypsum plaster</td>
<td>0.02 - 0.04</td>
<td>17 - 21</td>
<td>negligible</td>
</tr>
<tr>
<td>E-glass fibre</td>
<td>2 - 3</td>
<td>5 - 7</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 4.II Composites of A, E, and Alkali-resistant Glass Fibres (Reference 30)

<table>
<thead>
<tr>
<th>Chemical base</th>
<th>E-glass</th>
<th>A-glass</th>
<th>Alkali-resistant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si 02</td>
<td>52.4</td>
<td>72.2</td>
<td>71</td>
</tr>
<tr>
<td>K2 O</td>
<td>0.8</td>
<td>13.0</td>
<td>11</td>
</tr>
<tr>
<td>Na 20</td>
<td>0.8</td>
<td>13.0</td>
<td>11</td>
</tr>
<tr>
<td>B2 03</td>
<td>10.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Al2 03</td>
<td>14.4</td>
<td>1.8</td>
<td>1</td>
</tr>
<tr>
<td>Mg 0</td>
<td>5.2</td>
<td>3.5</td>
<td>-</td>
</tr>
<tr>
<td>Ca 0</td>
<td>16.6</td>
<td>9.5</td>
<td>-</td>
</tr>
<tr>
<td>Zr 02</td>
<td>-</td>
<td>-</td>
<td>16</td>
</tr>
<tr>
<td>Li 20</td>
<td>-</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td><strong>Approx. Total</strong></td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

**FIG. 4.7** TENSILE STRENGTH OF GLASS FIBRES IN THE AQUEOUS SOLUTION PHASE OF PORTLAND CEMENT AT 80°C.
logarithmic time-scale reinforces the idea of extrapolation. However, scientific or experimental evidence to confirm that the rate of deterioration of composite properties over service life (usually 25 to 40 years) of a G.R.C. composite follows the relationship suggested in Figures 4.8 and 4.9 is lacking. For this reason, present use of this material is experimental and confined to those applications where there is no risk of loss of life, e.g., as cladding panels, fencing posts, etc.

4.4.4 Elastic properties of G.R.C. and G.R.G.: Majumdar and Ryder (27) have assumed that composite failure occurs through interfacial bond failure and that \( \lambda \) may be found from expression 7 (see subsection 4.2.5). Tables 4.12 and 4.13 contain the nominal properties of cement, plaster and glass fibre, together with the calculated and experimental values of the composite stiffness and tensile strength (27). In the calculation, the glass strand strength has been taken as 70 per cent of the filament strength. It can be seen that significant differences exist between the calculated and experimental results, especially with the higher fibre volume fraction (see Table 4.13).

Majumdar, et al., have attributed this difference to the fall in the matrix density and strength when the proportion of fibres in the mix is higher than an optimum value. This optimum fibre volume fraction vs density is a function of fabrication process, fibre length and diameter (for spray-suction G.R.C. with 43mm long fibres, the optimum has been found to correspond to about 9 per cent by weight (30).) They state that with a fibre volume fraction less than the optimum, there is good agreement between theoretically predicted and experimental values. With higher levels of fibre inclusion, any contribution by the fibres to the composite stiffness is counteracted by the fall in the matrix stiffness due to increased porosity.

Quite apart from the above differences, what is more important in terms of this study is the rather low tensile strength and stiffness of these composites compared with the potentially high tensile strength and stiffness of glass fibre (see Tables 4.12 and 4.13). This may have a major economic implication which has been discussed at the end of this section.
### Table 4.12 Nominal Properties of Glass fibre, Gypsum and Cement (Reference 27)

<table>
<thead>
<tr>
<th>Property</th>
<th>Fibre</th>
<th>Plaster</th>
<th>Cement</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (GN/m$^2$)</td>
<td>76</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>$\sigma$ (N/mm$^2$)</td>
<td>1210</td>
<td>2.75</td>
<td>2.75</td>
</tr>
<tr>
<td>$\tau$ (N/mm$^2$)</td>
<td>-</td>
<td>5.52</td>
<td>10.34</td>
</tr>
<tr>
<td>$l$ (mm)</td>
<td>-</td>
<td>43</td>
<td>34</td>
</tr>
<tr>
<td>$l_c$ (mm)</td>
<td>-</td>
<td>22.2</td>
<td>11.8</td>
</tr>
</tbody>
</table>

### Table 4.13 Predicted and Experimental Properties of G.R.G. and G.R.C. (Reference 27)

<table>
<thead>
<tr>
<th>Property</th>
<th>G.R.G.</th>
<th>G.R.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre content (% wt.)</td>
<td>6.8</td>
<td>12.6</td>
</tr>
<tr>
<td>$V_f$</td>
<td>0.047</td>
<td>0.089</td>
</tr>
<tr>
<td>$E_c$ (GN/m$^2$) - Calculated</td>
<td>17.7</td>
<td>18.3</td>
</tr>
<tr>
<td>$E_c$ (GN/m$^2$) - Experimental</td>
<td>17.2</td>
<td>17.2</td>
</tr>
<tr>
<td>$\sigma_c$ (N/mm$^2$) - Calculated</td>
<td>15.40</td>
<td>29.65</td>
</tr>
<tr>
<td>$\sigma_c$ (N/mm$^2$) - Experimental</td>
<td>13.80</td>
<td>21.80</td>
</tr>
</tbody>
</table>
4.4.5 Impact behaviour:

Impact strength of G.R.G. composites has been shown to increase proportionally with the fibre volume fraction (28). For a given volume fraction of fibre, G.R.G. composites show higher resistance (up to 100 per cent), compared with G.R.C. This has been attributed to weaker interfacial bonding in G.R.G. which allows a greater absorption of energy by fibre pullout (Cook-Gordon theory, reference 31).

For G.R.C. sheets containing 5 per cent glass fibre, short term impact strengths of $20 - 25 \times 10^3 \text{ J/m}^2$ have been recorded using an Izod testing apparatus. This compares very favourably with $3 - 5 \times 10^3 \text{ J/m}^2$ for conventional asbestos-cement sheet. (26) Long term data on impact strength of G.R.C. are not available. However, present indications are that the impact strength falls with time (26) (see subsection 4.4.3).

4.4.6 Fire behaviour:

The composite constituents of G.R.G. and G.R.C. are inorganic materials which do not contribute to a fire load. The incorporation of glass fibre, however, modifies the matrix behaviour at elevated temperatures by preventing spalling and loss of integrity of the matrix. In a pure matrix subjected to extreme heat, rapid expansion occurs which, due to the brittle nature of the matrix, leads to spalling and its loss of integrity.

As an illustration (32), a $3 \times 3$ foot G.R.G. board, 9mm thick, containing 8 per cent by weight glass fibre, resisted the penetration of flame for over one hour when tested in a manner similar to the B.S. 476:8. The flexural strength of this board fell from 45 N/mm$^2$ to about 10 N/mm$^2$ (32). Unreinforced plaster board of the same thickness tested in a similar fashion collapsed after 10 to 15 minutes (32).

4.4.7 Limitations on G.R.G. applications:

G.R.G. loses up to 50 per cent of its strength on wetting. Although when it dries out it regains its strength, it is not suitable for any external applications or primary load-bearing internal applications, such as a suspended floor.
Given the assumption that G.R.C. is sufficiently durable, what would its prospects be in comparison with existing products? An essential ingredient of G.R.C. is alkali-resistant glass fibre such as that marketed as 'Cem-Fil'.

Production of E-glass fibre will be covered in Chapter 5. This glass composition melts at around 1300 to 1400°C. Addition of zirconia (see Table 4.11), increases the melting temperature and the higher the proportion of zirconia, the higher this temperature. Alkali-resisting properties of glass fibre are also related to the proportion of zirconia in the composition. Thus, a compromise must be reached. For economic reasons, glass compositions commercially used for production of alkali-resistant fibres melt at around 1700 to 1800°C. These compositions contain less zirconia than those initially developed. The rather high melting temperature of alkali-resistant glass implies not only increased energy input, but also use of a more complicated technology for the production process. These are reflected in the unit price of this material, which is about twice the price of E-glass fibre (c.f. Table 4.1). The price differential is expected to remain roughly unchanged even with substantially larger scales of production; the present price may indeed be partly subsidized by the producer for promotional reasons. This is mainly due to rising costs of energy, which will more than offset any significant saving brought about by larger scales of production.

G.R.C. has a low strength to weight ratio (see Table 4.14). From this it follows that to support a given system of external loading a higher thickness must be employed compared with other materials listed in Table 4.14. Thus, self-weight may contribute a very significant portion of the total design loadings. To carry this load, additional reinforcement must be incorporated in the composite.

Furthermore, since the weight is rather high, the amount of fibre used for structural reasons is expected to be high, even at low percentage of fibres, and its cost may constitute a sizeable portion of the total component cost. As an illustration, the B.R.E. (29) have developed an experimental G.R.C. purlin-tile system with a profile as shown in Figure 4.10. This is made of a 9mm thick sheet produced by the spray-suction process,
Table 4.14 Typical Specific Mechanical Properties of Certain Materials

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(MN/m²)</td>
<td>(MN/m²)</td>
<td>(MN/m²)</td>
<td>(GN/m²)</td>
</tr>
<tr>
<td>G.R.C. 4.3 wt. % glass</td>
<td>2</td>
<td>13.40</td>
<td>17.2</td>
<td>6.5</td>
<td>8</td>
</tr>
<tr>
<td>Polyester 55 wt. % glass</td>
<td>1.7</td>
<td>300</td>
<td>15</td>
<td>180</td>
<td>9</td>
</tr>
<tr>
<td>Polyester 30 wt. % glass</td>
<td>1.4</td>
<td>100</td>
<td>7</td>
<td>70</td>
<td>5</td>
</tr>
<tr>
<td>Mild Steel</td>
<td>7.8</td>
<td>400</td>
<td>200</td>
<td>70</td>
<td>25</td>
</tr>
<tr>
<td>Aluminium (Duralumin)</td>
<td>2.8</td>
<td>450</td>
<td>70</td>
<td>150</td>
<td>25</td>
</tr>
<tr>
<td>Timber (Douglas Fir)</td>
<td>0.5</td>
<td>75</td>
<td>10</td>
<td>150</td>
<td>20</td>
</tr>
<tr>
<td>Timber (Hickory)</td>
<td>0.8</td>
<td>150</td>
<td>15</td>
<td>200</td>
<td>19</td>
</tr>
</tbody>
</table>
FIG. 4.8 MODULUS OF RUPTURE OF GRC STORED IN AIR
(Ref. 26)

FIG. 4.9 IMPACT STRENGTH OF GRC STORED IN AIR
FIG. 4.10 GRC PURLIN TILES (TRANSVERSE TEST ON 3.66m SPAN

Table 4.15 Cost±-Performance Comparisons for 3 Different Roof- Constructions 5m wide x 8.5m long and 30° pitch.
Roof area 48m² — (After Reference 29)

<table>
<thead>
<tr>
<th>Roof Construction</th>
<th>Cost</th>
<th>Unit cost</th>
<th>Unit wt.</th>
</tr>
</thead>
<tbody>
<tr>
<td>G.R.C. purlin-tiles 40 @ £10</td>
<td>400</td>
<td>£10</td>
<td>68 (kg/m²)</td>
</tr>
<tr>
<td>Sealing strips, bolts, etc.</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fit to structure, bolt and seal</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>10</td>
<td>68 (kg/m²)</td>
</tr>
</tbody>
</table>

Simple lap concrete tiles:
Roof timber and construction 1.97m³
x £154/m³
Tiles, felt and battens, fitted
48m² @ £2.51/m²
I21 (tiles only)
424 8.95 44

Plain concrete tiles:
Roof timber and construction
303
Tiles fitted, etc. 48m² @ £4.21/m²
202 (tiles only)
505 10.50 68
containing 5 per cent by weight of 33mm alkali-resistant glass fibres. These purlin-tiles are intended to replace the whole roof/suspended-ceiling system of ordinary dwelling houses. Table 4.15 contains details of costing as carried out by the B.R.E. (29). The data used for estimation of the unit cost of the purlin-tile have not been given. However, from data in Table 4.15, it can be estimated that at least 0.9kg alkali-resistant glass fibre is needed to produce one metre of the purlin-tile. The cost due to this quantity of glass is likely to be around £90, or 45 per cent of the total cost of one metre of the above tile.

From the data included in Table 4.12, it is evident that, quite apart from problems of aesthetic acceptability of G.R.C., the purlin-tiles are not cheap substitutes for the traditional constructions, even assuming that such a G.R.C. construction becomes a commercial proposition.

One of the chief attractions of G.R.C. and G.R.G. composites is their fire resisting properties (see subsection 4.4.6). It has been claimed that these composites could eventually replace asbestos-based boards and sheets in many applications. Because of the potential health hazards associated with production and site use of asbestos-based materials, efficient substitutes are very much desired. However, on the grounds of the high costs of G.R.C. and G.R.G., it is unlikely that they would replace the family of asbestos products. Asbestos-based materials are still remarkably cheap: Thus, to supply and fix 150mm (6") corrugated asbestos-cement sheet costs around £4.15/m² fully inclusive, of which £1.28/m² or 31 per cent is the material cost of asbestos-cement sheet(33).

G.R.G. composites have originally been developed to accelerate the study of properties of composites of this nature and transfer the knowledge to G.R.C. composites. The development of the latter had been slow, partly due to handmade production of alkali-resistant glass fibre (now mechanical production is available in a pilot plant), and partly due to the time required for a cement matrix to harden.

G.R.G. boards and panels have not found, as yet, any commercial application. These boards are at a price disadvantage compared with plaster boards (a paper-faced plaster panel). Where special applications or complex shapes are required, cheap
fibres (mainly from plant leaves, e.g. sisal, hemp, etc.), are normally used to improve casting and impact resistance of ordinary plaster.

As was mentioned earlier, even as fire protection boards used in the interior of buildings, G.R.C. is not competitive with asbestos boards. For example, a 12mm thick G.R.C. board containing 5 per cent by weight glass fibre requires in excess of £1/m² worth of glass fibre alone. The finished board is unlikely to cost less than £1.50/m², which is approximately 100 per cent higher than the average asbestos boards (33).

The only development which has been claimed to be economically viable is the G.R.G. school partition system developed at the B.R.S. (32). The system meets the requirements of the relevant performance specifications of the Department of Education and Science and is within the D.E.S. cost limits. However, it has not as yet found any commercial applications. Non-availability of the potential market due to the present commitments of local authority consortia has been quoted as the reason.

G.R.G. boards can be used as the internal face in structural sandwich constructions to provide the required degree of fire resistance and also to assist in the overall stiffness of the panel. This will be considered in the succeeding chapters.

4.5. Steel fibre Reinforced Concrete (S.R.C.), and Polypropylene Concrete (P.P.C.), etc.

4.5.1 Steel fibre reinforced concrete (S.R.C.):
(a) Effects of fibre details: the practical mixing operations favour the use of 0.25mm diameter and 25mm long fibres (34). Theory predicts that both fibre length and diameter should have important effects on the composite properties. As with G.R.C., there is a limit on the inclusion of the fibres. In a concrete mix with 10mm maximum aggregate size, a maximum of 2 per cent by volume (i.e. 6.6 per cent by weight) can be included (34). With sand-cement mortars higher amounts are possible.

(b) Mixing and compaction: mixing of fibres into the
concrete mixing pan using a suitable mechanical dispenser is feasible. Workability of a mix containing steel fibre is reduced. Special mix design and study of the handling methods normally used on site are therefore essential. Effects of pencil type vibrators in compaction and fibre orientation have not been fully investigated.

(c) Properties: the strain capacity or toughness of steel fibre reinforced concrete has been quoted as a major property of these composites. The composite toughness is related to the fibre volume fraction (22), and is higher by a factor of 14 in the case of a composite containing 1 per cent fibres by volume. The increase in indirect tensile strength of the composite by addition of fibres is more substantial than in direct tensile loading (34). Measurements of the modulus in compression or in torsion of composites containing 4 per cent by volume of three dimensionally arranged fibres have shown no significant improvements compared with the base concrete. The impact resistance of the concrete is substantially increased with the addition of fibres (34). However, improved methods of impact-testing are currently under study in order to elucidate the impact behaviour of different materials under different conditions.

Incorporation of steel fibres improves the fatigue behaviour of the concrete. As an illustration, with composites containing 2 to 3 per cent fibres by volume, increases of up to 90 per cent in the first cracking strength have been observed after $2 \times 10^6$ cycles (22).

The observation reported by several authors on the mechanism of failure ascribes the composite failure to the fibre pullout. Improvements in the interfacial bond has an adverse effect on the ductility of these composites (34).

Durability of S.R.C. composites in different environments is currently under investigation. The fibres must be treated (e.g. stainless steel) if surface staining and corrosion are to be avoided (34).

Addition of steel fibres improves the behaviour of concrete in elevated temperatures.

(d) Applications: S.R.C. composites have been used as overlays on bridge decks and roads, mainly in the U.S.A. (20). The use of steel fibre in the construction of overlays utilizes
the crack-arresting properties of fibres, and savings on the overlay thickness have been reported. Improved skidding resistance of S.R.C. surfaces (15 per cent compared with plain concrete) is an added advantage. In the U.K., pre-cast concrete covers have been developed utilizing the improved impact resistance of the concrete. The improved resistance of F.R. concrete to cyclic loading has encouraged feasibility studies for such applications as industrial floor surfacing and concrete railway sleepers.

(e) Economics: Table 4.16 includes approximate cost guides for reinforcing concrete and cement paste by use of various fibres. Some composites included in Table 4.16 do not have practical application; the purpose of their inclusion is to facilitate cost-analysis of other composites.

Use of various quantities of fibres in Table 4.16 may give the false impression that equal performance has been aimed for. In fact, the percentages added are those which have been proposed for common applications and are therefore quite arbitrary.

It must also be noted that the composite cost-ratio is a measure of the increase in the unit cost of the matrix material only, and does not reflect the other relevant cost components. However, it serves to illustrate that S.F.C. is not a cheap material. Furthermore, not all of the fibres are aligned in the direction of stresses, and consequently some steel fibres are used inefficiently compared with ordinary reinforced concrete, where steel bars are used where needed. This explains why S.R.C. applications have been confined to special situations. Even for these special applications, no comparative cost data have been published. Where special properties of S.R.C. are worth paying for, its application can be considered, e.g. its improved resistance to cyclic loading combined with its higher flexural strength and improved skid resisting characteristics may lead to its eventual use in the construction of highways, airport runways and bridge decks. The ductility of S.R.C. is one of its useful attributes. This may be utilized in structural beams (in the place of normal concrete) in many heavily loaded situations, such as bridge beams, etc. The isotropic strength of S.R.C. makes it suitable material for the manufacture of thin-type components with highly complex stress
Table 4.16  Approximate Cost Ratios for Various Composites

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Material Costs</th>
<th>Fibre Content</th>
<th>Composite Cost Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(P/kg) (£/m$^3$)</td>
<td>(% wt.) (%) vol.)</td>
<td>Concrete</td>
</tr>
<tr>
<td>Concrete (O.P.C.)</td>
<td>- 10</td>
<td>- -</td>
<td>1.0</td>
</tr>
<tr>
<td>Cement Paste (W/C = 0.35)</td>
<td>- 30</td>
<td>- -</td>
<td>-</td>
</tr>
<tr>
<td>Asbestos</td>
<td>10 260</td>
<td>10 10</td>
<td>3.5</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>60 550</td>
<td>0.2 0.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Glass fibre (Cem-Fil)</td>
<td>100 2700</td>
<td>5 5</td>
<td>14.5</td>
</tr>
<tr>
<td>Steel</td>
<td>30 2150</td>
<td>6.6 2.0</td>
<td>5.3</td>
</tr>
<tr>
<td>Carbon fibre</td>
<td>6000 10600</td>
<td>2.5 3</td>
<td>32.8</td>
</tr>
</tbody>
</table>

Composite Cost Ratio = (cost of material + b% fibres)/(cost of material)
distribution, such as concrete shells. However, long term data on the composite durability are not available, and so far no external cladding applications have been reported.

4.5.2. Polypropylene concrete (P.P.C.):

4.5.2.1 Action of the fibre:

The addition of low-modulus fibres such as polypropylene (PP) and nylon to concrete does not increase its tensile or flexural strength significantly. This is because the fibre tensile modulus is less than the concrete tensile modulus and concrete reaches ultimate failure before fibres develop an effectively restraining stress. In addition, polymer-based fibres creep appreciably under sustained conditions of stressing.

Addition of these fibres has been found to increase the impact strength of hardened concrete (35). Under high speed conditions of loading, plastics exhibit much higher values of stiffness, e.g. polypropylene stiffness increases up to 3 times its normal value and reaches the stiffness of concrete. This indicates why polypropylene fibres are effective in impact loadings of P.P.C. (35).

4.5.2.2 Monofilament PP fibre concrete (Faircrete):

This material has been developed by J. Laing R & D Ltd. 0.1 to 2 per cent by volume of 0.3mm diameter PP fibres are randomly dispersed into a fresh mix using a modified form of conventional glass fibre chopper. The mix is also air-entrained using an appropriate additive. The fibres are used primarily to alter the rheological properties of fresh mix. The fibres in effect prevent migration of air bubbles to the surface and thus allows much greater amounts of air to be incorporated into the mix. Such a mix is highly thixotropic and allows imprinting and forming of various patterns on the surface without slumping-back (35). Use of lightweight aggregates with Faircrete lower the density to 700 kg/m³. Impact strength of Faircrete is appreciably higher than that of normal concrete.

The production of flat panels with a variety of surface textures and features in Faircrete has been mechanized; however, as with ordinary concrete, in situ casting using standard moulds may be more economic and technically preferred due to the relatively high costs of transport.
Faircrete has two limitations: (i) the weight, which cannot be reduced beyond ordinary lightweight concrete (i.e. the lowest density is of the order 700 kg/m$^3$), and (ii) the appearance which, despite texturing, is limited to those of concrete-based surfaces.

4.5.2.3. Fibrillated polypropylene fibre concrete (F.P.P.C.):

Fibrillated polypropylene twine is obtained by extrusion and stretching of a polypropylene tape (35). In the concrete mix, the twisted twine opens up in a network form and combines with the matrix. The reason for using fibrillated fibre is to increase the mechanical bond in the interface of polypropylene and the cement/concrete matrix. (Normal polypropylene has a poor mechanical bond with concrete.).

The prime motive for using PP tape in concrete is to increase its impact resistance as described in 4.5.2.1.

West's Piling and Construction Co. Ltd. use 0.5 per cent by volume of 40mm long fibrillated twines in the concrete mix used for piling shells. PP twine has replaced the previously used steel mesh, and in practical demonstrations an increase of up to 40 per cent in impact resistance has been observed (36).

Other added advantages have been described as: (i) the inertness of polypropylene to alkalinity or any reagent which does not attack concrete; (ii) increase in the ultimate elongation and limitation of propagation of cracks; (iii) some residual strength after cracking; and (iv) prevention of spalling and disintegration of concrete after failure (36).

Addition of PP fibres to concrete for use in blast-resistant structures has also been reported (reinforcing action has been achieved by use of normal steel bars).

From the cost point of view, addition of PP to concrete can increase the material costs by 30 per cent at a volume loading of 0.5 per cent (see Table 4.16). It is therefore clear that use of P.P.C. must be confined only to special cases. In normal structural work, use of P.P.C. will not normally bring about any savings on the amount of steel reinforcement required, so the additional cost due to its use cannot be justified. In thin pre-cast concrete panels and slabs, P.P.C. may offer some advantage regarding impact behaviour; however, for load-bearing purposes steel reinforcement must also be used.
4.5.3 Other Combinations:

4.5.3.1 Glass and carbon fibres in concrete:

Excessive damage suffered by carbon and glass fibres due to abrasion in a concrete mix rules out their direct use in normal mixes. As was mentioned earlier, incorporation of glass fibre into the cement slurry is carried out with care to avoid loss of strength and damage to the fibres. Glass or carbon fibre reinforced plastic pultruded bars with up to 60 per cent fibres unidirectionally aligned can be used in place of steel bars, but these bars are not capable of bending and anchorage, and, in the case of glass, have a lower modulus of elasticity (about 50 GN/m² compared with 200 GN/m² in the case of steel). Also, they creep under sustained loading conditions. In pre-stressed concrete, glass fibre-resin embedded rods may be beneficial as the lower modulus value results in reduced losses in pre-stress due to concrete shrinkage.

4.5.3.2 Asbestos in cement and concrete:

Normal asbestos fibres are very short (typically 5 mm) and have an unfavourable length to diameter ratio. Textiles quality asbestos fibres are available, but expensive. Health hazards associated with the use of asbestos on site or in a factory limit any further utilization of this material in the construction industry.

Asbestos-cement is a composite material used extensively in the construction industry for over 50 years. It suffers loss of impact strength of up to 50 per cent after 10 to 15 years' exposure. The asbestos content of normal asbestos-cement products ranges from 10 to 70 per cent.

4.5.3.3 Nylon fibres in concrete:

Nylon is considerably more expensive than polypropylene and has not been used in more recent developments.

4.5.3.4 Vegetable fibres in concrete:

B.R.S. have investigated the use of sisal for reinforcing normal concrete. The results indicated that too high a water cement ratio was needed owing to the high water absorption of these fibres. Also, the settling of concrete was retarded by organic impurities from the chopped fibres. Addition of up to 5 per cent by weight of chopped sisal fibres produced no additional strength.
Vegetable fibres, especially sisal, have been used traditionally in gypsum plaster matrix for in situ applications of decorative and complex surface features.
10. B.S. 4618: Section 4.2: 1972 (Resistance to Natural Weathering.)
ICI Petrochemicals Division, "Optimism Despite Oil Crisis." A report prepared by ICI and published on 6th September, 1974 in Rubber and Plastics Weekly.


CHAPTER 5  G.R.P. MATERIALS AND COMPONENTS

5.1 Development History:

No account of the development history of G.R.P. is complete without reference to the development history of glassfibre and polyester resins.

5.1.1 Development history of glassfibre:

During the eighteenth century coarse glassfibres were produced which in the form of woven fabrics were used for heat insulating applications(1). During the late 1930's, the production of monofilament glassfibre was started in the U.S.A.(1)

The main application of this product was for reinforcing electrical insulation systems for which a special type of glass composition, known as E-glass, was developed.

Discovery of E-glassfibre's good mechanical properties, especially its high tensile strength coupled with its high resistance to moisture paved the way for the use of this material for reinforcing thermosetting resins.

However, being amenable to damage under high compression moulding pressure, glassfibre was not used successfully until low pressure polyester resins were introduced.

The commercial production of E-glassfibre in the U.K. was started by Fibreglass Ltd (a subsidiary of Pilkington Brothers) under license from Owens-Corning Fibreglass Corporation of the U.S.A.

5.1.2 Development of unsaturated polyesters:

The history of polyester resins dates back to 1929 when Carothers(2) produced linear polyesters.

Bradley(2) in 1937 proved that unsaturated polyesters could be cross-linked to form solid infusible and insoluble products. This was complemented by work of Ellis(2) who showed that the rate of cross-linking was at least thirty times more in the presence of styrene. This paved the way for commercial development of polyester resins in 1941(2).

Since that year, advancement of the resin technology has been rapid; in the decade 1941-51, problems of cold setting (i.e. chemical cross-linking of linear polyesters
at room temperature), and air inhibition were solved.

The G.R.P industry was already established and in 1955 world production of reinforced polyesters reached an estimated 50,000 tonnes a year (2); the corresponding figure for 1968 has been estimated to be 500,000 tonnes (2).

5.1.3 Development of constructional uses of G.R.P.: 

The first application of G.R.P. in the construction industry was in the form of corrugated translucent roofing sheet which first appeared in the U.K. market in 1949 (2).

Translucent roof sheet is purely a utilitarian product used for natural lighting on roofs of asbestos-cement or steel-sheet covered industrial buildings.

Translucent roof sheet remained the principle application until 1964 when translucent G.R.P. roofing components were used to clad the sports hall at Warrier Street School, Newcastle-upon-Tyne (3). One of the earliest major uses of G.R.P. infill panels was in 1966/67 in the electronic workshop at R.A.F. Sealand where 1m x 3m high G.R.P. panels were chosen as substitutes to cast bronze panels (the latter had become too costly).

The G.L.C. SPI tower blocks of flats in London in 1966-68 was another major example where G.R.P. was used as the external shell in the construction of insulated composite window panels. Since then, a large number of interesting projects using structural or infill G.R.P. panels have been completed. This itself is an indication that G.R.P. has established a position in the construction industry.

In the period 1950-65, there had been several attempts to demonstrate the potential of G.R.P. in self-supporting applications. The all-plastics house project by French designers Schein, Magnant and Coulon is but one notable example of development of G.R.P. for structural applications (4).

The design of this house was based on an unusual concept of a snail's shell; it consisted of a 9m diameter circular centre piece with three bedrooms attached to it. Transparent acrylic panels were used to clad the other half.

Another more spectacular project was the Monsanto "house of the future" designed by Goody (4) and exhibited in 1957 at
Disneyland. It consisted of a central core with four wings projecting outwards. These wings were intended as bed and study rooms.

Neither of these projects advanced beyond experimental and promotional stage.

5.2 Polyester Resins:

5.2.1 Composition:

An unsaturated polyester resin has a molecular structure similar to the following diagram:

\[-A-G-B-G-A-G-B-G-A\]

Where A is a saturated diabasic acid or anhydride residue, B an unsaturated diabasic acid or anhydride residue and G is a diabasic glycol residue. In this form the resin is a viscous liquid which consists mainly of long chains of linear polymer with the molecular weight in the region of thousands.

If an unsaturated polymerisable compound -S- is introduced into the above resin, it interacts with the unsaturated grouping -B- of the above polymer chains and results in a three dimensionally cross-linked polymer as represented by the diagram below:

\[-S S S-\]
\[-S S S-\]

The resulting polymer is an infusible and insoluble plastic material with a very complex structure of considerable strength.

The cross-linking monomer -S- is usually incorporated into the resin by the resin manufacturers. However, the cross-linking reaction which is known as curing, is normally initiated by various agents, and takes place during the moulding and subsequent curing period.

As can be seen from the above diagram, in contrast with
phenolic, urea and melamine resins, the final polymerisation of polyester resins does not produce any aqueous by-product. This has made it possible to mould reinforced polyester mouldings at room temperature (contact mould process, see section 5.4).

The most common compounds used in the production of unsaturated polyester resins are maleic anhydride and phthalic anhydride as the unsaturated and saturated anhydrides respectively, together with ethylene or propylene glycol. Adipic or sebacic acids may also be used instead of phthalic anhydride in certain formulations.

Styrene is commonly used for cross-linking owing to its cheapness; methyl or butyl methacrylate, vinyl acetate, vinyl toluene, diallyl phthalate and triallyl cyanurate are also used as cross-linking monomers in special types of resins.

Properties of the final resin are affected by the type and quantities of acids, glycols and the cross-linking compounds used in the production of resin. Thus resins are formulated by the manufacturers each with specific characteristics for a particular application.

Table 5.1 contains typical values for general properties of typical resins:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>1.1 - 1.5</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>40 - 90 MN/m²</td>
</tr>
<tr>
<td>Tensile modulus</td>
<td>3.5 - 15 GN/m²</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>90 - 250 MN/m²</td>
</tr>
<tr>
<td>Impact strength</td>
<td>0.4 ft.xlb</td>
</tr>
<tr>
<td>Co-ef.of Linear expansion</td>
<td>10 - 18 x 10⁻⁵°C</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.21 W/m°C</td>
</tr>
<tr>
<td>Water absorption 24h @ 20°C</td>
<td>0.15%</td>
</tr>
</tbody>
</table>
Polyester resins for use in low pressure contact lamination are normally produced to BS3532. This standard contains the following classification for resins:

A - General purpose  
B - Improved general purpose  
C - Heat resistant  
D - Low flammability  
E - Very low flammability.

The criteria for the above classifications are included in Table 5.2 and 5.3 taken from the above standard. It can be seen that the requirements in these tables are related to quality control assessments, and are not directly correlated with service performance of the resins.

5.2.2 Curing:

The rate of curing of polyester resins is controlled by addition of curing agents commonly known as 'catalysts'; the most usual types are organic peroxides which decompose into free radicals either under influence of heat (hot curing) or by the chemical action of accelerators (cold curing).

5.2.2.1 Cold curing:

Catalysts used in the low pressure lamination of reinforced polyesters are normally either cyclohexanone peroxide (4%) or methyl ethyl ketone peroxide, (M.E.K.P., 2%). For practical and safety reasons, the former has been recommended in reference 5 in preference to the M.E.K.P. The catalyst resin has a pot life at room temperature of 8-30 hours, depending on the type of resin.

The most widely used accelerators for the above catalysts are cobalt naphthenate or octoate. The quantity of accelerator is normally between 1 to 4 percent by weight of resin, depending on the room temperature and the gel time required. The temperature of the moulding environment has a controlling effect on the setting time of the resin and is closely monitored (c.f. Fig. 5.1). Lamination and cold curing of the resin should not be carried out below 15°C. By application of heat to the mould or moulding, cold curing time may be
<table>
<thead>
<tr>
<th>Property</th>
<th>Max. or Min.</th>
<th>Unit</th>
<th>Test Method</th>
<th>Resin Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. of deflection † under load of cast resin</td>
<td>Min</td>
<td>°C</td>
<td>Ap'dix A BS 3532</td>
<td>A</td>
</tr>
<tr>
<td>Water absorption of cast resin †</td>
<td>Max</td>
<td>mg</td>
<td>Method 502 G BS 2782</td>
<td>B</td>
</tr>
<tr>
<td>Cross-breaking strength of laminate</td>
<td>Min</td>
<td>MN/m²</td>
<td>Method 304 BS 2782</td>
<td>C</td>
</tr>
<tr>
<td>Do. after 2h. in boiling water</td>
<td>Min</td>
<td>MN/m²</td>
<td>Ap'dix C BS 3532</td>
<td>D</td>
</tr>
<tr>
<td>Do. at the nominal def. temp. after 4h. at this temperature</td>
<td>Min</td>
<td>MN/m²</td>
<td>Ap'dix D BS 3532</td>
<td>E</td>
</tr>
<tr>
<td>Do. but after 68h.</td>
<td>Min</td>
<td>MN/m²</td>
<td>Ap'dix D BS 3532</td>
<td></td>
</tr>
<tr>
<td>Flammability</td>
<td></td>
<td></td>
<td>Ap'dix B BS 3532</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Very low</td>
</tr>
</tbody>
</table>

* Laminates prepared in accordance with Appendix N of BS 3532
† Casting of resin to be prepared in accordance with Appendix O of BS 3532
shortened. The temperature is initially below 35°C, rising gradually to about 60°C when the resin has set.

![Temperature vs. Gel Time](image)

**FIG. 5.1 EFFECT OF AMBIENT TEMPERATURE ON COLD CURING OF A TYPICAL POLYESTER RESIN (Ref. 5)**

It is essential that in any formulation the correct amounts of the recommended curing agents are used. If catalyst and accelerator are under used the final end-product may be undercured.

In addition to the effects of catalyst, accelerator and temperature the setting and curing of polyester resins are also affected by the following factors:

1. **Bulk of resin**: The polymerisation of a polyester resin results in evolution of a considerable amount of heat. If the heat accumulates in the bulk of resin or moulding it can cause the temperature to rise with the consequence of accelerating the rate of cure of the resin. Special consideration must therefore be given to fast-setting resin systems in thick mouldings to avoid too rapid a rise of temperature which may lead to the setting up of internal stresses due to the low thermal conductivity of solid resins.

2. **Loss of monomer through evaporation**: If the resin is made to gel too slowly, some of the monomer may be lost into the atmosphere. This may lead to underpolymerisation of the final resin with the consequence of inferior physical properties.

3. **Quantity and type of mineral fillers**: The setting time of a filled resin is increased by increasing the filler content. Particle size and type of fillers also affect the setting time of the resin.

4. **Presence of pigments**: Depending on the type of pigments
used the setting time may be increased or decreased.

(5) Moisture content: Presence of moisture retards the curing of the resin. Fillers and reinforcing fibres should be dry before use.

(6) The time-lag between the addition of the catalyst and accelerator: The longer this time the shorter is the setting time of the resin.

(7) Presence of inhibitors: Common inhibitors are phenols, phenol-formaldehyde resin dust, sulphur, rubber, copper and copper salts, carbon black and methanol. Small quantities of these compounds are sufficient to prevent the full polymerisation of the resin.

It must be emphasised that although an undercured resin has poor weathering and physical properties, the state of final curing and polymerisation of a resin cannot be determined accurately. The only way to ensure optimum properties is to control the conditions of curing as tightly as possible.

After the resin has set the polymerisation reaction continues slowly for about 2 weeks at normal room temperature. This stage is known as maturing and can be shortened by application of heat. Table 5.4 contains equivalent post-curing times and temperatures.

Fast-setting polymer systems have been formulated by addition of 2 percent benzoyl peroxide catalyst paste and up to 2 percent of an amine accelerator. However, this method does not ensure optimum final properties and the produced mouldings tend to yellow on ageing.

5.2.2.2 Hot curing:

The usual catalyst for hot curing resin formulations is benzoyl peroxide which is supplied as a paste dispersion. Normally about 2 percent of this compound is thoroughly dispersed in the resin.

Hot curing of polyester resin mouldings is carried out at a temperature of between 100°C to 140°C, for a period of between 1 to 10 minutes depending on the mould temperature, the type of resin and the bulk or the thickness of the moulding. Generally the higher the moulding temperature, the shorter the curing time.

5.2.3 Production of Unsaturated Polyester (UP) Resins:

The purpose of this subsection is to outline the current
### Table 5.3 Tolerances (BS 5532)

<table>
<thead>
<tr>
<th>Property</th>
<th>Test Method</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>Appendix F</td>
<td>± 0.01</td>
</tr>
<tr>
<td>Viscosity</td>
<td>G</td>
<td>± 30 per cent</td>
</tr>
<tr>
<td>Acid Value</td>
<td>H</td>
<td>± 4 mg KOH/g</td>
</tr>
<tr>
<td>Volatile Content</td>
<td>J</td>
<td>± 3 per cent</td>
</tr>
<tr>
<td>Gel time at 25°C</td>
<td>K</td>
<td>± 30 per cent</td>
</tr>
<tr>
<td>Gel time at 82°C</td>
<td>L</td>
<td>± 30 per cent</td>
</tr>
</tbody>
</table>

### Table 5.4 Recommended Equivalent Temperatures and Periods for Post-Curing (Ref. 5)

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Period (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>3</td>
</tr>
<tr>
<td>70</td>
<td>5</td>
</tr>
<tr>
<td>60</td>
<td>8.5</td>
</tr>
<tr>
<td>55</td>
<td>12</td>
</tr>
<tr>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
</tr>
</tbody>
</table>
level of technology employed for the production of unsaturated polyester resins and compare this with the general state of production technology in the plastics industry.

Statistical data on the size of the UP resin industry are presented in Tables 5.5 and 5.6; data on the PVC industry have been included in Table 5.7 for comparison. Estimates of the market share of the major U.K. producers of UP resins have been included in Table 5.8.

From these data it can be seen that the output of the biggest UP resin producer is likely to be in the region of 17100 tonnes, comprising some 30 to 40 different formulations based on six base resins. In contrast with polyesters, there is only one basic grade of PVC produced in relatively large outputs (see Table 5.7). This rather low output of individual UP resins has necessitated employment of batch production processes. The possibility of introducing continuous productive techniques is discussed below.

Unsaturated polyester resins are produced by repeated reaction of a bifunctional alcohol and bifunctional saturated anhydrides. Normally sulphuric acid is used as the esterification catalyst. The production process is slow and is similar to the simple esterification process. The major difference is that in the former, products with relatively high molecular weights are formed. The progress of the reaction has to be monitored closely in order to stop the reaction at a convenient point when the resin is still fusible and soluble.

In general, the equipment is designed for batch production which may be used to produce other similar resins such as alkyds for the paint industry. The temperature required is easily obtainable (around 140°C). The evolved water is removed and distilled from the reaction tank and the excess glycol is recycled. The process is intermittent and flexible since the quantity and type of reacting constituents can be changed in each run. However, it is more labour intensive, and has higher variable and lower fixed costs, compared to the continuous processes commonly employed for the production of thermoplastic polymers. The capacity of the batch-process can be easily increased by addition of further reaction tanks.

An improved process - probably the nearest to the concept
Table 5.5 Production of U.P. Resin by U.K. manufacturers
(Source: Business Monitor & Annual Abstracts of Statistics)

<table>
<thead>
<tr>
<th>(I) Year</th>
<th>(II) UP Resin (x10^3 T)</th>
<th>(III) Total Thermostat (x10^3 T)</th>
<th>(IV) (II) as % of (III)</th>
<th>(V) All synthetic resins (x10^3 T)</th>
<th>(VI) (II) as % of (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1963</td>
<td>13.9</td>
<td>250.2</td>
<td>5.5</td>
<td>756.2</td>
<td>1.84</td>
</tr>
<tr>
<td>1964</td>
<td>18.7</td>
<td>293.3</td>
<td>6.4</td>
<td>883.4</td>
<td>2.12</td>
</tr>
<tr>
<td>1965</td>
<td>24.6</td>
<td>317.0</td>
<td>7.8</td>
<td>957.3</td>
<td>2.57</td>
</tr>
<tr>
<td>1966</td>
<td>25.9</td>
<td>321.1</td>
<td>8.1</td>
<td>1017.0</td>
<td>2.55</td>
</tr>
<tr>
<td>1967</td>
<td>27.7</td>
<td>326.9</td>
<td>8.5</td>
<td>1108.3</td>
<td>2.50</td>
</tr>
<tr>
<td>1968</td>
<td>34.0</td>
<td>358.2</td>
<td>9.5</td>
<td>1233.6</td>
<td>2.76</td>
</tr>
<tr>
<td>1969</td>
<td>38.5</td>
<td>376.6</td>
<td>10.2</td>
<td>1319.0</td>
<td>2.88</td>
</tr>
<tr>
<td>1970</td>
<td>40.8</td>
<td>376.6</td>
<td>10.8</td>
<td>1448.0</td>
<td>2.82</td>
</tr>
<tr>
<td>1971</td>
<td>39.4</td>
<td>377.5</td>
<td>10.5</td>
<td>1446.9</td>
<td>2.72</td>
</tr>
<tr>
<td>1972</td>
<td>47.8</td>
<td>386.0</td>
<td>12.4</td>
<td>1607.6</td>
<td>2.98</td>
</tr>
<tr>
<td>1973*</td>
<td>65.8</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1974†</td>
<td>56.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* UP Resins including reactive monomer but excluding filler.
† A new enquiry was introduced.

Table 5.6 Market Size of UP Resins (U.K.)
(Source: Business Monitor)

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of a enterprises</th>
<th>Sales b (£ x10^3)</th>
<th>Export c (f. o.b. £ x10^3)</th>
<th>Imports c (c.i.f. £ x10^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>13</td>
<td>15659</td>
<td>849</td>
<td>1489</td>
</tr>
<tr>
<td>1974</td>
<td>15</td>
<td>24786</td>
<td>2043</td>
<td>1967</td>
</tr>
</tbody>
</table>

a one or more establishments under common-ownership; each establishment employing 25 or more persons.
b sales deliveries for the U.K. and abroad.
c includes D.M.C. & S.M.C.
Table 5.7  Market size of PVC including PVC copolymers (those containing over 50 percent VCM) (Source: Business Monitor)

<table>
<thead>
<tr>
<th>Year</th>
<th>No of enterprises</th>
<th>UK Production (x10^3 T)</th>
<th>Sales (x10^3 £)</th>
<th>Exports (f.o.b) (x10^3 £)</th>
<th>Imports (c.i.f) (x10^3 £)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>5</td>
<td>400.05</td>
<td>42884</td>
<td>16491</td>
<td>17868</td>
</tr>
<tr>
<td>1974</td>
<td>5</td>
<td>366.97</td>
<td>64433</td>
<td>26421</td>
<td>41239</td>
</tr>
</tbody>
</table>

For a and b refer to footnotes on Table 5.6

- c does not include rigid sheets, strip and film
- d Including the resin contents of latices, solutions and dispersions

Table 5.8  Estimates of the U.K. market share of UP Resin (Source: Ref 6)

<table>
<thead>
<tr>
<th>Producer No.</th>
<th>Market Share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>others</td>
<td>6</td>
</tr>
</tbody>
</table>
of continuous process - has been introduced in Germany by Bayer(8). It is termed the 'Cascade Process' and consists of a series of reaction tanks through which the mixture of the reactants travel. The esterification is gradually completed. The capacity of this plant is about 100,000 tonnes of resin per annum(8).

In the U.K. advances have been made in the computer monitoring of the progress of the esterification. This can ensure consistency of the resins produced at different times and locations(6).

5.2.4. Prospects for UP resins:

Any assessment of future prospects for polyester resins requires consideration of the following factors:

(I) Effects of production scales of the raw materials:
Styrene, ethylene glycol and phthalic anhydride are produced in relatively large quantities; styrene is substantially used in the production of polystyrene, acrylonitrile butadiene styrene (ABS) and impact polystyrene (SAN). Ethylene glycol is chiefly used as an antifreeze in cars and as a coolant fluid. Phthalic anhydride is widely used in the production of phthalate plasticizers and alkyd resins.

Maleic anhydride is mainly used for the production of unsaturated polyester resins. However, this compound is obtained by oxidation of benzene. The latter is a very common chemical intermediate produced on a very large scale from both oil and coal. Benzene is also used for production of styrene. Phthalic anhydride is usually obtained by oxidation of xylene (oil based route). However, an old method based on naphthalene is still in operation (coal based route)(9).

The unit costs of production of the above compounds are not only determined by the scale of production. In a petrochemical complex in addition to the main products, usually a number of by-products are also produced(10)(11). These by-products are normally used to produce one or more compounds in side plants adjacent to the main plant. Thus, the overall economy of operating a particular process in a particular market is dependent on the case under consideration. The prices of the produced compounds will to a large extent be decided by the market supply and demand for these materials(10)(11) (c.f. Table 5.9).
The informed opinion on the general price levels of the most commonly used compounds in the production of polyester resin is that maleic and isophthalic anhydrides are relatively expensive. (Isophthalic anhydride is used for the production of high quality gel coat resins. The term 'iso' refers to 'meta' position).

Phthalic anhydride, ethylene and propylene glycols are cheap and styrene is the cheapest diabasic compound used for cross-linking (c.f. Table 5.9, see also references 6,8 and 10).

(2) Effects of the production scale of UP resins: If large scale production of a polyester resin is undertaken by the cascade process, reductions of 30 to 35 percent in the unit cost of resin can be expected, other factors being equal (8). In practice the low market demand and the resin variety limit the size of production.

(3) Effects of cost and availability of oil: Figure 5.2 illustrates diagrammatically the production of 1000 kg of a typical polyester resin. The total energy input relevant to each process is also taken into consideration. It can be seen that 1033 kg of crude oil is required to produce 1000 kg of unsaturated polyester resin including the monomeric styrene. This is highly satisfactory when compared with common traditional materials which are more energy-intensive (see section 12.5 for detailed energy analysis of materials).

Theoretically a 100 percent rise in the price of crude oil should increase the unit cost of resins by a lesser amount, other factors being equal, since only a proportion of the total cost of raw materials and fuels, the rest being due to plant amortization, labour costs, overheads, profit, etc.

As an example, in 1973/74 the price of crude oil rose by about 300 percent. The resin prices in the period June 1972-June 1974 rose by approximately 100 percent (see Table 5.9). It is difficult to determine how much of the resin price increase had been due to the higher costs of the raw materials since other factors such as the general level of inflation, increased costs of labour and higher costs of plants could have influenced the prices of resins. Breakdown of resin prices in terms of the component costs is either not available or confidential.

The effect of any increase in the price of resin on the
Table 5.9  Market Prices of the Common Raw Materials used in the Production of Typical Polyester Resins (Sources: European Chemical News, Scott Bader and Co. Ltd.)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>£/1000 kg</td>
<td>index</td>
<td>£/1000 kg</td>
<td>index</td>
<td>£/1000 kg</td>
<td>index</td>
<td>£/1000 kg</td>
</tr>
<tr>
<td>June 1967</td>
<td>97.5</td>
<td>100</td>
<td>116.0</td>
<td>100</td>
<td>108.0</td>
<td>100</td>
<td>92.0</td>
</tr>
<tr>
<td>&quot; 1968</td>
<td>97.5</td>
<td>100</td>
<td>110.4</td>
<td>95</td>
<td>115.0</td>
<td>106.5</td>
<td>129.0</td>
</tr>
<tr>
<td>&quot; 1969</td>
<td>92.6</td>
<td>95</td>
<td>119.2</td>
<td>102.7</td>
<td>147.0</td>
<td>136</td>
<td>102.1</td>
</tr>
<tr>
<td>&quot; 1970</td>
<td>92.6</td>
<td>95</td>
<td>119.2</td>
<td>102.7</td>
<td>167.0</td>
<td>155</td>
<td>101.1</td>
</tr>
<tr>
<td>&quot; 1971</td>
<td>92.6</td>
<td>95</td>
<td>141.0</td>
<td>121.5</td>
<td>174.0</td>
<td>161</td>
<td>79.0</td>
</tr>
<tr>
<td>&quot; 1972</td>
<td>99.0</td>
<td>101.5</td>
<td>141.0</td>
<td>121.5</td>
<td>145.0</td>
<td>134</td>
<td>68.0</td>
</tr>
<tr>
<td>&quot; 1973</td>
<td>99.0</td>
<td>101.5</td>
<td>141.0</td>
<td>121.5</td>
<td>145.0</td>
<td>134</td>
<td>68.0</td>
</tr>
<tr>
<td>&quot; 1974</td>
<td>92.0</td>
<td>94.5</td>
<td>141.0</td>
<td>121.5</td>
<td>910.0</td>
<td>842</td>
<td>68.0</td>
</tr>
<tr>
<td>&quot; 1975</td>
<td>212.0</td>
<td>218.0</td>
<td>202.0</td>
<td>174</td>
<td>327.0</td>
<td>312</td>
<td>160.0</td>
</tr>
<tr>
<td>Nov. 1975</td>
<td>212.0</td>
<td>218.0</td>
<td>202.0</td>
<td>174</td>
<td>298.0</td>
<td>276</td>
<td>160.0</td>
</tr>
</tbody>
</table>

* - Converted from the price given for the German Market (1.32, 1.30 DM/kg, 1 DM = £1.883). No U.K. price published.

Notes: (1) Prices for polyester resins have been supplied by Messrs. Scott Bader (these prices have not changed in 1965 - 67 inclusive).
(2) From 1967 - 70 inclusive, prices have been given in Pence/lb in the original publications.
(3) R.T.D. = Road or Rail Tank Deliveries.
FIG. 5.2 DIAGRAMMATIC PRODUCTION OF 1,000 kg OF A TYPICAL POLYESTER RESIN (SOURCE: SCOTT BADER & CO. LTD.)
(Note: Fuel oil usage for each plant refers to total energy input)
5.3 Glassfibre:

5.3.1 Composition:

There are two types of compositions for production of glassfibre, viz: A-glass (or soda lime glass) and E-glass (or ‘electrical’ glass).

The chemical compositions of both A and E-glass fibres have been shown in Table 4.8; it can be seen that E-glass contains less silica and alkali (i.e. SiO₂, K₂O and Na₂O) compared with A-glass. It also contains approximately 25 percent B₂O₃ and Al₂O₃ compared with a figure of under 2 percent in the case of A-glass. E-glass also generally contains more MgO, CaO compared with A-glass.

The resistance of E-glass to acids is generally lower than that of A-glass. In addition A-glass is significantly cheaper than E-glass (1). However, E-glassfibre is almost universally used for reinforcing plastics materials (1) and in fact A-glassfibre is no longer manufactured (12); the reasons for this are as follows:

1 - The superior mechanical and electrical properties of E-glassfibre compared with A-glassfibre.
2 - The higher resistance of E-glassfibre to moisture (and hence higher durability) compared with A-glassfibre.

More recently a new glassfibre known as S-glassfibre has been developed by Owens-Corning Fiberglas Corporation (1); this glass is based on 'silica-alumina-magnesia' (1). Its actual composition is not known. S-glassfibre is claimed to be 40 percent stronger than E-glassfibre (1) and its resistance to temperature 100°C higher. However, S-glassfibre is much more expensive to produce (1), mainly because of its high energy requirements in the melting, refining and fibrizing stages of production.

Overall, E-glass is presently used substantially; this
is because(12) of its cheapness, its good textile processing, its suitability for use in electrical insulation and, last but not least, its good mechanical properties.

5.3.2 Manufacturing methods for E-glass fibre:

There are mainly two types of manufacturing processes: the marble process and the direct melt process.

5.3.2.1 The marble process:

This process involves blending the raw materials, melting, refining and annealing the glass into marbles; these marbles are then remelted in a separate stage and turned into glass fibres (see below).

In the first stage, the constituents of E-glass are weighed and mixed uniformly in a rotary pan; the resulting batch is transferred into a hopper and fed to a high temperature melting furnace; this furnace is usually fired using either oil or natural gas.

In the furnace, the temperature rises to approximately 1600°C; at this temperature all constituents interact and melt; the dissolved gases are then expelled and the homogeneous glass composition is then annealed into marbles.

The marbles are remelted in electrically-heated platinum crucibles which are generally known as 'bushings'.

The base of these bushings contain between 100 to 800 nipples of special design which carry orifices from which emerging glass beads are attenuated mechanically into filaments at a speed of 50 m/s. The filaments are sized and formed into strands which are wound on a high speed collet.

The fibre diameter is dependent on the size of the orifice, the viscosity of molten glass and the speed of attenuation; thus fibre diameter can be changed without having to alter the size of the hole in the bushing.

5.3.2.2 The direct melt process:

In this process, the refined molten glass is directly fed into an electrically-heated bushing, from which it is then drawn into filaments.

The major advantage of this process is in its lower energy requirement compared with the marble process; it requires
approximatley 50 percent less energy (12), because, unlike the marble process, in the direct melt process, molten glass need not be first annealed and then remelted.

The direct process which has been utilized since the early 1960's has now superseded the marble process (12). It involves larger scales of production and its technology has been improved continuously (see 5.3)

5.3.3 Sizing:

Virgin glass filaments are subject to mechanical damage and self abrasion; to minimize the effects of these, filaments are sized (or 'dressed') immediately after their production and the sized filaments bound together into strands. However, strands must not bind to each other and should be easily unwound at later processing stages such as production of roving, chopped strand mat, glasscloth etc.

There are two types of sizing, viz: 'textile size' and 'plastics size'.

The textile size is formulated (1) from a dextrinised starch and emulsified vegetable oil; its use makes possible textile processing of glass strands into glass fabrics. However, it is not compatible with polyester and epoxide resins and must be removed from glass fabrics before these can be used as reinforcement for such resins. In some cases, it is possible to use a special coupling agent in order to use the textile-sized glass fibre directly with UP and EP resins (1).

The plastics size is based on polyvinyl acetate and contains a suitable coupling agent. This type of sizing is compatible with UP, EP and phenolic resins; the use of coupling agent results in an improved bond between the resin and the sized glass fibre. However, this type of sizing is not suitable for textile processing of fibres.

Recent developments in this field (1) have resulted in plastics sizes which enable textile processing of fibres without excessive fibre damage whilst being at the same time compatible with the above resins.

5.3.4 Typical properties of E-glass fibre:

Table 5.10 shows typical properties of E-glass fibre. It can be seen that for the tensile strength a range of 1400-2000
\( \text{MN/m}^2 \) has been given; in fact, the tensile strength of virgin fibre is independent of the fibre diameter (1) and is approximately 3450 \( \text{MN/m}^2 \). This loss of strength (roughly 50 percent on average) is mainly due to fibre damage during the processing of this material (1).

Table 5.10 Typical properties of E-glassfibre (Source ref. 1)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre diameter*</td>
<td>3.5 to 15 ( \mu ). mm</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.55</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>70 ( \text{GN/m}^2 )</td>
</tr>
<tr>
<td>Ult. elongation</td>
<td>2.5 percent</td>
</tr>
<tr>
<td>Ult. tensile strength</td>
<td>1400 - 2000 ( \text{MN/m}^2 )</td>
</tr>
<tr>
<td>Creep</td>
<td>negligible</td>
</tr>
<tr>
<td>Coeff. of thermal Exp.</td>
<td>( 4.7 \text{ m/m x 10}^{-6} \text{C} )</td>
</tr>
<tr>
<td>Coeff. of thermal Conduct</td>
<td>1.05 (( \text{W/mK} ))</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.548</td>
</tr>
<tr>
<td>Resistance to temperature</td>
<td>(&lt; 550\text{°C} )</td>
</tr>
</tbody>
</table>

* - Normally 10-11 \( \mu \). mm.

However, as has been noted in 4.2.2, the average tensile strength of glassfibre is still highly satisfactory in G.R.P. composites. The tensile modulus (E) is, on the other hand, rather low (c.f. Fig. 4.1). The low value of E has resulted in the relatively low flexural rigidity of G.R.P. laminates; this, as will be seen later, has a major effect on the design of G.R.P. components, etc.

5.3.5 Glassfibre products used in G.R.P. composites:

Fig. 5.3 shows the variety of products commercially available; these are based on E-glassfibre and are generally subject to various BS specifications. To avoid lengthy discussion, a brief description of glass roving and chopped strand mat only, has been given below. As will be seen later, these are of special interest to this study.
FIG. 5.3 DIAGRAMMATIC REPRESENTATION OF VARIOUS GLASSFIBRE PRODUCTS PRODUCED FROM E-GLASS FILAMENTS
5.3.5.1 Rovings:

A number of sized strands may be wound together; the strand count in a roving may be varied depending on the type of application.

As may be seen from Table 5.11, rovings are generally the cheapest type of glassfibre reinforcement; this is because rovings require the least processing before being despatched to users.

The use of rovings in the G.R.P. industry has increased significantly during recent years(12); this is due to large G.R.P. companies purchasing rovings and further processing these into sheet moulding compounds, etc (see 7.2).

However, chopped strand mat is still used considerably more than roving(12).

The end uses of rovings are as follows:

1 - In the spray-up processing of G.R.P.
2 - In the Filament winding technique.
3 - In the Pultrusion process.
4 - Conversion to woven rovings.

(The production processes for G.R.P. will be considered in a more appropriate place).

BS3691:1969 specifies the quality control requirements for rovings to be used for reinforcing polyester and epoxide resins; the properties controlled are set out in Table 1 of this standard. They include roving count, moisture content, loss on ignition, (see Appendix C of BS3691) and cross-breaking strengths (both in dry and wet conditions to Appendices D to F). It is worth noting that the quality of woven rovings is controlled by parts 1 to 3 of BS3396:1970.

5.3.5.2 Chopped strand mat (c.s.m.):

This is a sheet-like mat formed by binding randomly distributed chopped strands; the average mass per unit area of the mat generally ranges from 300, 450, 600 and 900 g/m².

The quality aspects of c.s.m. are covered by BS3496:1973; the properties controlled are set out in Table 1 of the above standard. They include: moisture content, loss on ignition, average mass per unit area and its percentage variation and cross-breaking strength of laminates made from representative samples.
Table 5.11 Typical price range for glass rovings and chopped strand mat*

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>£/T</td>
<td>index</td>
<td>£/T</td>
<td>index</td>
<td>£/T</td>
</tr>
<tr>
<td>Roving (loose)</td>
<td>Spray-up preform etc</td>
<td>&lt;1</td>
<td>605</td>
<td>100</td>
<td>710</td>
<td>117</td>
<td>885</td>
</tr>
<tr>
<td>Roving (Palletised)</td>
<td>&quot; &quot;</td>
<td>&lt;1</td>
<td>515</td>
<td>100</td>
<td>610</td>
<td>118.5</td>
<td>735</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>&quot; &quot;</td>
<td>&gt;5</td>
<td>405</td>
<td>100</td>
<td>480</td>
<td>118.5</td>
<td>665</td>
</tr>
<tr>
<td>C.S.M. (loose)</td>
<td>Hand-lay-up, etc</td>
<td>&lt;1</td>
<td>785</td>
<td>100</td>
<td>880</td>
<td>112</td>
<td>1035</td>
</tr>
<tr>
<td>C.S.M. (Palletised)</td>
<td>&quot; &quot;</td>
<td>&lt;1</td>
<td>685</td>
<td>100</td>
<td>780</td>
<td>114</td>
<td>915</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>&quot; &quot;</td>
<td>&gt;5</td>
<td>605</td>
<td>100</td>
<td>690</td>
<td>114</td>
<td>805</td>
</tr>
</tbody>
</table>

* Prices are expressed net of V.A.T.; they are for standard products to the relevant BS specification
(Source: Messrs BTR Reinforced Plastics Ltd)
As may be seen from Table 5.11, c.s.m. is more expensive than rovings, e.g. in July 1976, for quantities of less than 1 tonne delivered in palletised form, the price of c.s.m. was 32.5 percent higher than the corresponding price for rovings; in the same month, for quantities greater than 5 tonnes, c.s.m. costed 35 percent more than rovings. The chief attraction of c.s.m. is the ease of its incorporation in the hand-lay-up method; the thickness of the laminate and the fact that its glass content can be controlled more accurately compared with the spray-up technique.

A general point of interest emerges from the pricing strategy recorded in Table 5.11, i.e. small users (those purchasing loose quantities of glassfibre products weighing less than 1 tonne) have to pay between 30 to 33.5 percent more compared with large users (those purchasing palletised quantities greater than 5 tonnes). A similar pricing strategy is followed by the major polyester resin manufacturers(6).

5.3.6 Economics of glassfibre production:

For production of glassfibre to be internationally competitive, the scale of production must be of the order of 20,000 tonnes per annum(12). The capital investment required is of the order of £20m. for a full complex employing the direct melt process plus a high degree of mechanization such as computerized control of the melting process in the furnace, etc.

The newest glassfibre manufacturing complex in the U.K. (belonging to Fibreglasses Ltd) was opened in Wrexham in 1971; this plant had an initial capacity of 20,000 tonnes; however, its capacity has since been extended by adding a new furnace(12).

The latest glassfibre manufacturing complex in Europe (belonging to Vitrofil, a subsidiary of Montedisons) opened in 1975 in Italy(13); its capacity is of the order of 14,000 tonnes p.a. However, it will be more than doubled by 1978 when a second furnace comes into operation. The present workforce is about 380 but when the second furnace is added it will rise to 460(13). The total investment in the Italian project was 35 billion lira (roughly £25m) in the first stage(13).

The highly capital-intensive nature of glassfibre production means that only large manufacturing companies are able to enter the market; in fact, in the U.K., there are
only two manufacturers whose production economics and pricing policies are kept secret.

The production processes are generally those of high technologies developed in the U.S.A. and are subject to the patent rights; thus, the intensive efforts by the author to obtain valid data on the economics of glassfibre production have failed.

However, some general information has been obtained. The market for glassfibre is highly competitive and the current production capacities are under-utilised worldwide (12). There are no data on the U.K. market share of each manufacturer and those of European competitors; there are some six major European companies active in the U.K. including the two U.K. manufacturers (i.e. Fibreglass Ltd and TBA Industrial Products Ltd., a member of the Turner and Newall Group). In addition there is some competition from Japan(12).

Although, the direct melt process is now universally employed, the production of glassfibre is still highly energy-intensive; some producers in the U.K. have been fortunate enough, because they have had long term contracts with the British Gas Corporation for supply of natural gas. Nevertheless, as can be seen from Table 5.11, the prices of glassfibre products have been rising sharply in recent years; clearly, a significant proportion of these price rises is expected to be attributable to the cost of energy. No precise comparison can be made due to the lack of data; however, the raw materials for glassfibre are generally inexpensive. Therefore, the production cost has two major components, viz: capital repayment or depreciation charges for plant, etc, and energy costs.

In section 12.5, Table 12.11, a figure of 25 GJ/tonne has been given for glass container; in the subsequent parts of this section (e.g. Table 12.14), this figure is doubled and used for the energy input per tonne of E-glassfibre. This is the author's best estimate and has been used for ease of energy calculation for G.R.P. products (see Table 12.14). The indications are that the real figure is of the same order. It should be noted that soda lime glass which is normally used for production of glass containers has, in fact, a lower melting point compared with the E-glass composition. In addition, unlike the production of E-glassfibre, there is no
need for use of electrical energy and the standards of refining, quality control, etc., in the case of glass containers are lower.

As far as the economic viability of glassfibre is concerned, it can be seen that the high costs per unit volume or weight of this material is a problem for the G.R.P. industry (c.f. Table 5.11). The cost of glassfibre alone in a G.R.P. building panel weighing 15 kg/m² and containing 30 percent glass by weight ranges from approximately £4/m² in the case of rovings costing £320 per net tonne to £7/m² in the case of loosely delivered c.s.m. costing £1440/tonne. These figures include an allowance for wastage of materials.

The average cost is likely to be nearer the latter figure (approximately £6/m²); this is because, as will be seen later (section 7.2), most G.R.P. moulders use c.s.m. and their purchases are likely to be comparatively small.

The high unit costs of glassfibre and fire-retardant polyester resins (noted in Table 5.9), mean that the raw material costs in the above example is presently of the order of £14/m²; the implications of these have been considered in chapter 14.

5.4 Properties of G.R.P. Composites:

5.4.1 Mechanical properties:

The effects of glass content on the mechanical properties of G.R.P. may be seen by reference to Figs. 5.4, 5.5 and 5.6 which are taken from reference 5.

Inclusion of more than 55 percent (by weight) of glassfibre in the contact moulding of random laminates results in a drop in the tensile strength (dotted line on Fig. 5.4). The reason is that glassfibre at these percentages is not completely impregnated by the resin(14). Glassfibre contents around 30 percent by weight (18 to 19 percent by volume) are commonly used in the contact-moulding of random G.R.P. laminates. Table 5.12 shows the effect of glass content on the mechanical properties of the above laminates(5).

A comparison between the mechanical properties of G.R.P., aluminium alloys and mild steel has been made in Table 5.13; it can be seen that whilst G.R.P. has a comparable specific strength, its specific modulus is rather low.
FIG. 5.4 TENSILE STRENGTH OF RANDOM G.R.P. LAMINATES vs GLASS CONTENT

FIG. 5.5 TENSILE MODULUS vs GLASS CONTENT

FIG. 5.6 EFFECTS OF ORIENTATION OF GLASSFIBRE ON TENSILE STRENGTH
The deformational behaviour of G.R.P. approximates to a straight line up to the point of failure, although, the extent of deformation will depend upon a number of factors (see section 4.2). This behaviour is not similar to that of steel which is only elastic up to a strain of 0.2 percent. However, elongation of G.R.P. at break is between 1 and 2 percent compared with 40 percent for steel; hence G.R.P. may be considered as a relatively brittle material.

Creep data on G.R.P. show that glass cloth laminates are superior to the glass mat laminates (Fig 5.7).

Fatigue properties of G.R.P. are shown in Fig 5.8; it can be seen that glass cloth laminates have higher fatigue resistance. There is insufficient data reported on the fatigue behaviour of random G.R.P. laminates in service (see 4.2.8 and 6.2.1).

Table 5.12 Typical Values of Properties of Random G.R.P. Laminates for Various Glass Contents (Ref5)

<table>
<thead>
<tr>
<th>Resin: glass ratio by weight</th>
<th>2:1</th>
<th>2.5:1</th>
<th>3:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass content, wt.%</td>
<td>33</td>
<td>29</td>
<td>25</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.5</td>
<td>1.45</td>
<td>1.4</td>
</tr>
<tr>
<td>Tensile Strength (MN/m²)</td>
<td>120</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>Bend Strength (MN/m²)</td>
<td>210</td>
<td>175</td>
<td>140</td>
</tr>
<tr>
<td>Modulus in Bend (GN/m²)</td>
<td>8</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Water Absorption, 24h(%wt)</td>
<td>0.16</td>
<td>0.14</td>
<td>0.12</td>
</tr>
</tbody>
</table>

5.4.2 Physical properties:

Table 5.14 contains typical thermal properties of G.R.P. laminates. The coefficient of thermal expansion of random G.R.P. laminates is very close to those of aluminium alloys and softwood timber. This has made it possible to combine these materials for technical and economic reasons (see 5.7).

By using a special type of polyester resin which has a light refractive index similar to E-glass fibre, translucent laminates can be produced. Such laminates may be used to form a structural or cladding member on roof or walls to
provide an adequate level of daylighting. The thermal insulation of thin translucent members can be improved by use of a double-skin design. Light transmission of such members may be of the order of 65 percent which is adequate for the majority of practical applications. Natural lighting provided by translucent G.R.P. is glare free and can be arranged in a variety of colours by use of pigments. Special patterns may also be incorporated in G.R.P. translucent members. These may be achieved by use of existing patterned fabrics as a ply in the laminate.

Table 5.13 Comparison of Mechanical Properties of G.R.P. with Mild Steel and Light Alloys. (Ref 5)

<table>
<thead>
<tr>
<th>Property</th>
<th>Random G.R.P.</th>
<th>Unidirectional G.R.P.</th>
<th>Mild Steel</th>
<th>Aluminium alloys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>1.45</td>
<td>2.0</td>
<td>7.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Tensile Strength (MN/m²)</td>
<td>100</td>
<td>800</td>
<td>400</td>
<td>450</td>
</tr>
<tr>
<td>Tensile Modulus (GN/m²)</td>
<td>7</td>
<td>30</td>
<td>200</td>
<td>70</td>
</tr>
<tr>
<td>Compressive Strength (MN/m²)</td>
<td>150</td>
<td>350</td>
<td>250</td>
<td>80</td>
</tr>
<tr>
<td>Impact Strength (KJ/m²)</td>
<td>75</td>
<td>250</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Specific Tensile Strength (MN/m²)</td>
<td>70</td>
<td>400</td>
<td>50</td>
<td>160</td>
</tr>
<tr>
<td>Specific Modulus (GN/m²)</td>
<td>5</td>
<td>15</td>
<td>26</td>
<td>25</td>
</tr>
</tbody>
</table>
FIG. 5.7 TENSILE CREEP OF LAMINATES (23°C, 50% r.h.)
STRESS = 50% of u.t.s. (Ref.2)

FIG. 5.8 TYPICAL FATIGUE OF G.R.P. CLOTH LAMINATE
(23°C, 50% r.h. 9000/min)-(Ref.2)
Table 5.14 Thermal Properties of Engineering Materials (Ref 14)

<table>
<thead>
<tr>
<th>Material</th>
<th>Coeff. of Ther. Exp. m/m (°C×10^-6)</th>
<th>Thermal Conductivity (W/m°C)</th>
<th>Max. Working Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>11.3</td>
<td>46</td>
<td>400</td>
</tr>
<tr>
<td>Aluminium</td>
<td>23.0</td>
<td>140-190</td>
<td>200</td>
</tr>
<tr>
<td>Timber</td>
<td>5.4-54</td>
<td>0.124-0.24</td>
<td>-</td>
</tr>
<tr>
<td>Concrete</td>
<td>13.0</td>
<td>0.98</td>
<td>-</td>
</tr>
<tr>
<td>Brick</td>
<td>19.0</td>
<td>0.59</td>
<td>-</td>
</tr>
<tr>
<td>Random G.R.P.</td>
<td>22-36</td>
<td>0.2-0.24</td>
<td>175*</td>
</tr>
</tbody>
</table>

* Depending on the resin used.

The light transmission of translucent G.R.P. is influenced by the resin content. The higher the resin content the higher the light transmission. A high resin content - around 75% - is also required for good weathering properties of translucent laminates.

G.R.P. members used in the construction industry are commonly thin and are not therefore good sound insulators. The required degree of sound insulation is therefore provided for by composite design, e.g. by use of plaster board as lining material in buildings.

G.R.P. has good chemical resistance especially to acids. For alkaline conditions, P.V.C., polypropylene and some other thermoplastics are preferred as these show better resistance. However, thermoplastics are often used as lining materials providing for chemical resistance, and G.R.P. is used for mechanical strength and weathering protection. P.V.C. can be formed to the required shape. G.R.P. is then applied on the outer surface using the filament winding technique or other appropriate processes. The P.V.C./G.R.P. interface has to be abraded or chemically treated beforehand for good bonding. Large cylindrical tanks, process vessels, chimneys, pipes and ductings are produced in this manner.

5.4.3 Fire-behaviour and fire retardancy:

Some basic information on the fire behaviour of plastics has already been included in subsection 4.2.10.
Under present Building Regulations(15), use of any polymeric materials in the construction of load bearing elements for walls, floors and other structural components of a building is conditional on the presence of a non-combustible backing. However, in the case of self-supporting roofs, no additional requirements have been introduced for polymeric materials compared with the conventional materials.

It must be noted that these requirements are intended for containment of fire within the involved compartment and the safe evacuation of the building occupants. Thus, the regulations are not primarily designed to minimize the likely damages sustained by buildings and their contents (c.f. 10.2). G.R.P. is not a suitable material for static load-bearing applications such as columns or beams in multistorey structural frames and similar cases. This is due to its high cost, low rigidity and creep problems. G.R.P. is generally used in self supporting applications (termed load-bearing, since it also carries wind and snow loadings and the effects of maintenance). These include infill and cladding panels and also roofing. Internally, G.R.P. is used as space dividers, lining panels and decorative applications. 'Reaction-to-fire' tests have to be used to assess performance of G.R.P. in each of these applications.

In the case of roofing, two different tests apply, viz:
(a) the external fire exposure roof test; and
(b) the surface-spread of flame tests on the external and lining surfaces.

If the roof and its ceiling consist of one integrated structural plate, the internal surface of such roofing is tested to measure the surface spread of flame.

The BS476 part3 which was revised in 1975, will be used as the basis for testing the ability of a roof to act as a protective barrier against a fire in a nearby building, and also for testing the extent of any surface ignition. Four specimens of not less than 1.5m x 1.2m are tested; one of these is used for preliminary ignition test and the remaining ones are used for fire penetration and surface ignition tests. The specimens are representative of the roof construction including at least one typical joint which should be arranged to occur in the centre of the specimen. The specimen is tested at an angle as proposed for the actual construction, within
the range 1°-45°; the minimum angle is 1° for flat roofs. In the preliminary ignition test, no radiant heating is used. In this test, a test flame of specified length is applied to the upper surface of the mounted specimen at its centre and is kept there for a period of 1 minute. Continuation of flaming on the surface and fire penetration to the underside are observed. If the duration of flaming exceeds 5 minutes after the withdrawal of the test flame, or if the maximum distance of flaming in any direction exceeds 370mm, subsequent tests are not required and the performance of the specimen is expressed by the letter X. If the duration of flaming is less than 370mm the performance is expressed by the letter P. If penetration to the underside occurs in this test, the penetration time for the whole sample is taken as 1 minute.

In the fire penetration and surface ignition test, the specimen is subjected to a specified radiant heat which is, for example, similar to the intensity incident on a roof 7.5m above ground level from a fire 13.5m away in a building with a facade of 15m x 15m and 50 percent window opening. The test flame (representative of flying embers) is applied for a duration of 1 minute at 5, 10, 15, 30, 45 and 75 minutes after the start of the test. Any roof lights/dome lights etc may be tested by being mounted on the centre of a 1.5m x 1.2m non-combustible panel using the proposed method of construction. The test flame is moved slowly over the rooflight or kept in any position for a period of 15 seconds if the ignition of the surface seems imminent. The following observations are made:
(a) The time and location of any flaming.
(b) The time at which glowing or flaming occur on the underside including development of holes and fissures.
(c) Visual changes in appearance and any fall of molten material.
(d) The maximum distance of lateral flame spread on the upper surface occurring at any time.

The penetration time to the nearest minute is reported for each specimen (up to a duration of 90 minutes if required). The extent of surface ignition is also reported, together with other relevant information. Thus a performance of P60 indicates
that the specimen has passed the preliminary ignition test and has resisted the penetration of fire for a period of 60 minutes.

The minimum performance levels specified by the building regulations for various roofing applications are still based on the BS476:3, 1958, which used two letter codes: the first indicated the penetration time (A for not less than 1h, B for not less than 30 minutes, C for less than 30 minutes and D during the preliminary flame test); the second indicated the surface spread of flame (A none, B for not more than 21 inches, C for more than 21 in. and D for continuous burning for 5 minutes after withdrawal of the test flame).

The following table serves as a guide for similar penetration periods; the upper surface spread of flame is now tested independently using the BS476:6 and 7.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AA, AB, AC</td>
<td>P60</td>
</tr>
<tr>
<td>BA, BB, BC</td>
<td>P30</td>
</tr>
<tr>
<td>AD, BD, CA</td>
<td>P15</td>
</tr>
<tr>
<td>CB, CC, CD</td>
<td></td>
</tr>
<tr>
<td>unclassifiable</td>
<td>P5</td>
</tr>
</tbody>
</table>

The highest performance specified under the building regulation is AA. This may be replaced by P60 with class 1 and class 0 of flame spread in the upper and lower surfaces respectively. Such performance is possible with an opaque G.R.P. laminate using fire retardant resins both for the gel coat and in the main laminate. In addition, it is necessary to apply an intumescent coating on the internal/lining surface.

In the case of translucent G.R.P. sheeting, it is now generally understood that resistance to fire penetration is more important than the spread of flame on the upper surface. This is because the sizes of a rooflight and the total area of rooflights on any building are restricted by the building regulations and the possibility of flame spread is therefore reduced. Other hazards such as the emission of toxic gases and smoke, molten droplets, etc are also important considerations for the rooflights. The best combinations appear to be an adequate resistance to penetration of fire, non-production of
toxic gases and smoke and also absence of molten droplets. Extraction of smoke by ventilation can be another important function of the rooflight, in the case of internal fire.

The penetration of fire in the case of G.R.P. is resisted by the presence of the glassfibre phase. Thus, G.R.P. has the potential of achieving a good performance against the above mentioned requirements. In conditions of internal fire, the resin phase of the G.R.P. disappears, leaving a cobweb of glassfibre which can allow some degree of ventilation. Also, unlike P.V.C. and polystyrene, G.R.P. does not produce any falling lumps and droplets when subjected to extreme heating or flaming conditions.

The surface spread of flame test (BS476:7) uses a 900x900mm vertical radiation panel. A 230x900mm long specimen is cut from the laminate and mounted at right angles to the radiation panel. The radiation received by the specimen varies, being 37kW/m² at the end nearest to the heat source, decreasing to 7.5kW/m² at the far end. The hotter end is ignited for 1 minute. The spread of flame along the specimen after 1.5 and 10 minutes, or the extinction time if it is shorter, is measured. The results are classified according to the following scale:

<table>
<thead>
<tr>
<th>Classification</th>
<th>Spread of flame</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1</td>
<td>Not more than 165mm</td>
</tr>
<tr>
<td>Class 2</td>
<td>Not more than 215mm during first 1.5 minutes and not more than 455mm after 10 minutes or at extinction</td>
</tr>
<tr>
<td>Class 3</td>
<td>Not more than 265mm during first 1.5 minutes and not more than 710mm after 10 minutes.</td>
</tr>
<tr>
<td>Class 4</td>
<td>Exceeding class 3 limits</td>
</tr>
</tbody>
</table>

The spread of flame is an open type test which does not include the effects of ignitability, rate of heat release, smoke production and specimen orientation. Despite these shortcomings, it is still widely used, often in conjunction with the 'fire propagation' test (i.e. to BS 476:6).
with the "Fire-propagation" test uses a cubical furnace with an incombustible lining. A 228x228mm specimen is mounted on an incombustible backing. The specimen forms the lining of one vertical side of the furnace, opposite which are mounted two electrical units which, when switched on, apply an incident radiation of 28kW/m² on the centre of the specimen.

The specimen is initially subjected to small flames (0.5kW/m²) and after 2.5 minutes, the electrical elements are turned on. The emitted gases are directed through a chimney and cowl arrangement and the time/temperature curve of these gases are compared with those obtained from a known incombustible material; an 'index of performance' (I) is calculated using the following expression (16):

\[
I = i_1 + i_2 + i_3
\]

where: \(i_1\), \(i_2\) and \(i_3\) are sub-indices for the three periods measured at 0.5, 1 and 2 minutes intervals respectively;

- \(\Theta_m\) = temperature rise recorded for the material at time \(t\);
- \(\Theta_c\) = temperature rise recorded for the incombustible material at time \(t\); and
- \(t\) = time in minutes from the beginning of the test.

The sub-index \(i_1\) is a measure of early heat release under the influence of gas flames alone.

Experience on various lining materials have shown that the sub-index \(i_3\) has a relatively low value compared with \(i_2\) (16). Omission of \(i_3\) can improve the performance indices of those materials which have a high potential of heat release after prolonged exposure to severe heating conditions.

A low index of performance (I), represents a small contribution to the growth of fire.
The limitations of the fire-propagation test is in the state of orientation of the specimen; horizontal or inclined mounting of the specimen is not possible. This test does not represent the spread of flame on the surface of the specimen. However, it is a good measure of the time to 'flash-over' (16) (26).

The latter is a complex phenomenon; the flash-over time is usually taken as the point during fire development at which the temperature of all combustible surfaces has risen to such an extent that flammable gases are being produced and a merging of flames will result in the whole compartment becoming involved in fire.

The rating of class 0 in the building regulations corresponds to an index of performance of 12 or below, with the sub-index \( i \) being not greater than 6.

It must be noted that the above tests are relevant to one face and a specific thickness of a given material or composite; a different face or thickness of a material or composite layers of materials may achieve different classification.

The fire propagation test is significant in the case of G.R.P. as it gives a more relevant classification than the spread of flame test. G.R.P. is usually used as a thin laminate and has therefore a low potential of heat contribution.

Table 5.15 contains data on performance indices for G.R.P. and some other typical materials. It can be seen that flame-retardant grade G.R.P. laminates can achieve an index comparable to that of plasterboard. A coating of intumescent resin (suitable for internal surfaces) adequately retards combustion of organic materials present in the body of a laminate. However, a fire-retardant laminate with a gel coat especially formulated for good weathering properties, does not normally achieve the class 0 spread of flame; class 2 is the usual performance obtained with such laminates. Under the present building regulations (15), class 2 materials can only be used on elevations of buildings with a maximum height of 15m (50ft).

Control of smoke and noxious gases: Assessment of the hazards associated with production of smoke by wall and ceiling lining materials in conditions of fire is currently under study at the Fire Research Station.
Smoke and evolved gases can create both physiological hazards due to toxicity and irritancy effects, and psychological hazards due to reduced visibility through smoke, state of panic, etc.

Experiments for assessment of toxicity and irritancy of smoke and gases produced by different materials in various conditions of fire are being carried out both at the Fire Research Station and by the independent agencies (17); the aim is to find a simple procedure suitable for consideration as a British Standard.

However, the optical density of smoke produced by different materials is covered by the draft standard DD36:74; provided the vision has not been affected by any irritancy, the optical density will be related directly to the visibility through the smoke (17).

Factors influencing the production of smoke from a given material are:

1. The mode of combustion, i.e. whether the material is burning with a flame or is smouldering.
2. The state of ventilation.
3. The intensity incident radiation.

The measurement of 'optical density' of smoke produced from small specimens in standard conditions under both flaming and non-flaming modes of combustion is the subject of the above draft (17).

For each mode of combustion of a given material, 3 specimens of 228 x 228 mm are tested using the apparatus of fire-propagation. The smoke produced from the fire propagation apparatus is directed to a smoke-tight chamber. In this chamber, the smoke is diluted by operating a fan and transmittance of a parallel beam of light falling onto a photoelectric cell is measured. From this an optical density (D) is calculated using the following expression:

\[ D = - \log_{10} \left( \frac{T}{100} \right) \]

Where \( T \) is the mean transmittance of 3 specimens for each material under given combustible conditions (\( T \) must be calculated using the method specified in DD36:74).

The test report, in addition to the full description of specimens and the results, must contain information on the optimum power input for smouldering conditions (usually determined to the nearest 0.1 kW by experiment), and toxicity of gases evolved.
The greater the amount of smoke produced from a specimen, the higher will be the optical density or the lower will be the visibility.

Although no performance requirements in terms of the above test have yet been proposed, the limited data available indicates (18) that under non-flaming conditions of combustion, mineral-based products with relatively insignificant quantities of combustible materials have a low optical density, whereas G.R.P. laminates and hardboard have a comparatively high optical density. (Typical visibility values of 1 to 1.2 m. have been reported for G.R.P.) (18).

As can be seen the conditions of the above tests are not necessarily simulative or representative of actual fire conditions. Nevertheless pending some essential refinements, especially to improve the classification of the common constructional materials (present classification is too narrow to reflect the differences between materials of different characteristics, e.g. G.R.P. and hardboard), the test is scientifically sound and safe limits of optical density related to actual constructional applications can reduce the smoke hazards.

Introduction of any standard related to the above draft proposal may affect G.R.P. in the following applications:

(1) - External applications, i.e. complete G.R.P. roofings and external elevational uses, especially areas adjacent to the fire exits and windows of buildings.

(2) - Internal applications, i.e. space dividers, lighting and decorative panels, also underside of G.R.P. roofing panels (where no lining is present), etc.

In the case of flame-retardant grades of polyester resins, the potential smoke problem is high, since both Hetacid resins and chlorinated paraffin/antimony trioxide-filled resins rely on the generation of smoke to limit the availability of oxygen and to retard further decomposition of the organic matter.

Other methods of imparting fire retardancy to G.R.P. panels include addition of mineral fillers such as calcium carbonate, china clay, asbestos and alumina-trihydride. These fillers generally reduce the amount of combustible materials by replacing some of the resin in the body of a laminate. In the case of alumina-trihydride, the filler has
additional effects of flame retardancy and smoke reduction due to the significant quantity of heat (claimed to be about 45k Cal/100g of alumina-trihydride approximately) absorbed by the endothermic reaction of the decomposition of this material into alumina and water(19). The former has been claimed to act as a protective inorganic layer to the bulk of the reinforced organic material lying underneath, and the latter evolves as steam which restricts access of oxygen to the burning surface(19). However, filler contents higher than 100 pints of filler to 100 parts of resin by weight, are required to achieve any significant level of fire retardancy. In the hand-lay-up method of production of G.R.P., the filler loading is restricted to 25-75 parts per weight of resin (the general level being 40 to 50). It is therefore necessary to add between 2 to 15 and between 1 to 10 parts per weight of resin antimony trioxide and chlorinated paraffin (e.g. Cerecolor) respectively, depending on whether class 2 or 1 is desired. As will be seen, inclusion of fillers in the gel coat detracts from the weathering properties of the gel coat. One solution to this problem has been to apply or spray a thin film of resin onto the mould surface. After this has gelled a layer of stone chippings of fine size is sprayed and rolled onto the gel coat. The latter is then covered by another thin coat of gel coat resin and allowed to gel before normal laying-up or spraying-up of the laminate is commenced. A further approach has been to finish the laminate with an exposed aggregate surface. As will be noted (c.f. section 7.2), this has not been popular with architects and considered aesthetically inferior.

Current research on polyester resins is directed to development of resins which are sufficiently fire-retardant and at the same time produce less smoke in conditions of fire.

A review of the history of actual fire behaviour of G.R.P.: At this point, it is considered relevant to review the history of actual fire behaviour of G.R.P. panels; this may be considered as another source of data on this topic. However, there is very limited information on the actual fire behaviour of these panels. The following three case histories
have been found suitable. These will now be considered below.

The first case is a recent fire in a large dental surgery building in West London. Ten treatment rooms had been built as extensions to an existing building which was used as reception, X-ray room and laboratories. The external walls of the extension were constructed from a self-supporting system of G.R.P. panels. The panels were of a sandwich construction type consisting of a 1350g/m² (4.2 oz) glass/fire retardant resin laminate with 25mm thick rigid core of polyurethane foam. These panels were designed to meet, in combination with the lining, a one hour fire resistance requirement. The treatment rooms were situated in two rows of five at either side of a corridor, off the main building. The plant room which housed a compressor and the electrical equipment was also enclosed by single skin G.R.P. panels. It was located at the farthest end of the corridor opposite the main building and was separated by a brick wall from the treatment rooms. Fire-retardant G.R.P. panels were used as the internal partitions separating the treatment rooms from each other.

The roof of the extension was of timber-on-timber supported on steel beams and columns. The ceiling was of a class 0 asbestos with aluminium supports. A computer-controlled dispatch system delivered sterilized items to the treatment rooms, through a P.V.C. tube. The roof space was used to house this tube and other services. The fire was started by an electrical fault in the plant room and spread through the roof space to the rest of the building. Some of the treatment rooms were damaged directly by the fire and the rest on the up-wind side of the building by smoke. The fire broke through one point on the G.R.P. panels. The roof construction to the extension was totally destroyed as the timber beams burnt and the aluminium supports melted in the fire. The fire lasted for an hour before being extinguished; there were difficulties in reaching the seat of fire, because of G.R.P. panels. No loss of life had been reported, but the fire gutted much of the interior. The fire behaviour of these G.R.P. panels was considered satisfactory. The premises are to be rebuilt using the same method of construction as before but with appropriate modifications, mainly to contain smoke.
The second case is the full scale fire carried out on a construction, representing a classroom extension in Pulwood, Preston, Lancs, which was carried out at the Warrington Research Centre (21) on behalf of the Lancashire County Council. The experiment proved that G.R.P./phenolic foam composite structure met all the existing performance requirements relating to conditions of fire, though it illustrated that the generation of a considerable amount of smoke may be hazardous. The structure consisted of an outer skin of 3mm, increasing to 6mm near the joints, of G.R.P. laminate with an internal phenolic foam backing, 50mm thick, moulded onto the panel. The former provided the durability and structural requirements and the latter provided the insulation, impact and fire retardancy as well as fire resistance. It is interesting to note that the earlier design had been a sandwich construction of G.R.P. skins (3 and 6mm for outer and inner faces respectively) with a core of phenolic foam (22). The panel was tested for fire resistance with the 6mm G.R.P. face exposed to the furnace. This face burnt completely in a matter of minutes turning into ashes; large volumes of black smoke and toxic gases were also produced from the fire retardant G.R.P. laminate during the early stage of this test (24).

The full scale tests carried out included three identical fire chambers constructed from five brick columns built at the corner of a pentagon. A steel frame constructed from five angles was positioned on top of the brick supports. Asbestos-cement sheets were used for cladding all five sides thus forming an enclosure with each side 2.3m wide and 2.15m high. An opening of 0.7m wide x 2.0m high was left for access and the floors of the three chambers were covered with concrete flags.

Associated with the first chamber a roof was constructed consisting of five triangular-based pyramid modules of G.R.P. outer skin and phenolic foam backing, with joint and assembly as was proposed for the actual construction of the classroom extension at Pulwood School, Preston. The roof was supported by the horizontal steel work.

In the second chamber, a five-sided pyramidal roof was constructed with a roof volume equivalent to the previous
case, using five 7"x 2" timber joists running from the corners of the steel frame to the apex of the roof. Glassfibre insulation was laid between the timbers and held in position by battens fixed to the underside of joists. To these was fixed a fibre board. The outer surface of joists were clad with 20mm plywood, and finished with a three-layer bitumastic mineral felt water-proofing membrane.

The third roof had an identical geometry to the G.R.P./phenolic roof but was constructed from an acrylic sheet. Each module consisted of three pieces of acrylic sheet joined together using cleats and bolts. The purpose of this roof was to illustrate the vast differences which existed between the fire behaviour of different plastics based materials in general and acrylics and G.R.P./phenolic composites in particular.

The fire loadings in each of the chambers consisted of an identical number of wooden cribs. Special precautions were taken to ensure that all the cribs were ignited simultaneously. Five thermocouples were used to monitor and record the internal temperature about 150mm away from the phenolic lining. Five thermocouples were also used to record the temperature on the external surface of G.R.P. skin.

The acrylic roof collapsed about five minutes after the time of ignition. The roof with timber construction lasted for a duration of about 18 minutes. The G.R.P./phenolic foam roof was free from collapse after 30 minutes. The internal time/temperature curve in the fire chamber was in excess of the B.S. curve. The temperature rise on the G.R.P. surface reached 136°C at 15 minutes (at joint 103°C). The corresponding specified temperature rise in the BS476 part 8 test is 140°C. There had been no combustion of the G.R.P. skin. However, more smoke was produced from this construction compared with the other two constructions(21). This large smoke generation has been attributed to the incomplete combustion due to restricted supply of oxygen(21).

The third case history is the ad-hoc fire test carried out on a typical panel of Mondial House at the Yarsley Testing Laboratories(23). The panel which measured 6 x 11ft with a return wing of 4ft, consisted of a fire retardant laminate with a 25mm rigid polyurethane foam core and a gel
coat containing 10 percent inert fillers. The exposed surface of the panel had achieved class 2 spread of flame. No fire resisting test to the BS476 part 8 on this panel had been reported. The ad-hoc test had been designed to assess the reaction of the panel to an incendiary device (taken as a one pound weight of petroleum spirit with a calorific value of about 18,000 B.T.U.). The panel which was supported on its wing on four concrete plinths was subjected to a gas flame of 195W (40,000 B.T.U./min). The observations confirmed that there was not an uncontrolled spread of flame over the surface, that the panel did not collapse and that there was significant quantities of black smoke from the panel at an early stage (4th to 7th minute). The fire did not penetrate through the panel thickness although in the area in contact with the flame the resin and polyurethane foam core had disappeared.

The outline given of the observations on the behaviour of G.R.P. in fire indicate that the material is capable of being engineered to the required specification within the limitations explained earlier. Also, the last ad-hoc test demonstrated that the surface spread of flame to the BS476 part 7 had relevance to the actual fire conditions (i.e. control of spread of flame).

However, a question which has been in the mind of the authorities stems from the complex profiles of G.R.P. or other materials containing combustible materials (25). None of the BS tests have provision for specimen orientation. Other shortcomings of the BS test are that they do not reflect the effects of thermal characteristics of the compartment in fire and the effects of the state of ventilation in that compartment. The former factor can be significant in the case of G.R.P. insulated panels since such designs tend to add to the fire severity as opposed to a sheet of glazing which loses heat rapidly (26).

5.4.4 Long term durability:
Factors affecting the long term durability of plastics in normal exposure conditions have already been outlined (c.f. subsection 4.2.7). Polyester resins made to present day specifications have not undergone long-term weathering
and durability trials to any time scale comparable to the assumed life of a building which is commonly taken as 50 years. The environments in which the proposed building panel must perform has a major effect on the durability of G.R.P. The extent to which mechanical properties of G.R.P. decline with time because of the natural agents have not been established. However, changes in appearance of G.R.P. panels in service have been observed; these have not been related to the degree of retention of mechanical properties. Statements have been made by the resin producers and G.R.P. fabricators that these do not undermine the mechanical properties of G.R.P. and are simply based on surface phenomena.

Durability and weathering performance of a G.R.P. laminate depend critically on the following factors:

(a) Correct choice of resins for the gel coat and the main body of laminate, appropriate type of reinforcement and correct design and specification formulations for the particular product, e.g. whether or not the proposed surface finish and colour are compatible with service conditions, etc.

(b) Adequate level of quality control to ensure suitability of the production environment, the correct fabrication procedure and, above all, a high degree of cure for the resin.

If a laminate is produced with due regard to these factors, it should be durable and slight colour changes or loss of gloss may be acceptable from an engineering point of view.

G.R.P. may be regarded as impervious to rainwater and moisture in normal building applications. For applications where G.R.P. is in contact with hot water, special types of resins are preferred. These show an improved resin/glass fibre bond. Failure of G.R.P. occurs by water penetrating the glassfibre/resin interface and initiating bond breakdown.

Compliance of the polyester resins with the BS3532 gives some assurance of the likely performance of a fully cured G.R.P. moulding. However, to a large extent, the quality of the gel coat determines the weathering, water and chemical resistance of G.R.P. Fig 5.9 to 5.13 indicate different weathering characteristics of various resins and laminates.
It can be seen from Fig 5.11 that fillers have deleterious effects on weathering and are added only to the extent which prevent severe drainage of the freshly applied gel coat (5).

The strength retention of G.R.P. made with a typical good quality polyester resin, immersed in distilled water at 20°C has been studied. Two laminates were made between two sheets of Cellophane. Gel coats were omitted. After post-curing at 80°C for 3h the edges of one of the laminates were sealed and both were immersed in the distilled water. The Bend strength retention after 300 days immersion was 89 and 93 percent of the original values respectively for the unsealed and sealed specimens (5). The corresponding figures for retention of flexural modulus (stiffness) were respectively 89 and 97 percent of the original values (5).

In practice, higher values for strength and modulus retention are attainable since one surface of a G.R.P. laminate is usually in contact with water and this is protected by a gel coat. Distilled water has been found to be more detrimental to G.R.P. than either normal or sea-water (5).

Data on actual performance of early building uses of G.R.P. are of two types:

(a) - Those relevant to translucent corrugated sheeting. Use of Hetacid resins in these laminates has not been accompanied with good weathering performance. The Agrément Board (27) infer that fire-retardant translucent laminates are not expected to have a life (taken as 60% of loss of the original light transmission) greater than 10 years, whereas with good quality general purpose resins, all life in the region of 30 years may be expected. These design guides are based on the actual weathering performance and the work undertaken at the B.R.S. during the last 15 years.

(b) - Data relevant to structural use of G.R.P.: Both translucent and opaque uses of G.R.P. panels are relatively new. One of the earliest uses of translucent panels was in 1964 in the Newcastle Sports Hall (3). The loss in translucency has been from 30 percent to a mere 6 percent; however due to large areas of roof being translucent, the overall level of daylighting is still considered as satisfactory (3). A fire-retardant resin with a white tinted gel coat has been used for the manufacture of these G.R.P. panels. The gel coat has changed to a brownish-yellow. However it is not considered
FIG. 5.9 LIGHT TRANSMISSION OF TRANSLUCENT G.R.P.
SHEETING AT VARIOUS RESIN CONTENTS (Ref. 5)

FIG. 5.10 EFFECTS OF WEATHERING ON GLOSS RETENTION
OF TWO TYPE E RESIN LAMINATES WITH GEL COAT

FIG. 5.11 EFFECTS OF FILLERS INCORPORATED IN GEL COATS
OF LAMINATES ON WEATHERING OF THESE LAMINATES
FIG. 5.12 EFFECTS OF WEATHERING OF G.R.P LAMINATES WITH VARIOUS SURFACES (Ref. 5)

FIG. 5.13 EQUIVALENT DISCOLORATION (YELLOWING) OF G.R.P LAMINATES AFTER NATURAL EXPOSURE AND AFTER ACCELERATED WEATHERING (Ref. 5)
as unattractive. The Golden Mile Centre—an entertainment building in Blackpool—was constructed in 1968. On the roof translucent pyramid units of 4 x 4m base and 3m high were used. The translucent surfaces have darkened producing patchy discoloration. Again, the overall level of lighting is considered as satisfactory(3). Problems of discoloration and variations of the hue and appearance of accumulated dirt patches on the surface of translucent laminates have been common, particularly with fire-retardant Het-acid resin laminates(3).

As a case of opaque and pigmented panels, R.A.F. Sealand, constructed in 1966/67, is a good example. There are very few minor durability problems associated with performance of G.R.P. infill panels of 1m x 3m high. The panels have a concave shape with a random texture of dark bronze colour. No signs of weathering have appeared on this surface except on one panel which has been subjected to continuous exposure to water from an overflow pipe. The water path has left a discoloration mark on the panel surface. Some local defects of gel-coat flaking have drawn attention to the compaction problems of the laminate behind a highly-textured surface. Nevertheless, the panels are considered structurally sound(3).

It must be remembered that pigmented G.R.P. panels are much more durable than translucent ones owing to the presence of pigments which absorb much of the ultra-violet energy with little noticeable change in appearance. Dark brown has been used repeatedly for this reason.

Taken as a whole, there have not been any structural failures with G.R.P. so far; some panels have shown signs of gel coat defects (crazing and blistering). However, the time-scale of applications are too short for drawing any general conclusions.

5.5 Methods of Producing G.R.P. Panels, Systems and Structures:

5.5.1 Introduction:

G.R.P. systems and structures are normally constructed by the assembly of identical G.R.P. panels or units joined together using a variety of jointing techniques. Odd units
for corners or returns are often unavoidable; for these separate moulds must be made. Master patterns constructed from demountable components, may be designed so that they enable a variety of G.R.P. moulds (and in turn panels) to be produced by altering the arrangement of assembly of the components. Jointing components may also be made of G.R.P. It is thus appropriate to discuss methods of producing G.R.P. panels or units.

5.5.2 Contact moulding process:

The contact moulding process uses a single mould, male or female depending on which surface of the moulding a smooth finish is desired. The moulding operations may be carried out without application of heat or pressure. This process has been successfully used to produce both short and long runs of a unit. As will be seen from the brief outline below, it does not require a relatively large capital investment and is still the predominant production process in the reinforced plastics industry. Contact moulding process may divided into two different processes, viz: (a) hand-lay-up; and (b) spray-up technique. These will be discussed separately, after a brief account of the preparation of moulds which is similar in both processes.

Moulds are usually made of G.R.P. using the contact moulding process. Master patterns can be made from timber, timber and plywood, metal or plaster over a timber framework. The porous surfaces must be sealed with a solution of shellac or cellulose acetate before waxing and polishing. A G.R.P. mould is usually made much stronger than the mouldings to be produced from it. The gel coat is 0.5-0.6mm which is thicker than the normal thickness for mouldings (i.e. 0.25-0.4mm). The mould thickness is usually twice that of the moulding. However, in large moulds, it is usually less than twice and the mould is stiffened by the introduction of ribs on the reverse side. Split moulds where necessary, may also be made on a one-piece pattern. The connecting flanges are usually made 50 percent thicker than the normal mould thickness. Additional stiffening with metal inserts are usually necessary to ensure adequate strength against localized loads imposed by nuts and bolts and clamps. The moulds are not released
from the patterns until after at least 7 days and preferably 14 days. This is to ensure that the overall dimensions of the moulds are not distorted by shrinkage.

Polyvinyl alcohol solution is normally used as a release agent. A thin film applied by a cloth or sponge, or sprayed is adequate. This is allowed to dry thoroughly before laminating is commenced.

Gel coat is a high quality polyester resin which is used to protect the main body of the laminate against weathering. It may be pigmented and applied by brush or paint roller. Alternatively, it may be sprayed. The thickness must be controlled to 0.25mm-0.4mm. If it is too thin it will not fully cure and the fibre pattern may be visible, and if it is too thick it may crack or craze. In some applications a surfacing tissue is pressed onto the freshly applied gel coat to reinforce the gel coat and provide a resin-rich surface. The main laminating operations can be commenced immediately after the laying of the surfacing tissue. If no surfacing tissue is used then the gel coat is allowed to gel (i.e. when it has reached a tacky stage) before the lamination is commenced using either hand-lay-up or spray-up technique.

5.5.2.1 Hand-lay-up technique:

A liberal coat of resin is applied by a brush or roller or sprayed over the set gel coat. The first layer of the reinforcement which is usually prepared beforehand is laid. The most usual reinforcement is chopped strandmat; however, woven rovings or unidirectional rovings may be incorporated. The reinforcement is pressed into the resin and consolidated with a brush or roller. The resin should fully impregnate the reinforcement and air bubbles should be worked out before further lamination. Special care must be taken to ensure that the reinforcement is thoroughly consolidated into the corners, recesses and shaped parts. Subsequent layers of glassfibre and resin may be built up in a similar fashion. The stiffening ribs may be incorporated before the last layer of the laminate is applied. Metal inserts can also be incorporated during the laminating process. Trimming operations are carried out whilst the moulding is in a soft rubbery state and is still in the mould.

The chief advantages of this process are: flexibility,
i.e. the ease of incorporating various reinforcement combinations, and its improved uniformity of thickness, especially when glass mats and fabrics are used. The majority of fabricators in the industry employ this technique which, as mentioned before, requires a minimum amount of capital investment.

5.5.2.2 Spray-up technique:

This process is based on the simultaneous deposition of polyester resin and chopped glass fibre, normally 20-25 mm long, using spraying equipment. The process has been available for many years but has not been widely used in the past. However, it is gradually being employed by some fabricators, although others have special reservations to the process. A variety of commercial equipment is available; these are different in detail but are based on the following two techniques:

(1) - The Twin-pot system: In this type of equipment a two part resin is used, one catalysed and the other accelerated. The two systems are separately fed to the twin nozzles of a spray gun. Glass fibre rovings are chopped by a chopper and deposited onto the mould surface simultaneously with the converged streams of resins.

(2) - The catalyst injection system: In this type of equipment only one resin system is used which is pre-accelerated. The catalyst is accurately metered and added to the resin as the resin is passed through a single nozzle. The glass fibre is chopped and added in the same way as before.

Consolidation of the laminate and removal of the air bubbles must be carried out by rolling in the manner described previously. The consistency of the glass-resin mixture and uniformity of the thickness are difficult to maintain unless the operator is sufficiently skilled.

Spraying of resin can be carried out and reinforcement added by hand in a manner similar to the hand lay-up process. This process is estimated to show a saving of 20-25 percent in labour costs(6); the complete process, i.e. including use of a glass chopper, has been claimed to show a saving of up to 50 percent in labour costs compared with the hand-lay-up method(28). These claims have not been confirmed by other fabricators who state that labour used for the setting-up and cleaning of the equipment must be taken into consideration.
They also claim that control of thickness of the laminate is difficult and there is too much wastage of materials.

The spraying technique is suitable for larger volumes of production than the hand-lay-up method. It is suitable for series production of not very complicated profiles.

Fig 5.14 illustrates schematically the hand-lay-up production process.

5.5.3 Matched-die moulding:

Matched-die mouldings may be divided into the following processes: (a) hot press moulding; (b) cold press moulding; and (c) resin injection moulding.

5.5.3.1 Hot press moulding:

This is a process particularly suitable for the production of very long runs of identical units. In this process a correct quantity of hot curing catalysed resin (see 5.2.2.2 and below) and reinforcement is placed between the heated male and female moulds in the press. The press is then closed exerting a pressure of between 350 to 3500 kN/m² and a temperature of 100-170°C (see Fig.5.15). Production cycles are normally between 2 to 4 minutes.

The dies must be accurately finished and are made of chrome-plated steel and polished. However, depending on the quality of finish and the production volume, other metals may be utilized. The following may serve as a very general guide:

1. Aluminium 100-200 mouldings.
2. Kirksite 100-5,000 "
3. Meehanite and close grain cast iron 1,000-5,000 mouldings
4. Mild steel 1,000-50,000 "
5. Hardened steel, chromed up to 200,000.

The reinforcement may be preformed by the use of a screen of a fine metal mesh suitably shaped to the contours of the mould. By applying negative or positive pressure, chopped glassfibres are collected in the desired thickness on the screen. A spray of resinous binder is applied and then the pre-form is transferred into an oven at about 150°C.
Schematic Diagram: Contact Moulding: eg Building Cladding Panel

Hand Lamination

- Gel Coat
- Lamination
- Released

Core Material
- Lamination
- Stiffening
- Trimming
- Stripped from mould
- Post Cure
- Finishing Operations
- Finished Moulding

Stiffening
- Trimming
- Stripped from pattern
- Post Cure
- Finishing Operations
- Finished GRP Mould

Timber master mould
- Finished to high polish

production of one or more moulds as dictated by production quantity of mouldings required

FIG. 5.14

See Text
HOT PRESS MOULDING

SHEET MOULDING COMPOUNDS

DOUGH MOULDING COMPOUNDS

RESIN PRE-IMPREGNATED GLASS CLOTH/MAT INCORPORATING PIGMENT, FILLERS, ADDITIVES, SUPPLIED IN SHEET FORM

INTIMATE MIXTURE OF CHOPPED STRAND GLASS FIBRE, RESIN, PIGMENT, FILLERS, ADDITIVES, SUPPLIED IN FORM OF A DOUGH

TAILORED BY CUTTING TO CONFORM TO APPROX SHAPE/MATERIAL WT REQUIRED

INDIVIDUAL WEIGHED QUANTITIES PREPARED CONFORMING TO MOULDING WEIGHT REQUIRED

MATCHED HYDRAULIC METAL TOOL SET DIRECT/INDIRECT HEATED

HYDRAULIC OR MECHANICAL PRESS

OPEN PRESS

CHARGE

CLOSE PRESS

DWELL TIME-TEMP-PRESSURE

OPEN PRESS

TOOL AIR BLAST CLEANED

MOULDING EJECTED REMOVED BY HAND

TRIMMED/DEFLASHED

FINISHED MOULDIING

FIG. 5.15
after which it is loaded into the metal dies.

Alternatively, fibre-reinforced polyester moulding compounds may be used. These are D.M.C., B.M.C. and S.M.C. Dough Moulding Compound (D.M.C.) is a ready-to-use mixture of catalysed polyester resins containing fillers, and 15 to 20 percent fibre of either 3-12mm E glass or sisal. D.M.C. is used for small mouldings where bulk properties are more important than the strength. Bulk Moulding Compound (B.M.C.) is basically the same as D.M.C. except that isophthalic polyester resins are used to ensure better quality and finish and, more important, to give improved heat resistance.

Alkali metal oxides are used to chemically thicken the resin. Thermoplastic additives may be incorporated to improve the surface finish. Sheet Moulding Compound (S.M.C.) which is also referred to as 'Prepreg' is a sheet of polyester resin impregnated glass mat or fabric sandwiched between thin films of polyethylene. The mixture contains fillers and when stored in correct conditions, it has a storage life of about 6 months. The fibres are 12-25mm long and the fibre contents normally range from 20 to 35 percent by weight. Alkali-metal oxides are used to thicken the mixture chemically and thermoplastic additives may be used to reduce surface imperfections(5).

The release agent in all forms of hot press moulding is normally zinc stearate which is added to the resin or mixture. This compound migrates to the surface as the material polymerizes.

As was mentioned previously, the main criterion for employing the hot-press moulding technique is the production volume since both tooling and press costs are high. However, occasionally other criteria such as uniformity of thickness, consistency of qualities, etc. may require employment of this process.

Hot-press moulding, especially using S.M.C. with improved strength, is significant to the building industry. The main technical limitation of this process is the size of mouldings, though this limitation can be overcome to a large extent with employment of larger moulding presses recently introduced. One such press with a table size of up to 3m x 10m, was exhibited by Rudolf Meyer at the recent K75 Exhibition of Plastics and Rubbers held in Dusseldorf, West Germany(29).
This press is suitable for both hot-press moulding and cold-press moulding techniques.

5.5.3.2 Cold-press moulding:

This process is economic for a production volume of between (5) 200 to 2,000 mouldings. In this process, no heating is required and the moulding pressure may be as low as 100 kN/m². Moulds may be made of G.R.P., steel or concrete with resin polished surfaces. The production cycle averages between 15 to 20 minutes. Glass to resin ratio can be as high as 50 percent by weight and as with the hot-press moulding process, much higher levels of fillers can be incorporated, compared with the contact moulding process; thus, much improved strength, stiffness and fire-retardancy can be obtained.

In cold-press moulding, a gel coat may be applied or sprayed onto the mould surfaces (usually one mould only). A hydraulic press is generally used for large mouldings. Static loads may be used in simple moulding with the help of a hydraulic jack if necessary.

Resin systems used include the general-purpose and flame-retardant, filled or unfilled; with the general-purpose resins, it is possible to use highly reactive catalysts. However, with the flame-retardant resins, fast curing can be achieved by application of heat as described previously.

5.5.3.3 Resin-injection moulding:

This is a process particularly suitable for smaller production runs compared with the cold-press moulding (30). The matched-moulds which are made either of either G.R.P. or light metals, should resist an internal pressure of up to 400 kN/m². Incorporation of gel coat is possible by spraying onto the mould surface. A low viscosity resin is usually used; however, with recent equipment, high viscosity resins (filled) can also be injected successfully. Glass contents may range from 20 to 25 percent by weight, whilst higher glass contents of up to 40 percent by weight may be included conveniently (5). The incorporation of sisal mat can increase the bulk and improve the flow of the resin.

The specified quantity of reinforcement and the core
material are placed over the bottom half of the mould. For better trimming, the glass mats may be allowed to be slightly longer than the mould perimeter. The edges are trimmed after the resin has gelled and the moulding is in a rubbery state. The two moulds are clamped together and the catalysed resin is injected until it fills up all the space between the fibres and seeps through the edges. At this stage the injection is discontinued and the cure is commenced.

The resin injection process has many advantages over the cold press moulding, some of which are as follows:

(i) Lower initial capital outlay, since a press is not required.

(ii) Greater flexibility in moulding operations.

(iii) More economic production of deep draw parts, particularly when a high surface gloss is required.

A modified version of the injection moulding employs a press similar to the cold press moulding. The resin may be drawn by introducing a negative pressure. This process, which is known as "Suction and Squeeze" (S.A.S) has been claimed to be economic for producing unit numbers of 1000 or more. The capital outlay is higher than the simple injection technique, but the labour content is greatly reduced. The ram pressure can be applied at various stages during the impregnation process to ensure a fully consolidated moulding.

The semi-machanized processes especially the injection moulding and S.A.S. processes are very relevant to the construction industry, since G.R.P. cladding panels, designed for major building projects or for standardized building units provide the minimum volume production required for economic use of these processes.

5.5.3.4 The advantages of the matched die-moulding over the contact moulding process are:

(a) Smooth surfaces on both sides of the moulding.

(b) Consistency in the moulding thickness.

(c) Reduced labour costs resulting in reduction of the total costs per piece for medium to large volumes of production.

(d) Improved and consistent quality control including the control of resin to glass ratio.

(e) Higher strengths and rigidities and improved fire
performance due to higher levels of glass fibre and fillers.
(f) Improved space utilisation and faster production cycles.

5.5.4 Other production processes:
These include continuous production of corrugated (or flat) roof sheeting, the filament winding technique, pultrusion and centrifugal moulding.

5.5.4.1 Manufacture of roof sheeting:
Continuous processes are usually employed to produce roof sheeting, except when non-standard profiles are desired, in which case the hand-lay method may be employed(5). There are several mechanized processes but these are based on the same principle which involves sandwiching a layer of glass-fibre and resin between two regenerated release films, usually Cellophane or Melinex. The sandwich is then subjected to pressure by a series of rollers which expel the air and ensure uniform thickness. The next stage is corrugation and curing which takes place in an oven.

The production is fully mechanized and a variety of standard profiles may be obtained by altering the dies or rollers(31). Special types of resins have been introduced, each compatible with a particular process producing optimum results in the end product.

An extension of this process in current years has been to produce opaque shiplap profiles for vertical cladding of dwelling houses and similar applications where it substitutes traditional wooden shiplap. It is usually used to cover other visually inferior materials such as clinker block.

5.5.4.2 Filament winding:
This technique is not suitable for producing G.R.P. panels but is used for the production of large cylindrical tanks, chimneys, pipes and ducting. Recently it has been used to produce large structures of various shapes. This may be of significance in the production of domical roofs, etc.

The filament winding process involves impregnating a continuous glass roving by passing it through a resin bath. The impregnated glass roving is then wound on to a rotating
meldrel or in case of composite laminates, onto the rotating liner which is made of PVC, polypropylene or special grades of metals. The angle of winding to the longitudinal axis of rotation can be varied within the usual range of 25°-85° to give the required strength characteristics.

Other types of reinforcement may be used. These include woven tapes, chopped strand mat, etc. (5)

5.5.4.3 Pultrusion:

This process is particularly suitable for production of standard G.R.P. profiles, e.g. rods, tubes and a range of various profiles with different strength characteristics. Recent processes are capable of producing larger sections suitable for a variety of applications such as lamp posts. The process basically consists of pultruding resin impregnated rovings through heated dies. Resin systems are of the hot curing types and a variety of reinforcements can be incorporated to give the required longitudinal and transverse strength characteristics.

Although tooling costs (i.e. dies) are generally lower than in the case of the hot press moulding, the end product is not cheap compared to the contact moulding process. However, for very long runs of production, pultrusion can show significant cost-saving, of the order of 20 percent (32) on a cost/performance basis compared with the contact moulding process. This process is technically superior to the contact moulding and is capable of further development. It is now technically feasible to utilize pultrusion for production of a range of standard G.R.P. load-bearing sections with known strength characteristics. These can be filled with various lightweight materials to improve the load-bearing performance.

5.5.4.4 Centrifugal moulding:

This process involves laying chopped rovings or glass mat inside a hollow mandrel and impregnating with the catalysed resin. By rotating the mandrel the laminate is consolidated. This process is suitable for production of tubes, pipes and cylinders of up to 5m in diameter (5).
5.5.5 Quality control requirements:

At present the quality control of various reinforced plastics mouldings is covered by the BS 4549. As with other British Standards, this specification is based on performance criteria, compliance with which must be assessed by a routine programme of testing. Of particular importance is part 1 of this BS specification dealing with mouldings produced from chopped strand mats or randomly deposited glassfibre which is summarized below.

(a) Materials: When the materials are specified to comply with any BS specification, it becomes the suppliers responsibility to guarantee the same.

(b) Selection of test specimens and frequency of testing: Test specimens for the assessment of hardness and residue on ignition must be taken from the actual mouldings. For other tests, specimens taken from a special flat moulding made from the same materials and under identical fabrication conditions may be adequate. Sampling and testing frequency must be sufficient to be representative of the product quality.

(c) Preliminary examination: Each moulding must be examined visually for defects such as protruding fibres, pits, blisters, crazing and cracks, voids, bubbles, resin rich or resin starved areas, surface tackiness and presence of foreign matter.

(d) Dimensions: Tolerances on dimensions must be agreed. Normal acceptable tolerances for the thickness of a moulding are given in Table 5.16. Thickness may be measured using a micrometer with an anvil of not less than 12mm diameter or in the case of large mouldings a magnetic thickness instrument.

(e) Glass content: In general if the nominal glass content is specified as N%, the variation must be within \((N-2.5)\%\) to \((N+7.5)\%\). If there are no mineral fillers used in a moulding, the residue on ignition can serve as a quick control to the glass content. For mouldings, containing such fillers, Method 107K of the BS 2782 may be used as a basis for determining the glass content.

(f) Degree of cure: The 'Barcol' hardness of a moulding is taken as a measure of its degree of cure. The minimum value should be at least 90 percent of the Barcol value.
Table 5.15 Performance Indices for G.R.P. and for selected other materials (Source: ref. 16, supplemented by additional data from the Fire Research Station)

<table>
<thead>
<tr>
<th>Material</th>
<th>Treatment/facing</th>
<th>Thickness</th>
<th>I</th>
<th>1</th>
<th>1.2+1.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>G.R.P. (c.s.m.)</td>
<td>gelcoat</td>
<td>3.6</td>
<td>22.9</td>
<td>9.9</td>
<td>11</td>
</tr>
<tr>
<td>&quot; (woven roving)</td>
<td>&quot;</td>
<td>4.6</td>
<td>18.7</td>
<td>9.0</td>
<td>9.3</td>
</tr>
<tr>
<td>&quot; sheet</td>
<td>flame-retardant</td>
<td>3.0</td>
<td>11.1</td>
<td>4.0</td>
<td>6.2</td>
</tr>
<tr>
<td>&quot; (woven roving)</td>
<td>intumescent gelcoat</td>
<td>4.9</td>
<td>9.1</td>
<td>1.1</td>
<td>7.1</td>
</tr>
<tr>
<td>&quot; laminate</td>
<td>flame-retardant grade</td>
<td>3</td>
<td>11.2</td>
<td>4.0</td>
<td>7.2</td>
</tr>
<tr>
<td>Softwood</td>
<td>-</td>
<td>18</td>
<td>42.5</td>
<td>17.2</td>
<td>25.3</td>
</tr>
<tr>
<td>Hardwood</td>
<td>-</td>
<td>19</td>
<td>34.9</td>
<td>9.5</td>
<td>25.4</td>
</tr>
<tr>
<td>Hardboard</td>
<td>-</td>
<td>5</td>
<td>30.1</td>
<td>10.5</td>
<td>19.6</td>
</tr>
<tr>
<td>Softwood</td>
<td>intumescent coating</td>
<td>19</td>
<td>15.1</td>
<td>5.8</td>
<td>9.3</td>
</tr>
<tr>
<td>Hardboard</td>
<td>&quot;</td>
<td>5</td>
<td>16.4</td>
<td>4.0</td>
<td>12.4</td>
</tr>
<tr>
<td>Polyurethane foam</td>
<td>flame-retardant grade</td>
<td>35</td>
<td>38.7</td>
<td>28.3</td>
<td>11.4</td>
</tr>
<tr>
<td>&quot;</td>
<td>&quot;</td>
<td>15</td>
<td>28.6</td>
<td>23.4</td>
<td>5.2</td>
</tr>
<tr>
<td>Acrylic sheet</td>
<td>-</td>
<td>3</td>
<td>39.8</td>
<td>20</td>
<td>19.8</td>
</tr>
<tr>
<td>Melamine-faced hardboard</td>
<td>-</td>
<td>6</td>
<td>32.3</td>
<td>12.4</td>
<td>19.9</td>
</tr>
<tr>
<td>P.V.C.</td>
<td>-</td>
<td>3</td>
<td>16.8</td>
<td>5.9</td>
<td>10.9</td>
</tr>
<tr>
<td>Melamine/phenolic laminate</td>
<td>flame retardant</td>
<td>2</td>
<td>7.2</td>
<td>1.5</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Table 5.15 (contd)

<table>
<thead>
<tr>
<th>Material</th>
<th>Treatment/facing</th>
<th>Thickness</th>
<th>I</th>
<th>$i_1$</th>
<th>$i_{2+i_{1}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asbestos-board</td>
<td>Wood Veneer 0.8mm thick</td>
<td>19</td>
<td>22.2</td>
<td>12.2</td>
<td>10.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>PVC film 0.4mm thick</td>
<td>9</td>
<td>7.4</td>
<td>5.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Steel sheet</td>
<td>resin coated</td>
<td>3</td>
<td>11.9</td>
<td>3.9</td>
<td>8.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>PVC coating 0.3mm</td>
<td>3</td>
<td>5.5</td>
<td>2.2</td>
<td>3.3</td>
</tr>
<tr>
<td>&quot;</td>
<td>painted one side</td>
<td>3</td>
<td>1.7</td>
<td>1.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Mineral fibre tile with organic binder</td>
<td>Emulsion painted coat</td>
<td>22</td>
<td>16.6</td>
<td>7.7</td>
<td>8.9</td>
</tr>
<tr>
<td>Plasterboard</td>
<td></td>
<td>9</td>
<td>9.7</td>
<td>5.7</td>
<td>4.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>Emulsion painted</td>
<td>13</td>
<td>9.0</td>
<td>5.2</td>
<td>3.8</td>
</tr>
<tr>
<td>&quot;</td>
<td>PVC film, 0.2mm</td>
<td>9</td>
<td>10.0</td>
<td>5.4</td>
<td>4.6</td>
</tr>
<tr>
<td>&quot;</td>
<td></td>
<td>13</td>
<td>9.9</td>
<td>5.8</td>
<td>4.1</td>
</tr>
</tbody>
</table>
specified by the resin manufacturer. As the Barcol value is temperature-dependent, either a test temperature must be specified with a tolerance±2°C or minimum values given for a range of temperatures. In some cases it may be necessary to determine the hardness of the gel coat as well as the main laminate. The testing procedure is detailed in Appendix A of the BS 4549, Part 1. The variation in the 'hardness-reading' is dependent on the degree of hardness of the material; it is less in harder materials, (Barcol value 50 and higher). The number of readings required for a reinforced plastics (non-homogeneous) material is usually between 5 to 20.

(g) Gross-breaking strength: The minimum value for this property which is determined in accordance with Method 304D of BS 2782, should be agreed.

(h) Other requirements: It may be necessary to specify agreed limits for a number of other properties as listed in Table 5.17.

Table 5.16 Tolerances for the Thickness of a Moulding

<table>
<thead>
<tr>
<th>Nominal thickness (mm)</th>
<th>Open Mould (mm)</th>
<th>Closed mould (mm)</th>
<th>Matched mould (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up to but not including 1.5</td>
<td>- 0.25 to + 0.50</td>
<td>+ 0.20</td>
<td>+ 0.18</td>
</tr>
<tr>
<td>1.5 but not including 3</td>
<td>+ 0.75</td>
<td>+ 0.30</td>
<td>+ 0.20</td>
</tr>
<tr>
<td>3 but not including 6</td>
<td>+ 1.1</td>
<td>+ 0.50</td>
<td>+ 0.30</td>
</tr>
<tr>
<td>6 but not including 12</td>
<td>+ 1.5</td>
<td>+ 0.75</td>
<td>+ 0.40</td>
</tr>
<tr>
<td>12 but not including 25</td>
<td>+ 2.0</td>
<td>+ 1.4</td>
<td>+ 0.50</td>
</tr>
<tr>
<td>25 and over</td>
<td>+ 3.0</td>
<td>+ 1.9</td>
<td>+ 0.65</td>
</tr>
</tbody>
</table>

It is worth noting that the requirements of the BS 4549 part 1 are not always satisfied especially in the contact moulding process. Some fabricators reason that some of these requirements are difficult to comply with. For example variation of the thickness (c.f. Table 5.16) and variations of the glass content cannot be closely controlled with the
contact moulding process. They also consider that these requirements are not always relevant to the product quality requirements in service.

However, it must be emphasised that compliance with the BS4549 makes the task of the designer less complicated since he can be assured of the variation expected and can design accordingly.

Table 5.17 Quality Control Test Methods

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Test Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flammability</td>
<td>Appendix B of BS4549</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>Method 301M of BS2782</td>
</tr>
<tr>
<td>Impact Strength</td>
<td>&quot; 306A &quot; &quot; &quot;  &quot;</td>
</tr>
<tr>
<td>Bolt Bearing Strength</td>
<td>Appendix C of BS4549</td>
</tr>
<tr>
<td>Elastic Modulus in Bend</td>
<td>Method 302D of BS 2782</td>
</tr>
<tr>
<td>Water Absorption</td>
<td>Method 502G of BS 2782</td>
</tr>
</tbody>
</table>

5.6 Installed Cost Analysis:

5.6.1 Costs of G.R.P. panels:

The total installed cost may be divided into the following components: (a) tooling and plant charges; and (b) piece cost.

5.6.1.1 Tooling and plant charges:

The tooling charge is derived from the amortization of the total tooling costs over the total number of units made. Plant (i.e. equipment) charges are more difficult to calculate. These are derived by first depreciating the total value of the relevant equipment to yield the annual cost. This cost is then amortized over the annual production volume. In the case of the hand-lay-up method of fabrication pattern and moulds write-offs constitute principle tooling charge; rent, rates and other similar cost items are usually
accounted for in overheads.

In the U.K., the contact moulding process accounts for over 70 percent of all reinforced plastics articles produced (33). Furthermore, the hand-lay-up method of fabrication is predominant (see Section 5.5)

Pattern and G.R.P. mould costs vary with the complexity of the geometric shape of the units. Timber patterns for simple profiles cost around £100-120 per sq. m. G.R.P. moulds cost £60-70 per sq.m. In the case of a small number of repetitive units, a timber mould would be sufficient.

The tooling charges, assuming a timber pattern and one G.R.P. mould, range from £22 to £0.8 per sq.m. for unit numbers of 5 to 300 respectively (see Table 5.18).

**Table 5.18** Tooling charges in Contact Moulding vs Unit Number

<table>
<thead>
<tr>
<th>Unit Number</th>
<th>5</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. Tooling charge (£/m²)</td>
<td>22</td>
<td>7</td>
<td>3.5</td>
<td>2.34</td>
<td>1.75</td>
<td>1.20</td>
<td>0.9</td>
<td>0.80</td>
</tr>
</tbody>
</table>

@ Based on costs of one timber mould only.

Based on costs of a timber pattern and 2 G.R.P. moulds.

**Table 5.19** Approximate Total Piece Cost(6) of Hand Laminated G.R.P. Panels (Oct. 1975; source: Messrs Arimat Ltd)

<table>
<thead>
<tr>
<th>Glass Content (g/m²)</th>
<th>Nominal thickness (mm)</th>
<th>Material cost (£/m²)</th>
<th>Labour cost (£/m²)</th>
<th>Total piece cost (£/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>450*</td>
<td>1.25</td>
<td>2.16</td>
<td>1.0</td>
<td>5.50</td>
</tr>
<tr>
<td>900</td>
<td>25-2.75</td>
<td>4.00</td>
<td>1.69</td>
<td>10.50</td>
</tr>
<tr>
<td>1350</td>
<td>3.5-4</td>
<td>6.0</td>
<td>2.15</td>
<td>14.65</td>
</tr>
<tr>
<td>1800</td>
<td>5-6</td>
<td>8.0</td>
<td>3.0</td>
<td>19.50</td>
</tr>
<tr>
<td>✱</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2250</td>
<td>7-8</td>
<td>10.0</td>
<td>4.0</td>
<td>25.0</td>
</tr>
<tr>
<td>2700</td>
<td>9-10</td>
<td>12.0</td>
<td>5.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>

* Hypothetical case

† Incorporation of core becomes essential to reduce total cost
cost. However, the figures beneath this line are based on solid G.R.P.

a Does not include managerial and clerical charges.

b Ex-works total materials and labour cost plus overhead and profit charges. It does include any allowances for tooling, delivery and installation costs. For a 1350g/m² with a simple profile and 50 numbers off, the selling price inclusive of all charges is, according to Messrs. Anmac, of the order of £25/m² (Prices usually range from £22/m² to £50/m² depending on the numbers off, size, shape and the panel specification).

More complex shapes will increase the tooling charges significantly, e.g. an increase of £100 per sq.m. in the tooling costs (a fairly extreme case); can push up the tooling charges by £1/m² to £2.75/m², for a production run of 100.

In the case of hot-press moulding the tooling costs are high. This means that for the hot-press moulding to be economically competitive, the unit repetition must be at least of the order of 4,000 to 10,000 (see Section 5.5). However, if the unit repetition is very high, e.g. of the order of 100,000, the effects of the tooling and plant charges on the total finished cost of the moulding will be relatively small making this process very competitive compared with the contact moulding process. This comment applies to other processes, although to different extents (see Section 5.5).

5.6.1.2 Piece cost:

The piece cost may be considered as composed of the following:

a - Materials
b - Labour
c - Overheads and profit
d - Transport and fixing

Table 5.19 gives information on material, labour, overhead and profit costs for the hand-lay-up method of lamination, including the gel coat.

The spray-up technique has been claimed to require between 30 to 50 percent less labour than is given in the
above mentioned table. However, additional cost items due to the use of spray-up equipment and material wastages must be taken into consideration (c.f. Section 55).

In the case of the hand-lay-up method, overheads are usually charged as a percentage of the labour costs (normally 160%) (34). Profit charges are around 20 percent of materials, labour and overhead charges (34).

Transport and fixing charges are dependent on the type and size of panels and the site distance from the factory. These are generally considered to be low compared with other cost items (34). Fixing costs can be reduced by a correct design approach so as to eliminate the use of scaffolding and other costly equipment. If these needs are satisfied, fixing costs can be as low as 5 percent of the total piece cost. Transport costs are usually low provided that the panel sizes do not exceed the dimensions of the lorry and the shape of the panel is such that as many as possible can be accommodated on a lorry.

An appraisal of the above cost-analysis relevant to the contact moulding process reveals that the typical total installed cost i.e. the selling price inclusive of all charges for G.R.P. panels ranges from £22-£50/m² depending on the case under consideration. It is worth recording that in the case of self-supporting G.R.P. roofs, the cost-analysis is basically unchanged (35).

A fully insulated G.R.P. panel of sandwich construction type which has a fully finished internal surface is likely to cost more than a single skin G.R.P. lined with plasterboard and insulated by use of 50mm fibreglass quilt or a single skin G.R.P. mounted on a concrete blockwall. (e.g. Thermalite, see 'Installed cost comparison' below).

As can be seen by reference to Table 5.19, the total piece cost excluding transport and fixing, is dependent on the quantity of G.R.P. materials used. It rises rapidly as the thickness increases and becomes prohibitively expensive with thicknesses greater than 5mm, i.e. in comparison with alternative materials (see Table 5.6.2). As the stiffness of a flat panel is a function of its thickness, if the laminate thickness is inadequate buckling may occur which
can make the panel aesthetically unacceptable due to visual distortion. In practice, the stiffness of a panel is increased by other methods in order to keep down the amount of G.R.P. materials used. These will be discussed in Section 5.7.

5.6.2 Installed cost comparison:
In order to proceed with his study, it has been assumed that G.R.P. panels with an installed-cost ranging from £25-30 have been provided using one or more techniques to be described in Section 5.7, e.g. by introduction of stiffening ribs and or shaping of the panels coupled with local variations in the laminate thickness or reinforcement to suit the stress distribution, etc. In the remaining part of this section, attention will be focused on comparison of installed-costs between G.R.P. panelling and certain conventional constructions. It is realized that such cost-comparisons are not necessarily accurate due to different technical and aesthetic attributes of the materials and forms of construction. An example of technical differences may be seen by reference to Fig. 5.16 which shows substantial weight variations between alternative roofing systems(35). Furthermore, size and location of a construction project can have significant influence on the costs.

Indirect costs - e.g. early completion of a project - have been ignored. Maintenance costs have also been excluded. However, it must be noted that many traditional materials such as brick are relatively maintenance free.

Table 5.20 contains estimates for typical installed or finished costs of certain conventional constructions (not necessarily of equal performance). A brief specification has been given for each construction form. G.R.P. roofing data have also been given. These data should be sufficient to give a feel of where G.R.P. fits within the many alternative design formulations available to designers. It must be noted that in the current inflationary economic climate any cost data can be out of date very quickly. However, it is clear that use of G.R.P. in any form is an expensive option for the designers. An intelligent appraisal of the data included in Table 5.20 confirms that the use of G.R.P.
Fig 5.16  Weight vs Span for Various Roofing Types (Ref. 35)

- Concrete
- Timber
- Asbestos
- Steel Deck
- GRP Sandwich Deck
Table 5.20 Typical costs for certain conventional constructions (see Note 1)

<table>
<thead>
<tr>
<th>Type of Construction</th>
<th>Cost (£/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I - External walls and windows:</strong></td>
<td></td>
</tr>
<tr>
<td>1 - Facing brick, single (half brick thick):</td>
<td></td>
</tr>
<tr>
<td>a - (Fletton Rustic, p.c. £22/1000)</td>
<td>8.50</td>
</tr>
<tr>
<td>b - (Stock, 2nd. hard, p.c. £65/1000)</td>
<td>13.50</td>
</tr>
<tr>
<td>c - (Dorking, sandfaced, p.c. £90/1000)</td>
<td>15.50</td>
</tr>
<tr>
<td>2 - Cavity brick wall (flat):</td>
<td></td>
</tr>
<tr>
<td>a - Lowest: consisting of half brick thick, Fletton Rustic and 75mm Thermalite inner leaf, plastered, cavity insulated, emulsion paint, brick jointing</td>
<td>18.0</td>
</tr>
<tr>
<td>b - Ditto but with average quality facing brick</td>
<td>21.0</td>
</tr>
<tr>
<td>c - Ditto but with high quality facing brick</td>
<td>24.0</td>
</tr>
<tr>
<td>3 - Concrete blockwall consisting of:</td>
<td></td>
</tr>
<tr>
<td>a - 140mm solid Thermalite, faced with machine-made sand-faced tiles including the backing felt</td>
<td>20.0</td>
</tr>
<tr>
<td>b - Ditto but using hand-made tiles</td>
<td>23.0</td>
</tr>
<tr>
<td>4 - Concrete walls; site cast consisting of:</td>
<td></td>
</tr>
<tr>
<td>a - Solid wall 150mm thick reinforced concrete, exposed aggregate finish, fair face interior finish</td>
<td>26.0</td>
</tr>
<tr>
<td>b - Ditto but 225mm thick</td>
<td>29.0</td>
</tr>
<tr>
<td>5 - Natural stone:</td>
<td></td>
</tr>
<tr>
<td>75mm Ancaster stone facing slabs and fixings (excluding the substrate wall)</td>
<td>65.0</td>
</tr>
<tr>
<td>6 - Curtain walls:</td>
<td></td>
</tr>
<tr>
<td>a - Galvanized steel, standard grid curtain walling (excluding glazing and infill panels)</td>
<td>45.0</td>
</tr>
<tr>
<td>b - Ditto but anodized aluminium</td>
<td>51.0</td>
</tr>
<tr>
<td>7 - Windows: consisting of 3mm clear sheet glass with:</td>
<td></td>
</tr>
<tr>
<td>a - Module 100, metal windows painted frame</td>
<td>28.0</td>
</tr>
</tbody>
</table>

Note 1: 
- Costs are approximate and may vary depending on location and specifications.
- Prices are exclusive of VAT.
- Costs are for standard installations; additional charges may apply for more complex or bespoke projects.
<table>
<thead>
<tr>
<th>Type of construction</th>
<th>Cost (\£/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 - softwood to BS 644 part 1</td>
<td>23.0</td>
</tr>
<tr>
<td><strong>II - Internal walls and partitions:</strong></td>
<td></td>
</tr>
<tr>
<td>1 - Loadbearing walls:</td>
<td></td>
</tr>
<tr>
<td>a - 100mm lightweight concrete block plastered both sides, emulsion painted</td>
<td>12.0</td>
</tr>
<tr>
<td>b - one brick thick Fletton brick finished as above</td>
<td>19.0</td>
</tr>
<tr>
<td>2 - Partitions:</td>
<td></td>
</tr>
<tr>
<td>a - 50mm single skin demountable steel partition self-finish</td>
<td>17.0</td>
</tr>
<tr>
<td>b - 50mm demountable steel partition fully-glazed</td>
<td>18.0</td>
</tr>
<tr>
<td><strong>III - Roofs: (cost per m² of plan area)</strong></td>
<td></td>
</tr>
<tr>
<td>1 - 35° pitched roof constructed from timber rafters, ceiling joints, underlining</td>
<td></td>
</tr>
<tr>
<td>felt, concrete tiles, including plaster ceiling board, finished</td>
<td>21.0</td>
</tr>
<tr>
<td>2 - Flat roof, 175mm thick timber joists with wood-wool slab, felt, insulation,</td>
<td></td>
</tr>
<tr>
<td>plaster ceiling board, finished</td>
<td>24.0</td>
</tr>
<tr>
<td>3 - Flat roof, reinforced concrete 185mm thick, 25mm wood-wool slab, sand-cement</td>
<td></td>
</tr>
<tr>
<td>screed, 19mm mastic asphalt, suspended ceiling of 19mm acoustic tiles</td>
<td>27.0</td>
</tr>
<tr>
<td>4 - Industrial roofs (structure &amp; sub-frame cost approximately £8/m²):</td>
<td></td>
</tr>
<tr>
<td>a - Big-six insulated asbestos-cement sheeting, incorporating lining panels</td>
<td>16.0</td>
</tr>
<tr>
<td>b - Galvanized steel, fibre board lined top surface felt roofing stone chippings</td>
<td>17.0</td>
</tr>
<tr>
<td>etc.</td>
<td></td>
</tr>
<tr>
<td>c - Double skin translucent G.R.P. roof sheeting, class AB (40% discount on list</td>
<td>14.5</td>
</tr>
<tr>
<td>price)</td>
<td></td>
</tr>
<tr>
<td>d - Ditto but class 1 (40% discount on list price)</td>
<td>16.5</td>
</tr>
</tbody>
</table>
### Table 5.20 (contd)

<table>
<thead>
<tr>
<th>Type of Construction</th>
<th>Cost (£/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>III - Roofs (contd)</strong></td>
<td></td>
</tr>
<tr>
<td>5 - G.R.P. roofing, one way decking, single skin with G.R.P. sandwich beams (RFS DECKTOP system, see reference 35):</td>
<td></td>
</tr>
<tr>
<td>a - Span 4m (cost given in reference 35 increased by 30%)</td>
<td>27.0</td>
</tr>
<tr>
<td>b - Span 6m (cost given in reference 35 increased by 30%)</td>
<td>30.0</td>
</tr>
<tr>
<td>c - Span 8m (cost given in reference 35 increased by 30%)</td>
<td>33.0</td>
</tr>
</tbody>
</table>

**Note 1:** Estimates in the above Table are based on the Spon's Architects' and Builders' Price Book, 1976 ed., modified to reflect the latest market prices published in the Architects' Journal (1975 prices).
panels for the construction of dwelling houses is uneconomic compared with the existing forms of construction. In the case of G.R.P. self-supporting roof, a standard G.R.P. folded-plate double skin construction would cost in excess of £20 per sq. m. (36). If sandwich construction is employed to improve insulation and structural performances, costs would be in excess of £22/m². This means that on a first cost comparison, G.R.P. roofing is more expensive than alternative roofing (see Table 5.20; see also reference 35).

Leaving the highly price-sensitive and competitive housing market, the use of G.R.P. can be considered in buildings with higher budgets in terms of cost per sq. m: offices, shop fronts, institutions and amenity buildings are but a few examples.

In the case of the large scale utilization of modular or system cladding/roofing, introduction of mechanized processes can bring down the total installed costs significantly (e.g. by some 20 percent according to one authority, refer Section 5.5). This is due to reduction in labour costs.

As was mentioned earlier, feasibility and economic studies are needed in each design to ensure that material properties are utilized in the most economic form. Such studies may prove an apparently expensive material more economic in terms of the total costs compared with the cheaper alternatives. There are also occasions when higher costs of using a material in preference to the cheaper alternatives can be justified in terms of quality and preference.

Another aspect worth considering is the effects of high costs of energy on the prices of construction materials (see Section 2.2 and Chapter 12). A study of these trends reveals that the gap between G.R.P. and other materials should have narrowed. However, this does not seem to have happened since prices of both polyester resins and glassfibre have risen considerably (see 5.2 and 5.3). Furthermore, prices of certain materials, even after huge increases in recent years, are still economically favourable in an installed cost comparison (Reference 37; also Table 5.20).
Table 5.21 Relative Rigidity of Various Sandwich Laminates in Bending (Ref. 40)

<table>
<thead>
<tr>
<th>Total thickness (mm)</th>
<th>Solid G.R.P</th>
<th>2x1.5mm GRP with core</th>
<th>2x3mm GRP with core</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.018</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>1.6</td>
<td>1.3</td>
<td>1.6</td>
</tr>
<tr>
<td>10</td>
<td>5.3</td>
<td>3.2</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>12.5</td>
<td>3.7</td>
<td>10</td>
</tr>
<tr>
<td>19</td>
<td>42</td>
<td>18</td>
<td>29</td>
</tr>
<tr>
<td>25</td>
<td>100</td>
<td>34</td>
<td>58</td>
</tr>
<tr>
<td>32</td>
<td>195</td>
<td>52</td>
<td>94</td>
</tr>
<tr>
<td>38</td>
<td>337</td>
<td>77</td>
<td>143</td>
</tr>
<tr>
<td>44</td>
<td>536</td>
<td>104</td>
<td>197</td>
</tr>
<tr>
<td>50</td>
<td>800</td>
<td>145</td>
<td>266</td>
</tr>
</tbody>
</table>

Table 5.22 Various Core Materials Normally Used (Ref.39)

<table>
<thead>
<tr>
<th>Type of Core</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expanded Rigid PVC</td>
<td>Strength and good bond</td>
<td>softens at 60°C</td>
</tr>
<tr>
<td>Formed Rigid - Polyurethane</td>
<td>low cost and reasonable strength</td>
<td>liable to fatigue</td>
</tr>
<tr>
<td>Balsa Wood</td>
<td>strength and good bond</td>
<td>expensive</td>
</tr>
<tr>
<td>Paper and cardboard</td>
<td>cheap and good bond</td>
<td>face patterning</td>
</tr>
<tr>
<td>Phenolic Foam</td>
<td>good fire properties</td>
<td>fragile and weak</td>
</tr>
</tbody>
</table>

N.B.- Expanded polystyrene is not compatible with polyester resins (see text).
5.7 Methods of Stiffening G.R.P. Panels and Structures:

5.7.1 General considerations:

The modulus of elasticity in bending of a G.R.P. laminate containing 30 percent by weight of random glassfibre is of the order of 70N/m². This is considerably less than the corresponding modulus of mild steel which is around 200GN/m². Thus, for an equivalent degree of stiffness, the thickness of the G.R.P. laminate should be at least 3.1 times that of mild steel; this involves extra material and is costly. Also, it implies extra weight, a factor not acceptable when a minimum-weight design is aimed for.

A possible solution to this problem could be to allow for excessive deflections or deformations of the panel or structure. However, large deflections, e.g. in excess of 1/25 of the roof span, can be unsightly and can create visual distortion.

At the same time, it must be remembered that too stiff a structure in G.R.P. is uneconomic. For this reason, larger values of deflections, especially under intermittent loading conditions, can be acceptable. This is consistent with the flexible nature of G.R.P. and unlike steel or aluminium, it is possible for a G.R.P. structure to fully recover on unloading without damaging its finishes.

Thus, it is not only unreasonable but uneconomic to apply the deflection criteria relevant to that of structural steel. At the present time, there are no accepted limits for deflection of G.R.P. structures. This implies an economic penalty for G.R.P., particularly as the district surveyors usually insist on applying the building regulations literally.

There are several ways of improving the stiffness of a structure, viz:

(a) variation in the laminate thickness and reinforcement;
(b) introduction of stiffening ribs;
(c) sandwich construction; and
(d) introduction of geometrical configuration.

In practice, it may be necessary to combine all these techniques in order to achieve the required stiffness in a structure.
FIG. 5.17 DETAILS OF LAMINATING A G.R.P. STIFFENING RIB

FIG. 5.18 RIB CONSTRUCTION IN A SANDWICH TYPE LAMINATE
5.7.2 Variation in the laminate thickness and reinforcement:

The usual practice is to increase the laminate thickness towards the panel edges and/or to introduce edge flanges (used for connecting the adjacent panels to each other and to the supporting structure).

Another method is to increase the glass content around the panel edges, e.g. by use of rovings, etc, especially in local points of stress concentration. The use of rovings or woven-rovings in conjunction with c.s.m. is particularly suited to the hand-lay-up process.

Incorporation of mineral fillers in the main body of the laminate can increase the laminate stiffness and should be considered. Press moulding techniques allow higher levels of filler loading compared with the contact moulding process.

5.7.3 Introduction of stiffening ribs:

This method is widely used, especially in the contact-moulding process. A system of stiffening ribs may be designed to support the central part of the panel; an area where the highest deflection normally occurs.

Mild steel, aluminium profiles or wooden bars may be used in a rectangular form as the panel frame; however, aluminium profiles are recommended, because they have a linear thermal coefficient of a similar order to that of a random G.R.P. laminate (see Table 5.14). In practice, softwood timber is preferred owing to its cheapness and its good adhesion to G.R.P. at the time of moulding.

To avoid conflict of thermal movements, it is advisable to use G.R.P. ribs which can be laminated on the reverse side of the panel. Such forms may be either hollow, in which case they are prefabricated beforehand and overlaminated onto the back of panel, or they may be formed in place using cheap materials as the formers, e.g. a piece of rigid polyurethane foam, a rope or a plastic pipe, etc. These are usually covered by layers of resin-impregnated c.s.m. choppings (see Fig. 5.17).

The correct time for laminating the G.R.P. ribs is determined by the type and shape of panel and the type of the former. It must be noted that the thickness of the panel must be adequate, otherwise it could be distorted by
shrinkage of the laminate of the rib (see Fig. 5.17). Also, care should be taken to ensure that the main laminate is adequately cured before the rib is constructed.

When timber and metal sections are used, a mechanical key between these and the G.R.P. laminate is essential, as the interfacial adhesion can be rendered ineffective by differential thermal movement.

It is also possible to incorporate perforated sheet material, i.e. 'pegboard', asbestos pegboard or sheet metal, in the middle of the laminate. This method is not popular because of lack of flexibility in panel shapes (mostly flat). As with ribs, the pattern of perforation may show on the panel surface due to the shrinkage effects in the thickness of the laminate (39). In addition, this method is not economic compared with other stiffening methods.

Ribs may be employed to increase the stiffness of a panel of sandwich construction design. In this case, a design similar to Fig. 5.18 is normally used for maximum stiffening effects.

5.7.4 Sandwich construction:

A structural sandwich consists of thin fixings of strong materials such as G.R.P. laminates or steel sheets bonded to thick cores of relatively weaker lightweight materials such as cellular plastics. The basic principle is similar to that of an I beam, which offers a high degree of rigidity for a given quantity of material. In a structural sandwich, the facings take the place of the flanges and the core takes the place of the web. The core not only resists the shear, but also keeps the facings at the required distance apart and helps to resist wrinkling or buckling of the faces. It must therefore possess adequate strength and rigidity to perform its function and must be bonded effectively to the facings.

The structural analysis and design of sandwich construction together with other structures will be discussed in Chapter 6. However, to appreciate the effectiveness of the sandwich principle, reference may be made to data in Table 5.21. The data, which have been taken from reference 40, show that the rigidity of a sandwich construction 44mm
thick, with two 1.5mm G.R.P. skins is approximately equivalent to that of a 32mm thick panel with two 3mm G.R.P. skins, or that of a 25mm thick panel of solid G.R.P. laminate.

The low density core may be balsa wood, cellular plastics or a honeycomb made of paper, glassfibre or metal (see Table 5.22). Expanded unplasticized PVC is compatible with polyester resin laminates. Any surface skin on the foam must be abraded for improved bond.

Expanded polystyrene must be treated and sealed using an epoxide-based coating or a polyvinyl acetate emulsion of fairly high solid content.

Phenolic foam is not attacked by polyester resin. The new phenolic foams have a closed-cell structure. However, for improved adhesion, the surface of the foam slabs should be coated with UP or EP resins, etc.

Rigid polyurethane foam can be used either as prefabricated slabs or alternatively foamed in situ. Although sealing is not required, the surface skin of the slabs needs roughening for improved bond. G.R.P. connectors are necessary to ensure maximum structural connection (see Fig 5.19). This is because, polyurethane foam exhibits shear failure in the first layer of material behind the facings.

![Fig. 5.19 Use of G.R.P. Connectors](image)

Polyurethane foam is also prone to failure under fatigue conditions of wind loading (39). This implies that the initial stiffness of the sandwich panel may be lost in the long term. Because of these problems, some designers have designed the structure from a solid G.R.P. laminate (41); an appropriate thickness of polyurethane foam has been bonded onto the reverse side covered by a thin G.R.P. laminate, to provide for thermal insulation and assist in resisting local buckling (41).

Independent experimental evidence (42) also points to
the weakness of rigid polyurethane foam core.

Structural sandwich panels may warp(45), since there is normally a temperature gradient across the thickness because of the insulating effects of the core. Also, the thermal movements of the facing materials are usually different. If these are not adequately taken into consideration, they could lead to high stresses being set up in the laminate and an eventual failure of the panel. It is not surprising to note that some designers resist the structural use of G.R.P. sandwich panels, because of the problems associated with thermal movements.

Although, fire-retardant grades of polyurethane formulations have been developed and are in current use, it is also possible to modify the fire behaviour of the foam using inorganic lightweight fillers such as blown glass balls or sintered clay with a particle size of 10 to 30mm. Any two-component foam mixture may be used such as polyurethane polyester or phenolics. The required quantity of a filler can be placed in a mould and injected with a reaction foam. On hardening of the foam, a composite with a particular set of properties may be obtained. The density of such composites have been reported to be within the range 250-500 kg/m^3, but is generally around 400kg/m^3 (44). Blown glass balls are generally used(44) which improve the compressive strength of polyurethane from 0.1MN/m^2 to 1-2MN/m^2. The fire behaviour of a G.R.P. sandwich construction element filled with such composite foams have been described as follows(44): The G.R.P. skin exposed to a severe fire will decompose. The surface layer of the composite foam then turns into a carbonized black material, which in conjunction with the filler forms a highly effective protective layer to the remaining material. Thus, fire-resistance periods of the order of 60, 90, and even 120 minutes may be obtained by a panel 100mm thick(44).

5.7.5 Introduction of geometrical configurations:

The basic technique is the same for a panel or a structure. The structure is shaped to increase its overall rigidity and to improve its resistance to buckling. Shaping or corrugating of a panel may be required even for short
spans (e.g. greater than 0.5m). The shapes are designed as an integral part of general styling of the panel and the overall structure.

This characteristic of G.R.P. has been fully realized in the design of boats, since the geometry of the hull contributes significantly to the rigidity of the structure. Folded-plates, pyramids, composite folded-plate structures, domes and shells are the commonest forms of structures which are very efficient in terms of structural engineering in G.R.P. The effectiveness of any profile may be checked by application of structural engineering techniques; this will be considered in Chapter 6.

It must be noted that despite great enthusiasm expressed by individual architects (e.g. Quarmby(45)), for the architecture of G.R.P. structures, the majority of architects and engineers have not taken up the idea of folded-plate and shell structures for general use(4). The reasons for this lack of apparent response must be sought in increased costs, lack of functional suitability, incompatibility with commercially available mechanical, electrical, etc., services, incompatibility with the existing townscapes, etc. These aspects have been analysed in detail in Chapters 6,8,9,10 and 11(see also 5.6).
CHAPTER 5 References.

8. Interview notes with Mr. J. Wickings, B.F. Chemicals, on 12th February 1975.
10. Interview notes with Mr. J.J. Zonsveld (three sessions), (Information related to Shell Chemicals' operations).
12. Interview notes with Mr. Gray, Messrs. Fibreglass Ltd, on 24th September 1975.
14. Lecture notes by L. Holloway, University of Surrey.
18. See Fire Research Note No. 749, F.R.S.
21. Report of a "Special Investigation made on behalf of


32. Interview notes with Mr. Hodgson, Messrs. BTR Reinforced Plastics Ltd., on 18th July 1975.


Chapter 5 References (contd)


42. Langlie, C., "Sandwich Construction: A Practical Approach for Use by Designers," paper presented at a sym. on the use of Plastics (see reference 4).


6.1 Service Performance Requirements of Load Bearing and Infill Panels:

The performance requirements of panels proposed for domestic houses, schools, offices, etc. may be found by reference to the Building Regulations, the appropriate BS Codes of Practice and other publications such as the B.R.S. Digests and Handbooks. They are based on known performances of existing buildings.

Structures not included in the Building Regulations and BS Codes often fall into special categories which are controlled to meet the specific requirements of the authority concerned. For example, design of hospitals are generally controlled by the Health Authorities who have developed the required performance specification.

Special one-off buildings are sometimes needed for which there may be no specially written performance statements. In these cases, it is essential to formulate the performance requirements together with the appropriate criteria for their evaluation, i.e. methods of testing and assurance to ensure that the requirements are adequately met during the design life of the building.

It must be noted that the performance requirements may also stem from the client or users' needs; such requirements will supersede those assumed by any of the above codes.

As was mentioned in chapter 5, for economic and technical reasons, G.R.P. is normally used in the form of thin-shell panels, generally in the following applications:

1. External walls
2. Roofs
3. Partition/lining panels

A brief study of the general performance requirements related to each of the above uses has been included below.

6.1.1 External walls:

Two types of panels are normally used on the external walls: (a) load bearing panels which may form part of a space structure or self-supporting panels fixed to the
structure of a building (known as infill-panels); and (b) cladding panels which are normally supported by a sub-frame which itself is supported by the main structure.

The following is a summary of the general performance requirements for a typical load-bearing (e.g. a composite or sandwich) panel. However, much of what has been included are relevant to the cladding panels in conjunction with their sub-frame and backing materials.

6.1.1.1. Panel dimensions:

Guides which have been published by the Department of the Environment (D.O.E.) may be used. These guides are not mandatory but contain recommendations for the preferred dimensions of the building panels. At present, most of the Local Authority works are to a common system of dimensions and tolerances.

Panel dimensions must be related to the requirements for openings to accommodate doors, windows, ventilators, etc. Type of the production process selected together with the transport and handling operations may impose limits on the panel dimensions.

6.1.1.2. Loading:

The panel/structure must be capable of withstanding the most likely combinations of the following loads with an appropriate factor of safety (see section 6.2). Deformations and deflections should be limited so as not to cause undue distress to the building occupants or impair the efficiency of the joints and create visual distortion. The main loads are:

(a) Dead load due to self-weight, weights of fixtures and the adjoining panels.

(b) Wind load: BS CP3: Chapter V, part 2 specifies a detailed procedure for calculating the wind loading of panels and the wind loading of the whole structure. However, this code does not cover some of the cases likely to be encountered in the design of roofs and space structures. The 'Wind loading handbook' published by B.R.E. (1) gives additional design data. This problem will be considered in more detail in subsection 6.6.1.

For the design of panels and their fixings, CP3 gives wind loadings more severe than the wind loading for the structure as a whole. This is due to the possibility of
localized high wind pressures or suctions which cause most of the damages due to wind (1). In the case of normal facades formed by fairly flat panels, the calculations for wind loading are relatively simple.

(c) Soft and hard body impact loads. The Agrément Board recommends (2) the following tests:

- Soft body impact test: a 50 kg sand bag dropped from a height of 2 metres.
- Hard body impact test: a 1 kg steel ball dropped from a height of 1 metre.

It must be noted that the requirements for resistance to the impact forces depend on the position of the panel in the building and the use to which the building is put. For some panels, the requirements are usually higher than those specified by the Agrément Board. It may therefore be necessary to carry out simulative or representative impact tests on a prototype panel.

(d) Maintenance load: The BS CP3 Chapter V part 1 specifies that the covering or cladding must be capable of withstanding a concentrated load of 0.9 kN on 125 mm x 125mm at any place; together with the impact loading this may determine the thickness of the cladding panels.

(e) Loads due to thermal and differential movements: Joints may be designed to accommodate the panel movements. However, panels may still be restrained by the fixings. Also a panel may be under stress because of the tendency to warping due to the possibility of a thermal gradient across the thickness. In the case of G.R.P. panelling supported by a separate structure, there is the possibility of differential movements. If fixing and joints are not designed to accommodate these movements, then they may exert considerable loads onto the panels.

6.1.1.3 Fire-resistance: An understanding of the fire behaviour of a building and evaluation of the likely fire hazards are necessary in an efficient design. BS CP3 Chapter IV parts 1 to 3 and BS CP153 part 4 describe the basic stages in the development of a fire and steps necessary to confine the fire and protect the escape routes. The designer must familiarize himself with these codes before attempting to interpret the rules for the structural fire precautions as
Part E of the Building Regulations specifies minimum periods of "fire-resistance" performance for external walls of buildings depending on their purpose group, their size, and their distance from the relevant boundary line (unprotected areas - as defined by the Building Regulations - are excluded from the requirement for the fire-resistance performances).

The minimum fire-resistance performance applicable to all structures is 30 minutes (to BS 476: part 3).

Internal surface spread of flame must not exceed the limits set out in the Building Regulations. According to Table 13 of the Regulations, Class 1 is commonly specified except for the circulation spaces and protected shafts where Class 0 must be used.

External surface spread of flame is also controlled in a similar fashion; Class 0 for buildings higher than 15 m (50 ft.) and Class 2 for buildings lower than 15 m (50 ft.) are required provided the distance from the boundary is not less than 1.20 m and the wall is not part of a gallery.

It must be emphasized that the insurance ratings for buildings are based on separate standards of fire resistance. These standards are related to the potential extent of damage likely to be caused by fire. Thus, the proposed building may be intended to comply with the specific requirements of incombustibility under any of the five Standards (I to V) issued by the Fire Officers Committee.

6.1.1.4 Thermal insulation:

The thermal behaviour of a building is complex; BS CP3 Chapter II describes the factors affecting the internal environment of a building together with appropriate design recommendations. Thermal insulation of buildings are also controlled by the Building Regulations or in the case of industrial buildings by a separate Act.

The property commonly used for the design of a panel or for comparing the degree of thermal insulation achieved by various constructions, is the 'thermal transmittance value' (known as U-value), is expressed in Watts per sq. metre degree Celsius (W/m²°C). For example a 280 mm (11") normal cavity brick wall (unventilated) and plastered, has a typical U-value of 1.70 W/m²°C. A similar degree of
thermal insulation is achieved by approximately 15mm rigid polyurethane foam or 20mm phenolic foam with two skins.

The recommended maximum U-values for housing are as set out below (3)

<table>
<thead>
<tr>
<th>Type of Building Element</th>
<th>U-value (W/m²°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External walls</td>
<td>0.85 - 1.15</td>
</tr>
<tr>
<td>Ground floors</td>
<td>0.35 - 0.85</td>
</tr>
<tr>
<td>Roof including ceiling</td>
<td>0.55 - 0.85</td>
</tr>
</tbody>
</table>

6.1.1.5 Sound insulation:

BS CP3 Chapter III (1972) and BS CP153 part 3 (1972) give guidance on the design of building elements and components to ensure adequate sound insulation and noise reduction for various types of buildings and locations.

The usual minimum degree of sound insulation is 30dB but higher values are normally specified.

6.1.1.6 Weather and abrasion resistance:

The panel construction must resist the ingress of water under all likely combinations of wind and rain. The exposed surfaces of the panels must withstand the abrasion caused by the wind blown sands during the design life of the construction.

6.1.1.7 Appearance:

Exposed surface texture and colour must be consistent and conform to the agreed sample.

6.1.1.8 Durability:

The panels and construction must continue to meet the performance requirements throughout the design life of the buildings. BS CP3 Chapter IX contains guidance on the durability aspects of a number of traditional materials under various conditions. However, this document does not include any reference to G.R.P. panels.

6.1.1.9 Maintenance:

Details of the maintenance requirements, in order to satisfy the durability aspects of the panels, must be given.
6.1.2.1. Dimensions:

As 6.1.1.1, except that openings for doors and windows are no longer required. However, roof (or dome) lights may be required. (In the case of G.R.P., translucent panels may be used as an integrated part of the roof).

6.1.2.2. Loading:

General as 6.1.1.2.
(a) Dead loads as 6.1.1.2a
(b) Wind loads as 6.1.1.2b
(c) Impact loads as 6.1.1.2c
(d) Imposed loads other than wind loads (including snow).

BS CP3 Chapter V part 1 gives data for the design loads of the roofs (including sloping roofs). The following loads are for flat and sloping roofs (up to 10°):

(i) Access provided to the roof (in addition to that necessary for cleaning and repair): The loading consists of either a uniformly distributed (U.D.L.) load of 1.5 kN/m² measured on plan, or a concentrated load of 1.8 kN on 300x300mm, whichever produces greater stresses.

(ii) Access is not provided to the roof (other than that necessary for cleaning and repair): The loading consists of either a U.D.L. of 0.75 kN/m² or a concentrated load of 0.9kN on a square 300x300mm, whichever produces greater stresses.

(iii) Maintenance load: In addition to (i) or (ii), the roof covering must be capable of sustaining a concentrated load of 0.9 kN on any square of 125x125mm.

(e) Loads due to thermal and differential movements: as 6.1.1.2e.

6.1.2.3. Fire resistance:

The ability of a roof covering to protect the building against an external source of fire is assessed by the application of BS 476 Part 3 1975. In the majority of cases, a minimum performance of P60 is required under the Building Regulations.

Spread of flame on the external surface of the roof must conform to the rules of the Building Regulations; Class 1 is commonly specified and Class 2 permitted in certain situations.

The internal surfaces of the roof (or lining material) must not support the propagation and spread of fire. Usually
Class 1 is required except in circulation areas and protected shafts where Class 0 is specified. (In small rooms, as defined by the Building Regulations, Class 3 spread of flame is permitted for materials of the lining to walls and ceiling.

6.1.2.4 Thermal Insulation:
The overall maximum U-value is specified for the roof in each of the categories of the buildings covered by the Building Regulations and other associated statutes. As an example, the roof of industrial buildings (other than those which are unheated) must have an overall U-value not greater than 1.7 W/m²°C, provided the total surface resistance is about 0.149.

6.1.2.5 Sound insulation:
As 6.1.1.5.

6.1.2.6 Weather resistance:
As 6.1.1.6.

6.1.2.7 Appearance:
Roofs may have both an external and an internal architectural finish; the latter applies where no separate lining material is present. The texture and colour should be consistent and must conform to the agreed samples.

6.1.2.8 Durability:
As 6.1.1.8.

6.1.2.9 Maintenance:
As 6.1.1.9

6.1.3 Partitions and internal lining:
6.1.3.1 Dimensions:
As 6.1.1.1 except that windows are not usually required. It is desirable to incorporate recesses for the electric conduits and other services.

6.1.3.2 Loads:
(a) Dead loads as 6.1.1.2 a
(b) Impact loads as 6.1.1.2 c.
6.1.3.3 Fire-resistance:
Partitions are not normally designed for any 'fire-resisting' performance. However, the ability of the surfaces to resist the spread of flame is to be determined; normally Class 1 is required (except for circulation areas and protected shafts where Class 0 is specified).

6.1.3.4 Thermal insulation:
Thermal insulation is not normally required except in special compartments, e.g. cold stores, etc.

6.1.3.5 Sound insulation:
30 dB is the usual minimum performance required. In many situations a higher performance is specified.

6.1.3.6 Weather resistance:
Not required.

6.1.3.7 Appearance:
As 6.1.1.7.

6.1.3.8 Durability:
As 6.1.1.8.

6.1.3.9 Maintenance requirements:
As 6.1.1.9.

6.2 Design Criteria and Procedure:

6.2.1 Design criteria and safety factors:
There is no nationally agreed code of practice for the design of G.R.P. panels and structures. The following procedure has been formulated by the author after reviewing the available literature and published data, and also after holding various discussions with the leading designers in this field. It must be realized that such a procedure is essentially of a discretionary nature; the implications will be discussed at the end of this chapter.

The study of properties of G.R.P. in chapters 4 and 5
and deflection criteria for the design of G.R.P. panels and structures. However, after satisfying these criteria, it will still be necessary to check the stresses likely to be induced under the worst loading combinations, in order to ensure that an adequate safety margin is available.

In section 6.1, it was shown that there are no nationally agreed limits for deformation and deflection of G.R.P. (and many other materials) panels and structures; it is therefore vital to establish what the safe limits are, to be adopted as criteria.

The data on the wind speed (dynamic pressure) and direction collected by the Meteorological Office show that wind speed and direction change rapidly with time\(^1\); these conditions are characteristics of dynamic loading. However, wind loads calculated from CP3 Chapter V are assumed to be static in nature. Newberry, et al\(^1\) state that this assumption is generally correct for the types of buildings covered by the above code, because both the rate of wind loading and the frequency of peak loading are low in relation to the natural frequencies of most structures\(^1\), except for flexible structures with very low structural damping, such as suspension bridges, tall masts, chimneys and similar structures. These have natural frequencies lower than about 0.3Hz; they lie outside the scope of BS CP3 Chapter V.

Structures formed wholly by G.R.P. panels or segments are unlikely to be tall; thus, eddy-shedding frequencies, \(n\), as calculated from the following formula, are naturally lower than their natural frequencies:

\[
n = S \times \frac{\bar{v}}{b}
\]

where \(n\) = eddy shedding frequency in Hz, \(\bar{v}\) = mean wind speed in m/s; and \(b\) = breadth in m, across the wind direction.

It should be noted that the natural frequency of a structure of one degree of freedom is directly proportional to the square root of its stiffness divided by its mass; this means that although the stiffness of a G.R.P. structure may be low, its natural frequency is not necessarily low. Tests performed on a model of the structure for various wind speeds can be useful in determining the possibility of resonant oscillation. The resonant oscillation has the
In addition to this phenomenon, the effects of repeated buffeting loads, even from fairly frequent winds, which are not necessarily of high magnitudes, may be significant in the case of G.R.P. load-bearing panels. It will be seen from a brief review of the behaviour of G.R.P. under fluctuating loads that the assumption of static wind loading is not generally appropriate for the design of G.R.P. panels and structures.

Smith, et al. (3) have shown that for a given cycle of alternate loading of a constant amplitude and under standard laboratory conditions, the fatigue strength of G.R.P. specimens fall rapidly with the increase in the mean stress (see Fig. 6.1)

![Diagram showing the relationship between mean stress and alternating stress amplitude for various failure cycles.](image-url)

**FIG 6.1** THE RELATIONSHIP BETWEEN THE MEAN STRESS AND THE ALTERNATING STRESS AMPLITUDE FOR VARIOUS FAILURE CYCLES (AFTER SMITH AND OWEN REF. 3)
Owen (4) has shown that for a relatively low cycle of alternate loading, the stress amplitude necessary to initiate the first damage in the G.R.P. composite is low, i.e. of the order of 30% of the ultimate tensile strength. For example a chopped strand mat/polyester laminate tested by Owen (4) at zero mean stress, 200° and 40-42 r.h., sustained damage in the form of debonding, first at a cycle of 10 when the alternate tensile stress amplitude was approximately one-third of the ultimate tensile strength. The damage was confined to debonding between the matrix and the fibres lying normal to the direction of the load. The next stage of failure, which was in the form of cracking of the matrix, occurred at very much higher cycles (of the order of 10⁴) for the same loading magnitude under the same laboratory conditions (4). Total failure (or separation) for the above test under the same conditions was delayed until a cycle of approximately 10⁶.

It must be noted that the failure process is progressive, i.e. after the matrix has cracked, the cracks propagate and cross the filaments aligned in the direction of load. Breakage of these filaments leads to the total separation of the specimen ends.

Although for a given number of cycles, the separation stress is considerably higher than that of the initial debonding stress, for many practical applications, it is the onset of the damage which is relevant, i.e. once there is significant damage in the material of the panel, there is the possibility of loss of integrity and/or deterioration by the action of impact and accidental forces etc.

Unlike G.R.P., fatigue failure of the common metals is normally initiated by one or a few microscopic surface cracks. These cracks do not affect the structural integrity of the products until the cracks propagate into the body of the metal under a cyclic loading which corresponds to approximately 90 percent of the life of the metal (4).

Data on dynamic loadings of G.R.P. panels, representative of those experienced in various service conditions, are not available and the results of the alternating loading tests of high frequencies cannot be applied directly in the structural design of panels (4). In the absence of such data, it is reasonable to assume that a maximum total tensile or flexural creep strain of about 0.15 to 0.2 percent is the safe limit.
and the overall deformation or deflection of G.R.P. panels and structures must be related to this creep strain limit.

It should be noted that the suggested rule not only allows for the safe creep and recovery mechanism of G.R.P. under intermittent loads but also incorporates the dynamic behaviour of G.R.P. under a system of fluctuating loads caused by wind, snow or by other imposed loads (see section 6.1).

An attempt has been made by the author to formulate a method for calculating the actual creep strains and comparing these with the assumed limits. The tensile or flexural creep modulus values are to be determined from isochoronous stress/strain curves obtained experimentally on representative specimens at the laboratory under the conditions which are specified and given below. The creep modulus values are slopes of these curves at points corresponding to a strain of 0.2 percent (see subsection 4.2.3.)

To simplify the loading for the purpose of design, the dead load may be multiplied by a factor of 1.3 and added to other design loads. This will compensate for the long term creep due to the permanency of the dead load (2); the loss of accuracy involved in this loading calculation is normally insignificant as the dead load generally comprises a small proportion of the total design loads.

In Britain, snow loading is usually of short term duration; depending on the geographical location of the building, a creep duration of 100 h may be sufficient for the calculation of deformation (The next higher creep duration recommended by BS 4618: Section 1.1 is 1,000h which is unduly high for this purpose).

For design purposes, it may be assumed that the mechanical properties of G.R.P. are not adversely affected by the action of moisture in normal G.R.P. applications on buildings. If the standard room conditions of 20°C and 65r.h. are used for creep tests relevant to the snow conditions, then both an adequate safety margin is secured and the costly low-temperature testing is avoided. In the case of wind loading, higher temperatures (of the order of 50-60°C) are recommended together with higher levels of relative humidity; the latter affects the mechanical properties of G.R.P. to an insignificant extent compared to the former. A creep duration of 24h appears to be sufficient for the calculation of deflection or
deformation under the design wind loads.

A creep duration of 24h also appears to be sufficient for the calculation of deformation under the design maintenance load of 0.9kN. However, this load is neither permanent nor frequent; thus, it is unnecessary to assume a cyclic or fatigue loading condition. The ability of the panel skin to sustain this load can be checked in a 24h test on the full size prototype panel by measuring the maximum creep deflection. Similarly, soft and hard body impact tests are generally performed on a prototype unit, and the extent of damage received reported; if necessary, the design may then be modified in order to strengthen the weak parts.

It may be postulated that theoretical deflections may be calculated independently under snow and wind loads and loads due to the differential thermal effects. Summation of the deflection values corresponding to the worst likely combination of loads will result in the total predicted deflection.

So far no factor of safety has been applied due to the effects of weathering, ageing, normal wear and abrasion of G.R.P. (see subsection 4.2.7). It is suggested that the creep modulus values obtained from the laboratory results be halved and the resulting figures used as the design values for the calculation of deformations, e.g. assuming the 100h, 0.2 percent strain, creep flexural modulus of a chopped strand mat G.R.P. laminate at 20 °C and 65% r.h. has been determined in the laboratory to be 4.2 GN/m². Half this figure, 2.1 GN/m² is to be used as the design value for the calculation of strains and the deformation under the imposed snow loads plus 1.3 times the dead load.

6.2.2. Summary of the design procedure:

1 - Carry out laboratory tests on small representative specimens to determine the 0.2 percent flexural and/or tensile- depending on the behaviour of the proposed structure-creep strain moduli for the following durations and conditions:
   (a) snow: 100h creep test, 20 °C and 65% r.h.
   (b) wind: 24h creep test, 50-60 °C and 65% r.h.
   (c) thermal effects: 12h creep, 50-60 °C and 65% r.h.

2 - Divide the above moduli by 2 (to ensure an adequate
safety margin against the long term effects of weathering, see 6.2.1), to arrive at the design values for the calculations of creep deformation.

3 - Carry out the structural analysis to calculate the applied loads and the bending and torsional moments at each section of the panel or structure under each of the following loads, using the relevant design value for the modulus:
   (a) snow + 1.3 times dead load.
   (b) wind load + 1.3 times dead load.
   (c) loads due to thermal effects.

4 - Design the section such that the total creep strain arising from the worst likely combination of the service loads does not exceed the accepted limit of 0.15 – 0.2 percent. It must be noted that the choice of single plate or sandwich construction to carry the induced stresses is dependent on the type of structure, the magnitude of loads, the need to satisfy 'thermal insulation' and 'fire-resistance' performance requirements and the total costs.

5 - Calculate the available factors of safety on the creep stresses likely to be generated in any section under the worst likely combinations of loads.

6 - Modify the design as appropriate in order to satisfy the requirements arising from 4 and 5, above.

7 - Manufacture a prototype panel (or a small scale model) for 'resistance-to-penetration' testing under the concentrated maintenance load, and for impact testing. Other tests relevant to the service performance requirements of panels may be determined by testing either a Representative sample or full scale panels together with the joint assembly, etc. Alternatively, some requirements may be regarded as satisfied from previous experience or other sources of knowledge.

8 - Carry out (if necessary), full scale loading trials on the structure to determine the creep strains, deformation or deflection, etc. and compare these with the theoretical calculations.
Modify the design to ensure that all the above requirements are satisfied at economic levels.

6.3 Structural Forms for Use with G.R.P. Panels and Structures:

The purpose of the structural analysis is to calculate the type, magnitude and direction of all forces and moments likely to be generated under the action of the external forces.

The methods for the structural analysis of a single panel are generally similar to those used for a whole structure of the same geometrical characteristics and under the same support conditions. Thus, it will be sufficient to discuss the analysis for the most commonly used structural forms. The design can then be carried out with due consideration for the nature of the structure and the relevant practical aspects. In this section these structural forms are introduced and in the next section their analysis is considered.

The structural forms may be divided in the following classes:

(1) Folded-plates
(2) Shells

6.3.1 Folded-plates:

Folded-plate structures may be divided into the following categories: (a) prismatic; (b) pyramidal; (c) prismoidal; and (d) composite folded-plates.

6.3.1.1 Prismatic forms:

A prismatic structure consists of rectangular plates of the following profiles, supported on rigid end diaphragms (Fig. 6.2)

As can be seen each form has a basic repetitive beam unit which is assumed to span the end diaphragms.

Prismatic folded-plate structures are the commonest forms used for G.R.P. roofs. Corrugated profiles may also be regarded as prismatic folded-plates.
6.3.1.2 Pyramidal forms:

A pyramid may have a regular polygon as its base which may range from a triangle to a circle; the latter is the base of the cone. Shallow pyramidal forms are generally designed for infill or cladding panels on elevations of conventional buildings. Pyramidal units are also used as load-bearing modules in composite folded-plate structures.

Plates forming walls of a thin-skin G.R.P. pyramid are prone to buckling under a comparatively low loading intensity (5). The buckling of these plates causes the load to be transferred to stiffer lines formed by joints and fold-lines. Because of this tendency to buckling, a large pyramid is not normally used as a structural form; smaller pyramidal modules known as 'modular cladding' (6) are preferred. The modules may have a variety of geometries and are supported by a grid frame (Fig 6.3). These forms of structures are good for creating unusual roofscapes or for other special constructions.

Ball, et al. (6), in a study of the overall cost/performance undertaken for various forms of G.R.P. roofing, point out that the modular pyramidal roofing is likely to be uneconomic compared with prismatic roofing, even after
optimisation of the design and production costs.

The pyramidal units may be connected at the top and bottom to grids of other structural materials, as shown in Figure 6.4. If the bottom edges of the pyramids are sufficiently stiffened and jointed to each other, they can form the bottom grid. In either case, the resulting structure — known as 'space decking' or 'stressed-skin-system' — is basically composite in nature. The top and bottom grids are assumed to carry tension and compression, and the pyramids are assumed to carry the shearing forces. However, it must be noted that each individual pyramid is subjected to horizontal forces at the apex and along the bottom edges; these forces induce a system of stresses in the pyramid walls, causing them to buckle in much the same way as in the previous cases where the pyramids were not interconnected. In stressed-skin systems, the size of pyramids are normally small therefore the plate bucklings are usually small; these systems generally fail through the compression buckling of the top-struts.

It has been shown that the stressed-skin systems are not efficient forms for using G.R.P., both for structural and practical reasons. In addition, they are generally more costly than prismatic structures.

6.3.1.3 Prismatic forms:

A prismatic form is essentially intermediate between a single pyramid and a prismatic structure. Alternatively, it may be assumed as a prismatic structure with inclined end diaphragms (Fig 6.5)
6.3.1.4 Composite folded-plates:

A composite folded-plate structure is characterized by both longitudinal and transverse fold-lines, as may be seen from the examples shown in Figures 6.6 to 6.8. For design
purposes, portal frames may be assumed to consist of individual frames joined to each other; each frame can be designed independently on a two-dimensional basis. Folded-plate domes and space structures have a three-dimensional behaviour (Figures 6.7 and 6.8).

Barrel vaults may be designed as an extension of the space-decking, i.e. pyramidal modules may be connected at their apexes by aluminium or steel struts (8).

Three-Pinned Portal Frame  Two-Pinned Portal Frame

FIG. 6.6 EXAMPLES OF COMPOSITE FOLDED-PLATES

FIG. 6.7 A COMPOSITE FOLDED-PLATE DOME WITH A THREE-DIMENSIONAL BEHAVIOUR

6.3.2 Shells:

Shells may be divided into two basic types:

(a) Singly curved shells, also known as developable surfaces

(b) Doubly curved shells
6.3.2.1 Singly curved shells:

Singly curved surfaces have zero curvature in one principle direction; curvatures of all points in the other principle direction are of the same sign but not necessarily constant. Barrel vaults of circular cross sections which are supported on rigid end-diaphragms are examples of singly curved shells (Fig. 6.9).

If the span/width ratio of a barrel vault is high, its behaviour approximates to that of a beam of constant curved cross-section. However, behaviour of vaults with a low span/width ratio is essentially different.

Barrel vaults and folded-plate arches can be flattened into planes without having to stretch or shrink; these are
therefore prone to buckling under unsymmetrical loading conditions. Use of ribbing or sandwich construction will increase the resistance of barrel vaults and arches to buckling instability.

6.3.2.2 Doubly curved shells

Doubly curved shells are divided into two categories: synclastic or anticlastic.

The synclastic surfaces have two principle curvatures of the same sign, (i.e. both are either positive or negative) spherical or elliptical domes are examples of synclastic shells. Domes are compression membranes and with a thin G.R.P. shell the compression forces may cause an overall buckling instability. Use of ribbing or sandwich construction increases the resistance of domes to this type of instability. Other examples of synclastic shells include the elliptic-paraboloid, the ellipsoid and the toroid.

Synclastic shells behaving principally as tension membranes may be conceived as inverted domes or elliptic paraboloid, etc. Shells of this type or any other type which behave mainly in tension are more compatible with the nature of G.R.P. than compression membrane shells. However, there are practical limitations on the use of this type of shell.

The anticlastic surfaces which are also known as 'saddle surfaces', have two principle curvatures of opposing signs. A hyperbolic-paraboloid is an anticlastic shell. Anticlastic shells have much greater resistance to buckling than the compression synclastic shells. By connecting identical units of hyperbolic-paraboloids a variety of shells with outstanding architectural characters can be obtained; examples of these are domes constructed from identical prefabricated hyperbolic-paraboloid segments over a market at Argenteuil in Paris. Three domes of this type have been designed by du Chateau (8) and constructed in France with spans of 18 to 30m.

It must be noted that under uniformly distributed loadings on a horizontal projection, a hyperbolic-paraboloid shell is under tensile membrane forces only. Other conditions of loadings will induce bending moments. The degree of restraint around boundaries have more significant effects on the stress distribution in hyperbolic-paraboloid structures.
Apart from the above geometrical forms, other less familiar geometries can be conceived with varying degrees of structural efficiencies. However, the trend in the past has been to use shells with simple overall geometries, e.g., spherical domes with ridges formed by joint lines, etc. Tooling costs generally have a determining effect on the use of shells. Generally speaking, patterns with curved surfaces cost twice as much per m² than flat surfaces. Nevertheless, there is ample evidence (8) that G.R.P. shells are more economic than either metal or concrete ones. (see also 'The Architect and Fibreglass Composites', published by Messrs. Fibreglass Ltd. 1972).

6.4 Analytical Methods Used for Folded-Plate and Shell Structures:

A distinction may be made between the approximate analytical methods applicable to a family of structures and the more accurate methods which are theoretically applicable to all structures. The following discussion is based on a review of the approximate methods of analysis, with passing references to the more accurate techniques. There are several reasons for this approach, viz:

(a) From all theoretical approaches, the finite elements method (described briefly later) is potentially suitable for the analysis of continuous structures. However, this method is not sufficiently advanced for general application to folded-plate structures and has two main drawbacks, viz: (i) it normally demands a large storage capacity in the computer; and (ii) its accuracy depends on the elemental division and the choice of the displacement function.

(b) In the majority of G.R.P. structures, especially the one-off projects, the computer-based analysis is uneconomic or lengthy.

(c) Even with a more sophisticated analytical technique, there is often a need for manual checking of the results.

(d) Regardless of the analytical technique, a full-scale loading trial on the structure or its part is usually unavoidable to establish the weaknesses overlooked in the analytical method.
G.R.P. shells and folded-plate structures have a very complex mechanical behaviour under different conditions of loading. However, by acceptance of certain assumptions, an 'idealized' structure may be conceived and substituted for the real structure; this hypothetical structure should possess two essential features:

(a) its mechanical behaviour should approximate that of the real structure; and

(b) its structural analysis must be considerably less complex than the analysis of the actual structure.

The analysis of folded-plates and shells will now be considered separately.

6.4.1 General assumptions applicable to folded-plate structures:

Benjamin (5), after reviewing the general literature on all folded-plate structures, concluded that plastics structures require special considerations. By means of experiments, he has found that the following simplifications may be made for the analysis of the above structures with a reasonable degree of accuracy:

1-Transverse behaviour of the plate:

1) If the transverse deflection of the plate, as distinct from the longitudinal deflection of the structure, is less than its thickness, stretching of the middle surface may be ignored. If the transverse deflection exceeds the plate thickness, it will be necessary to take into consideration the membrane effect of the stretched part of the plate.

2) The deflection of a plate with a sandwich construction can be assumed to consist of the following: (a) a component calculated from the application of the plate theory; and (b) a component due to the shearing deflection of the core.

3) The longitudinal deflection of the structure may be assumed to cause no relative displacements of the edges of the plates.

4) The deflection surface is assumed to follow the simplified formula.

5) The boundary conditions of the plate may be determined from the following rules:

- fully restrained conditions are assumed to
exist between two plates moulded in one piece.

b - simply supported conditions are assumed to exist between two plates which are bolted through their return flanges.

c - fully restrained conditions are assumed to exist between two plates whose flanges are permanently bonded together by means of a bonding agent.

II-The overall longitudinal behaviour of the structure:

Prismatic structures may be assumed as beams spanning the end diaphragms. Similarly, as will be seen, portal frames and some other composite folded-plates may be analysed by application of normal structural engineering techniques. However, the following aspects must be borne in mind (5):

(1) If the span/plate width ratio is less than 1.5, the deep-beam action is to be considered. This means that the straight line stress distribution along the plate width is not valid. However, the possibility of a span/plate width ratio less than 1.5 is remote with normal G.R.P. structures.

(2) If the plate width/thickness ratio is high (approximately > 100) and if the transverse load/deflection are excessive and also the compressive forces in the plane of the plate are large, the central portion of the plate buckles and becomes ineffective in resisting the applied stresses; at the ultimate stage, it may be assumed that a certain proportion of the plate width is effective with a uniform stress distribution (5).

In the case of sandwich constructions and when the transverse load/deflection are not excessive, and compressive in-plane forces are not large, the entire plate width may be assumed as effective with a straight line stress distribution.

6.4.2 Analysis of a prismatic structure:

Consider a prismatic structure formed by bolting successive units of prefabricated V-sections; each as shown in Fig.6.10. As was explained earlier, the transverse behaviour of each plate may be determined independently from the longitudinal behaviour of the structure.

Plate ABCD is assumed to be restrained on BD and simply supported on all other sides. Thus, bending moments are developed in both directions x and y; these moments are zero
along simply supported edges but must be calculated along line $BD(\bar{m}_x$ and $\bar{m}_y$).

$\bar{m}_x$ must be added to the main longitudinal moment (found by the beam action of the plate). Thus, the area along $BD$ must be designed for resisting stresses under the above moments and the transverse $\bar{m}_y$ moment.

There are several theoretical methods for the transverse analysis of plate $ABCD$, e.g. the finite elements method or the small deflection method explained in detail by Timoshenko (10). Both of these methods are capable of being applied to non-rectangular plates as well. However, as shown in ref. 5, these methods are generally lengthy; design charts based on these methods are not available. It is therefore easier - and safer - to employ the familiar 'strip-analysis' to calculate the transverse moment $\bar{m}_y$; by assuming the unit length as a propped cantilever spanning between the ridges and the valley (see Fig. 6.11).

**FIG. 6.10 TRANSVERSE ANALYSIS OF A PLATE**

**FIG. 6.11 PROPPED CANTILEVER**
Criticism of this method has concerned the omission of the smaller transverse moments in the x direction (5). This apparent shortcoming becomes less significant if, for the longitudinal analysis, the entire unit of V cross section is assumed as a deep beam and the cord stress calculated.

The above simplified transverse and longitudinal analytical techniques are reasonably correct for prismatic structures with a span/plate width ratio greater than 1.5. This is because, as has been reported by Benjamin, the reaction forces along lines BD and AC are approximately equal and constant except in the immediate vicinity of the supports. It must also be noted that the resistance of the plate skin at any point to a point load due to maintenance (c.f. 6.1) can override the transverse design of the plate. This is often the case with composite folded-plates and shells (see 6.3.2).

The analysis of other types of prismatic structures may be carried out in a similar manner; the horizontal plates are more prone to buckling than the inclined planes. They must be designed as transversely spanning between the inclined planes. The longitudinal analysis of all prismatic and other folded-plate structures may preferably be carried out by transforming the structure into an equivalent hypothetical skeletal structure, with discrete members positioned at the fold-lines. The skeletal structure may be analysed by application of the matrix methods with considerable ease (see 6.3.2).

6.4.3 Analysis of composite folded-plates:

The tendency is for composite folded-plate structures to use plates with smaller widths compared to prismatic structures. It follows therefore that for these plates the resistance to the concentrated design load of 0.9 kN (or 1.8 kN, see 6.1) may be more important than the transverse action of the plates.

Consider an internal typical plate of a composite folded-plate structure, as shown in Fig. 6.12. Depending on the plate dimension, a circle may be defined, which will indicate the extent of influence of the point load on the plate (see Fig. 6.12). The analysis of this circle can be substituted for the analysis of the plate without significant loss of accuracy (5).

Reference 5 contains formulae for determining deflections, bending moments and membrane forces (if any) of a typical
Circle of influence

Pad for application of the load

An internal plate

FIG. 6.12 CIRCLE OF INFLUENCE UNDER A POINT LOAD

plate from a folded-plate structure. Assuming the transverse deflection is small compared with the thickness of the plate, the maximum deflection \( w_d \) can be found from the following formula (10):

\[
W_d = \frac{P}{16\pi D} \left\{ \frac{(3+\nu)a^2}{(1+\nu)} + c^2 \cdot \log \frac{c}{a} - \frac{(7+3\nu)c^2}{4(1+\nu)} \right\}
\]

where: \( P \) = point load; \( a \) = radius of the plate; \( c \) = radius of the circular pad for applying the load; \( D \) = flexural rigidity of the plate; and \( \nu \) = Poisson's ratio.

In the case of a sandwich construction, a secondary shearing deformation \( w_s \) must also be calculated and added to the above (see 6.4.1).

Tangential moment \( M_t \) and radial moment \( M_r \) have an equal value at the centre of the influence circle and may be found from the following formula (5):
\[ M_r = M_t = \frac{P}{4\pi} \left( (1+v) \log \frac{a}{c} + 1 - \frac{(1-v)c^2}{4a^2} \right) = \frac{P(1+v)}{16\pi} \left( \frac{2(3+v)}{(1+v)} - 2 - \frac{c^2}{a^2} \times \left[ 1 + \frac{1-v}{1+v} \right] \right) \]

It follows from the above that the thickness of the plate should not be less than the given amount, approximately 3mm in the case of a random G.R.P. laminate. Whence, a G.R.P. structure can be economic when the required plate thickness for overall structural action is equal or greater than the thickness dictated by the local resistance to the design maintenance load. This means that folded-plate structural roofs are not usually economic for small spans.

Longitudinal behaviour of a composite folded-plate structure may be determined by assuming a constant average moment of inertia (\( I_{ave} \)) about the neutral axis of the profile; \( I_{ave} \) may be calculated by application of Simpson's rule (5) to the maximum and minimum values of the moments of inertia (\( I_{max} \) and \( I_{min} \)). The latter are normally found from the geometry of the structure. For example, consider the unit structure shown in Figure 6.8. The whole structure may be assumed to consist of successive units each functioning independently. Part of this structure is shown in Fig. 6.13. It can be seen that the moment of inertia varies with the angle \( \phi \). The maximum and minimum moments of inertia occur alternately at \( \phi = \frac{p\alpha}{4} \) and \( \phi = \frac{q\alpha}{4} \), respectively, where \( p \) and \( q \) have successive even and odd values respectively, and \( \alpha \) is the angle of a folded module (c.f. Fig. 6.8). From the geometry of the structure, \( I_{max} \) and \( I_{min} \) may be calculated (5):

\[ I_{max} = k \times \frac{d^3}{4} \]

\[ I_{min} = k \times \frac{d^3}{4} \]

\[ k = \frac{t}{12 \sin \phi} \quad (t = \text{the thickness of the plate}) \]
and $I_{ave}$ is found from the following formula (5):

$$\frac{1}{I_{ave}} = \frac{1}{3} \left[ \frac{1}{I_{max}} + \frac{2}{I_{min}} \right]$$

The underlying assumption in the above analysis is that no plate buckling is present and that the full width of the plate is effective. As was mentioned earlier, because of the local buckling in the central portions of thin plates, it is more realistic to assume that a reduced width of plate around the fold-lines will be effective.

**FIG. 6.13 PART OF THE FOLDED-PLATE ARCH OF FIG. 6.8.**
(After Benjamin, Reference 5)

**6.4.4 Basis for skeletal methods:**
Consider the single-skin prismatic structure shown in Figure 6.14. Under a combination of bending and compressive stresses (these stresses are normally generated under a UDL on a horizontal projection), and in the limit-state condition, certain parts of the plates will buckle and will become ineffective (dotted lines in Fig. 6.14). It may be seen that the structure may be assumed to consist of a series of top and bottom angles; the area of the top angle may be found by multiplying the relevant dimensions of the full
section by a 'reduction factor' (k) as shown in Fig. 6.14.

The reduction factor (k) may be found from the following formula (5):

\[
k = \frac{\sigma_{cc}}{\sigma_{pc}} \left[ 1 - \frac{3\left(\tan\left(\frac{\beta}{2}\right) - \frac{\beta}{2}\right)}{R_f} \right]
\]

where: \(\beta = \sin^{-1}\left(\frac{d}{c}\right)\), \(R_f = \frac{6 + 4 \times \frac{c}{A}}{4}\), and \(\sigma_{cc} = \)

the average crippling stress = \(0.455 \sqrt{(E_x \sigma)_c}\) where:

\(\sigma_{pc} = 0.2\%\) proof stress in compression (or its equivalent)

\(\sigma_{pt} = 0.2\%\) proof stress in tension (or its equivalent)

FIG. 6.14 TRANSFORMATION OF A PRISMATIC STRUCTURE
(After Benjamin, Reference 5)

The above analysis is relevant to the calculation of the ultimate load-bearing capacity of a prismatic structure. Benjamin (5) states that it is reasonable to assume that the same reduction factor is applicable for the analysis of structure under the normal working loads.
The difficulty with the above approach lies in determining both the proof and crippling compressive stresses for G.R.P. materials.

Attempts have been made by several authors (5), (7) and (8) to find simplified methods for the determination of the effective areas in any type of folded-plate structure. However, it has proved difficult to formulate any general method; in any structure the designer must make an appropriate assumption and verify this by loading trials.

In some cases the thickness of the plate is increased towards the edges; the mating-flanges are also made thicker than the normal thickness of the plate. In these cases, the area of the equivalent skeletal member may be assumed to comprise the total areas of the thickened parts and the adjoining flanges on a connection-line (9).

It must be noted that in the case of the folded-plate arch shown in Figure 6.8, Benjamin (5) reports good correlation between experimental observations on a model and the analytical values calculated on a reduced structure with each member assumed to be 16t (where t is the plate thickness) on either side of the fold line. This is equivalent to only 25 percent of the total plate area.

Alternatively, the finite elements method may be considered.

6.4.5. Finite elements method:
Consider a continuous structure as shown in Fig. 6.15, below:

The structure may be divided into a number of hypothetical finite elements of any shape by means of hypothetical lines or surfaces. The elements are assumed to be interconnected only at the nodes. It is also assumed that if the nodal
displacements are known, the behaviour of each element can be determined (11). The nodal displacements are normally expressed in terms of a set of functions. The choice of functions is such as to maintain the compatibility conditions between two neighbouring elements. The internal forces (and moments) applied to an element at each node can then be related to the components of the displacement at that node by the conditions of equilibrium of the node. The stiffness matrix of the structure is then formed by considering the contribution of each element (11). In practice, elements are chosen to be of a simple shape, e.g., triangles, rectangles, etc. External loads and moments are substituted with an equivalent system of loading applied at the nodes only. The matrix relationship between the nodal displacement (d) and the stiffness, (K) and the external load (w), may be established by the equations (11):

$$\bar{K} \times d = \bar{w}$$

The above relationship is then modified to take into account the conditions of supports and the result is:

$$\bar{K} \times \bar{d} = \bar{w}$$

The nodal displacements found from the above matrix equation are used together with the internal forces and moments for determining the behaviour of the elements in terms of stresses and strains. The reaction forces may be calculated from the local equilibrium consideration at the supports.

The accuracy of the results obtained depends on the number, shape(s) and distribution of the elements and also on the type(s) of functions proposed for defining the displacements. Use of a fine mesh for elements yields more accurate estimations of the stresses and strains, but requires very large storage capacity in the computer. Local violations may also occur both within the element itself and on the boundaries due to replacement of the actual loadings by the equivalent nodal system. Evaluation of the stiffness matrices can be very involved (11). In general, owing to these difficulties, this technique has not been applied in practice and remains to be developed further.
6.4.6 Methods for analysis of shells:

In the simple membrane theory of thin shells (10), it is assumed that the bending stresses are negligible and that each element of the shell is subjected to the meridional ($N_\phi$), hoop ($N_\theta$) and shear ($N_{\phi\theta}$) forces only as shown in Fig. 6.16.

![Diagram of Meridional, Hoop, and Shearing Forces](image)

**Fig. 6.16 Meridional, Hoop and Shearing Forces (per unit length) on an element of a shell.**

At points of discontinuity (e.g., at the supports), the above assumption is not valid and the bending stresses must be taken into consideration. In the case of a spherical dome with the base permitted to move horizontally, the following equations may be used for the calculation of the above forces (10):

**Dead load** $- q \delta$

$$N_\phi = \frac{-aq\delta}{1+\cos \phi} \quad \text{(compressive)}$$

$$N_\theta = aq\delta \left[ \frac{1}{1+\cos \phi} - \cos \phi \right] \quad \text{(compressive/tensile)}$$

$$N_{\phi\theta} = 0$$

**Uniform snow load on a horizontal projection**

$$N_\phi = \frac{-aq \delta}{2} \quad \text{(compressive)}$$

$$N_\theta = \frac{aq \delta}{2 \cos 2 \phi} \quad \text{(compressive/tensile)}$$
where: \( a \) = radius of the sphere of which the dome forms a part, \( \theta \) and \( \phi \) are meridional and hoop angles respectively, defining the position of the element on the dome surface (Fig. 6.17) If the base is horizontally restrained, bending moments and horizontal reactions will develop; these effects can be determined by application of a moment (\( M \)), and a horizontal force (\( H \)) at the base (5).

\[ \n_{\phi} = 0 \]

![Diagram showing dome elevation and plan with meridional and hoop angles labeled.]

**FIG. 6.17** MERIDIONAL AND HOOP ANGLES IN A SPHERICAL DOME

G.R.P. shells are normally formed by bolting G.R.P. segments together; the joint lines are generally stiffer than the central parts of the segments. In addition, stiffening ribs may be incorporated in the segments to increase its overall resistance to buckling. In these cases, an equivalent skeletal structure may be substituted for the shell; the analysis of the assumed structure may be analysed by one of the matrix methods of analysis.

Alternatively the finite elements method may be employed. This technique is particularly suitable for shells as compared with folded-plates. However, much remains to be resolved before the average practising engineer can use the finite elements technique; he probably needs a suite of computer
programs especially developed and tested for G.R.P. shells
(and probably other structures) to run for his particular
project.

The skeletal analysis appears to be more suitable for
the folded-plate structures where the deflection of the whole
structure must be determined. This deflection has been found
to be comparatively insensitive to variations in the effective
areas of the members (5). Furthermore, since the total dis­
placement of the structure is usually the ultimate design
criterion, the skeletal method can be a useful analytical tool.

### 6.5 Structural Design of G.R.P. Panels and Structures:

The purpose of the structural design of a panel or a
structure is to select the most economic combinations of
materials to carry the imposed loads at each section, with
an appropriate safety factor. Thus, the design and analysis
of a structure are interdependent and the usual procedure
takes the following routine:

(a) From past experience and preliminary calculations, an
appropriate thickness of a material or combination of materials
is selected, bearing in mind the non-structural performance
requirements, e.g. the need for thermal and sound insulation,
the required period of 'fire-resistance', the type of fixing
and jointing of panels, etc.

(b) The structural analysis for the panel or structure is
carried out and the applied forces and moments are calculated
at various sections. (For economic reasons, the forces and
moments are normally calculated at critical and selected
points only)

(c) From the calculated forces and moments, the stresses and
strains at each section are evaluated; these are compared
with the permissible design limits (see section 6.2). An
alternative method is to base the design on the limit state
philosophy. However, much work remains to be done before
G.R.P. structures could be designed on the limit state basis.

The next stage is to adjust the thickness of materials
or the quantity of reinforcement as may be necessary, whilst
bearing in mind the non-structural performance requirements
and the need for rationalized thickness/reinforcement variations as dictated by practical and economic considerations.

(d) Details of the fixing of the panels to the structure and/or jointing of the panels are worked out and prototypes or reduced models fabricated for testing purposes (if required).

(e) Full-scale or reduced-scale tests are performed on the prototype or the model respectively. Other tests as considered appropriate may also be carried out to ensure that all performance requirements are adequately satisfied. The testing of the efficiency of the proposed jointing in restricting the penetration of rainwater driven by wind is but one example of these tests.

(f) Final adjustments and rationalization are made to the panels or the fixing, jointing etc.

6.5.1 The influence of the non-structural requirements:

It has already been noted that non-structural performance requirements must be taken into consideration at the time of inception of the project. An example is the case of an external wall required to provide a specified maximum overall U-value and a specified minimum period of fire-resistance. These requirements may be simultaneously satisfied in the following typical ways:

(a) Use of a structural sandwich panel consisting of a G.R.P. external skin, a rigid core of foamed plastics and an internal board of a fire-resisting material (e.g. G.R.G.)

(b) Use of a structural sandwich panel consisting of two G.R.P. skins and a lightweight core made of a fire-resisting composite (see sections 4.4 and 4.5).

(c) Use of an articulated design consisting of a G.R.P. shell (as the load-bearing and weather protection medium followed by a layer of insulation (e.g. glass quilt) and a fire resistant backing material (e.g. plasterboard or asbestos board).

Only after deciding on a solution is it possible to do the structural analysis and design. It has been suggested that the structural design may be carried out and then
adjusted to satisfy the non-structural performance requirements. Such an approach is neither appropriate nor likely to lead to an economic solution. For instance, if, for structural reasons the minimum required core thickness in case (b) above, was 10mm of a specific material and if, for thermal insulation reasons, a minimum thickness of 20mm of the same material was needed, it is appropriate to base the structural design on a core of 20mm, from the outset.

Whereas the requirement of a minimum of 30 minutes fire-resistance for external walls restricts the choice to such systems as those mentioned above, the choice for roofs is wider, and the structural sandwich construction has a high potential. However, there is evidence (6), (17) and (23) that reliance on the structural performance of a sandwich design is not advisable, unless the design is verified by experimental techniques (see also subsection 6.5.3).

6.5.2 Design of a single skin G.R.P. structure:

The need for the G.R.P. skin to sustain the design maintenance load has already been noted. Moreover, the design of plates must take account of applied forces and moments as calculated in the transverse analysis of the plates (see 6.4.1 and 6.4.2).

Given the design characteristics of the laminate to be used, it is relatively easy to design a thickness which would satisfy the design criteria.

In single skin panels, ribs are usually designed in sandwich construction, which is discussed in the next section. If the sandwich action is ignored, then ribs may be designed as hollow beams and struts without difficulty.

Orthotropic laminates may be designed using the orthotropic formulae given in subsection 4.2.5; appropriate creep data should, however, be used in the place of elastic values given in the relevant equations (13).

6.5.3 Design of structural sandwich construction for beams, panels and struts:

In section 5.7 it was noted that a structurally efficient sandwich is likely to comprise two thin faces of G.R.P. encapsulating a thick low density rigid core (e.g. rigid polyurethane or phenolic foam).
As was noted in subsection 6.5.1, for external walls, sandwich constructions of a thin external face and a thick internal face are both technically appropriate and feasible; these sandwich constructions have a different behaviour from the thin-faced ones. Another possibility is that of a medium density stiff core encapsulated in two thin G.R.P. faces; behaviour of such a sandwich approximates that of the core acting in isolation.

The following idealization may be made for sandwich constructions consisting of two thin faces of G.R.P. encapsulating a thick low density rigid core (14):

1 - Because the stiffness of the core is lower than the stiffness of the faces, the contribution of the core to the overall flexural rigidity is negligible, and the direct stresses due to the bending of the member can be neglected.

2 - Because of the low stiffness of the core, the shear stress may be assumed to be constant across the depth of the core; as the faces are thin, the shear stress at these may be neglected.

3 - The faces are assumed to be kept at a correct distance apart by the core; this means that the stiffness of the core in the direction normal to the faces should be sufficient to resist the crushing effects of normal loads. There are two cases when this assumption can be invalidated: (a) crushing of the core under a concentrated load; and (b) the wrinkling of the faces.

(a) Crushing of the core under a concentrated load: If a concentrated load is applied to a sandwich of thin faces and a thick core, if the core is not sufficiently stiff, it yields and the faces bend locally suffering additional stresses. If the shear stiffness of the core is ignored, the problem is transformed to that of a long beam supported on a bed of springs with a uniform spring stiffness (k). This gives an approximate estimate (14) of the stresses induced locally in the faces and the core. Alternatively empirical formulae given in reference 5 may be used for calculation of the above stresses.

(b) The wrinkling instability of the faces: The critical wrinkling stress may be calculated from the formulae given in the standard text books (5) and (15). However, premature failure initiated by small irregularities in the
zones in the core may occur; these situations are not amenable to theoretical predictions (14) & (17). The most reliable method is to carry out compression tests on specimens from sandwich construction members (14).

In view of the above problems, it is suggested that sandwich construction members be designed according to the approximate rules given below; the adequacy of the design may be checked by loading trials as recommended in reference 17.

Allen (14) has shown that the behaviour of flat sandwich panels, sandwich beams and sandwich struts under both normal and inplane loading, is approximately dependent on three non-dimensional parameters of

\[ \frac{L_1}{L}, \frac{D_f}{D}, \text{ and } \frac{D}{L^2 D_0}, \]

where:

- \( L = \) The length of the beam (or shorter length of a panel)
- \( L_1 = \) The length of overhangs along the same direction as \( L \)
- \( D = \) The overall flexural rigidity of the member; For the beam shown in Fig. 6.18, the following formula may be used for the calculation of \( D \) (14).

\[
D = \frac{E_f}{1-v_f^2} \cdot \frac{bt^2}{2} + \frac{E_f}{1-v_f^2} \cdot \frac{bt^3}{6}
\]

\[ \text{where: } E_f = \text{design creep modulus of the facing material} \]
\[ v_f = \text{Poisson's ratio} \]
\[ D_f = \text{sum of flexural rigidities of the faces when} \]
they are acting in isolation = \( \frac{1}{1-\nu_f^2} x \frac{\partial^2 u}{\partial t^2} \)

\[ D = \text{shear stiffness} = G_c \times \frac{bd^2}{c} \]

where: \( G_c = \text{shear stiffness of the core} \)

Fig. 6.19 shows graphs of a ratio \( r_1 \) (to be defined below), against the parameter \( \frac{D}{D_f} \); each graph is for a particular value of the parameter \( \frac{L^2D_0}{D} \) \((L_1=0)\).

The ratio \( r_1 \) may be taken as an approximate estimate of the following (14):

(i) The ratio of deflection of a sandwich beam of span \( L \) to that of a solid beam of the facing material of the same dimensions under identical loading/support conditions.

(ii) The ratio of the deflection of a sandwich panel with transverse load and support on four sides (shorter span taken as \( L \)) to that of a solid panel of the same dimensions under identical loading/support conditions.

(iii) The ratio of the Euler load of a solid strut of length \( L \) to the critical load of a sandwich strut of the same dimensions under identical loading/support conditions.

(iv) The ratio of critical edge load of a simple panel supported on four sides (the shorter span is \( L \)) to the critical load of a sandwich panel of the same dimensions under identical loading/support conditions.

The graphs of Fig. 6.19 can be used for the design purposes as shown below (14):

(a) For large spans or very thin faces, when the ratio \( \frac{D}{L^2D_0} \) is less than 0.01, \( r_1 \) approaches unity. This means that the sandwich panel has the behaviour of a solid panel, i.e. the shearing deformation of the core may be ignored and the panel analysed by application of the ordinary bending theory.

(b) For a given sandwich beam (or panel or strut), the values of the parameters \( \frac{D}{L^2D_0} \) and \( \frac{D_f}{D} \) can be calculated and plotted in Fig. 6.19. If these give a point close to curve ABCG, the behaviour of the panel may be considered similar to that of
FIG. 6.19 RATIO $r_1$ PLOTTED AGAINST $D/I^2D_Q$ FOR VARIOUS $D_f/D$.

Curves are for beam with central point load and no overhang at the ends ($L_1 = 0$), but are useful for a wide range of sandwich structures.
an ordinary beam, except that additional shearing deformation must be taken into account. In the case of a sandwich strut, this means that the critical load is less than the critical load of a solid strut of the same dimensions.

Assuming $100 > \frac{d}{t} > 5.7$, then we have $0.01 \frac{D}{D} > 0.0001$. From Fig. 6.19, it may be seen that $\frac{D}{L^2D_0}$ must be less than 1 in order that the sandwich beam may be designed as an ordinary beam with additional deflection due to shear in the core. If the span is sufficiently large, the above requirement is usually fulfilled. Alternatively, the thickness of the faces and cores may be chosen such that for a given span $L$, the value of the above parameter works out less than 1.

For a point load ($P$) at the mid-span, the total deflection for the above case (i.e. thin-faced flat sandwich beam) is found from the following formula:

$$\Delta = \text{total deflection of a sandwich beam simply supported at each end}$$

$$\Delta = \frac{PL^3}{48D} + \frac{PL}{4D} \quad (*)$$

(c) Any point below the curve ABCG represents a beam (or a panel or strut) in which the faces are sufficiently thick to bend about their own neutral axis; such a panel must be analysed using the thick-face theory (15)&(16). Any point close to the horizontal region of any curve in Fig. 6.19 represents a beam in which there is no significant contribution from the core and the faces act as independent beams.

(d) If one face is corrugated or is sufficiently thick so as to bend about its own neutral axis, the resulting sandwich

(*) The general formula is:

$$\Delta = \frac{PL^3}{48D} + \frac{PL}{4D_0} \times \left(1 - \frac{D_f}{D}\right)^2 \times S_1$$

where: $S_1$ is a dimensionless coefficient which depends on $\frac{D_f}{D}$, $D$ and $\frac{L_1}{L}$. For a sandwich beam with thin faces and no overhangs at the ends ($\frac{L_1}{L} = 0$), $S_1$ approaches unity and $\frac{D_f}{D}$ becomes insignificant compared with unity.
may have values as high as 0.1 or more, for the parameter \( \frac{D_f}{D} \). From Fig. 6.19 it will be seen that unless the parameter \( \frac{D_f}{L \sqrt{D_0}} \) has a value less than 0.1, the point representing this sandwich would be placed below the curve ABCG. This indicates that the corrugated or thick face carries directly a significant proportion of the applied moments (16).

(e) If the member is not flat, then the analysis must be carried out as described in section 6.4; the design may then be based on the sandwich properties.

6.6 Problems Likely to be Encountered in the Analysis and Design of G.R.P. Panels and Structures:

From the review carried out in the previous sections, it can be seen that the problems are likely to be of two different types:

(1) Those associated with the estimation of the wind loading on folded-plates and shells.

(2) Those associated with the structural analysis and design of G.R.P. panels and structures

6.6.1 Problems of estimating the wind loading:

Shells and folded-plates are not covered by CP3 Chapter V, although a limited amount of information for prismatic roofs with no cantilevered projection, may be obtained from the data relevant to the multi-span roofs (see Table 11 of the code).

The wind loading handbook (1) contains some information for cylindrical arches and spherical domes. However, the authors have warned that the curved surfaces present difficulties for the estimation of the pressure and force coefficients, and that specialist advice should be sought for major constructions (1). This means that a wind tunnel test on the model of the structure is unavoidable. Dependence on such tests, as well as being expensive, can protract the design of simple G.R.P. structures and may adversely affect the designers' original intentions to use G.R.P.

Difficulties of this nature do not normally exist for conventional building forms; thus, flat or pitched roofs or rectangular-based buildings are both technically viable and
6.6.2 Problems associated with the analysis and design of G.R.P. structures:

Consider a roof to be designed for a building which consists of load bearing walls. The span is of small to medium range, so that the roof structure may be designed from any of the following materials: reinforced concrete, steel, timber, aluminium and G.R.P. The ground conditions are good and no restriction is imposed on the weight of the roof.

The degree of convenience attainable in the design of the roof with each of the above materials is considered below:

(i) Reinforced concrete: Design and analysis is relatively easy, since a flat roof may be considered using the design formulae or diagrams provided in the unified code: 'The Structural Use of Concrete, CP110: 1972'.

The design criteria, durability aspects and the safety factors are well understood and are covered in the code.

(ii) Steel: A variety of solutions are possible using standard sections, e.g. (a) Universal I beams for a flat roof (b) steel trusses for a flat or pitched roof (c) steel arches; and (d) double layer space frame for a flat roof construction. Structures of types (a), (b) and (c) may be designed to span the shorter length of the load bearing walls. All such structures can be specified with standard decking and covering systems.

For the analysis and design of structures (a), (b) and (c) there are numerous design aids and tables; 'Steel Designers' Manual' and BS 449 are but two comprehensive design aids.

The analysis and design of a double layer space frame may prove difficult (18). However, there are packages which simplify the problem to a large extent. For example NODUS (18) is a package offered by the British Steel Corporation, Tubes Division, which covers standardized systems of construction, for which a computer program is supplied so that the designer may carry out the analysis for his own structure (18)(19).

The design criteria, durability aspects and safety factors associated with various grades of steel are well covered by various design codes and standards.

(iii) Timber: CP112 parts 2 and 3 deals with design data on strength, elastic modulus, etc of various types of
timber and plywood. Methods for the design of timber structures are given, which cover joists, trussed rafters and other conventional skeletal structures. Specifications for bonding and jointing methods, workmanship, testing, preserving and maintenance of timber members are also given in CP112: 2 & 3. In addition to the above code, CP98: 1964, 'Preservative Treatments for Constructional Timber' gives extensive guidance on the durability and treatment aspects of timber.

Flat roofs of timber joists with standard coverings are relatively easy to design with the aid of these codes. However, in the case of a folded-plate or shell constructed from plywood, the design and analysis are difficult.

Plywood and timber structures have inferior performance regarding the structural continuity, weather and moisture resistance.

(iv) Aluminium: CP118: 1969, 'The Structural Use of Aluminium' gives design recommendations for use of aluminium in virtually all types of conventional structures. It also gives guidance on loading, testing, fabrication, erection and protection of aluminium. Additional design aids are available, e.g. 'Engineering Data for Aluminium Structures', provided by the Aluminium Association (20).

The design and analysis of a folded-plate or shell aluminium structure are difficult; in the case of major constructions, the tendency in the past has been either to use discrete structural members of standard types, as in the Swindon Dome (21), or to use whole aluminium structures of a specific type from an aluminium company. The TEMCOR system (22) is an example.

(v) G.R.P.: As has already been noted, a G.R.P. roof must assume an appropriate geometrical shape of folded-plates or shells, in order to be able to span an appreciable distance. The same remarks apply to G.R.P. structural envelopes.

Furthermore, there is no code of practice for the design of G.R.P. panels and structures; G.R.P. materials have many more design dimensions which can be very complex for average designers brought up with the traditional structural materials. Examples of these have already been noted; creep, temperature, material compositions, colour and texture, etc. cannot be overlooked or treated in a routine manner.
6.6.3 Summary of the problems:
The chief problems are as follows:

(a) - Wind loading data for G.R.P. structures are not available. Tunnel tests can protract the design of the normal structures and may be uneconomic.

(b) - Design parameters are not defined for G.R.P. Moreover, there are additional parameters which influence the mechanical behaviour of G.R.P. to a significant extent. These parameters are either non-existent or have insignificant effects on the mechanical behaviour of normal structures constructed from other materials.

(c) - Folded-plates and shells are difficult to analyse structurally; the resistance of these structures to buckling is sensitive to small changes in the geometry. With G.R.P., there is a need to utilize shaped forms to compensate for the lack of rigidity in this material.

(d) - There are generally no flexible packages for making the structural use of G.R.P. relatively easier, e.g. similar to NODUS (18)
CHAPTER 6: References.

Plastics Sandwich Panel Construction", Paper presented at the Univ. of Surrey (as ref 13)


17. Langlie, C., "Sandwich Construction: A Practical Approach For the Use of Designers", Paper (see ref. 13)


23. Interview notes with Mr. A Leggett, Messrs. Nasehen, Croft and Leggett, Consulting Civil and Structural Engineers, on the 17th Jan. 1975, and discussion on the design of the folded-plate roof structure for Morpeth Secondary School in East London (see also New Civil Engineer, 24th October 1974).
7.1 Statistics of the use of G.R.P. in the Construction Industry:

7.1.1. Time series of consumption:

The reinforced plastics industry is a new and growing industry with diverse products and markets. Thus, there are no published official statistics for production, consumption, etc., of G.R.P. products in the construction industry or in other industries. Also, despite an extensive search for other possible sources of data, no consistent and accurate set of data were traced. The following review of all the data gathered is therefore intended as giving indications of the order of magnitude of the quantities of G.R.P. used in the construction industry.

(1) Annual reviews: European Plastics News (formerly known as 'British Plastics' and then 'Europlastics') published annual statistics for main plastics, and for the end-uses in each January issue. Coverage of polyester resin ceased after 1973. The informed opinions in the industry are that these data are not collected on an accurate and consistent basis and cannot therefore be used for any price/consumption relationship. Table 7.1 contains the data extracted from the relevant issues of this journal; as has been explained in the table footnotes, there are various inconsistencies in the original figures, and column IV is not strictly usable. Columns V and VI of Table 7.1 have been plotted in Fig. 7.1 and indices of the same in Fig. 7.3

(2) Data supplied by Silenka (1): Tables 7.2 to 7.5 are summaries of statistics obtained from Silenka. However, the suppliers have not disclosed the accuracy and nature of these data. A comparison of data in Tables 7.1 and 7.2 has been
Table 7.1 Polyester Resin Consumption in the U.K. Construction Industry (Source: British Plastics - Europlastics - Plastics News)

<table>
<thead>
<tr>
<th>Year</th>
<th>Roof Sheetings</th>
<th>Cladding</th>
<th>Others*</th>
<th>Total Construction</th>
<th>Grand Total</th>
<th>All Industries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(10^3 tons)</td>
<td>% of Col. VI</td>
<td>(10^3 tons)</td>
<td>% of Col. VI</td>
<td>(10^3 tons)</td>
<td>% of Col. VI</td>
</tr>
<tr>
<td>1961</td>
<td>2.85</td>
<td>30</td>
<td>-</td>
<td>-</td>
<td>2.85</td>
<td>30</td>
</tr>
<tr>
<td>1962</td>
<td>2.75</td>
<td>25</td>
<td>-</td>
<td>-</td>
<td>2.97</td>
<td>27</td>
</tr>
<tr>
<td>1963</td>
<td>2.84</td>
<td>21</td>
<td>-</td>
<td>-</td>
<td>3.11</td>
<td>23</td>
</tr>
<tr>
<td>1964</td>
<td>3.50</td>
<td>19</td>
<td>-</td>
<td>-</td>
<td>4.10</td>
<td>22</td>
</tr>
<tr>
<td>1965</td>
<td>4.20</td>
<td>17</td>
<td>-</td>
<td>-</td>
<td>4.90</td>
<td>20</td>
</tr>
<tr>
<td>1966</td>
<td>4.50</td>
<td>17.5</td>
<td>-</td>
<td>-</td>
<td>5.5</td>
<td>21.5</td>
</tr>
<tr>
<td>1967</td>
<td>5.0</td>
<td>18</td>
<td>-</td>
<td>-</td>
<td>6.4</td>
<td>23</td>
</tr>
<tr>
<td>1968</td>
<td>5.1</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>7.8</td>
<td>23</td>
</tr>
<tr>
<td>1969</td>
<td>5.3</td>
<td>14</td>
<td>1.30</td>
<td>3.4</td>
<td>8.5</td>
<td>22.5</td>
</tr>
<tr>
<td>1970</td>
<td>5.5</td>
<td>13</td>
<td>1.50</td>
<td>3.5</td>
<td>8.9</td>
<td>21</td>
</tr>
<tr>
<td>1971</td>
<td>5.5</td>
<td>14.7</td>
<td>1.50</td>
<td>4</td>
<td>7.8</td>
<td>21</td>
</tr>
<tr>
<td>1972</td>
<td>5.5</td>
<td>10.7</td>
<td>1.50</td>
<td>3</td>
<td>9.2</td>
<td>18</td>
</tr>
<tr>
<td>1973</td>
<td>5.5</td>
<td>10.4</td>
<td>2.0</td>
<td>4</td>
<td>8.0</td>
<td>22</td>
</tr>
</tbody>
</table>

Note: The latest revised figures in each case are included.
- Implies no separate figures are available.
* Others, which includes cold water cisterns, etc. There are inaccuracies in the original figures given in the above journal separately under 'total consumption of polyester resin' and under 'Building and Construction Market'. 'Others' has been calculated by deducting the sum of columns II and III from column V and entering the result in column VI (see also the text).
1 Price reduction in this year.
2 Production figure. No figure for 1962 consumption is available, but import was 800 tons approximately and export was negligible.
### Table 7.2  G.R.P. consumption in Western Europe 1968 - 1973 in the construction industry

<table>
<thead>
<tr>
<th>Country</th>
<th>1968</th>
<th>%)</th>
<th>1969</th>
<th>%)</th>
<th>1970</th>
<th>%)</th>
<th>1971</th>
<th>%)</th>
<th>1972</th>
<th>%)</th>
<th>1973</th>
<th>%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W. Germany</td>
<td>18300</td>
<td>34,5</td>
<td>21300</td>
<td>29,6</td>
<td>23600</td>
<td>27,4</td>
<td>24800</td>
<td>27,2</td>
<td>26000</td>
<td>25,0</td>
<td>28500</td>
<td>23,4</td>
</tr>
<tr>
<td>France</td>
<td>16400</td>
<td>38,9</td>
<td>18000</td>
<td>36,7</td>
<td>19100</td>
<td>34,4</td>
<td>19900</td>
<td>35,1</td>
<td>20200</td>
<td>27,6</td>
<td>21700</td>
<td>25,5</td>
</tr>
<tr>
<td>U.K.</td>
<td>9800</td>
<td>26,5</td>
<td>11000</td>
<td>24,4</td>
<td>11500</td>
<td>22,9</td>
<td>12000</td>
<td>25,0</td>
<td>13300</td>
<td>22,9</td>
<td>15500</td>
<td>21,5</td>
</tr>
<tr>
<td>Italy</td>
<td>13000</td>
<td>49,4</td>
<td>15000</td>
<td>46,6</td>
<td>16800</td>
<td>42,0</td>
<td>17000</td>
<td>40,0</td>
<td>17800</td>
<td>35,5</td>
<td>22000</td>
<td>36,7</td>
</tr>
<tr>
<td>Netherlands</td>
<td>2000</td>
<td>31,3</td>
<td>2300</td>
<td>26,7</td>
<td>2000</td>
<td>25,7</td>
<td>3200</td>
<td>30,8</td>
<td>5300</td>
<td>39,5</td>
<td>6600</td>
<td>41,7</td>
</tr>
<tr>
<td>Belgium</td>
<td>3000</td>
<td>52,6</td>
<td>4450</td>
<td>61,8</td>
<td>4100</td>
<td>54,7</td>
<td>4700</td>
<td>58,0</td>
<td>4500</td>
<td>45,0</td>
<td>6700</td>
<td>50,8</td>
</tr>
<tr>
<td>Denmark</td>
<td>2200</td>
<td>44,0</td>
<td>2500</td>
<td>40,3</td>
<td>2200</td>
<td>29,3</td>
<td>1200</td>
<td>16,9</td>
<td>1300</td>
<td>15,3</td>
<td>1500</td>
<td>15,0</td>
</tr>
<tr>
<td>Ireland</td>
<td>300</td>
<td>50,0</td>
<td>300</td>
<td>42,8</td>
<td>350</td>
<td>44,9</td>
<td>400</td>
<td>44,4</td>
<td>600</td>
<td>46,1</td>
<td>700</td>
<td>41,2</td>
</tr>
<tr>
<td>Subtotal EEC</td>
<td>65000</td>
<td>36,9</td>
<td>74850</td>
<td>34,0</td>
<td>80250</td>
<td>31,2</td>
<td>83200</td>
<td>31,5</td>
<td>92000</td>
<td>28,9</td>
<td>103200</td>
<td>27,1</td>
</tr>
<tr>
<td>Sweden</td>
<td>1900</td>
<td>16,5</td>
<td>2000</td>
<td>13,3</td>
<td>2200</td>
<td>12,0</td>
<td>2200</td>
<td>11,7</td>
<td>2100</td>
<td>10,0</td>
<td>1500</td>
<td>6,0</td>
</tr>
<tr>
<td>Norway</td>
<td>900</td>
<td>12,0</td>
<td>1100</td>
<td>10,5</td>
<td>1200</td>
<td>9,2</td>
<td>1000</td>
<td>8,7</td>
<td>600</td>
<td>5,0</td>
<td>1000</td>
<td>6,7</td>
</tr>
<tr>
<td>Switzerland</td>
<td>1500</td>
<td>26,3</td>
<td>1800</td>
<td>25,4</td>
<td>2000</td>
<td>23,5</td>
<td>1500</td>
<td>18,3</td>
<td>2300</td>
<td>21,9</td>
<td>1400</td>
<td>12,7</td>
</tr>
<tr>
<td>Austria</td>
<td>500</td>
<td>20,0</td>
<td>700</td>
<td>32,0</td>
<td>800</td>
<td>17,4</td>
<td>700</td>
<td>16,9</td>
<td>1200</td>
<td>24,5</td>
<td>1900</td>
<td>25,3</td>
</tr>
<tr>
<td>Portugal</td>
<td>200</td>
<td>33,3</td>
<td>220</td>
<td>31,4</td>
<td>250</td>
<td>31,3</td>
<td>300</td>
<td>25,0</td>
<td>400</td>
<td>23,5</td>
<td>500</td>
<td>25,0</td>
</tr>
<tr>
<td>Spain</td>
<td>3900</td>
<td>54,2</td>
<td>4400</td>
<td>50,6</td>
<td>5000</td>
<td>49,0</td>
<td>6600</td>
<td>60,0</td>
<td>7600</td>
<td>48,7</td>
<td>10000</td>
<td>50,0</td>
</tr>
<tr>
<td>Finland</td>
<td>500</td>
<td>16,6</td>
<td>700</td>
<td>14,0</td>
<td>800</td>
<td>11,4</td>
<td>700</td>
<td>10,0</td>
<td>500</td>
<td>5,0</td>
<td>2000</td>
<td>20,8</td>
</tr>
<tr>
<td>Other</td>
<td>-</td>
<td>-</td>
<td>50</td>
<td>20,0</td>
<td>50</td>
<td>12,5</td>
<td>100</td>
<td>16,7</td>
<td>200</td>
<td>25,0</td>
<td>250</td>
<td>25,0</td>
</tr>
<tr>
<td>Subtotal</td>
<td>9400</td>
<td>24,1</td>
<td>10970</td>
<td>21,8</td>
<td>12300</td>
<td>19,5</td>
<td>13200</td>
<td>20,3</td>
<td>14450</td>
<td>18,9</td>
<td>19050</td>
<td>20,8</td>
</tr>
<tr>
<td>Grand Total</td>
<td>74400</td>
<td>34,7</td>
<td>85820</td>
<td>31,7</td>
<td>92550</td>
<td>28,9</td>
<td>96400</td>
<td>29,3</td>
<td>106450</td>
<td>26,3</td>
<td>122250</td>
<td>25,9</td>
</tr>
</tbody>
</table>

1) = % of total consumption

(Source: Silenka b.v. of Holland)
Table 7.3 Flat and corrugated sheets as a percentage of the G.R.P. construction industry by country in 1973.

<table>
<thead>
<tr>
<th>Country</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Germany</td>
<td>80%</td>
</tr>
<tr>
<td>France</td>
<td>69%</td>
</tr>
<tr>
<td>U.K.</td>
<td>25%</td>
</tr>
<tr>
<td>Italy</td>
<td>70%</td>
</tr>
<tr>
<td>Netherlands</td>
<td>23%</td>
</tr>
<tr>
<td>Belgium</td>
<td>85%</td>
</tr>
<tr>
<td>Denmark</td>
<td>15%</td>
</tr>
<tr>
<td>Ireland</td>
<td>15%</td>
</tr>
<tr>
<td>Sweden</td>
<td>15%</td>
</tr>
<tr>
<td>Norway</td>
<td>15%</td>
</tr>
<tr>
<td>Switzerland</td>
<td>85%</td>
</tr>
<tr>
<td>Austria</td>
<td>80%</td>
</tr>
<tr>
<td>Portugal</td>
<td>?</td>
</tr>
<tr>
<td>Spain</td>
<td>90%</td>
</tr>
<tr>
<td>Finland</td>
<td>25%</td>
</tr>
</tbody>
</table>

(Source: Silenka)

Table 7.4 G.R.P.-composites patterns of G.R.P. consumption in the construction sector (in metric tons).

<table>
<thead>
<tr>
<th>Japan</th>
<th>Year</th>
<th>Consumption (metric tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1968</td>
<td>20,000</td>
</tr>
<tr>
<td></td>
<td>1969</td>
<td>30,000</td>
</tr>
<tr>
<td></td>
<td>1970</td>
<td>45,000</td>
</tr>
<tr>
<td></td>
<td>1971</td>
<td>51,300</td>
</tr>
<tr>
<td></td>
<td>1972</td>
<td>80,000 (51% of total G.R.P.)</td>
</tr>
<tr>
<td></td>
<td>1973</td>
<td>96,800 (51% of total G.R.P.)</td>
</tr>
</tbody>
</table>

There were the following applications in 1973:
1. flat and corrugated sheets 17.6%
2. bathtubs and septic tanks 80.0%

(Source: Silenka)

Table 7.5 Consumption of G.R.P. in the U.S.A.

<table>
<thead>
<tr>
<th>Year</th>
<th>Consumption (metric tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>48,900</td>
</tr>
<tr>
<td>1969</td>
<td>56,200</td>
</tr>
<tr>
<td>1970</td>
<td>60,300</td>
</tr>
<tr>
<td>1971</td>
<td>67,900</td>
</tr>
<tr>
<td>1972</td>
<td>77,400</td>
</tr>
<tr>
<td>1973</td>
<td>97,500 (15% of total G.R.P.)</td>
</tr>
</tbody>
</table>

There were the following applications in 1973:
1. panel manufacturing 31%
2. tubs/showers 58%
3. concrete forming 2%
4. other applications 9%

(Source: Silenka)
undertaken below; assuming 0.7 tonne of resin = 1 tonne of G.R.P. sheeting, it can be seen that the above two sources give different estimates of G.R.P. consumption in the construction industry:

From Table 7.1:
Total G.R.P. sheeting = 5500 x 1.016 x 100/70 = 8000 tonnes

From Tables 7.2 and 7.3:
Total G.R.P. sheeting = 15000 x 25/100 = 3750 tonnes

A comparison of G.R.P. consumption in the U.K. and in the E.E.C. construction industries in absolute and relative terms is shown in Figs. 7.2 and 7.4 respectively (see also subsection 7.1.2).

(3) Data published in Rubber and Plastics Weekly, May 7th, 1976: These data are considered in (a) and (b) below:

(a) Estimated consumption of UF resins in 1975 in the U.K. and Western Europe: These are given in Table 7.6; according to the information contained in Rubber and Plastics Weekly, May 7th, 1976, the original sources of data are: "Industry and the B.P.F."

(For comparison of all the data see the end of this subsection; see also the discussion beneath Table 7.6).

In addition, the total sales value of G.R.P. products in the U.K. in 1975 was estimated to be roughly £85m; the total sales value of G.R.P. products in 1974 was estimated by this source to be between £100m and £110m.

(b) Estimated production of G.R.P. (including reinforced thermoplastics) by Fibreglass Ltd. as published in the above journal: Table 7.7 gives total production of G.R.P. in 1971 - 75 in the U.K. and the E.E.C. countries. Table 7.8 contains a breakdown of the U.K. production of G.R.P. by various sectors for 1971 - 75.

It must be noted that these figures include both reinforced thermoplastics and overseas sales of G.R.P. products; they are not therefore comparable to the G.R.P. consumption data. However, assuming on average 0.7 UPR to one tonne of G.R.P., the following comparison may be noted for 1975:

From Table 7.6:
Total G.R.P. consumption = 10000 x 100 = 14300 tonnes
Table 7.6 Estimated 1975 consumption of UPR in the U.K. and Western Europe (Source: R. and P.W., 7th May, 1976)

<table>
<thead>
<tr>
<th>Type of application: (Reinforced)</th>
<th>U.K.</th>
<th>% of total</th>
<th>Western Europe*</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>quantity (x 10^3 tonnes)</td>
<td>% of total</td>
<td>quantity (x 10^3 tonnes)</td>
<td>% of total</td>
</tr>
<tr>
<td>Building</td>
<td>10</td>
<td>25.4</td>
<td>62</td>
<td>26.8</td>
</tr>
<tr>
<td>Electrical</td>
<td>2.5</td>
<td>6.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Industrial</td>
<td>6</td>
<td>15.4</td>
<td>41</td>
<td>17.7</td>
</tr>
<tr>
<td>Marine</td>
<td>7</td>
<td>18.0</td>
<td>39</td>
<td>16.9</td>
</tr>
<tr>
<td>Tanks and pipes</td>
<td>4</td>
<td>10.2</td>
<td>38</td>
<td>16.5</td>
</tr>
<tr>
<td>Transport</td>
<td>7</td>
<td>18.0</td>
<td>25</td>
<td>10.8</td>
</tr>
<tr>
<td>Other</td>
<td>2.5</td>
<td>6.4</td>
<td>26</td>
<td>11.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>39.0</td>
<td>100.0</td>
<td>231</td>
<td>100.0</td>
</tr>
<tr>
<td><strong>Total including unreinforced applications</strong></td>
<td>46.0</td>
<td>N.A.</td>
<td>301</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

N.A. = not applicable

* - No definition of Western Europe has been given. However, assuming a conversion factor of 1.43 from UPR to G.R.P., it can be seen that the above figure of 231000 tonnes of UPR corresponds to 330 000 tonnes of G.R.P.; this figure is very close to a figure of 331000 tonnes given in Table 7.7; both of these figures are also close to a figure of 328100 tonnes of G.R.P. consumption in the EEC countries excluding Denmark; the latter figure has been calculated from data published in Reinforced Plastics, May 1976 issue, and Table 7.7; the difference, which is between 2000 to 3000 tonnes of G.R.P., may be attributable to the quantity of G.R.P. consumed in 1975 in Denmark.
Table 7.7 Total Production of G.R.P. in the U.K. and in the EEC countries.

<table>
<thead>
<tr>
<th>Year</th>
<th>U.K. (x 10^3 tonnes)</th>
<th>EEC (x 10^3 tonnes)</th>
<th>U.K. % of EEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>52</td>
<td>295</td>
<td>17.6</td>
</tr>
<tr>
<td>1972</td>
<td>63</td>
<td>356</td>
<td>17.7</td>
</tr>
<tr>
<td>1973</td>
<td>78</td>
<td>427</td>
<td>18.3</td>
</tr>
<tr>
<td>1974</td>
<td>68</td>
<td>392</td>
<td>17.3</td>
</tr>
<tr>
<td>1975</td>
<td>63</td>
<td>331</td>
<td>19.0</td>
</tr>
</tbody>
</table>

+ - Source: Messrs. Fibreglass

Table 7.8 Breakdown of the U.K. Production of G.R.P. by industry sector.

<table>
<thead>
<tr>
<th>Industry Sector</th>
<th>1971</th>
<th>1972</th>
<th>1973</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>q</td>
<td>% of total</td>
<td>q</td>
</tr>
<tr>
<td>Marine</td>
<td>10.8</td>
<td>20.8</td>
<td>14.0</td>
</tr>
<tr>
<td>Transport</td>
<td>12.0</td>
<td>23.1</td>
<td>13.9</td>
</tr>
<tr>
<td>Building</td>
<td>12.0</td>
<td>23.1</td>
<td>13.3</td>
</tr>
<tr>
<td>Pipes, tanks, etc</td>
<td>3.6</td>
<td>6.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Industrial</td>
<td>4.3</td>
<td>8.3</td>
<td>5.2</td>
</tr>
<tr>
<td>Electrical</td>
<td>5.1</td>
<td>9.8</td>
<td>6.5</td>
</tr>
<tr>
<td>Consumer/ Other</td>
<td>4.2</td>
<td>8.1</td>
<td>5.6</td>
</tr>
<tr>
<td>Total</td>
<td>52.0</td>
<td>100</td>
<td>63.0</td>
</tr>
</tbody>
</table>

+ - Source: Messrs. Fibreglass
Total G.R.P. production = 12200 tonnes

Thus, the production data supplied by Messrs. Fibreglass are, in fact, less than the consumption data given in Table 7.6. Another useful conclusion is that the use of reinforced thermoplastics in the construction market is not significant, otherwise it would have been reflected in the above difference in total G.R.P. consumption (note that the first figure is for reinforced polyester resins only). A study of data on import and export of UP resins and moulding compounds as published in the Business Monitor EQ 276.1 indicates that the respective figures are generally small in comparison with the total U.K. production, e.g. in 1974 exports and imports were 4773 tonnes (£2.043m) and 4262 tonnes (£1.967m) respectively. Generally speaking, the U.K. market prices of these materials have been below those of West European countries; this situation has favoured the seclusion of the U.K. market to some extent (see also Europlastics, January 1974).

The general consensus of expert opinions in the industry confirms the figures, i.e. the effects of exports, imports and stock changes of UP resins as related to the construction market have been negligible, i.e. production figures have been approximately equal to the consumption data.

The data for consumption of G.R.P. in the U.K. construction industry given by sources (2) and (3) in Tables 7.2 and 7.8 respectively agree; this is illustrated in Table 7.9 and in Fig. 7.2.

However, as seen from Table 7.9, there are significant differences between the above sources in the figure for 'total E.E.C.' In addition, there is no information available on the accuracy, consistency and methods of data collection in either case.

(4) Data supplied by an industrial expert (2) on the consumption of G.R.P. sheeting in the construction industry: For 1973, this source has given a total of 9000 tonnes of sheeting divided in the following manner (2):

(i) G.R.P. sheeting: has been estimated to account for 7000 tons (approximately 78%) of the total supplied by three major companies (see below) using fully mechanized production processes; these companies are believed
Table 7.9  Comparison between the G.R.P. data given by Sources (2) and (3) for the U.K. and the EEC.

<table>
<thead>
<tr>
<th>Year</th>
<th>1971</th>
<th>1972</th>
<th>1973</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total U.K., Source (2) (tonnes)</td>
<td>12000</td>
<td>13300</td>
<td>15500</td>
</tr>
<tr>
<td>Total U.K., Source (3) (tonnes)</td>
<td>12000</td>
<td>13300</td>
<td>15700</td>
</tr>
<tr>
<td>Difference (tonnes)</td>
<td>0</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>Total EEC, Source (2) (tonnes)</td>
<td>256400</td>
<td>318100</td>
<td>382000</td>
</tr>
<tr>
<td>Total EEC, Source (3) (tonnes)</td>
<td>295000</td>
<td>356000</td>
<td>427000</td>
</tr>
<tr>
<td>Difference (tonnes)</td>
<td>38600</td>
<td>37900</td>
<td>45000</td>
</tr>
</tbody>
</table>
to account for over 90 per cent of the total G.R.P. sheeting produced in the U.K.

British Industrial Plastics
(Turner & Newall) - 'Filon' 2800 tons (40%)
B.M. Plastics Ltd. - 'Tri-Lite' 2800 tons (40%)
Cape Universal Cladding Ltd. - 'Unilux' 1400 tons (20%)

(ii) PVC sheeting: 2000 tons of PVC sheeting is equally divided between the following producers:
Sintlon Ltd., Rubberoid Ltd., and Marley Ltd.

(5) Data given by Powell (3): For 1969, Powell (3) has quoted a figure of 9979 tonnes of G.R.P. as the total quantity consumed in the construction market; G.R.P. sheeting has been estimated as 77 per cent of this total (or approximately 7680 tons).

(6) Data given by Crowder (4): For 1969, Crowder (4) gives a total of 5000 tons or approximately 3 x 10^6 m^2 of G.R.P. sheeting as the quantity used in the U.K.


Table 7.10 Estimates of U.K. Consumption of UPR in the Construction Market (Reference 5)

<table>
<thead>
<tr>
<th>Year</th>
<th>1968</th>
<th>1964</th>
<th>1970</th>
<th>1971^P</th>
</tr>
</thead>
<tbody>
<tr>
<td>UPR (x 10^3 tonnes)</td>
<td>5.00</td>
<td>8.50</td>
<td>8.90</td>
<td>7.80</td>
</tr>
<tr>
<td>G.R.P.* (x 10^3 tonnes)</td>
<td>7.14</td>
<td>12.13</td>
<td>12.71</td>
<td>11.13</td>
</tr>
</tbody>
</table>

P - Provisional
* - Taken as 1.43 times the resin (0.7 resin to 1 G.R.P.)

(8) Estimated data by ICI (6): These are considered under (a) and (b) below:

(a) The total UPR used in reinforced plastics applications: This is shown in Table 7.11
Table 7.11 Estimates given by ICI Petrochemical Division for total UPR in all reinforced plastics applications (U.K. only)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>UPR (x 10^3 tonnes)</td>
<td>42</td>
<td>57</td>
<td>55</td>
<td>48</td>
<td>50</td>
</tr>
</tbody>
</table>

* - predicted value by ICI (Reference 6)
" - expected value (approximate)

Reasonable growth is expected for 1977/78.

(b) The consumption of UPR in the U.K. construction industry: Present consumption has been estimated by ICI (6) to be approximately 9100 tonnes, of which approximately 5000 tonnes is used for G.R.P. sheeting. No figure for G.R.P. cladding has been given, but it has been stated that the cladding applications account for the next major usage of G.R.P. in the construction industry (6).

In addition to the above sources, many other potential sources of data were also approached (e.g. the British Plastics Federation, the Rubber and Plastics Research Association, etc.). However, no useful conclusions resulted from these efforts.

From the brief review carried out under (1) to (8) above, and assuming 0.7 tonne of UPR to 1 tonne of G.R.P., it can be calculated that the total consumption of G.R.P. in the U.K. construction industry varies considerably according to the given sources. For example, for 1975, the figures are as follows:

From Table 7.1 17000 tonnes
From Table 7.2 15500 tonnes
From Table 7.8 15700 tonnes

Estimates of the total G.R.P. sheeting used in the construction industry in 1973 are as follows:

From Table 7.1 8000 tonnes
From Tables 7.2 and 7.3 3750 tonnes
From (4) above 7000 tonnes
From ICI (1975) 7150 tonnes

Figure 7.5 illustrates the relative changes in data from column V of Table 7.1 and row 3 of Table 7.2. assuming a constant conversion factor from total UPR to total G.R.P. during...
FIG. 7.1 CONSUMPTION OF UP RESIN IN THE U.K. CONSTRUCTION INDUSTRY (TABLES 7.1 AND 7.11)
FIG. 7.2 CONSUMPTION OF GRP IN THE U.K. CONSTRUCTION INDUSTRY AND THE E.E.C. CONSTRUCTION INDUSTRIES (TABLES 7.2, 7.8 AND 7.11)

The figure for this point has been calculated from Table 7.8, and data published in Reinforced Plastics, May 1976 (an allowance of approximately 1,000 tonnes GRP has been made for Denmark.)
the period 1968 to 1973, the relevant indices should be the same. As may be seen, this is not so, especially for 1971, where the two indices differ by some 22.5 per cent. Such a difference cannot be attributed to variation in the conversion factor because, as will be seen later, during 1968 to 1973 there has been very little shift from one production process to another. Thus, the differences confirm the unreliability of the available data.

There are many reasons for the present situation besides those outlined at the beginning of this section; chiefly:

(a) There are three major G.R.P. sheeting producers controlling over 90 per cent of the U.K. market; publication of any accurate data on the total consumption, etc., may enable each of these producers to estimate the others' shares of the market. This may infringe the relevant legal provision. The same applies to the two major U.K. glass fibre producers.

(b) In the case of custom-made G.R.P. panels, as will be seen later (section 7.2), there are many moulders whose production capacities are not generally geared to any particular field. Furthermore, the quantity of G.R.P. produced by each of these is generally small. The total employment of a large proportion of these firms is below the minimum figure set by the government for inclusion in the official statistical enquiries. Thus, even if the official statistics (e.g. those collected under MLH 496 (5)) were separately analysed and published for G.R.P., they would exclude a considerable proportion of the output of this sector of the industry.

(c) Another factor which may cause further omission of the output of G.R.P. in all sectors (i.e. sheeting, cladding, etc.) is caused as an artefact of the official industrial classification. In some cases, G.R.P. production may comprise a small division of a mainly non-G.R.P. producing company. In these cases, since the business is not classified to MLH 496 (5), its G.R.P. output will not be recorded as G.R.P. products.

(d) It is a general concensus in the G.R.P. industry that G.R.P. baths and sanitary-ware, together with a number of other products, constitute a low proportion of the total G.R.P. consumption in the construction market (see 7.1.2). In addition, some of the above products are also produced by non-plastics (or captive) industries who are generally producers of traditional materials. As was seen in (b) above, in such cases,
the G.R.P. products are not recorded separately.

(e) The total quantity of G.R.P. used in each sector of the construction market is low compared with the quantities of plastics in general (see Table 7.12). Thus, it is probably uneconomic to attempt detailed statistical coverage of G.R.P. usage.

Table 7.12 Estimated U.K. consumption of selected plastics in 1970 in selected markets (Reference 5)

<table>
<thead>
<tr>
<th>Plastic material</th>
<th>User's Industry</th>
<th>Consumption (1970) (x 10^3 tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low density poly-ethylene (LDPE)</td>
<td>Packing</td>
<td>168</td>
</tr>
<tr>
<td>Polyvinyl chloride (PVC)</td>
<td>Building</td>
<td>134.9</td>
</tr>
<tr>
<td>Urea- and melamine formaldehyde (UF + MF)</td>
<td>Building</td>
<td>63.2</td>
</tr>
<tr>
<td>Polyvinyl chloride (PVC)</td>
<td>Electrical Products</td>
<td>57.3</td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>Packaging</td>
<td>52</td>
</tr>
<tr>
<td>Glass fibre reinforced polyester resin* (G.R.P.)</td>
<td>Construction</td>
<td>11.5</td>
</tr>
</tbody>
</table>

* Figure quoted from Table 7.2.

7.1.2 Growth pattern:

7.1.2.1 Comparison within the U.K.:

Table 13 and Fig. 7.3, which are based on Table 7.1, show the indices of the total consumption of UPR in the U.K. construction industry and the total consumption of UPR in all U.K. industries. It may be seen that the former has fallen slightly relative to the latter. However, since the accuracy of the original data is in doubt, it is meaningless to try to explain such slight differences in the above trends. Rather, in a broader sense, it is reasonable to state that the growth of G.R.P. in the construction industry has kept up well with the
### Table 7.13 Indices of Total Consumption of UPR in the U.K.
Construction and all Industries (Based on Table 7.1)

<table>
<thead>
<tr>
<th>Year</th>
<th>Index of Total UPR in Construction (1968 = 100)</th>
<th>Index of Total UPR in all Industries (1968 = 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1961</td>
<td>36.6</td>
<td>28.0</td>
</tr>
<tr>
<td>1962</td>
<td>38.1</td>
<td>32.4</td>
</tr>
<tr>
<td>1963</td>
<td>39.9</td>
<td>39.8</td>
</tr>
<tr>
<td>1964</td>
<td>52.6</td>
<td>55.0</td>
</tr>
<tr>
<td>1965</td>
<td>62.9</td>
<td>73.7</td>
</tr>
<tr>
<td>1966</td>
<td>70.5</td>
<td>76.7</td>
</tr>
<tr>
<td>1967</td>
<td>82.0</td>
<td>82.0</td>
</tr>
<tr>
<td>1968</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>1969</td>
<td>109.0</td>
<td>112.0</td>
</tr>
<tr>
<td>1970</td>
<td>114.0</td>
<td>125.2</td>
</tr>
<tr>
<td>1971</td>
<td>100.0</td>
<td>110.5</td>
</tr>
<tr>
<td>1972</td>
<td>118.0</td>
<td>150.2</td>
</tr>
<tr>
<td>1973</td>
<td>154.0</td>
<td>161.2</td>
</tr>
</tbody>
</table>

### Table 7.14 Indices of Total Consumption of G.R.P. in the U.K.
Construction and in the EEC Construction Industries (Based on Table 7.2)

<table>
<thead>
<tr>
<th>Year</th>
<th>Index of Total G.R.P. in U.K. Construction (1968 = 100)</th>
<th>Index of Total G.R.P. in EEC Construction (1968 = 100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>1969</td>
<td>112.2</td>
<td>115.0</td>
</tr>
<tr>
<td>1970</td>
<td>117.3</td>
<td>123.5</td>
</tr>
<tr>
<td>1971</td>
<td>122.3</td>
<td>127</td>
</tr>
<tr>
<td>1972</td>
<td>135.8</td>
<td>140.0</td>
</tr>
<tr>
<td>1973</td>
<td>158.0</td>
<td>159.0</td>
</tr>
<tr>
<td>1974</td>
<td>145.0&lt;sup&gt;+&lt;/sup&gt;</td>
<td>xx</td>
</tr>
<tr>
<td>1975</td>
<td>124.5&lt;sup&gt;+&lt;/sup&gt;</td>
<td>115.0&lt;sup&gt;+&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Notes to Table 7.14:

xx - No data available
+ - These figures are calculated from Table 7.8
⊙ - Partly estimated (see note in Fig. 7.2)

Table 7.15 Indices of the total UPR and G.R.P. in the U.K. Construction Industry compared with the Indices of Construction Output. \((1968 = 100)\)

<table>
<thead>
<tr>
<th>Year</th>
<th>Index of (a) construction output (All works)</th>
<th>Index of (a) construction output (New works)</th>
<th>Index of (b) total UPR in U.K. construction</th>
<th>Index of (c) total G.R.P. in U.K. construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1963</td>
<td>76.2</td>
<td>70.5</td>
<td>39.9</td>
<td>--</td>
</tr>
<tr>
<td>1964</td>
<td>85.2</td>
<td>82.3</td>
<td>52.6</td>
<td>--</td>
</tr>
<tr>
<td>1965</td>
<td>89.9</td>
<td>88.1</td>
<td>62.9</td>
<td>--</td>
</tr>
<tr>
<td>1966</td>
<td>91.5</td>
<td>89.8</td>
<td>70.5</td>
<td>--</td>
</tr>
<tr>
<td>1967</td>
<td>97.8</td>
<td>97.3</td>
<td>82.0</td>
<td>--</td>
</tr>
<tr>
<td>1968</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>1969</td>
<td>99.5</td>
<td>100.2</td>
<td>109.0</td>
<td>112.2</td>
</tr>
<tr>
<td>1970</td>
<td>97.8</td>
<td>98.0</td>
<td>114.0</td>
<td>117.3</td>
</tr>
<tr>
<td>1971</td>
<td>100.4</td>
<td>101.4</td>
<td>100.0</td>
<td>122.3</td>
</tr>
<tr>
<td>1972</td>
<td>102.0</td>
<td>101.2</td>
<td>118.0</td>
<td>135.8</td>
</tr>
<tr>
<td>1973</td>
<td>105.3</td>
<td>104.0</td>
<td>154.0</td>
<td>158.0</td>
</tr>
<tr>
<td>1974</td>
<td>96.5</td>
<td>94.4</td>
<td>--</td>
<td>145.0</td>
</tr>
</tbody>
</table>

-- No figure is available

(a) - Indices constructed from Table III of Housing and Construction Statistics, D.O.E.
(b) - Taken from the second column of Table 7.13
(c) - Taken from the second column of Table 7.14
FIG. 7.3 INDICES OF THE TOTAL UPR USED IN THE U.K. CONSTRUCTION INDUSTRY AND ALL INDUSTRIES (BASED ON TABLE 7.13)
Total G.R.P. in the EEC construction industry

Total G.R.P. in the U.K. construction industry

Partly estimated (see note in Fig. 7.2)

FIG. 7.4 INDICES OF TOTAL G.R.P. CONSUMPTION IN THE U.K. CONSTRUCTION INDUSTRY AND THE E.E.C. CONSTRUCTION INDUSTRIES (BASED ON TABLE 7.14)
FIG. 7.5 INDICES OF THE UPR AND GRP USED IN THE U.K. CONSTRUCTION INDUSTRY (BASED ON TABLE 7.15)
growth of G.R.P. in all industries.

7.1.2.2 Comparison with the E.E.C. construction industries:

Table 7.14 and Fig. 7.4 are based on Table 7.2 and illustrate the indices of the consumption of G.R.P. in the U.K. and in the E.E.C. construction industries. It may be noted that the U.K. consumption has not fallen significantly relative to the E.E.C. construction industries; furthermore, based on the data in Table 7.7, where it is evident that in 1971 to 1975, the U.K. has steadily increased its total G.R.P. production relative to the E.E.C., it would be expected that the U.K. construction share has also grown faster than those of the E.E.C. This point is, in fact, proven for 1975, when, according to the data in Table 7.14, the index relevant to the U.K. construction was 124.5 compared with the index relevant to the E.E.C. construction industries, which has been estimated to be 115.0 (1968 = 100). However, according to an economic survey carried out by C. Gintrand (Reinforced Plastics, May, 1976), it is impossible to establish a generally applicable cause and effect relationship explaining the difference in total consumption of G.R.P. in various E.E.C. countries.

7.1.2.3 Growth of G.R.P. relative to the construction output:

Table 7.15 and Fig. 7.5 indicate how the indices for the total consumption of G.R.P. in the construction industry compare with the indices representing the construction output. Although there are disagreements between the two graphs representing G.R.P. (i.e. a dip in 1971), they both indicate, on average, an annual growth rate of approximately 10 per cent (corresponding to a compound rate of about 5 per cent per annum), between 1968 and 1973 inclusive. The construction output shows little growth during the same period.

In order to explain this growth, it would be worth while to study the components of the growth in general. That is, the growth of plastics may be assumed to be the sum of two components (5):

1. Existing growth: This is a function of growth of the users' industries. The growth of the users' industries is dependent on the growth in gross domestic product (GDP).

2. Penetration growth: This component of growth is dependent on the continuous substitution of plastics for other materials/products and also development of new products.
example, PVC rainwater goods have been replacing cast iron and other similar traditional products during the last two decades. This substitution growth would continue for a short period if the construction output stays static. However, in the long term, and after the growth of PVC rainwater goods reaches the saturation level, it could decline unless new products or new applications are introduced.

As G.R.P. sheeting has not grown since 1968/69, much of the growth of G.R.P. consumption in the construction industry can be attributed to cladding applications such as roofs, fascia, lining and partition panels and space structures. Because the construction output has not grown to any comparable extent, it can be said that the growth of G.R.P. has been characteristic of 'penetration growth'. The pattern of growth in each sub-market will now be considered in more detail below:

7.1.2.4 Pattern of growth in G.R.P. corrugated sheeting:

In its present state of use, G.R.P. corrugated sheeting is a static market, and expectations in the industry are that this situation will remain unchanged (5), (7) and (8). The consumption of G.R.P. sheeting in the U.K. construction industry in 1975 has been predicted by a major producer to be some 20 per cent below that of the previous year (7).

As may be seen from Figures 7.5 and 7.6, the demand for G.R.P. sheeting is dependent on the following:

cont'd over, page 305
(1) The output of construction industry, (other than repair and maintenance). The demand for G.R.P. sheeting is mainly dependent on the demand for corrugated sheet materials in roofing applications of industrial buildings (i.e. factories and warehouses, etc.). Thus, the demand for G.R.P. is a 'derived demand'. This view is essentially confirmed by Messrs. Fibreglass in their review of present G.R.P. markets in Plastics and Rubber Weekly, May 7th, 1976.

(2) The competition from rigid PVC: Extruded rigid clear PVC sheeting has virtually captured the whole 'non-industrial' sector of the construction industry. This material has been cheaper than G.R.P. and is produced in the U.K. and also imported from Japan (7).

PVC sheeting has inferior 'light-diffusing', 'fire-resisting' and mechanical properties compared with G.R.P. sheeting. Incorporation of a wire-mesh can mechanically strengthen the PVC sheeting and can prevent melting and 'lump-dropping' of PVC in the event of a fire.

It may be observed that where special attributes of G.R.P. sheeting are not required, its use cannot be justified economically. This is because translucent sheeting is basically a functional material and has little effect on the overall appearance/aesthetics of the building.

It was originally planned to develop a price/consumption model of the type shown in Fig. 7.6. However, data for such work were not obtainable and the idea was subsequently abandoned.

G.R.P. corrugated or roof sheeting is an accepted material by all sections of the construction industry, including 'fire authorities', clients, insurers of buildings, etc. (see section 10.2). This is because G.R.P. roof sheeting has been constantly improved and up-dated since its introduction in 1952; these product improvements have been necessary because of the successive performance requirements which have been introduced by various authorities ever since.

7.1.2.5 Pattern of growth in G.R.P. cladding, including roofs, fascia, partition and lining panels, plus space structures:

This is a relatively new market, dominated by small to medium sized companies employing mainly the contact moulding process. There are no official statistics on this rather diverse
Fig. 7.6 SPECIFICATION OF A MODEL FOR G.R.P. SHEETING

\[ P_s = \text{Index of price for G.R.P. Sheeting.} \]

\[ P_{p.v.c.} = \text{"" "" "" P.V.C. ""} \]

\[ I = \text{Base price index (H. and C. S's D.O.E.).} \]

\[ C_a = \text{Index of consumption of corrugated asbestos-cement sheet.} \]

\[ C_i = \text{Index of steel and iron.} \]

\[ O_c = \text{Index of output for the construction industry.} \]

\[ X_1 = \log \left( \frac{P_s}{I} \right). \]

\[ X_2 = \log \left( \frac{P_s}{P_{p.v.c.}} \right). \]

\[ X_3 = \log (C_a). \]

\[ X_4 = \log (C_i). \]

\[ X_5 = \log (O_c). \]

\[ Y = \log \text{ (consumption of G.R.P. Sheeting in an index form).} \]

The model is as follows:

\[ Y = a + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 X_5 \]

where \( a \) is a constant; \( b_1, b_2, b_3, b_4, b_5 \) are relevant elasticities.

Data needed for the period 1960 – 1974 of the following quantities:

2. Price of P.V.C.
However, the resin manufacturers have estimated that in 1972, just over 2000 tonnes of UPR was used on external cladding applications (9). Johns (9), has estimated that the above quantity is roughly equivalent to some 418,000 m$^2$ of G.R.P. laminate. The size of the potential market has been estimated to be many times greater than the present size of the market - 10 to 20 times for external cladding, according to Smith (10).

There are two basic reasons why G.R.P. cladding (etc.) has had an unclear pattern of growth in the construction industry:

(1) Process of learning and acceptance: The use of G.R.P. in the above applications constitutes the development and use of entirely new products. As will be seen in later sections of this chapter, designers are still experimenting with G.R.P. and are learning about its capabilities and the methods of utilizing this material. Quite apart from the non-availability of the past data on sales, the use of any type of fitted S-shaped curve to such data can produce misleading estimates of the rate of growth, since the growth of G.R.P. may accelerate in an unpredictable pattern (11).  

(2) Heterogeneity of products: The bulk of G.R.P. panels used in the construction industry are custom-moulded, mainly for a variety of one-off projects. These panels do not have identical technical and economic characteristics and cannot be classed as homogeneous products. This makes the task of defining the growth rate even more complicated.

Nevertheless, as has already been stated, the present use of these G.R.P. applications has the characteristics of 'penetration growth' since G.R.P. replaces other materials such as copper, aluminium, stainless steel, stone, concrete, etc. Chapters 8 to 11 discuss factors affecting the attitudes of the users.

### 7.1.2.6 Miscellaneous G.R.P. products:

These include the following:

1. Sanitary ware
2. Cold water cisterns
3. Pipes and ducts
4. Formwork/shuttering for concrete
5. General building applications (such as swimming pools, decorative internal panels, etc.)

Products such as sanitary ware, cold water cisterns, pipes and ducts are generally produced on a proprietary basis; in the
manufacture of these goods, thermoplastics have to a large extent replaced G.R.P. wholly or partly (i.e. in dual composites, c.f. section 5.5). For example, bath tubs are normally moulded from acrylic sheets using the thermoforming technique; G.R.P. is then sprayed on the reverse side of these acrylic mouldings to improve their mechanical properties.

Powell (12) has estimated that some 200 tonnes of G.R.P. is used in formwork/shuttering applications for concrete. However, G.R.P. is mainly used for production of non-standard components, normally to specific requirements, employing the contact moulding process (13). The standardized formwork/shuttering components for concrete are usually manufactured from polypropylene, employing the thermoforming technique (13).

There are two main reasons for the inability of G.R.P. to compete with thermoplastics in the above applications:

(i) There are no statutory performance requirements associated with use of the above products in buildings. It may be argued that thermoplastics have inferior fire and mechanical properties compared with G.R.P. However, not all of these properties are needed in these applications; in fact, thermoplastics sanitary ware have superior appearance and are more resistant to household detergents than hand-laminated G.R.P. Cracking and abrasion of the gel coat are examples of failures frequently observed in G.R.P. bathroom components (14).

(ii) It is more economic to produce the above products in thermoplastics, especially polypropylene. This is because with a unit repetition greater than about 1000, the thermoforming technique of moulding thermoplastics sheets becomes more economic compared with the contact moulding of G.R.P.

However, with the hot-press moulding process, superior quality products in G.R.P. may be provided at economic levels, provided the unit repetition is greater than about 10,000 (3). In the U.S.A., 25 per cent (in California 50 per cent) of all bathrooms installed are from hot-press moulded G.R.P., generally in one piece (4). In the U.K., hot-press moulded cold water cisterns are produced and marketed successfully by a large G.R.P. processing company (2). The same company is, however, reluctant to enter the sanitary ware market, since this market is to a large extent controlled by the traditional sanitary goods producers; some of these have their own plastics processing outfit.
These traditional suppliers have the advantage of an established distribution and sales network (2).

Production of acrylic/G.R.P. bathroom components (i.e. tubs, basins, etc.), according to Messrs. Fibreglass (P and R W, May 7th, 1976), "has made substantial gains at the expense of competitive non-plastics materials." However, no data have been reported on the size of this sub-market; the demand for these products has been linked to the availability of government funds for modernization of old houses.

According to Europlastics, April 1974, the consumption of acrylic sheet in the sanitary ware sub-market in 1972 and 1973 totalled 2500 and 3200 tonnes respectively. The same journal (British Plastics, January 1970) gives an estimated consumption of acrylic sheet in sanitary ware sub-market in 1968 and 1969 as approximately 800 and 1000 tonnes respectively.

Assuming the present consumption of acrylic sheet in the sanitary market to be around 3000 tonnes, it would be expected that the amount of G.R.P. used would be less than this figure, since some manufacturers use G.R.P. only for strengthening bath tubs, whereas acrylic sheet is used for wash basins, side panels and other components as well.

The proprietary G.R.P. products outlined above tend to have economic characteristics similar to consumer durables, i.e. they may exhibit a price elasticity of demand greater than unity.

7.2 The G.R.P. Processing Industry:

7.2.1 Sources of data and classification:

The statistical representation of the G.R.P. processing industry has proved a difficult task, because nobody knows precisely how many companies exist and in which markets they operate. As has already been noted in previous sections, the official classifications of the companies for participation in the periodical statistical business enquiries automatically excludes a large number of G.R.P. processing companies due to their small sizes. Furthermore, the mixed statistical presentation of the G.R.P. companies together with the rest of the plastics processing firms in the Business Monitor PQ 496 makes it virtually impossible to draw any useful conclusion from this
Initially, it was hoped that all G.R.P. processing companies could be interviewed, so that the industrial structure might be quantified.

Unfortunately, it soon became clear that a precise statistical representation of the industry could take up a long time and could incur expenditure beyond the resources of this project. A compromise has therefore been made by focusing attention on the companies who were known to have been interested or involved in the construction market. Further, it was decided to carry out a selective number of interviews and supplement the information from other available sources. Thus, a sample of 10 companies were interviewed and additional information extracted from the following sources:

- Building Research Establishment, Appendix to the paper on G.R.P. cladding in the construction industry by J.R. Crowder, published in December 1973 by B.R.E.
- Study of Accounts of 32 firms at Companies' House.
- British Railways, Eastern Region (correspondence).
- British Plastics Federation, Information sheets.
- Reinforced Plastics (Monthly Journal, Section on Buyers' Guide).
- Miscellaneous Sources; e.g. 'Guide to Key British Enterprises', Volumes I and II, 1975/76 by Dun and Bradstreet Ltd., KOMPASS: U.K. 1975, Rubber and Plastics Weekly, etc.

The results have been summarized in Table 7.16. However, it must be emphasized that, owing to the reasons outlined earlier, this table is neither exhaustive nor precise. Nevertheless, it was felt that the major characteristics of the industry can be identified from Table 7.16, aided by detailed interview notes, published information, etc.

G.R.P. processing firms with an interest in the construction market may conveniently be divided into two groups:

1. Group I, comprising those companies who mainly cater for the custom-moulding of one-off projects.
2. Group II, comprising those companies who are not generally interested in the low rates of production which are usually associated with the custom-moulding projects.
<table>
<thead>
<tr>
<th>Name of the company</th>
<th>Whether subsidiary (S) or independent (I)</th>
<th>Whether private (P) or public (Pb)</th>
<th>Company of member (M)</th>
<th>Main construction interests or experience (CSY)</th>
<th>Interests in other industries</th>
<th>Event company's business</th>
<th>Turnover (Export %) and date (Lm)</th>
</tr>
</thead>
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<td>Anscrow Ltd.</td>
<td>I</td>
<td>P</td>
<td>None</td>
<td>None</td>
<td>B.A.C.E.</td>
<td>5.0 (30%)</td>
<td>4.1 (1968)</td>
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<td>I</td>
<td>P</td>
<td>None</td>
<td>None</td>
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<td>5.0 (30%)</td>
<td>4.1 (1968)</td>
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<td>B &amp; C Plastics Ltd.</td>
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<td>P</td>
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<td>None</td>
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<td>0.0 (0%)</td>
<td>0.0 (1967)</td>
</tr>
<tr>
<td>Brancal Plastics Ltd.</td>
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<td>P</td>
<td>None</td>
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<td>B.A.C.E.</td>
<td>1.0 (50%)</td>
<td>0.0 (1967)</td>
</tr>
<tr>
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<td>P</td>
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<td>None</td>
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<td>1.0 (50%)</td>
<td>0.0 (1967)</td>
</tr>
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<td>P</td>
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<td>None</td>
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<td>P</td>
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<td>0.75 (50%)</td>
<td>0.065 (1963)</td>
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<td>I</td>
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<td>None</td>
<td>None</td>
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<td>0.065 (1963)</td>
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<td>A.G. Plastics Industries Ltd.</td>
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<td>None</td>
<td>None</td>
<td>B.A.C.E.</td>
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<td>0.065 (1963)</td>
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<td>Sword (1960) Ltd.</td>
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<td>P</td>
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<td>None</td>
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<td>0.065 (1963)</td>
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<td>Composite Design &amp; Buildings Ltd.</td>
<td>S</td>
<td>P</td>
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<td>None</td>
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<td>0.065 (1963)</td>
</tr>
<tr>
<td>Sweny Waters &amp; Co. Ltd.</td>
<td>I</td>
<td>P</td>
<td>None</td>
<td>None</td>
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<td>0.065 (1963)</td>
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<tr>
<td>H.B. Robertson (H.K.) Ltd.</td>
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<td>P</td>
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<td>None</td>
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<td>0.065 (1963)</td>
</tr>
<tr>
<td>Backington Conway Ltd.</td>
<td>I</td>
<td>P</td>
<td>None</td>
<td>None</td>
<td>B.A.C.E.</td>
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<td>0.065 (1963)</td>
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<tr>
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<td>P</td>
<td>None</td>
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<td>B.A.C.E.</td>
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<td>0.065 (1963)</td>
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<td>0.065 (1963)</td>
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<td>P</td>
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<td>None</td>
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<td>0.53 (50%)</td>
<td>0.065 (1963)</td>
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<td>None</td>
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<td>0.065 (1963)</td>
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<tr>
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<td>None</td>
<td>B.A.C.E.</td>
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<td>0.065 (1963)</td>
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<td>None</td>
<td>B.A.C.E.</td>
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<td>0.065 (1963)</td>
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<td>Proprietary Products (Type + proportion of business)</td>
<td>No. of years involved in the construction market (expanding or contracting?)</td>
<td>Principle methods of fabrication (CUM: (33%)</td>
<td>Types of service offered (1992: (75%)</td>
<td>Type of expansion (1992): (75%)</td>
<td>Main Source of Information</td>
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<td></td>
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<tr>
<td>------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
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<td>FOLDED PLATE STAINLESS STEEL/CLASS 316/304/316L/317/304L (3%)</td>
<td>7 EXP</td>
<td>HL</td>
<td>DS+MS</td>
<td>100 NO NO</td>
<td>LF RANKED NORTH 1961</td>
<td>C6 = 90% N = 10% INTERVIEW 1975</td>
<td></td>
</tr>
<tr>
<td>BULKINS (8%)</td>
<td>9 EXP</td>
<td>HL, SOME SP</td>
<td>LS</td>
<td>75 NO NO</td>
<td>FAILED LF</td>
<td>SURRY 1965</td>
<td>N = 60% C6 = 40% INTERVIEW 1975</td>
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<td>EXCEPTING BUILDINGS</td>
<td>MAINLY 4 EXP</td>
<td>HL</td>
<td>POLYURETHANE FOAM</td>
<td>MS</td>
<td>80 YES YES</td>
<td>LEAD</td>
<td>INTERVIEW 1975</td>
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<td>NEGATIVELY</td>
<td>MAINLY ESTABLISHING</td>
<td>HL</td>
<td>MS+MS</td>
<td>100 NO NO</td>
<td>LEEDS</td>
<td>INTERVIEW 1975</td>
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<tr>
<td>DEMENTS + DOF.</td>
<td>MAINLY 6 CONT.</td>
<td>HL</td>
<td>MS+MS</td>
<td>100 NO NO</td>
<td>LEICHS</td>
<td>INTERVIEW 1975</td>
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<td>PREFERENCE: RANKS, ETC. (4%)</td>
<td>15</td>
<td>HL+SU</td>
<td>DS+MS</td>
<td>70 NO NO</td>
<td>BRADBURY</td>
<td>INTERVIEW 1975</td>
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<tr>
<td>NONE</td>
<td>MAINLY 4</td>
<td>HL+SU</td>
<td>EXPERIMENTAL WORK</td>
<td>10-15 NO NO</td>
<td>HANTS</td>
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<td>PP (RESINFORM PANELS = 30%)</td>
<td>MAINLY 13</td>
<td>HEL</td>
<td>DS+MS</td>
<td>10-15 NO NO</td>
<td>WAREHOUSES EXP</td>
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<td></td>
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<tr>
<td>1-2</td>
<td>HL+SU</td>
<td>HEL</td>
<td>MS+M</td>
<td>10 NO NO</td>
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<tr>
<td>HEL+SU</td>
<td>HEL</td>
<td>MS+M</td>
<td>10 NO NO</td>
<td>SUFFOLK</td>
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<tr>
<td>HEL</td>
<td>MS+M</td>
<td>10 NO NO</td>
<td>ESSEX</td>
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<tr>
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<td>MS+M</td>
<td>10 NO NO</td>
<td>LEICHS</td>
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<tr>
<td>HEL, CP, YAC FORMING</td>
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<td>D5+MS</td>
<td>20 (25) 20 (25) NO NO</td>
<td>LEICHS</td>
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<td>HEL, CP, RI</td>
<td>5000 YES NO</td>
<td>MS+M</td>
<td>2000 NO NO</td>
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<td>10 NO NO</td>
<td>DS</td>
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<tr>
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<td>MS+M</td>
<td>10 NO NO</td>
<td>URBAN</td>
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<td>MS+M</td>
<td>10 NO NO</td>
<td>LEICHS</td>
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<td>MS+M</td>
<td>1950 NO NO</td>
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<tr>
<td>HEL</td>
<td>MS+M</td>
<td>10 NO NO</td>
<td>LANCs</td>
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<tr>
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<td>MR</td>
<td>EB GUIDE 75</td>
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<td>MR</td>
<td>EB GUIDE 75</td>
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<td>HEL</td>
<td>MS+M</td>
<td>10 NO NO</td>
<td>MR</td>
<td>EB GUIDE 75</td>
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<td>Name of the company</td>
<td>Whether subsidiary (S) or independent (I) or member company (M)</td>
<td>Whether private (P) or public (Pub) company</td>
<td>Main construction interests or experience (C/M, PP, SW, GB)</td>
<td>Interest in other industries</td>
<td>Current company's business</td>
<td>Annual turnover (in £000)</td>
<td>Initial share data (c.m.)</td>
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<td>North East Glassfibre Ltd.</td>
<td>I</td>
<td>P</td>
<td>CPM CF</td>
<td>TANKS, ANS HOPPERS, BOMBS, TOYS, ETC.</td>
<td>GRP - 10 (GROUP 2, 6)</td>
<td>6, 651</td>
<td>(GROUP 5) 1-63</td>
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<td>Wa. Monks (Builder Merchants) Ltd.</td>
<td>I</td>
<td>P</td>
<td>CPM, PP CaF, OTHER GOODS, B.W, GB</td>
<td>NONE</td>
<td>GROUP 7</td>
<td>0-312</td>
<td>(GROUP 5) 1-63</td>
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<td>Flaxite Ltd.</td>
<td>S</td>
<td>P</td>
<td>P.C.F.B</td>
<td>CHEMICAL, PIPES, VEHICLE, COMPONENTS ETC</td>
<td>GROUP 5</td>
<td>0-110</td>
<td>(GROUP 5) 1-63</td>
</tr>
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<td>Glass fibre Ltd. &amp; Glass fibre Ltd.</td>
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<td>P</td>
<td>G &amp; E</td>
<td>ALL INDUSTRIES THOROUGHBRED</td>
<td>GROUP 5</td>
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<td>(GROUP 5) 1-63</td>
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<td>Plastic Reinforced (Liverpool) Ltd.</td>
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<td>P</td>
<td>CPM, LIGHT METAL, PIPES, ETC.</td>
<td>INSULATION, RIGID P.U.</td>
<td>GROUP 5</td>
<td>0-088</td>
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</tr>
<tr>
<td>Proctor &amp; Lavender (Cladding) Ltd.</td>
<td>S</td>
<td>P</td>
<td>CPM, PP</td>
<td>BACK &amp; THE MANUFACTURED PANELS, PIPING SPECIALISTS</td>
<td>GROUP 5</td>
<td>0-25</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Leeings Plastics (Buildex) Ltd.</td>
<td>I</td>
<td>P</td>
<td>CPM</td>
<td>NOT KNOWN</td>
<td>GROUP 5</td>
<td>0-135</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Structural Plastics Laminates Ltd.</td>
<td>S</td>
<td>P</td>
<td>CPM, (PVC + ABS)</td>
<td>CHEMICAL, PIPES (PVC, ABS)</td>
<td>GROUP 5</td>
<td>0-24</td>
<td>(GROUP 5) 1-63</td>
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<tr>
<td>Thomas Thomson (B.R.D.) Ltd.</td>
<td>S</td>
<td>P</td>
<td>CPM</td>
<td>NOT KNOWN</td>
<td>GROUP 5</td>
<td>0-55</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>W &amp; J Tod Ltd.</td>
<td>S</td>
<td>P</td>
<td>CPM, GB</td>
<td>NURSERY, GARDEN, CONCRETE, VEHICLE, ETC</td>
<td>GROUP 5</td>
<td>0-24</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>F.Vernon-Smith &amp; Co. Ltd.</td>
<td>S</td>
<td>P</td>
<td>GB, CPM</td>
<td>INSULATION, RIGID, P.U.</td>
<td>GROUP 5</td>
<td>0-148</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Vulcan Plastics Ltd.</td>
<td>I</td>
<td>P</td>
<td>CPM, PP</td>
<td>NONE</td>
<td>GROUP 5</td>
<td>0-079</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Westpol Products Ltd.</td>
<td>I</td>
<td>P</td>
<td>CPM, GB, SW, ROOF SHEETING</td>
<td>NOT KNOWN, CHEMICAL, PIPES, VEHICLE ETC</td>
<td>GROUP 5</td>
<td>0-24</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Whaley Wielding Co. Ltd.</td>
<td>I</td>
<td>P</td>
<td>SHRE METAL, CPM</td>
<td>NOT KNOWN</td>
<td>GROUP 5</td>
<td>0-161</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Winston Engineering (Fibres) Division Ltd.</td>
<td>S</td>
<td>P</td>
<td>CPM, GB</td>
<td>CHEMICAL, PIPES, FOR FOOD INDUSTRIES, UNICATE.</td>
<td>GROUP 5</td>
<td>3-115</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Stelli (U.K.) Ltd.</td>
<td>S</td>
<td>P</td>
<td>P.P (STONE FINISHED CLADDING SHEET) - FIRST MAJOR, TANKS</td>
<td>CHEMICAL, PIPES, VEHICLE ETC</td>
<td>GROUP 5</td>
<td>0-24</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Redland Ltd.</td>
<td>M</td>
<td>P</td>
<td>P.P (AS above)</td>
<td>NOT KNOWN</td>
<td>GROUP 5</td>
<td>7 (E = 12, M)</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Marley Ltd.</td>
<td>M</td>
<td>P</td>
<td>P.P, GB</td>
<td>NOT KNOWN</td>
<td>GROUP 5</td>
<td>7 (E = 12, M)</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>MR Reinforced Plastics Ltd.</td>
<td>M</td>
<td>P</td>
<td>CPM, GB</td>
<td>NOT KNOWN</td>
<td>GROUP 5</td>
<td>7 (E = 12, M)</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Pernall Gloucester Ltd.</td>
<td>M</td>
<td>P</td>
<td>CPM, GA, PIPES</td>
<td>CHEMICALS, TANKS</td>
<td>GROUP 5</td>
<td>7 (E = 12, M)</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Mulberry &amp; Harvey Ltd.</td>
<td>I</td>
<td>P</td>
<td>CPM, GB, PIPES</td>
<td>CHEMICALS, TANKS</td>
<td>GROUP 5</td>
<td>7 (E = 12, M)</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>E.I.P. Ltd. &amp; TAC Construction Materials Ltd.</td>
<td>S</td>
<td>P</td>
<td>CPM, CPM (TAC)</td>
<td>CHEMICALS, PIPES, TANKS, VEHICLE</td>
<td>GROUP 5</td>
<td>6 (E = 12, M)</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Cape Universal Ltd.</td>
<td>S</td>
<td>P</td>
<td>CPM, CPM (TAC)</td>
<td>CHEMICALS, PIPES, TANKS, VEHICLE</td>
<td>GROUP 5</td>
<td>68</td>
<td>(GROUP 5) 1-63</td>
</tr>
<tr>
<td>Billy Martin Ltd.</td>
<td>I</td>
<td>P</td>
<td>G.R.P SHEETING</td>
<td>CHEMICALS, PIPES, TANKS, VEHICLE</td>
<td>GROUP 5</td>
<td>1-77</td>
<td>(GROUP 5) 1-63</td>
</tr>
</tbody>
</table>

1-CMP - Custom moulded panels; 2-TP - Proprietary panels/systems;
3-SW - Sanitary ware including baths & - CTP - Concrete formwork/shuttering;
4-BP - General building products (both proprietary and custom-made);
5-ML - Handle method; 6-OP - Spray-up method; 7-CP - Cold press moulding;
8-FO - Hot press moulding; 9-A - Automatic injection; 10-F - Filament winding;
11-PT - Pultrusion; 12-AC - Autoclave curing; 13-IE - Installation equipment;
14-TF - Full service (i.e., DESIGN, MFG, sales, service, etc.);
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Because of distinct differences between virtually all aspects of the business activities of the above groups, it has been decided to study each group independently and then compare the two groups with each other. A general comparison with the whole plastics processing industry has been carried out when considering the structure of Group I companies. Accurate data for such comparisons in the case of Group II have not been available. Finally, a brief discussion has been included regarding the future stability and development of the industry.

7.2.2 The industrial structure of Group I companies:

7.2.2.1 Number of companies:

It has been estimated that there are probably between 50 and 60 companies whose total employment is greater than 5 and who are either active or interested in the construction market.

7.2.2.2 Analysis of ownership and dates of establishing:

Table 7.17 contains the analysis of the ownership of a sample of 36 companies in Group I. It can be seen that half of the companies in the sample were found to be either divisions of the parent companies or subsidiaries functioning under independent management; 50 per cent of these were found to be directly owned by the construction materials producers (6 out of 9) and by the building and civil engineering contractors (3 out of 9). The other subsidiaries were found to be owned by the electrical, mechanical, engineering and dairy industries.

From Table 7.16 it may be seen that companies owned by the building and civil engineering contractors and construction materials producers tended to be larger than the remaining companies.

The independent companies were generally found to be smaller than subsidiaries. From the files of subsidiary companies, it was found that some of the subsidiaries were originally established as independent private companies and were subsequently acquired by non-G.R.P. companies. The probable reason for this tendency is the desire of the acquiring companies to enter the G.R.P. business either because they considered it to be a profitable addition to their business or to acquire the technology for development of new products and components or a combination of both.

From Table 7.18 it may be seen that most of the G.R.P. companies in Group I have been registered during 1955/70, usually as private companies. This is not unexpected in view of the fact that polyester resins were first produced on a commercial scale in the mid-fifties.
Table 7.17 Company Ownership in Group I G.R.P. Companies
(sample of 36 companies)

<table>
<thead>
<tr>
<th>Type of Ownership</th>
<th>Number</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent</td>
<td>18</td>
<td>50</td>
</tr>
<tr>
<td>Subsidiaries owned by Construction Materials Producers</td>
<td>6</td>
<td>16.5</td>
</tr>
<tr>
<td>Subsidiaries owned by Building and Civil Engineering Contractors</td>
<td>3</td>
<td>8.5</td>
</tr>
<tr>
<td>Subsidiaries owned by Other Industries</td>
<td>9</td>
<td>25</td>
</tr>
<tr>
<td>Total</td>
<td>36</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 7.18 Analysis of Registration dates of a sample of 30 companies (Group I)

<table>
<thead>
<tr>
<th>Year of Registration</th>
<th>Number</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before 1949</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>1949 - 54</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1955 - 59</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>1960 - 64</td>
<td>8</td>
<td>27</td>
</tr>
<tr>
<td>1965 - 69</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>1970 - 74</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>30</td>
<td>100</td>
</tr>
</tbody>
</table>

* - Originally, 4 of these companies were established as construction materials producers, 1 as transportation equipment engineers and the remaining company as a high pressure thermoset resin moulder.
7.2.2.3 Size distribution in Group I companies:

Tables 7.19 and 7.20 contain total employment and annual sales turnover distributions respectively for a sample of 36 companies. The samples are somewhat biased, because they are mainly constructed from information related to bigger companies; it is likely that the companies not included in the above samples have total employment figures below 50, with the majority being in the range 5 to 30.

Table 7.19 Employment Distribution of a Sample of 36 Companies in Group I. (Data are not related to a particular year; see Table 7.16. The same applies to Table 7.20).

<table>
<thead>
<tr>
<th>Total Employment</th>
<th>Number</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2</td>
<td>5.5</td>
</tr>
<tr>
<td>50 - 100</td>
<td>17</td>
<td>47</td>
</tr>
<tr>
<td>30 - 49</td>
<td>8</td>
<td>22.5</td>
</tr>
<tr>
<td>30</td>
<td>9</td>
<td>25</td>
</tr>
<tr>
<td>Total</td>
<td>36</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 7.20 Annual Sales Turnover Distribution of a sample of 36 Companies in Group I.

<table>
<thead>
<tr>
<th>Annual Sales Turnover (£m)</th>
<th>Number</th>
<th>% of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>5.5</td>
</tr>
<tr>
<td>0.5 - 1</td>
<td>15</td>
<td>42</td>
</tr>
<tr>
<td>0.3 - 0.49</td>
<td>8</td>
<td>22</td>
</tr>
<tr>
<td>0.3</td>
<td>11</td>
<td>30.5</td>
</tr>
<tr>
<td>Total</td>
<td>36</td>
<td>100</td>
</tr>
</tbody>
</table>
As can be seen from Table 7.19, only two of all samples had a total employment of greater than 100, and none greater than 250. In fact, one of the biggest, English Electric Co., has a total employment of 250. However, besides G.R.P., the company are involved in other plastics moulding and other activities. These two companies accounted for less than 5 per cent of the total employment, which is strikingly different from the total employment distribution of the whole plastics processing industry, where, companies with a total employment between 100 and 500 accounted for over 50 per cent of the total employment (5).

Table 7.21 shows breakdown of the fixed assets of a typical privately owned G.R.P. processing company in Group I with an annual sales turnover close to £0.4m (figures in the table have been rounded to the nearest £100).

Table 7.21 Breakdown of the Fixed Assets of a Typical G.R.P. Company in Group I (Source: Accounts held at the Companies' House).

<table>
<thead>
<tr>
<th>Type of Asset</th>
<th>Value @ cost (£)</th>
<th>Accumulated Depreciation (£)</th>
<th>Total (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machinery and Moulds</td>
<td>7800</td>
<td>6700</td>
<td>14500</td>
</tr>
<tr>
<td>Motor vehicles</td>
<td>4500</td>
<td>3500</td>
<td>8000</td>
</tr>
<tr>
<td>Small tools</td>
<td>600</td>
<td>100</td>
<td>700</td>
</tr>
<tr>
<td>Office Equipment and</td>
<td>600</td>
<td>300</td>
<td>900</td>
</tr>
<tr>
<td>Furniture</td>
<td></td>
<td></td>
<td>900</td>
</tr>
<tr>
<td>Land, Building, etc.</td>
<td>45300</td>
<td>1000</td>
<td>46300</td>
</tr>
<tr>
<td>Total</td>
<td>58800</td>
<td>11600</td>
<td>70400</td>
</tr>
</tbody>
</table>

It must be noted that some G.R.P. processing companies do not own the factory/office space in which they operate; the total fixed assets of a company with rented or leased factory space will be even smaller than the above figures.

The comparison with the whole plastics processing industry is noteworthy, as the average fixed assets per company in the
whole plastics processing industry is likely to be in the region of £0.4m to £6.5m (5).

The remarkable disagreement between the two groups may be explained in terms of production process; the former group employ the contact-moulding process which requires very little capital investment in machinery and equipment, whereas the latter group have to employ capital intensive processing machinery (5).

7.2.2.4 Profitability:

A study of the accounts of a sample of 20 companies showed that the return on capital employed varied considerably from year to year and from company to company. In 1974, a quarter of these companies had shown trading losses, nearly half had shown modest profit (10 to 20 per cent of turnover), and the remaining quarter had shown high profits (greater than 20 per cent of turnover), though these were mainly engaged on specialist types of work such as production of components for defence contracts, anti-corrosion pipes, etc. One of the companies to show the highest loss was engaged mainly on the manufacture of plants for the dairy process-industry using stainless steel, G.R.P., etc. (refer Table 7.16).

If the directors' fees are taken into account, the majority of G.R.P. companies can be considered to have been profitable with returns on capital as high as 60 to 70 per cent.

Most of the G.R.P. companies in Group I had retained the generated profits for further expansion of their business. However, none of these companies had committed themselves to any large scale capital investment.

7.2.2.5 Main markets:

The majority of Group I companies have the policy of smoothing their workflow. Because of considerable flexibility associated with the contact-moulding process, these companies are able to accept orders from virtually any industry with unit repetition as low as 10. The tendency to maximize the capacity rather than specialize in particular markets is a general feature of the whole plastics processing industry (5) (see also Group II G.R.P. companies).

In recent times, there has been sufficient work from the construction industry to enable a few firms to specialize in this market.
7.2.2.6 Capacity:

The production capacity of these companies cannot be quantified to any reasonable degree of accuracy because of the following reasons:

(1) The production capacity is a function of the number of moulds available (c.f. section 5.5).

(2) The production capacity is a function of the rate of curing of the UP resin (see section 5.2).

(3) There is a limit for efficient production in a given shop floor space. However, any available shop floor space can normally be prepared easily for the production of G.R.P. components employing the contact moulding process.

(4) The available managerial, technical and supervisory staff and skilled workers limit the production capacity. This is because G.R.P. is not only a quality-sensitive material, but in most cases, in addition to the task of costing all proposals received, the companies are usually required to prepare laminating drawings and specifications for their successful bids, particularly for the small contracts, where employment of a G.R.P. consultant by the architect cannot be economically justified. However, most companies are able to stretch their staff and labour resources to some extent.

(5) The established practice of providing goods and services in advance of payment in building and civil engineering sub-contracting means that, in addition to the usual sureties required as part of the contract, the bidding company must be prepared to raise at least up to one third of the contract value in advance. In the case of large contracts (£0.5m plus), there are only a handful of firms capable of such undertakings.

(6) Because of the considerable flexibility associated with the contact moulding process, it is easy for Group I G.R.P. companies to switch over their resources from one industry to another. Thus, it is impossible to quote any meaningful figure for the capacity of the G.R.P. industry related to the construction industry.

At present, it is estimated by the author that Group I G.R.P. companies are able to allocate up to 10 000 tonnes per annum of their G.R.P. production capacity to the construction industry. The highest annual consumption of G.R.P. in the construction market was in 1973, when an estimated figure of 15700 tonnes of G.R.P., including sheeting, has been quoted by
Messrs. Fibreglass (see Table 7.3). The highest total annual consumption of G.R.P. in all industries was during the same period, when, according to the same source, upwards of 78000 tonnes of G.R.P. was produced.

7.2.2.7 Methods of obtaining business:

It has generally been a feature of the Group I companies to obtain construction orders through competitive bidding. Only one out of the eight companies interviewed had carried out some market research, and even in this case, it had been confined to G.R.P. municipal and hut products.

These companies usually rely on the incoming enquiries from architects and other potential specifiers or users as a method of bidding and obtaining business.

Most companies in Group I are generally too small to have a marketing department, and, because of diversity of markets and products, they cannot afford the multiple costs of commissioning independent market researches.

Most companies rely on their past records of achievement as means of selling their services to their prospective clients. Advertising and promotion of G.R.P. by Group I in the construction market has not been concerted or effective and has been confined mainly to sales literature. Some regular advertising has been carried out by one of the major UP resin producers. However, the aims of these advertisements have been: (a) to promote the company's image as a quality resin producer; (b) to illustrate the potential of G.R.P.; and (c) to introduce the actual resins and products. Thus, most of the advertising has necessarily appeared in the plastics trade journals (e.g. Rubber and Plastics Weekly, Reinforced Plastics Monthly), aiming to increase the particular producer's share of the UPR market.

7.2.2.8 Composition of the employment:

The total employment of a typical G.R.P. company may be divided into two parts: staff and production team.

(a) Staff: Managers of most independent companies are normally owners of these companies. These owners have a variety of backgrounds, mostly associated with the plastics industry. The companies in Group I do not generally employ full-time professional and graduate staff. Their design team consists of one or two draughtsmen led by one of the managers.
Although some companies employ professional estimators, the majority are not capable of costing a job accurately. This is realized from widely varying quotations usually submitted for a given job by several companies against a set of identical design and specification documents.

(b) Production team: About quarter of the total workers on the shop floor are engaged on the production of patterns and moulds. Most pattern makers have to be recruited from suitably trained and experienced carpenters. Even with skilled carpenters, it usually takes between one and two years to develop the skills required for precision tool making. The training usually takes place in the factory.

Laminators account for up to half of the production team. They are semi-skilled and their training takes about 5 to 6 months on the shop floor. The rest of the production team (about a quarter) are unskilled labourers.

7.2.2.9 Research and development (R & D):

The official definition of R & D includes the following categories (15):

(a) Basic research: work undertaken for the advancement of knowledge without specific commercial objectives.

(b) Applied research: work undertaken with either a general or specific commercial objective in view.

(c) Development: work directed to the introduction or improvement of specific products or applications up to successful commercial production and marketing. This includes technical service and market development efforts up to the point of commercial production.

The Group I G.R.P. processing companies have not undertaken any basic or applied research. They have also spent very little money and effort on the development of products. They exchange of information on practical aspects of the contact-moulding process (e.g. information related to achieving surface textures and finishes is treated as fully confidential), has been non-existent. It has therefore been necessary for each company to experiment individually.

There are several reasons for the lack of concerted effort
on R & D; chiefly:

(1) Most companies are too small in terms of capital expenditure and cannot afford the high costs of R & D. It has been suggested (5) that an annual spending of at least £100,000 is needed to run an effective multidisciplinary research team; clearly this is beyond the resources of the majority of the G.R.P. companies in Group I. In the case of subsidiaries, parent companies are generally unwilling to absorb the high costs of R & D, especially in connection with development and marketing of cladding and structural systems. They are suspicious of the success of these systems and usually point to the past failures, e.g. the case of GLC blocks of flats SF1 and SF2 constructed in London is frequently cited. The company involved in this scheme was Indulex Engineering, who spent some £30,000 in 1967/68 on the manufacturing costs of the matched-metal dies for the hot-press moulding of the external shells of the cladding panels for the above blocks. The company had hoped to secure further orders for identical shells to be produced from the same dies in order to recoup their original capital investment. However, their hopes did not materialize, as apparently no other authority in the country wanted to repeat the same type of panels on their buildings.

The general question of acceptability and economic viability of mass-produced standard panels/systems or package designs will be considered in Chapter 8&11. However, it is sufficient to mention here that most holding companies are only interested in short term investment with little or no risk involved.

(2) The unit repetition in most custom-designed G.R.P. projects is below 500 and is typically below 100. As such, the contact-moulding process is the most economic production process. Thus, even with considerable growth in the output of some Group I G.R.P. companies operating in the construction market, there has been little economic pressure to change the processing technique and employ semi- or fully mechanized processes.

In the case of medium to large contracts, the employment of semi-mechanized production processes may show significant cost savings compared with the contact-moulding process. Indeed, for production of G.R.P. roof modules for Covent Garden Flower Market in Nine Elms, London, some development work on the catalysed-resin injection moulding process was undertaken by Armshire
Mickleover Transport (an ex-subsidiary of Unigate who ceased trading after the completion of the above project).

Of particular interest to this study is the reluctance of most G.R.P. companies to make use of the improved production equipment offered by the equipment manufacturers. An example is the use of present spray-up equipment for G.R.P. moulding which has improved performance over the earlier versions of such equipment and has been utilized by a few companies (e.g. by Glasdons and by H.H. Robertson).

(3) The average G.R.P. company in Group I does not employ any professional staff. In addition, most independent companies are unwilling to raise outside investment. This is partly due to the fear of losing their control over the affairs of the company and partly due to the managers' lack of modern enterprise.

7.2.2.10 Trade Association:

The British Plastics Federation (BPF) have a 'Reinforced Plastics Group' (RPG) whose membership is open to those companies engaged in the processing of reinforced plastics and also those who produce the basic materials and machinery for the reinforced plastics industry. The aims of the RPG are to protect, promote and widen the interests of the industry as a whole. However, coverage of the G.R.P. companies in Group I is probably less than 10 per cent. In fact, the coverage by the BPF of the whole plastics processing industry is also limited to about 10 per cent of all firms (5), though in 1971 these accounted for 40 per cent of the total output (5).

The BPF is generally dominated by large multi-million pound companies. The general feeling amongst Group I companies is that at present joining the BPF is expensive and does not produce any increase in the volume of business.

It must be noted that in 1975 the RPG of the BPF introduced a 'Quality Mark' scheme. The aim of the scheme is to raise the general standards of the G.R.P. processing industry by awarding an annually renewable 'Quality Mark' to those companies who satisfy the independent inspection authority (Lloyds' Register, Industrial Services) that they comply with the minimum standards laid down in a code of practice by the BPF.

The BPF hold the view that the scheme can gain general acceptance and increase the quality of reinforced plastics products. Success of the scheme will depend not only on its general acceptance by the G.R.P. companies. It will also depend on the
The response by Group I companies has not so far been encouraging (see Table 7.16). The reasons, according to the three largest companies interviewed, are: (a) the fees are high (£310 for the first award and £110 for annual renewal); and (b) the specifiers/users are concerned with the total costs of their projects. Thus, in practice, they normally select the lowest bid. (In the case of public authorities, they are bound to select the lowest tender.) Lowest tenders may have been placed by unscrupulous moulders who can offer cheaper but less reliable products by lowering the manufacturing standards.

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7.2.2.11 Bankruptcies:

According to the information available, there have been three liquidations and two mergers in the period 1970 to 1975 amongst the Group I companies.

As has already been noted, the industry suffers from cash flow problems, as it is not able to generate sufficient profits to finance itself. This reason was responsible for the liquidation of Armshire Reinforced Plastics in 1975. Their factory in Slough was closed and the company merged with Shererville Reinforced Plastics, operating from a Bedford area. Armshire Reinforced Plastics Ltd. was a small company with a total employment of about 50 engaged on custom-moulding of G.R.P., employing the hand-lay-up cold press and resin injection (S.A.S.) injection processes.

Another notable example of liquidation was that of Mickleover Transport, previously mentioned. The chief reason for withdrawal of Mickleovers from the construction market was their failure to make money, which in turn was associated with their lack of familiarity with the construction market and their inability to estimate the costs and recover the extras incidental on most construction sites. Furthermore, the parent company did not approve of one-off jobs and were looking towards setting up continuous production lines.

Other mergers or liquidations were generally thought to have been caused either by lack of capital funds to advance beyond the formation stage, or due to cash flow problems.

7.2.2.12 Constraints for new entrants:

From previous discussions, the following constraints appear to exist for the new entrants:

(1) Capital investment: The amount of capital required for long term investment in equipment is not high, provided the hand-lay-up technique is employed. In the case of spraying, capital costs tend to be higher, but not very much - typically £2500 to £5000. The factory space need not be purchased; it may be leased or rented in a typical industrial estate, and advantage may be taken of the government's regional development funds.

(2) Skilled labour: It has already been noted that pattern and mould makers are skilled, whilst laminators are semi-skilled.

A new entrant to the industry does not necessarily need pattern makers, since there are many firms specializing in making
patterns to order. G.R.P. laminators may be recruited or trained. Training of the laminators may prove difficult. However, the past tendency has been for one of the partners of new companies to have come from the G.R.P. industry with sufficient know-how in all practical aspects of production.

(5) Working capital and provision of sureties: These two constraints are effective in the construction market. Assuming that a newly formed company can raise sufficient working capital for handling a contract, it would still need to provide sureties, usually from a bank, in order to be able to enter into a contract with the public and most private clients. Provision of such sureties is normally subject to several fairly successful trading years. In addition, in the case of government and many other authorities such as the General Post Office, the awarding of contracts/orders is restricted to the approved companies; a newly formed company must satisfy the relevant authority that it is technically capable of producing the goods and services satisfactorily before approval is granted.

(4) Market development: In addition to provision of appropriate production facilities and manpower, a firm must be able to obtain production orders. In the construction market, a sub-contracting company must demonstrate that it is capable of producing the goods to the required standards. Successful past experience is normally the only way by which a company can do this.

A new entrant will find it difficult to sell its services unless it spends a considerable part of its resources on trials, tests and demonstration schemes. Even these efforts will not necessarily guarantee any market. However, at times of rising demand and capacity/supply shortages, securing of work may be less difficult, especially if attention is focused on small jobs which are not normally attractive for established companies.

It must be noted that some G.R.P. companies had originally been established as boat-builders and have therefore been able to satisfy their clients in the construction industry with relative ease.
7.2.3 The structure of Group II companies:

Table 7.16 shows a sample of 11 companies, of which 3 produce and market proprietary cladding panels, 3 are involved in the production of G.R.P. sheeting and the remaining 5 are engaged in production of a variety of trade and proprietary products (trade products are those which are moulded for customer industries, usually as components).

7.2.3.1 Proprietary flat cladding panels producers:

'Poluroc' and 'Stenni' are proprietary flat cladding panels manufactured in standard sizes by continuous processes and finished with stone chippings. 'Petrarch' is also produced on a continuous basis but differs in composition, since it is really a reconstituted stone. The market information available indicates that these products have not been popular in this country because of the following reasons:

(i) Site labour requirements: these cladding panels must be cut, fitted and fixed on backing supports, usually timber or aluminium profiles. Cutting, drilling and general machining of these panels is difficult, and the panel edges tend to fracture. The whole process is labour intensive. One of the normal chief advantages of G.R.P. is its ability to be moulded into complex and large panels incorporating most of the sub-components in one piece, thus eliminating the need for the above site operations.

(ii) Performance: Use of standard sizes of cladding panels requires assembly of a variety of components, fixing, jointing, etc. The greater the number of these, the higher the risk of failure of the construction against the penetration of moisture and air, etc.

(iii) Total costs: Because of higher material costs and because of the above factors, the total installed costs of the unit area of the above panels are necessarily in excess of traditional boards such as PVC-faced plywood or PVC-coated corrugated aluminium sheeting, lead-faced plywood, etc.

(iv) Aesthetics: The use of stone chippings on the surface of G.R.P. is considered as 'cheating'. Also, the use of flat sheets entails flat surfaces; this means that 'mould-ability' and other architectural characteristics of G.R.P. are lost.

'Stenni' was originally developed in Norway in 1965.
'Polyroc' is similar to 'Stenni' but has been developed by a Sussex-based company. 'Petrarch' has been developed by Redlands Cladding Division. Redlands have been very active in the production and marketing of G.R.P. pipes. As will be seen throughout the remaining part of this section, the tendency has been for major constructional materials manufacturers and suppliers such as Redlands to concentrate on mass-produced standard products.

Redlands are a group of companies with public shareholders. The group's 1975 sales turnover was about £185m (20) and total employment close to 7500. The main products manufactured by Redlands are concrete roofing tiles, bricks, pre-stressed and pre-cast concrete. Redlands are also engaged in quarrying sand, gravel, granite and limestone. Other activities by the group include plant engineering, road marking and contracting the treatment and disposal of industrial waste.

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7.2.3.2 G.R.P. roof sheeting producers:

The capital cost of the equipment for the continuous mechanical production of G.R.P. sheeting is in the region of £0.75m (7). This factor, coupled with price competition in the market, has meant that only major companies could operate the process. Thus, as has already been noted, 3 companies control over 90 per cent of the home market, though the G.R.P. sheeting constitutes a relatively small part of the total activities of these companies - typically 5 to 10 per cent in the case of British Industrial Plasties and Cape Universal.

British Industrial Plastics (BIP) is a subsidiary of the Turner & Newall group. Turner & Newall are an enterprise controlling 7 manufacturing companies in the U.K., including TAC Construction Materials and TBA Industrial Products, 24 overseas subsidiaries and 22 associated companies. The group's annual turnover is over £300m. Non-asbestos products contribute approximately 40 per cent to the worldwide turnover and 50 per cent to the U.K. turnover.

Turner & Newall produce a wide range of materials and products, notably asbestos-based products, plastics materials and products, glass and mineral fibres, rubber, cork, etc.

BIP manufacture a range of thermoplastics, unsaturated polyester and melamine resins. The company also manufactures a range of finished and semi-finished products for various industries, including G.R.P. sheeting. In addition to G.R.P. sheeting, BIP have recently introduced a G.R.P. shiplap cladding board. The need for this product in domestic and medium-cost range buildings was identified by market research (7). The intention is to provide a superior substitute for timber and PVC shiplap boards. Timber shiplap requires regular maintenance, and the thermal movement of PVC shiplap has been claimed to be high (7). It is premature to comment on the success or failure of this product, though it appears that some of the comments made earlier on flat G.R.P. cladding sheets equally apply to this product.

The timing of the introduction of this product is significant. It was planned and developed at a time when the price of timber was soaring to unprecedented levels and at the same time, sales of the company's G.R.P. sheeting was static or falling.
BIP carry out applied research on other aspects of G.R.P. technology, such as improvements on the fire performance of G.R.P. in general and UP resins in particular. Development work by BIP and other companies in the Turner & Newall group include composite panels of foam filled sandwiches, etc. However, it is not known whether Turner & Newall are considering development of any substitute for their asbestos-based products. The latter products have been under constant public pressure in recent years to be withdrawn from the market because of the health hazards associated with asbestos. It must be noted that such development work is not beyond the resources of Turner & Newall, not only because of their considerably large resources, etc., but also due to their involvement in glass fibre technology. One of their subsidiaries, TBA Industrial Products, produce a range of glass fibre products, mixed-fibre fabrics, etc. TAC Construction Materials, another subsidiary of Turner & Newall, manufacture a range of materials and products for construction, automotive, chemical and ship-building industries. These include bricks, insulation materials, pipes, hot-press moulded SMC products, fire protection boards, etc.

Cape Universal is also another major group of companies engaged in the manufacture of asbestos-based products, pitch fibre pipes, flint bricks and G.R.P. sheeting. The group's total employment is about 7400. The group's financial performance as published in the 'Sunday Times' (April 25th, 1976) is set out in Table 7.22.

Table 7.22 Financial Performance of Cape Industries (Source: Accounts published in the Sunday Times)

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<td></td>
<td></td>
<td>1974</td>
<td>1975</td>
<td>% change (II/II)</td>
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<tr>
<td>Turnover</td>
<td>£81.3m</td>
<td>£107m</td>
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<tr>
<td>Pre-tax Profit</td>
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<td>£10.2m</td>
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<td>Earnings per share</td>
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<td>29.6p</td>
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Cape Universal's fortune has also been associated with the asbestos business.

Of interest to this study is the early involvement (1964) of Cape Universal with the hand-lay production of translucent G.R.P. roofing units used to cover the dome of Wharrier Street School's sports hall in Newcastle-upon-Tyne. This project was in fact the first major step forward for G.R.P. from a purely utilitarian roof sheeting to a more important structural material. However, Cape Universal have since withdrawn from the one-off custom-moulding business because, in common with other major companies, they have higher overheads and are unable to compete with the smaller companies with lower overheads. (8)

Cape Universal are considering development of a suitable substitute for asbestos-cement and other asbestos-based products. A current patent by Cape Universal (16) is related to the development of an 'asbestos-free' fire-resistant building board, comprising vermiculite and organic fibres with a melting point close to 140°C and a water-based inorganic binder. This development, which uses known technologies, is an evidence of the search by Cape Universal for gradual reduction of the group's dependence on asbestos products. Another development programme by Cape Universal and in association with one polyester resin producer is aimed at producing class 0 polyester resin for use in production of a new type of translucent G.R.P. sheeting which will be able to substitute for asbestos-cement completely (8). The development work is expected to take up to two years. This is a bold step forward for G.R.P.; and illustrates the type and size of the market development which interests the Group II G.R.P. processing companies.

Information on the main business and size of the third major G.R.P. producer is not available. However, it is known that the firm is a producer and distributor of a range of plastics materials, products and ancillaries.

7.2.3.3 Other G.R.P. processors:

Some information on TAC Construction Materials (Turner & Newall) has been given in the preceding part. A brief review of Marleys will be made at the end of this part, after discussing the remaining three companies: BTR Reinforced Plastics, Permali Gloucester and Fothergill & Harvey, who are mainly 'industrial trade-moulders' and have not had long term association with the construction industry.
BTR Reinforced Plastics, with a total employment of 170, is a subsidiary of the BTR group. The group's annual sales turnover exceeds £100m - 50 per cent of which is contributed from the group's overseas companies. BTR control 13 U.K.-based companies (including Permali, which was taken over in 1975), 14 overseas companies and 5 associated companies. The activities of these companies are arranged in five sections: The Industrial Group, The Automotive Group, The Material Handling Group, The Consumer Group and The BTR Associates North Sea Oil Involvement and Overseas Companies.

In addition, BTR have central laboratories situated in Burton-on-Trent. The laboratories are engaged in a variety of research and development work, basically those referred to them by the member companies. Liaison with the outside research institutions is also maintained.

BTR Reinforced Plastics have extensive hot-press moulding facilities and operate newly installed pultrusion equipment. The company sells some 60 per cent of its output to the construction industry. Products range from cold water cisterns, metre cupboards and pultruded profiles to sectional storage tanks, though this latter is mainly used for industrial purposes. Most of these products were originally developed to specific requirements of industrial and wholesale customers. An example is the metre cupboard, which was developed and produced for one of the gas boards.

BTR Reinforced Plastics carry out some R & D locally. The improvement of the 'heat-resistance' of the company's sectional tank is but one example. The idea is to use a skin of bisphenol-based G.R.P. as the lining to the existing G.R.P. sectional tank. This can extend the application of the tank to hotter working conditions (up to 20°C) (2). Because of corrosion-resistant properties of G.R.P., the market for the above tank is assured in the chemical industry (2).

Permali Gloucester, with a total employment of 1050, is a newly acquired (1975) subsidiary of the BTR group. This company functions under the following five divisions:

(1) The Laminating Division: offers a wide range of wood, paper and glass fibre based laminates.

(2) The Moulding Division: offers a trade-moulding service for various glass fibre/resin compounds and includes design,
fabrication of moulds/tools and production of the actual components.

(3) The Injection Moulding Division: produces thermoplastics mouldings in a variety of moulding materials.

(4) The Insulating Division: produces electrical boards, etc.

(5) The Electrical Division: which caters for production of components for the electrical industry, etc.

The production processes operated by Permali are hot and cold press moulding and filament winding techniques. Proprietary products include pipes, ducts, tanks and containers. The company is principally dependent on trade-moulding of components for virtually any industry. For example, the company have been responsible for development of seat shells for British Railways and for the National Bus Company. The shells are produced from SMC using the hot-press moulding process.

Fothergill & Harvey are also a large company with a total employment of 1100 and an annual sales total of about £7m. They produce carbon-fibre woven fabrics in a combination of glass and carbon fibres, DMC and SMC as well as operating hot-press moulding, filament winding, pultrusion and pressure/vacuum bag moulding. Pressure/vacuum bag moulding is essentially similar to the contact-moulding process, except that the laminate consolidation is either carried out by application of pressure in a rubber bag or by sucking a rubber membrane onto the moulding.

Fothergill & Harvey are also industrial and trade moulders, operating in virtually all industries. In addition, they market a variety of proprietary products, including fluorocarbon composites for the aircraft industry.

Marleys are a group of companies with a total employment of 12000, operating 25 U.K. and 16 overseas factories, 47 depots, and 140 shops in the U.K. The group's activities include manufacturing, selling and fixing roof tiles, floor tiles and floor coverings; extruded PVC plumbing, drainage and cladding products; manufacturing and erecting of concrete buildings, PVC sheeting and plastic film, folding doors, fencing, baths, polyurethane moulded foam padding for motor and furniture industries and retailers in home care and the do-it yourself market.

The G.R.P. side of Marleys is a small part of Marley
Extrusions, whose main products are extruded PVC goods and some other thermoplastics (e.g. ABS). Thus, G.R.P. moulding is relatively insignificant to Marleys. The group is, however, heavily committed to other plastics materials.

Marleys have a high record of successful innovations in the U.K. construction industry (18), especially for domestic and medium-cost building applications. For example, concrete tiles were originally developed and marketed by Marleys.

A feature of the marketing strategy by Marleys is to diversify the range of products supplied to the potential customers. For instance, they supply retracting doors for small domestic garages in G.R.P., ABS, PVC-coated aluminium, PVC-coated steel, painted softwood, coated and polished softwood, etc.

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7.2.3.4 Summary of the main characteristics of GroupII companies:

(1) The dominance of major companies: As has already been noted, the major multi-million pound companies dominate this sector of the industry. It was also found that the traditional construction materials producers are committed to a large extent to the development of G.R.P., especially with a view to introducing standard products for the mass market in the construction industry.

(2) The dependence on mechanized production processes: The companies in Group II depend on mechanized production processes.
These companies have higher overheads, administration and selling costs. Thus, they are not competitive in the field of labour-intensive production processes.

(3) Investment: There is no information on the amount of capital invested by these companies on plant and machinery for processing G.R.P. into finished products. It was, however, noted that capital investment is relatively high for continuous production processes. The same is true with the hot-press process. In the short term, it is arguable whether the industry needs further investment in actual machinery, since it is presently working below 75 per cent full capacity. In the long term, the need for investment is acute. Although, judging by the resources of these companies, one is tempted to conclude that these companies have access to sufficient funds for long term investment, the actual position is less clear.

Factors affecting the investment decisions in the construction materials manufacturing industry are numerous. However, from the studies carried out by Bowley (18), it appears that a rising trend in demand for materials and products is a stimulus for expansion of the output. This coupled with the presence of market competition tends to accelerate the introduction of innovations in production processes, especially those concerned with reducing the market prices of the materials and products. However, influence of other factors such as confidence in the ultimate potential of an investment, the length of time taken by an investment to repay itself, the general state of the economy, the conservatism of the management of the company concerned, the effect of the new investment on the company's existing products, the company's policy towards its shareholders, etc., must not be discounted.

The investment by the construction materials producers in the past has been directed towards development of proprietary standard products aimed at the mass market (e.g. 'Petrarch' by Redlands); development of these products in G.R.P. have not had any major effect in the market or appearance of buildings.

The investment by the industrial trade moulders has been directly linked with the volume of business and the need for installing further machinery to meet a rising demand in the trade-moulding business persistent up to the current economic recession. There is some evidence (2) and (5) to suggest that
these companies are evaluating the potential of the construction market. This is not only due to the fall-off in the business volume as a result of the economic recession. The competition suffered by G.R.P. from thermoplastics, particularly polypropylene, has been significant enough to force some trade moulders to look around for new markets. However, there is no evidence that these companies have advanced in the construction market as some consider that the risks are high(2) unless a potential client is forthcoming or the risks are shared by other sectors of the industry, i.e. resin and glass fibre producers.

(4) Marketing: Marketing embraces such indispensable operations as market research, product and market planning, promotion of sales, selling and customer service as well as the promotion of image of the company and its products. Adoption of a flexible approach to the changing needs of potential customers requires guidance of R & D, in order to ensure that through continuous product improvements, the performance of the product surpasses those of the competitive products. Other concerns of marketing are the effectiveness of the sales team and the technical data sheets. The sales team should not only be concerned with the provision of supply, but also be familiar with the intricacies of the users' market and customers' requirements. Similarly, the technical data sheets should give details of costs as well as performance tests relevant to the users.

The marketing operations of the traditional construction materials producers such as Turner & Newall, Cape Universal, Redlands and Marleys may be considered as satisfactory. These companies in general benefit not only from their familiarity and long term association with the construction industry (some are linked with the main contractors), they also benefit from established distribution and sales outlets both in the U.K. and abroad. Furthermore, they have in the past introduced some of the key construction materials and have been associated with production and marketing of the others. Thus, they are able to draw upon their experience and their contacts within the construction industry for judging the timing and appropriateness of an innovation. These qualities would be expected to have stimulated a higher degree of utilization of G.R.P. in the constructional application. However, there are other factors such
as technical, historical, etc., which will be considered in a more appropriate place.

The industrial trade moulders such as BTR Reinforced Plastics, Permali and Fothergill & Harvey started as makers of components to customers' orders, with the objective of maximising the machine running time. Thus they have done very little in the way of opening up new applications in the construction market.

(5) Research and development: Very little money and effort have been spent by Group II G.R.P. processing companies on basic research for new discoveries, etc. Applied research (often in the form of assessments of the properties of reinforced plastics for constructional applications, methods of improving these, etc.) has received little attention (14) or has been left to others, e.g. to the glass fibre and resin manufacturers, universities, Rubber and Plastics Research Association (RAPRA), Plastics and Rubber Institute, Building Research Establishment, Royal Aircraft Establishment, etc.

Development of new G.R.P. products and markets by the traditional construction materials suppliers has already been noted. The areas where development could be directed are industrialized systems, where there has been surprisingly little development work undertaken, either on exploration of aesthetics or on technical or on economic potential of G.R.P. This subject is further discussed in Chapter 11.

In the case of industrial trade moulders, R & D efforts have generally been geared to the development of components and products on behalf of the customers. However, some applied research has also been carried out by these companies. An example is the work by BTR Laboratories on the processing of DMC components. By careful modification of certain moulds, they are able to cause the random arrangement of fibres in DMC to assume a preferred orientation during the brief flow stage while the press closes. This can improve the mechanical properties of such DMC-based components in the preferred direction (17).

The change of strategy by the above companies from customer-orientated R & D to market and product orientated R & D will no doubt be of ultimate benefit to the well-being and growth of these companies.

Some co-operative research is carried out by RAPRA. There
have been suggestions (5) that greater use should be made of the co-operative R & D at RAPRA by groups of companies. The result of such work would be confidential and would be available to the original patrons only.

RAPRA's total income in 1970 was £0.5m (5), 21 per cent of which came from government grants, 46 per cent from members' subscriptions and contributions to specific projects and 10 per cent from contract research, half of which again came from the government. The remaining 23 per cent was from technical service, sales of publications and royalties (5).

(6) Trade Association: 6 of the companies listed under Group II in Table 7.16 are members of the BPF. In addition, BTR Reinforced Plastics, Pemali, BIP and Redlands have applied for and received the BPF Quality Mark.

It is perhaps significant that the BPF Reinforced Plastics Group is dominated by these companies and the resin and glass fibre producers. However, this is not unique to the reinforced plastics sector, as the BPF covers only one eighth of the firms in the plastics industry, though these account for half of the industry's output (19). The Federation have recently embarked on a membership drive (19) to become more representative of the plastics industry as a whole.

(7) Constraints against new entrants: A distinction may be made between the industrial trade-moulding market and the standard products markets.

(a) Constraints against the new entrants to the trade-moulding markets:

(i) Availability of sufficient capital for purchase of plant and machinery: The minimum amount of capital required will depend on the type of processes under consideration, but in most cases, the total capital outlay is likely to be in excess of £1.0m for the establishment of an efficient production unit.

(ii) Availability of skilled workers: Manufacture of matched-metal dies and other tools required highly skilled workers and special precision equipment. However, this work may be handed over to specialized tool-making companies.

Press-moulders and other operators are semi-skilled. Recruiting of these may prove difficult, particularly when there is an upward trend in the moulding business. The availability of this category of workers, who usually require special training, has been the subject of numerous discussions between the industry
and the Rubber and Plastics Training Board.

(iii) Marketing: Breaking into the industry may be facilitated by a prevailing shortage of capacity in the industry. Offers of price reduction and attractive delivery terms may then produce a contract or an order. However, a lot of business skills are necessary to launch a new company successfully in this market.

If there is surplus capacity in the industry, there will be intensive competition for the available orders; in such conditions, the existing firms may be in a much stronger position and outbid the new firm.

(b) Constraints against the new entrants into the standard mass-produced market: In addition to the constraints (i) to (iii) above, the following obstacles must also be overcome to break into the markets controlled by construction materials producers:

(iv) Establishing a sales and distribution network: This is a vital part of the whole marketing operations and may require considerable capital and personnel, because most marketing outlets are controlled by the existing producers.

(v) Trade names, patent rights, etc.: The tendency has been for proprietary products to be protected by patent rights and trade names. So, it will be necessary to develop a new product or to acquire the production rights for a product under a licensing arrangement in order to enter into the market.

(vi) Time-lag between the development stage and the full-scale production stage of a new product: Construction products must be sufficiently durable. If the durability/life of a new product is uncertain, it may take some years before it can be effectively accepted by the construction industry. This time-lag may be relatively unimportant to the existing producers but vital to the continued existence of a newly formed company.

The above constraints have effectively barred new entrants into the standard products market and established a state of oligopoly. However, there is evidence that the industrial trade-moulders are gradually establishing themselves in the construction market.
7.2.4 Comparison between Groups I and II processors:

The most striking differences between the two groups are as below:

7.2.4.1 Differences in production technologies:

The gap between the production technologies as generally employed by Groups I and II is so wide that some experts have suggested different designations be used for the materials processed by employment of each production process.

7.2.4.2 Difference in size:

Most Group I companies are small compared with most companies in Group II. However, a more accurate comparison must be based on the assets devoted to the production of G.R.P. as distinct from the parent or captive company's total assets.

7.2.4.3 Predominance of the construction materials producers:

As has been observed, in both groups the construction materials manufacturers own and control a large part of the industry. However, in the case of most companies in Group II, the long term interest in G.R.P. is more substantial and in one case (Turner & Newall) is vital. This is because of the considerable capital invested in the production machinery, etc.

7.2.4.4 Methods of obtaining business:

The majority of the companies in Group I rely on the continuation of one-off custom-moulding projects as means of obtaining production orders.

Of all the companies in Group II, the construction materials manufacturers have a more active role in developing markets and proprietary products for the standard mass market. In contrast to them, the industrial and trade moulders rely mainly on the continuation of production orders for trade-moulding of components for the users' industries. However, none of the companies in Group II appeared to be interested in one-off low-volume custom moulding business employing the labour intensive contact moulding process.

7.2.4.5 Investment in machinery:

The Group I companies have not in general committed
Most Group I companies cannot afford large scale long term investment. Raising of outside finance by independent companies is not always possible or desired by the management of these companies.

Although most Group II companies are capable of long term large scale investment, they cannot necessarily commit themselves to such undertakings with ease.

7.2.4.6 R & D:

With the exception of one production process - 'S.A.S', developed by Armshire Reinforced Plastics - the companies in Group I have not undertaken or commissioned any R & D on a significant scale. Most managers of these companies do some practical R & D associated with facilitating the application of the contact-moulding process.

Although most companies in Group II have undertaken some R & D, they have not, until the recent economic recession, felt the need for more expenditure on marketing and R & D. One of the main reasons for this situation is that the rising demand and natural expansion of the use of G.R.P. components by the users' industries have kept the processors busy; they have as a result paid little attention to the development of products for the construction industry.

7.2.4.7 Constraints against new entries:

As has already been noted, there are some constraints against new entrants into the market held by the Group I companies. The chief constraints are: (i) securing business orders; (ii) financing of fair-sized contracts; and (iii) employment of skilled laminators.

It is worth noting that one way of breaking into the market is to acquire shares in an established small company in the field.

Some of these constraints are ineffective if the demand for custom-moulding panels is in excess of supply, because the potential users may be forced to employ newly established firms in order to avoid large delays in the completion of their projects, etc. If, however, the supply exceeds the demand, the competition for the orders is intense; the small companies can face cash flow
companies can face cash flow problems and may be squeezed out of the market altogether. (In fact, there is evidence that some of the companies in Group I are experiencing these problems.)

Constraints against new entrants in the markets controlled by Group II companies have already been noted; it is evident that the size of capital required, the structure of the market, etc., will limit the number of potential entrants.

7.2.5 Future trends:

7.2.5.1 The Group I G.R.P. processing companies:
In the immediate future, little change will be expected in the industrial structure of these companies. Most companies will consolidate their position in the market by rationalizing their operations and specializing in one or two markets. However, the long term situation is less certain and will depend to a large degree on the new technological developments in the field of processing composites and on the relative economics of these composites compared with traditional materials such as timber, metals, concrete, brick, etc. The dependence of these companies on labour-intensive production processes may be regarded as an inherent weakness which can, in the long term, change the balance against them.

7.2.5.2 The Group II G.R.P. companies:
Developments in new processes such as pultrusion and further advancement in hot-press moulding of SMC will strengthen the position of most G.R.P. processors operating these processes.

The public pressure against asbestos-based products may force the construction materials manufacturers concerned to increase their search for alternative materials. Whether or not G.R.P. will be developed as a possible alternative to asbestos-cement sheet is the subject of current speculation. At least as seen by Pilkingtons, G.R.C. is the obvious answer to the problem and is being marketed to this effect.

Although increased use of industrialized building systems is a stimulus, it does not necessarily ensure a market for any G.R.P. system. Other factors, such as economic competitiveness, aesthetic appeal, performance in service and
general suitability will influence the demand for these systems (see Chapter 11)
1. Correspondence file with Messrs. Silenka, b.v., Horgezand, Holland, P.O. Box 50 (1975); Silenka is a glass fibre producer who has a small share of the U.K. market.
2. Interview notes with Messrs. BTR Reinforced Plastics Ltd., 18th July, 1975.
6. Correspondence file with ICI Petrochemicals Division on 14th August, 1975.
8. Interview notes with Cape Universal Ltd. on 2nd July, 1975.
12. Interview notes with Mr. D. Powell, Polyplan Ltd., 12th November, 1974, Brighton.
15. Statistics of Science and Technology, published by DTI - DES.
DEVELOPMENT AND USE
OF COMPOSITE FIBROUS MATERIALS
IN THE U.K. CONSTRUCTION INDUSTRY

VOLUME 2

A thesis submitted in partial fulfilment of the requirements for the degree of Ph.D of the University of Surrey

ALI JAAPARI, B.Sc., M.Sc.

1977
8.1 Sources of Data:

The main data for this part of the study have been collected by a comprehensive postal survey; the survey results have been amplified and augmented by selective interviews and other sources such as published information.

Some five hundred and fifty questionnaires were sent to representatives of four different groups of specifiers - county and district architects, architects in private practice, consulting structural engineers and a mixed selected sample - in the first half of 1975 to collect and analyse data on service, performance, perceived advantages and disadvantages of G.R.P., indications of the extent and rate of penetration of G.R.P. into the construction market and the difference in attitudes of each group on the use of G.R.P. panels. Information on production methods, insofar as these affect individual attitudes towards the use of G.R.P., was also collected.

A paper based on the results of this study has been prepared and presented to the international bi-annual conference on reinforced plastics, sponsored by the B.P.F. and held in Brighton in November 1976. To avoid duplication, parts of this paper have been adapted and used in this chapter.

8.2 Description of the Samples:

Four independent samples have been investigated; each was compiled independently and each firm/person appears in only one sample; this avoids any form of interdependency. The samples are as follows:

8.2.1 County and District Architects of England and Wales:

For the purposes of this study, the sample chosen may be considered to comprise the population of all new authorities who had, at the time of sampling, an architectural department (estimated number is 192). The response rate was about 70 per cent (see Table 8.1).

8.2.2 Architects in private practice:

A random sample of 192 architectural firms was taken from RIBA's Directory of Practices. It was estimated that, excluding the branches of each firm, there was a total of 2770 firms in
Britain; the sample therefore constituted approximately 7 per cent of this population. The response rate was about 46 per cent.

8.2.3 Consulting structural engineers:

A random sample of 90 firms was prepared from those members of the Association of Consulting Engineers who were based in Britain and, in addition, were wholly or partly concerned with the design of structures and buildings. The total number of such firms was estimated from the Consulting Engineers' Year Book 1975 to be around 215. The sample was therefore 42 per cent of the population, which may be considered as fully representative. The response rate was about 49 per cent.

8.2.4 A biased sample:

This sample was compiled from the list of those who had attended a symposium on the use of plastics for load-bearing and infill panels, held in September 1974 at the University of Surrey. In this list the specifiers comprised the following:

(a) forty three architects, the majority of whom were in private practice. Some of these architects belonged to various public authorities, namely British Rail, London Transport, the Department of the Environment and the Greater London Council.

(b) twenty structural engineers belonging to private practices, the Department of the Environment, etc.

(c) a building and civil engineering contractor (national), and a timber-framed system building manufacturer, both of whom had used G.R.P, as a cladding material.

As the response rate on this sample was 70 per cent, it is likely that specifiers in this group were more familiar with and/or interested in the use of G.R.P. compared with other groups.

8.3 Types of Data Collected:

The questionnaire used in the postal survey may be inspected in Appendix A. It can be seen that the information required is of a qualitative nature. There are three basic reasons for adopting a qualitative approach:

(a) Heterogeneity of construction projects: Although it is possible to class certain buildings as having similar product characteristics (e.g. dwelling houses), the majority of buildings are designed individually using different solutions. The conditions and geometry of site, the nature of surroundings and the availability of materials are but some external factors which may affect the design of a building. Thus, it is not possible to classify
buildings according to their functions and consider each class as homogeneous products.

(b) Heterogeneity of G.R.P. applications: The variety of G.R.P. applications, especially custom-designed cases, has already been noted. Similarly, it has been observed that the total installed costs of G.R.P. panels per m$^2$ is a function of the panel design, method of manufacture and the unit repetition.

(c) Because of (a) and (b) above, the saving or additional costs incurring as a result of an attribute of G.R.P. is not consistent from one construction project to another. In addition, as will be seen, some of the advantages or disadvantages of G.R.P. are difficult to quantify in monetary terms.

It was therefore decided to ask specifiers to give their overall conclusions reached on this subject. It was also hoped that, by choosing a reasonably large sample size, the effect of project variations on the overall pattern of results could be minimized, provided the response rate was not unduly low.

Amplification of the findings of this survey was planned in the following manner:

(i) Quantitative theoretical cost comparisons based on certain typical designs using the available and published data. This has been carried out in Chapter 5.

(ii) Interviews and discussions both within the reinforced plastics industry, including the raw materials producers, and within the construction industry, with particular emphasis on the designers concerned with G.R.P. Information from the former group concerned the selling of G.R.P. to the construction users, and the information from the latter group was related to the actual case histories.

8.4 General Pattern of the Results:

Table 8.1 shows the general pattern of results. It can be seen that about 50 per cent of the 321 specifiers who participated in the survey had used G.R.P. panels; 72 per cent of these were generally satisfied with the performance of G.R.P. panels in service; 13.5 per cent were partially satisfied, and the remaining 14.5 per cent were dissatisfied. The overall response rate was about 59 per cent.

About 57 per cent of those who had G.R.P. experience had used G.R.P. load-bearing panels. A definition of a load-bearing panel is given in Appendix A.
Table 8.1 - Analysis of the Results from the G.R.P. survey in the Construction Industry.

<table>
<thead>
<tr>
<th>I Sample</th>
<th>II Sample size</th>
<th>III % of populat. approx.</th>
<th>IV No of returns</th>
<th>V Response rate</th>
<th>VI with G.R.P. experience</th>
<th>VII Loadbearing experience</th>
<th>VIII Non-Loadbearing experience</th>
<th>IX Satisfied</th>
<th>X Partially satisfied</th>
<th>XI Dissatisfied</th>
</tr>
</thead>
<tbody>
<tr>
<td>County &amp; District Architects,</td>
<td>192</td>
<td>100</td>
<td>133</td>
<td>69</td>
<td>61</td>
<td>46</td>
<td>36</td>
<td>59</td>
<td>25</td>
<td>41</td>
</tr>
<tr>
<td>England and Wales (L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Architectural Practices</td>
<td>192</td>
<td>7</td>
<td>91</td>
<td>475</td>
<td>41</td>
<td>45</td>
<td>16</td>
<td>39</td>
<td>25</td>
<td>61</td>
</tr>
<tr>
<td>Britain (A)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consulting Structural</td>
<td>90</td>
<td>42</td>
<td>46</td>
<td>51</td>
<td>17</td>
<td>37</td>
<td>11</td>
<td>65</td>
<td>6</td>
<td>35</td>
</tr>
<tr>
<td>Engineers (Britain) (C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hand Picked Sample (S)</td>
<td>73*</td>
<td>N.A</td>
<td>51†</td>
<td>70</td>
<td>38</td>
<td>74.5</td>
<td>27</td>
<td>71</td>
<td>11</td>
<td>29</td>
</tr>
<tr>
<td>All samples</td>
<td>547</td>
<td>N.A</td>
<td>321</td>
<td>58.5</td>
<td>157</td>
<td>49</td>
<td>90</td>
<td>57</td>
<td>66</td>
<td>43</td>
</tr>
<tr>
<td>combined (L+A+C+S)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* includes 19 questionnaires from the pilot survey.
† includes 18 returns from the pilot survey.
N.A - Not applicable.
As may be seen by reference to the above mentioned Appendix, the questionnaire does not contain a 'partially satisfied' category. It was originally thought that taking an overall view of the cost and service performance aspects of his G.R.P. panels, each respondent (user) could classify himself either as a 'satisfied' or dissatisfied 'user. In practice, it turned out that some respondents preferred to classify themselves as 'partially satisfied'; this was necessarily taken into account at the time of analysis of the data.

Caution must be exercised in interpreting the general state of satisfaction, because most G.R.P. projects have been executed in the last 10 years (c.f. section 7.1 and see also later parts of this chapter), and, as such, have not withstood the test of time; in fact, several designers specifically referred to this point in their replies.

Table 8.2 shows the age distribution of all G.R.P. projects referred to in the questionnaire by specifiers (i.e. in reply to questions 2a to 2c and 4a to 4c inclusive; see Appendix A).

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Number of projects</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2</td>
<td>87</td>
<td>34.5</td>
</tr>
<tr>
<td>2 - 6</td>
<td>110</td>
<td>43.5</td>
</tr>
<tr>
<td>&gt; 6</td>
<td>55</td>
<td>22.0</td>
</tr>
<tr>
<td>Total</td>
<td>252</td>
<td>100.0</td>
</tr>
</tbody>
</table>

This Table indicates that the number of projects undertaken in G.R.P. is rising. However, this is not an accurate method of determining the size of the market or the rate of penetration of G.R.P. into the construction into the construction market, because G.R.P. projects are not necessarily of an equivalent value. Further, the above data are based on 4 samples of unequal degrees of representativeness, with the possibility of multiple counting of a single project. Nevertheless, these data confirm a rising trend in the utilization of G.R.P. panels in the construction industry (see also section 7.1).
In order to determine possible associations between the samples prior to the pooling of the results, the following statistical tests of significance have been carried out:

8.4.1 Degree of satisfaction against the project age:

This test may be considered as a useful tool by which to check whether or not improvements in UP resin formulations and improvements in other aspects of G.R.P. technology are reflected in the survey results in the form of a gradual increase in the level of users' satisfaction.

Table 8.3 shows the $\chi^2$ test of significance for all samples combined; testing of each sample independently is not advisable due to several entries coming to less than the recommended figure for such tests (i.e. 6).

Table 8.3 Testing of Degree of Satisfaction vs Age of Projects

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Satisfied</th>
<th>Part. Sat.</th>
<th>Dissat.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>obs. exp.</td>
<td>obs. exp.</td>
<td>obs. exp.</td>
<td></td>
</tr>
<tr>
<td>&lt; 2</td>
<td>65  63</td>
<td>16  13.8</td>
<td>6  10.0</td>
<td>87</td>
</tr>
<tr>
<td>2 - 6</td>
<td>80  80</td>
<td>15  17.5</td>
<td>15  12.7</td>
<td>110</td>
</tr>
<tr>
<td>&gt; 6</td>
<td>38  40</td>
<td>9   8.7</td>
<td>8   6.3</td>
<td>55</td>
</tr>
<tr>
<td>Total</td>
<td>183</td>
<td>40</td>
<td>29</td>
<td>252</td>
</tr>
</tbody>
</table>

$\chi^2 = 3.33$ ) on the evidence of these data and $\chi^2 = 4$ ) at 5% level of significance, there is no association between age of projects and level of satisfaction.

Tabulated value at 5% level of significance is 9.49.

The result of the above test indicates that the general state of satisfaction has not altered significantly with time. In other words, even though there may have been improvements in all aspects of G.R.P. technology, these have not affected the users' satisfaction to any measurable degree.

8.4.2 Type of sample against project age distribution:

This test may be assumed as a guide to whether or not there has been any variation with time in the number of projects undertaken by each group relative to others, i.e. whether or not one group of designers has used more G.R.P. relative to the others.
### Table 8.4 Sample type vs Project age

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>(L) obs.</th>
<th>exp.</th>
<th>(A) obs.</th>
<th>exp.</th>
<th>(S) obs.</th>
<th>exp.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2</td>
<td>34</td>
<td>34</td>
<td>16</td>
<td>19.6</td>
<td>28</td>
<td>24.4</td>
<td>78</td>
</tr>
<tr>
<td>2-6</td>
<td>48</td>
<td>42.8</td>
<td>24</td>
<td>24.6</td>
<td>26</td>
<td>30.6</td>
<td>98</td>
</tr>
<tr>
<td>&gt; 6</td>
<td>17</td>
<td>22.2</td>
<td>17</td>
<td>12.8</td>
<td>17</td>
<td>16.0</td>
<td>51</td>
</tr>
<tr>
<td>Total</td>
<td>99</td>
<td>57</td>
<td>71</td>
<td></td>
<td></td>
<td></td>
<td>227</td>
</tr>
</tbody>
</table>

\[ \chi^2 = 5.34 \]

Tabulated value @ 5% level of significance = 9.49

On the evidence of these data and at 5 per cent level of significance, there is no association between project age and the above sample types.

### Table 8.5 Sample type vs Project age

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>(L) obs.</th>
<th>exp.</th>
<th>(A) obs.</th>
<th>exp.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 2</td>
<td>34</td>
<td>31.8</td>
<td>16</td>
<td>18.3</td>
<td>50</td>
</tr>
<tr>
<td>2-6</td>
<td>48</td>
<td>45.7</td>
<td>24</td>
<td>26.3</td>
<td>72</td>
</tr>
<tr>
<td>&gt; 6</td>
<td>17</td>
<td>21.6</td>
<td>17</td>
<td>12.4</td>
<td>34</td>
</tr>
<tr>
<td>Total</td>
<td>99</td>
<td>57</td>
<td>156</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \chi^2 = 3.15 \]

Tabulated value at 5% level of significance = 5.99

On the evidence of these data and at 5% level of significance, there is no association between the above sample types and project age.

### Table 8.6 Type of Application vs Degree of satisfaction

<table>
<thead>
<tr>
<th>Type of Application</th>
<th>Satisfied</th>
<th>Part. Satisfied</th>
<th>Dissatisfied</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>obs.</td>
<td>exp.</td>
<td>obs.</td>
<td>exp.</td>
</tr>
<tr>
<td>Load-bearing</td>
<td>64</td>
<td>64.2</td>
<td>16</td>
<td>12.6</td>
</tr>
<tr>
<td>Non-Load-bearing</td>
<td>48</td>
<td>47.8</td>
<td>6</td>
<td>9.4</td>
</tr>
<tr>
<td>Total</td>
<td>112</td>
<td>112</td>
<td>22</td>
<td>22</td>
</tr>
</tbody>
</table>

\[ \chi^2 \cong 3.93 \]

Tabulated value at 5% level of significance = 5.99

On the evidence of these data and at 5 per cent level of significance, there is no association between type of application and degree of satisfaction.
To avoid using entries less than 6, it has been necessary to eliminate the sample representing the consulting structural engineers; this may have additional benefits, because, generally speaking, engineers are less involved in the choice of non-structural materials, especially those materials, such as G.R.P., which have architectural impacts upon the whole design of a building. Thus, omission of the above sample facilitates digestion of the results of the following tests.

Tables 8.4 and 8.5 contain the necessary calculations.

It may be concluded from Tables 8.4 and 8.5 that none of the above groups has changed its rate of using G.R.P. panels relative to others. This is not an unexpected result, as the use of G.R.P. panels has been confined mainly to custom-designed one-off buildings.

8.4.3 Type of application against degree of satisfaction:

This test is a useful way of detecting if there has been any difference in the degrees of success achieved by G.R.P. in 'load-bearing' and 'non-load-bearing' applications (for a definition of load-bearing see Appendix A).

As may be observed, the result indicates that the state of satisfaction is not associated with the type of application. This means that the specifiers do not appear to prefer G.R.P. for one type of application (e.g. cladding) as compared with other types (e.g. self-supporting structures). However, it must be remembered that, according to the applied definition (c.f. Appendix A), there is some overlap between the 'load-bearing' and 'non-load-bearing' applications and the result must therefore be interpreted strictly in conjunction with the given definition.

8.4.4 Summary of the statistical tests:

The overall result of the above tests indicates that, on the evidence of the collected data, apart from allowable variations in the data, there are no inconsistencies between the various groups of specifiers; and that the data may be pooled together for subsequent studies. This includes sample (S), which was originally thought to be biased.

8.5 Ranking of Perceived Advantages and Disadvantages of G.R.P. Panels:

Table 8.7 shows the ranking of the advantages and disadvan-
tages of G.R.P. panels; the argument symbols used are given in the notes to Table 8.7.

N.T.A. and N.T.R. indicate the number of times accepted and the number of times rejected respectively, and both refer to the total number of specifiers within each sub-group who have accepted or rejected the argument as a valid reason for their satisfaction or dissatisfaction. This may be illustrated by referring to the first column of the result in Table 8.7, which shows that 'Improved Appearance, IA' due to the use of G.R.P. was considered 38 times as a reason for satisfaction by the local authority architects with G.R.P. experience (i.e. about 60 authorities, c.f. Table 8.1). The same sub-group rejected this argument 3 times; these two results are shown in rows 1 and 2 of column 1 in Table 8.7. It should be remembered that each returned questionnaire refers to a particular project or group of projects; pooling of the results can therefore create a problem. Moreover, the relative importance of suggested advantages and disadvantages of particular cases has been ignored; for instance, different degrees of benefit which would result from 'low maintenance' requirements or 'ease of site erection' of G.R.P. panels have not been taken into account. Using a system of weighting when filling in the above questionnaire by the participants was considered at the outset of the project but rejected on the grounds of impracticability.

Reasons for satisfaction and dissatisfaction, in the case of specifiers with G.R.P. experience, have been taken as perceived advantages and disadvantages respectively of G.R.P. In the case of specifiers without G.R.P. experience, the reasons for their intentions to consider the use of G.R.P. in their future projects have been taken as perceived advantages; similarly, the reasons for their intentions of excluding the use of G.R.P. in their future projects have been taken as perceived disadvantages (c.f. Appendix A).

Referring to Table 8.7, it can be seen that 'improved appearance' (+105, -13) and 'low maintenance requirements' (+104, -9) of G.R.P. panels are the greatest advantages of this material as perceived by specifiers with G.R.P. experience (group 1); followed in descending order by 'ease of shaping' (+87, -15), 'ease of site erection' (+75, -18), 'improved overall economy' (+52, -51) and 'less foundation and structural provision' (+48, -40).
Table 8.7 Ranking of Perceived Advantages and Disadvantages of G.R.P. Panels

<table>
<thead>
<tr>
<th>SAMPLE DESIGNATION</th>
<th>DESCRIPTION</th>
<th>GROUP 1 WITH G.R.P. EXPERIENCE</th>
<th>GROUP 2 WITHOUT G.R.P. EXPERIENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>REASONS FOR SATISFACTION</td>
<td>REASONS FOR DISSATISFACTION</td>
</tr>
<tr>
<td>L</td>
<td>Arg't symbol</td>
<td>IA LM ES EE LF IE</td>
<td>SD DP IC FR EP EC</td>
</tr>
<tr>
<td>N.T.A.</td>
<td>38 38 34 28 25 24</td>
<td>14 13 11 8 7 7</td>
<td>40 35 34 25 23</td>
</tr>
<tr>
<td>N.T.R.</td>
<td>-3 -3 -3 -5 -11 -16</td>
<td>-7 -5 -7 -11 -12 -12</td>
<td>-2 -2 -3 -4 -16</td>
</tr>
<tr>
<td>A</td>
<td>Arg't symbol</td>
<td>LM ES IA EE LF IE</td>
<td>SD DP FR IC EC EP</td>
</tr>
<tr>
<td>N.T.A.</td>
<td>31 30 28 19 16 15</td>
<td>4 2 2 2 2 0</td>
<td>32 30 26 24 20</td>
</tr>
<tr>
<td>N.T.R.</td>
<td>-1 -4 -4 -9 -15 -18</td>
<td>-2 -2 -2 -2 -3 -4</td>
<td>-2 -7 -6 -9 -4</td>
</tr>
<tr>
<td>C</td>
<td>Arg't symbol</td>
<td>IA EE LM ES IE LF</td>
<td>DP IC SD</td>
</tr>
<tr>
<td>N.T.A.</td>
<td>12 11 9 9 6 3</td>
<td>2 1 +1</td>
<td>9 8 6 5 5</td>
</tr>
<tr>
<td>N.T.R.</td>
<td>-3 -1 -2 -4 -7 -11</td>
<td>-0 -0</td>
<td>-0 -0 -0</td>
</tr>
<tr>
<td>S</td>
<td>Arg't symbol</td>
<td>IA LM EE LF ES IE</td>
<td>SD EC IC FR DP EP</td>
</tr>
<tr>
<td>N.T.A.</td>
<td>27 26 17 14 14 7</td>
<td>5 5 4 4 3 1</td>
<td>18 17 15 15 4</td>
</tr>
<tr>
<td>N.T.R.</td>
<td>-3 -3 -3 -3 -4 -10</td>
<td>-1 -1 -2 -3 -2 -3</td>
<td>-1 -1 -1 -3 -10</td>
</tr>
<tr>
<td>L + A</td>
<td>Arg't symbol</td>
<td>IA LM ES EE IE LF</td>
<td>SD DP IC FR EC EP</td>
</tr>
<tr>
<td>N.T.A.</td>
<td>105 104 87 75 52 48</td>
<td>24 20 18 14 14 6</td>
<td>98 86 85 65 57</td>
</tr>
</tbody>
</table>
The argument symbols used in this table have the following meaning; each symbol represents one of the questions on the questionnaire 5.1 to 5.6, 5.8 to 5.13, 6.1 to 6.5, 6.7 to 6.11:

5.1 Improved appearance = IA
5.2 Low maintenance = LM
5.3 Less foundation and structural provisions = LF
5.4 Improved overall economy = IE
5.5 Ease of shaping = ES
5.6 Ease of site erection = EE
5.8 Increased fire risk = FR
5.9 Significant degradation = SD
5.10 Design and jointing problems = DP
5.11 Increased overall costs = IC
5.12 Site erection problems = EP
5.13 Extra cleaning problems = EC
6.1 as 5.1 = IA
6.2 Lightness in weight = LL
6.3 as 5.5 = ES
6.4 as 5.4 = IE
6.5 Corrosion resistant = CR
6.7 as 5.8 = FR
6.8 as 5.10 = DP
6.9 as 5.9 = SD
6.10 as 5.12 = EP
6.11 as 5.11 = IC
Under the disadvantages heading, as perceived by the above group, it can be seen that 'significant degradation' (+24, -10) of exposed panels is the most prominent; followed in descending order by 'design and jointing problems' (+20, -9), 'increased costs' (+18, -11), 'increased fire risks' (+14, -16), 'extra cleaning requirements' (+14, -16) and 'site erection problems' (+8, -19).

Those specifiers who did not have previous G.R.P. experience (group 2) considered 'lightness of weight' (+98, -5) as the most useful advantage of this material, followed in descending order by 'ease of shaping' (+86, -10), 'improved appearance' (+85, -13), 'resistance to corrosion' (+65, -9), and 'improved overall economy' (+57, -36).

Opposite the disadvantages heading as perceived by the above group, 'increased fire risks' (+18, -2) is the most conspicuous, followed in descending order by 'design and jointing problems' (+14, -4), 'increased costs' (+13, -3) and 'site erection problems' (+12, -6).

These findings have been discussed in detail below:

8.6 Advantages of G.R.P. Panels:

8.6.1 Improved appearance (aesthetics):

The question of current trends in architectural design of buildings will be considered in a more appropriate place; the purpose of this discussion is to throw some light on the nature of G.R.P. as an aesthetic medium as perceived by the architectural profession.

As may be seen from Table 8.7, 67 per cent of specifiers with G.R.P. experience agreed that G.R.P. panels had given an attractive appearance to their buildings, compared to 8 per cent agreeing to the contrary. (The total proportion of satisfied specifiers amounted to 72 per cent as shown in Table 8.1. However, this is not an accurate basis for comparison, since the figures of advantages and disadvantages of G.R.P. in Table 8.7 are affected by 13.5 per cent who were partially satisfied. By the same token, the total proportion of dissatisfied specifiers, i.e. 14.5 per cent, cannot be used for any meaningful comparison. Comparisons with these percentages have therefore been excluded throughout this study.)

'Improved appearance' was ranked by Group 2 specifiers as the
third greatest advantage of G.R.P. panels; 43 per cent agreed that G.R.P. was architecturally pleasing and 6.5 per cent rejected the same idea.

Although it seems that the overwhelming majority of specifiers have apparently subscribed to the view that G.R.P. is architecturally pleasing, they are not necessarily using the same set of criteria for their assessment. This is because aesthetic assessment of any building is still based on subjective judgments and varies considerably with the type of education, training and experience of the specifiers. Further, prevailing trends in fashion and in architectural idiom will influence aesthetic acceptance of any material.

Divergency of opinions amongst members of the profession is best illustrated by some of the special comments made by various specifiers on this subject (see Table 8.8)

The following points of interest may be noted from Table 8.8:

1. Some architects consider the colour and gloss finish of G.R.P. surfaces as architecturally attractive; however, this view is not generally shared by others.

2. A number of architects see the aesthetic potential of G.R.P. in its versatility and its ability to simulate other materials or surface textures, etc.; e.g. one architect likened G.R.P. to other 'mouldable' materials such as terra-cotta or cast iron, which used to be moulded into building components in the past.

3. Unlike the above groups, some architects consider that G.R.P. panels and structures could provide greater opportunities for aesthetic innovation, i.e. producing buildings of individual-istic architectural characteristics, or enhancing the aesthetic appeal of established architecture (e.g. 'international functionalism'; see Chapter 9 for more details on these aspects).

4. Finally, there are also other architects who either believe that the aesthetic appearance of G.R.P. panels is not superior to that of alternative materials, such as brick, or that it is difficult to handle the aesthetic design of G.R.P. in a satisfactory manner, i.e. either due to the problems stemming from the relatively low value of modulus of G.R.P. in bending, or because the number of architectural parameters such as scale, colour, texture, etc., to be resolved satisfactorily are numerous, and in many cases, the end result is not satisfactory because of the practical limitations associated with the manufacturing of G.R.P. panels.
Table 8.8 Perceived Aesthetics/Architectural Character of G.R.P.

<table>
<thead>
<tr>
<th>Type of Organs (a) (Ref.Code)</th>
<th>Any G.R.P. exp.?</th>
<th>Satisfaction (b)</th>
<th>Intentions (c)</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri-arch. (AF - 1)</td>
<td>yes</td>
<td>part.sat.</td>
<td></td>
<td>Perhaps from the architects' point of view, the most significant fact is that it can open up avenues of design which have not yet been fully explored using other materials and permits possible progress along the lines of componentised design - one wonders what Gropius and Bauhaus would have produced with G.R.P. at the time</td>
</tr>
<tr>
<td>pri-arch. (AQ - 4)</td>
<td>yes</td>
<td>satisfied</td>
<td></td>
<td>G.R.P. panels were used as a decorative finish and chosen for that reason</td>
</tr>
<tr>
<td>pri-arch. (AQ - 5)</td>
<td>yes</td>
<td>satisfied</td>
<td></td>
<td>Colours restricted - either too bold or too dull. No natural weathering characteristics. Little variations for the eye - can engender a negative architectural feeling.</td>
</tr>
<tr>
<td>pri-arch. (AQ - 13)</td>
<td>yes</td>
<td>satisfied</td>
<td></td>
<td>G.R.P. was able to simulate a texture and colour effect that I was looking for. Very versatile as to the appearance and moulding.</td>
</tr>
<tr>
<td>pri-arch. (ANN-4)</td>
<td>no</td>
<td>yes</td>
<td></td>
<td>G.R.P. joins more traditional moulded building materials (terra-cotta and cast-iron) as a suitable material for multiple production of ornaments. This fact may prove important for its future use by architects.</td>
</tr>
<tr>
<td>pri-arch. (ANN-7)</td>
<td>no</td>
<td>yes</td>
<td></td>
<td>I consider this material to be primarily useful for forming maintenance free decorative features, more especially with metallic powder finishes that will be otherwise more costly to construct or maintain.</td>
</tr>
<tr>
<td>pri-arch. (ANN-6)</td>
<td>no</td>
<td>no</td>
<td></td>
<td>A preference in the building types I design (mainly Ecclesiastical) for natural materials, bulk, etc.</td>
</tr>
<tr>
<td>dist.arch. (LP - 2)</td>
<td>yes</td>
<td>satisfied</td>
<td></td>
<td>G.R.P. satisfied the needs in terms of colour, aesthetic appearance and met the needs in terms of design and with insulation the necessary U-values.</td>
</tr>
<tr>
<td>dist.arch. (LP - 14)</td>
<td>yes</td>
<td>satisfied</td>
<td></td>
<td>Since the material is of high mouldability, to achieve sufficient strength in itself, I feel new directions in architecture are widely open. Also, G.R.P. is self-coloured with a wide choice of colours.</td>
</tr>
<tr>
<td>count-arch. (LP - 17)</td>
<td>yes</td>
<td>satisfied</td>
<td></td>
<td>Exposed aggregate G.R.P. panels although successful on the part of the users and the client (pleased), are visually cheating, many would think, and this is the main consideration.</td>
</tr>
<tr>
<td>dist.arch. (LP - 36)</td>
<td>yes</td>
<td>satisfied</td>
<td></td>
<td>G.R.P. is an attractive material, both visually and in tactile sense, but it is difficult to accept aesthetically on housing since this is a field in which prejudice for traditional materials is very strong.</td>
</tr>
<tr>
<td>Type of Organisation</td>
<td>Any G.R.P. exp.?</td>
<td>Satisfaction (b)</td>
<td>Comment(s) made</td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------</td>
<td>------------------</td>
<td>-----------------</td>
<td></td>
</tr>
<tr>
<td>dist-arch (LQ-20)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>G.R.P. might be considered for certain industrial buildings. Brickwork is more pleasing in appearance and has no real defects which are not fully understood by the building industry.</td>
<td></td>
</tr>
<tr>
<td>dist-arch (LQ-25)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>Faceted design as often required by manufacturers is visually restrictive.</td>
<td></td>
</tr>
<tr>
<td>dist.-arch (LNN-23)</td>
<td>no</td>
<td>yes</td>
<td>G.R.P. panels are not inherently &quot;architecturally pleasing&quot;</td>
<td></td>
</tr>
<tr>
<td>dist-arch (LNN-1)</td>
<td>no</td>
<td>no</td>
<td>G.R.P. is not architecturally pleasing</td>
<td></td>
</tr>
<tr>
<td>dist-arch (LNN-7)</td>
<td>no</td>
<td>no</td>
<td>The use of stereotyped units would impose severe restrictions upon design, particularly in view of the large areas of cladding normally involved and upon which the whole character of a building can depend</td>
<td></td>
</tr>
<tr>
<td>consult-eng. (LQ-4)</td>
<td>yes</td>
<td>satisfied</td>
<td>Too much attention is given to making G.R.P. look like some other material than trying to develop it as a totally new product.</td>
<td></td>
</tr>
<tr>
<td>consult-eng. (CNW-11)</td>
<td>no</td>
<td>yes</td>
<td>The use of G.R.P. appeals to me, because it provides the opportunity of using colour in building appearance</td>
<td></td>
</tr>
<tr>
<td>pri-arch (SP-5)</td>
<td>yes</td>
<td>satisfied</td>
<td>I think G.R.P. units should express the plastic quality of this material and not to imitate pre-cast concrete in form and finish</td>
<td></td>
</tr>
<tr>
<td>pri-arch (SP-9)</td>
<td>yes</td>
<td>satisfied</td>
<td>I do not consider 'originality' for its own sake to be a valid architectural perquisite. Difficult material to handle aesthetically, i.e. scale of units, colour and texture in relation to the surroundings. Texturing of surfaces, e.g. reeding has advantages, especially where long lengths of flat surfaces are involved.</td>
<td></td>
</tr>
<tr>
<td>pri-arch (SP-10)</td>
<td>yes</td>
<td>satisfied</td>
<td>Main advantage of G.R.P. is infinite range of colours and possibility of three dimensional form.</td>
<td></td>
</tr>
<tr>
<td>pri-arch (SNW-9)</td>
<td>no</td>
<td>yes</td>
<td>Expressive of our current culture</td>
<td></td>
</tr>
</tbody>
</table>

Notes:

(a) Type of organisation refers to the following:
- "pri-arch" = architects in private practice;
- "dist.-arch" = district architect (including borough, city, etc.);
- "county-arch." = country architect; and finally
- "consult.-eng." = consulting structural engineers.

The first letter of "Ref.code" refers to the sample concerned; the rest identifies the particular questionnaire from which the displayed comment has been extracted.

(b) "satisfaction" refers to the state of satisfaction which applies in the case of those with G.R.P. experience.

(c) Entry of 'yes' or 'no' in this column which appears when the preceding column shows "no", indicates that the specifier concerned "is" or "is not" prepared to consider the use of G.R.P. panels in his future projects.

* The heading and foot-notes described in this part will be assumed applicable in the remaining parts of this chapter.
8.6.2 Low maintenance requirements:
Over 66 per cent of the specifiers with G.R.P. experience agreed that 'low maintenance requirements' of G.R.P. was an advantage of this material, whilst 5 per cent rejected the same. The corresponding figures for those without G.R.P. experience are 33 and 4.6 per cent respectively (i.e. as represented by 'corrosion-resistance' = CR in Table 8.7); to this group, this property of G.R.P. constituted the fifth most important advantage of this material.

However, as has already been stated, for most projects it is rather too early to arrive at any meaningful conclusion on the long term maintenance requirements of G.R.P. panels in service. The present evidence indicates that in some cases the panels require some sort of maintenance.

Comments made by some specifiers in relation to the durability and weathering characteristics of G.R.P. panels may be noted in Table 8.9.

8.6.3 Ease of shaping:
This property of G.R.P. refers to the ability of this material to be moulded into virtually any shape, depending on practical limitations associated with production processes and with manufacturing of original patterns and dies.

'Ease of shaping' was found to be perceived as the third major advantage of G.R.P. by those who had G.R.P. experience; almost 55 per cent stated that this property of G.R.P. was an important reason for their satisfaction, as compared with approximately 9.5 per cent rejecting the same argument.

To those without G.R.P. experience, 'ease of shaping' constituted the second biggest advantage of this material; over 43 per cent subscribed to this view and 5 per cent dismissed it.

Table 8.10 contains a selection of special comments made by specifiers on the above property of G.R.P.

It must be noted that there is some overlap between 'ease of shaping' and 'aesthetics' of using G.R.P. panels. This is because efficient structural use of G.R.P. normally involves shaping of this material to increase the stiffness of the structure; this in turn affects the overall form/geometry of the building (c.f. Table 8.8).
Table 8.9 Perceived State of Durability and Natural Weathering of G.R.P. Panels

<table>
<thead>
<tr>
<th>Type of Organis. (ref.code)</th>
<th>Any G.R.P. exp.?</th>
<th>Satisfaction or Intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri-arch (AP-1)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>UV still problematic</td>
</tr>
<tr>
<td>pri-arch. (ANN-7)</td>
<td>no</td>
<td>yes</td>
<td>As a general facing material, I would be dubious about any long term jointing and surface appearance &quot;weathering&quot; problems.</td>
</tr>
<tr>
<td>pri-arch (ANN-31)</td>
<td>no</td>
<td>yes</td>
<td>G.R.P. does not weather in a pleasing way but simply deteriorates. It is not a quality material</td>
</tr>
<tr>
<td>pri-arch (ANN-4)</td>
<td>no</td>
<td>no</td>
<td>Would not use G.R.P. because of weathering.</td>
</tr>
<tr>
<td>consult-eng (CQ-4)</td>
<td>yes</td>
<td>satisfied</td>
<td>There is insufficient long term exposure information available.</td>
</tr>
<tr>
<td>county-arch (LP-8)</td>
<td>yes</td>
<td>satisfied</td>
<td>Gel coat finish to be more durable</td>
</tr>
<tr>
<td>dist.-arch. (LP-22)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>Discoloration is an open question. How long does white stay white?</td>
</tr>
<tr>
<td>dist.-arch. (LP-28)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>Discoloration of translucent panels and a gradual emphasising of the glass-fibre pattern. Translucent use must be limited to where the appearance does not matter or where it is hidden as behind a lay light.</td>
</tr>
<tr>
<td>dist.-arch (LP-32)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>Colour fastness is a problem.</td>
</tr>
<tr>
<td>country-arch. (LQ-17)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>Our concern would be the ability of gel coat to stand the test of time</td>
</tr>
<tr>
<td>country-arch. (LQ-19)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>We are disappointed by reaction to weathering of G.R.P. (especially as we are in a rural area).</td>
</tr>
<tr>
<td>country-arch. (LQ-24)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>Surface deterioration occurred fairly quickly</td>
</tr>
<tr>
<td>dist.-arch. (LNN-5)</td>
<td>no</td>
<td>no</td>
<td>We were disappointed with the durability and weathering quality of a G.R.P. swimming pool cover erected in the Lincoln area.</td>
</tr>
<tr>
<td>dist.-arch (LNN-7)</td>
<td>no</td>
<td>no</td>
<td>The lack of stability in color particularly of the brighter ones</td>
</tr>
<tr>
<td>dist.-arch (LNN-10)</td>
<td>no</td>
<td>no</td>
<td>Would be prepared to consider using G.R.P. if it has proved itself sufficiently long period of time</td>
</tr>
<tr>
<td>pri-arch (SP-9)</td>
<td>yes</td>
<td>satisfied</td>
<td>Life of the material still to be proved in practice.</td>
</tr>
<tr>
<td>consult. eng. (SP-13)</td>
<td>yes</td>
<td>satisfied</td>
<td>Durability? Too early to draw conclusion</td>
</tr>
<tr>
<td>pri-arch (SP-20)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>Insufficient hard information on length of satisfactory life under various conditions of use and exposure. This makes it impossible to give unqualified recommendations to clients.</td>
</tr>
<tr>
<td>Build.6 Civil Eng. contract. (SQ-8)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>On some projects colour fastness a serious problem.</td>
</tr>
<tr>
<td>pri-arch (SQ-9)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>Gel coat has faded leaving a cloudy appearance.</td>
</tr>
</tbody>
</table>

* See Table 8.8 for notes
Table 8.10+ Comments on Ease of Shaping of G.R.P.

<table>
<thead>
<tr>
<th>Type of organisation (Ref. code)</th>
<th>any satisfaction</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri. arch. (ANW - 30)</td>
<td>no</td>
<td>possibility of designing shapes, profiles and colours economically for long runs.</td>
</tr>
<tr>
<td>dist. arch. (LP - 19)</td>
<td>yes satisfied</td>
<td>G.R.P. good for the envelope of sports complex including swimming pool.</td>
</tr>
<tr>
<td>county arch. (LP - 23)</td>
<td>yes part. sat.</td>
<td>The possible advantages of G.R.P. seem enormous, but these have not yet proved so in practice from the architect's point of view.</td>
</tr>
<tr>
<td>county arch. (LP - 27)</td>
<td>yes part. sat.</td>
<td>G.R.P. can provide reasonably cheap solutions to some architectural problems.</td>
</tr>
<tr>
<td>pri. arch. (SQ - 1)</td>
<td>yes satisfied</td>
<td>Use of G.R.P. allows for complicated shape and contrasting colours within each unit.</td>
</tr>
</tbody>
</table>

+ - see Table 8.8 for notes.
8.6.4 Ease of site erection:

This property of G.R.P. panels results from their lightness in weight, large panel sizes, ease of incorporating glazing, insulation and lining materials (i.e. elimination of all wet trades), and finally, ease of forming sophisticated panel jointing/connections which are not normally possible with precast concrete panels. It must also be noted that, by careful consideration of the above factors at the planning/design stage of the building, it may be possible to reduce, or even eliminate, the need for extensive scaffolding and support or the need for employing heavy cranes/hoisting equipment and handling devices.

An ideal case would be fully glazed, insulated, lined and finished lightweight panels delivered to site and erected by unskilled labourers from within the structure or with a minimum of external support/propping. Thus, the skills of designers and the experience of manufacturers and site erectors will to a large extent determine the success and quality of the end results.

'Ease of site erection' ranked in fourth position as a perceived advantage of G.R.P. panels by those with G.R.P. experience (c.f. Table 8.7); nearly 48 per cent of the above group agreed that 'ease of site erection' was one of the main reasons for their satisfaction, compared to 11.5 per cent (approximately) who did not subscribe to this view.

To those without G.R.P. experience, 'lightness in weight' constituted the greatest advantage of G.R.P. panels, with 50 per cent (approximately) contributing to this argument and only 2.5 per cent rejecting the same. Table 8.11 contains a selection of special comments made by specifiers in relation to the above attribute of G.R.P. panels.

8.6.5 Improved overall economy:

Nearly 33 per cent of those who had used G.R.P. agreed that the use of this material had been more economic compared to alternative facing materials, whereas 32.5 per cent rejected the same argument. As will be seen later, 'increased total costs' compared with alternative facing materials constitutes the third biggest disadvantage of G.R.P. as perceived by the above group.

The specifiers without G.R.P. experience did not generally show a different pattern of expectation; approximately 29 per cent thought use of G.R.P. could result in overall costs savings, whereas 18 per cent disagreed. The potential cost-saving of G.R.P. was ranked as the last advantage of this material by the
Table 8.11 Comments made on potential of G.R.P. panels

<table>
<thead>
<tr>
<th>Type of organ.</th>
<th>Any G.R.P. exp.?</th>
<th>Satisfaction or Intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri-arch (ANW-28)</td>
<td>no</td>
<td>yes</td>
<td>Potential for high performance, thin wall, high insulation</td>
</tr>
<tr>
<td>dist-arch (LNW-10)</td>
<td>no</td>
<td>yes</td>
<td>I am in favour of G.R.P. to be developed for system buildings particularly</td>
</tr>
<tr>
<td>dist-arch (LNW-27)</td>
<td>no</td>
<td>yes</td>
<td>G.R.P. has a future, particularly when economic means have been devised to produce a sandwich with insulation as an in-filling.</td>
</tr>
<tr>
<td>pri-arch (SNW-5)</td>
<td>no</td>
<td>yes</td>
<td>G.R.P. panels are simple and fast to erect.</td>
</tr>
<tr>
<td>pri-arch (SNW-6)</td>
<td>no</td>
<td>yes</td>
<td>The main advantage in industrial building (factory) construction may be speed of construction and the elimination of certain following trades. This may result in a net cost saving.</td>
</tr>
<tr>
<td>Chief-arch B &amp; C E Contractor</td>
<td>no</td>
<td>yes</td>
<td>G.R.P. panels have some value in that they shorten the erection time on timber-frame systems. They cost more per m² but reduce the overhead.</td>
</tr>
</tbody>
</table>

* See Table 8.8 for notes
above group.

It is not surprising to find such a wide disagreement on the cost effectiveness of G.R.P. panels amongst the specifiers, in view of the facts outlined in 8.3 and 8.6.4 above. In some cases, the costs have escalated far beyond the estimated limits because of unforeseen site problems. However, the continuing rise in the prices of UP resins and glass fibre due to multiple increases in the price of oil and the general level of inflation must have detracted from the cost-effectiveness of G.R.P., especially in the case of large protracted contracts.

Table 8.12 displays a selection of special comments made by the specifiers on the economics of G.R.P. panels.

A study of these comments reveals the following points:

(1) The average cost of using G.R.P. panels relative to that of alternative materials has generally determined, to a large extent, its level of utilization in the construction industry; and, as the use of these panels has not normally resulted in significant overall cost-savings in the past, the level of utilization of G.R.P. has remained relatively low and has been confined to one-off buildings.

(2) Part of the failure of cost-effectiveness of G.R.P. panels can be attributed to the suppliers' failure to produce panels at competitive prices and also their failure to ensure that the users have received real benefits approximating to those estimated at the initial design stage.

(3) Observations by several specifiers indicate that, despite increases in the cost of site labour, it is still more economic to assemble components of a composite construction on site, compared with the factory produced sandwich panels.

(4) The above factors and the general pattern of economics of G.R.P. panels suggest that, quite apart from the effects of costs of basic materials, there is an inherent economic weakness associated with G.R.P.; this weakness is probably the inefficient use of labour in the contact-moulding process.

(5) Requirements for adequate structural rigidity of G.R.P. panels entail use of complex designs or use of stiffer materials as reinforcement; in either case, this adds considerably to the total bill.

(6) A useful general conclusion is that the average cost of using G.R.P. panels must be reduced relative to the average cost of using alternative materials before its large scale application
<table>
<thead>
<tr>
<th>Type of Organis. (ref.code)</th>
<th>Any G.R.P. or exp.?</th>
<th>Satisfaction or Intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri-arch (AP-1)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>Minimal cost saving.</td>
</tr>
<tr>
<td>pri-arch (AQ-13)</td>
<td>yes</td>
<td>satisfied</td>
<td>Generally too costly, otherwise most satisfying aesthetically with good weight reduction and stress resistance. Very versatile as to the appearance and moulding.</td>
</tr>
<tr>
<td>pri-arch (ANW-2)</td>
<td>no</td>
<td>yes</td>
<td>G.R.P. has the facility to be moulded into complex shapes more cheaply than other materials when small quantities are required. Where complex shapes are not required, the other materials are probably going to be more competitive. In many design situations, it is not justifiable to spend money purely on complex shapes where simple shapes suffice. Therefore, other materials get used leaving G.R.P. out in the cold as a fringe activity.</td>
</tr>
<tr>
<td>pri-arch (ANW-31)</td>
<td>no</td>
<td>yes</td>
<td>We have no evidence at present that G.R.P. cladding is cheaper to use than other cladding panels. We think that G.R.P. panels can be justified only if they became economical which they may for buildings of unusual shapes: circular or domical.</td>
</tr>
<tr>
<td>Consult. eng. (CP-1)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>Extreme cost inflation detracts from this material. Most sub-contractors are now unwilling to quote for G.R.P. at all.</td>
</tr>
<tr>
<td>Consult. eng. (CP-5)</td>
<td>yes</td>
<td>satisfied</td>
<td>The use of G.R.P. panels for an 11 m diameter segmental dome to cover lime silos as they protrude through a water treatment plant roof. Structural G.R.P. appeared to be the best solution both for economy and appearance, particularly the latter.</td>
</tr>
<tr>
<td>Consult. eng. (CNN-1)</td>
<td>no</td>
<td>no</td>
<td>G.R.P. not good value!</td>
</tr>
<tr>
<td>dist.-arch (LP-14)</td>
<td>yes</td>
<td>satisfied</td>
<td>From my experience, G.R.P. is only economical compared with conventional materials when used for self-supporting structures without the help of steel and concrete.</td>
</tr>
<tr>
<td>country-arch (LP-17)</td>
<td>yes</td>
<td>satisfied</td>
<td>G.R.P. still seems to be expensive compared with traditional materials.</td>
</tr>
<tr>
<td>country-arch (LP-18)</td>
<td>yes</td>
<td>satisfied</td>
<td>It is still cheaper to assemble the components of a sandwich wall on site. Labour costs rising may change this situation.</td>
</tr>
<tr>
<td>dist.-arch (LP-29)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>More expertise by sub-contractors could have made our case a great success in the costs being less than half that of a traditional roof. At present, a limited number of manufacturers are aware of all the technical problems in this field and the work done by these firms is so costly as to be barely competitive.</td>
</tr>
<tr>
<td>dist.-arch (LP-31)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>G.R.P. panels were found to be more expensive G.R.P. manufacturers not able to produce good quality end-products at competitive prices.</td>
</tr>
<tr>
<td>dist.-arch (LP-36)</td>
<td>yes</td>
<td>satisfied</td>
<td>G.R.P. panels were comparable in price and ought to be relatively maintenance free.</td>
</tr>
<tr>
<td>Type of Organis.</td>
<td>Any G.R.P. exp.?</td>
<td>Satisfaction or Intention</td>
<td>Comment(s) made</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
<td>-------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>countr-y-arch</td>
<td>yes</td>
<td>dissatisfied</td>
<td>Although in an early stage of development, manufacturing techniques for G.R.C. products are much less labour intensive and already seem to show a cost-saving on G.R.P. other than those resulting from cheaper materials.</td>
</tr>
<tr>
<td>(LQ-24)</td>
<td></td>
<td></td>
<td>G.R.P. initially appeared to be economic but oil/plastics price explosion made the final cost expensive.</td>
</tr>
<tr>
<td>dist.-arch</td>
<td>no</td>
<td>yes</td>
<td>It is difficult to obtain tenders for composite panels and when obtained more expensive than traditional forms of construction.</td>
</tr>
<tr>
<td>(LNN-8)</td>
<td></td>
<td></td>
<td>Several quotations were obtained on the basis of a large number of identical units, but the cost was far too high and the idea was abandoned.</td>
</tr>
<tr>
<td>(LNN-17)</td>
<td></td>
<td></td>
<td>A large area of G.R.P. panelling was designed for use on a swimming pool hall, but the cost was uneconomic.</td>
</tr>
<tr>
<td>countr-y-arch</td>
<td>no</td>
<td>yes</td>
<td>Recent proposals to use G.R.P. cladding extensively mainly for fascias were rejected on grounds of cost only.</td>
</tr>
<tr>
<td>(LNN-27)</td>
<td></td>
<td></td>
<td>Northumberland C.C. co-members of the SCOLA consortium have used G.R.P. cladding but found it to be prohibitively expensive. I think, it would have to be cheaper than traditional materials before its use could be considered by this authority for anything other than a one-off special building.</td>
</tr>
<tr>
<td>dir.-arch</td>
<td>no</td>
<td>no</td>
<td>Would consider use of G.R.P. if it is economically viable and is appropriate material for a particular design.</td>
</tr>
<tr>
<td>(LNN-10)</td>
<td></td>
<td></td>
<td>One turns towards G.R.C. products as the prices of G.R.P. are too high nowadays and the product design call for further reinforcement by other materials for adequate rigidity.</td>
</tr>
<tr>
<td>pri.-arch</td>
<td>yes</td>
<td>part-satisfied</td>
<td>Experience seems to have shown that G.R.P. cannot compete with traditional building materials when length of life and overall cost of the element are combined in comparison. However, there are advantages in certain situations which may over-ride its inherent limitations of basic material cost and life. It would be useful, if these specialised applications could be properly defined for practitioners.</td>
</tr>
<tr>
<td>(SP-20)</td>
<td></td>
<td></td>
<td>With the rising price of oil based products, we consider G.R.P. has received a considerable set-back in its introduction into the construction industry. Cost is crucial and there are now other products being developed such as G.R.C. which combines many of the qualities of G.R.P. with good fire-resisting properties at a lower cost. I regret, because of these factors, my enthusiasm for the material has waned over recent months.</td>
</tr>
<tr>
<td>pri.-arch</td>
<td>yes</td>
<td>satisfied</td>
<td>Range of prices between highest and lowest in G.R.P. tenders is of greatest concern, since each company was meant to be supplying against identical specification.</td>
</tr>
<tr>
<td>(SNW-8)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* For Notes See Table 8.8
8.6.6 Reduced foundation and structural provision:

Use of a system of lightweight panels reduces the total static load of the building. Thus, in theory, lighter structural frames may be used and foundation costs may be lowered whenever G.R.P. panels are employed on a building. However, in practice, for reasons of economy, most buildings use either load-bearing walls or a reinforced concrete structural frame as their load-bearing systems. As the weight of such systems normally constitutes the greater part of the total static loads, the potential weight saving due to use of lightweight panels is minimal and may affect the total structural and foundation costs only marginally. It should be remembered that present use of G.R.P. panels is confined to buildings of under 15m high, or about 3 storeys in height above ground level; load-bearing walls are generally used for these buildings, which are relatively unaltered if G.R.P. infill panels are used on one or two elevations.

There are a number of situations in which the effects of weight-saving due to the use of G.R.P. or other lightweight materials on the total costs of foundation and structural provision become significant, viz:

(a) poor ground conditions: where the load-bearing capacity of the ground is low;

(b) vertical extension to an existing building: where the additional weight of the extension may seriously undermine the structural stability or other structural aspects of the existing building;

(c) use of light structural frames: apart from (a) and (b) above, there may be a need for 'fast' and 'dry' construction (e.g. to save time, etc). The usual solution is to use timber or steel or aluminium profiles; the cost of these framings and their foundation provision is usually a function of the total static load; hence, the use of lightweight panels results in a significant cost-saving.

It has already been noted that the use of lightweight panels generally reduces transport, handling and fixing costs, regardless of the type of structure used; these benefits of G.R.P. panels must not be confused with the likely benefits due to reduction in the total weight of building as described above.

As may be expected, the above advantage of G.R.P. panels was perceived as the sixth most important; about 30.5 per cent of
those with G.R.P. experience agreed that the use of G.R.P. panels had reduced the costs of foundation and structural provision in their cases, whereas 25.5 per cent rejected the same (c.f. Table 8.7).

8.6.7 Other advantages of G.R.P. panels:

These are as follows:

8.6.7.1 Suitability for high thermal insulation (i.e. with rigid foamed-cores of polyisocyanurate or phenolics or polyurethane):

Although PVC-coated steel sheet or aluminium sheet may be used as facings to flat sandwich panels, they cannot compete with G.R.P. in low to medium runs of production or when shaped, recessed or complex panels are required. Even on nominally flat sandwich panels, there are usually some requirements in the form of sub-components (e.g. rainwater pipes, sills, etc), or recesses, overhangs, etc., which may make the use of G.R.P. more favourable.

The need for provision of higher standards of thermal insulation is best reflected in the currently published proposals for amending the Building Regulations; the aim is to raise the general standards of thermal insulation in non-domestic buildings. When introduced, the required standard may make the use of composite panels, with an insulation layer, more economic compared with traditional solid or cavity wall constructions. In the long term, this may make introduction of standard mass-produced composite panels inevitable.

Table 8.13 contains a selection of special comments made by specifiers on the potential of G.R.P. for the above purpose.

In corrosive environments (such as coastal areas) and also in polluted atmospheres, the use of G.R.P. as the external facing material of a sandwich construction is preferable to metals on account of the corrosion- and pollution-resistant properties of this material.

8.6.7.2 Impact resistance:

Unlike asbestos-cement sheets, G.R.P. is not susceptible to shattering in direct impacts; the impact failure of G.R.P. panels is usually localized and the damage is not beyond repair, though the repair patch will not match the original laminate in colour, due to the different rate of curing of the resin, etc.

G.R.P. is said to be fairly vandal-proof, but not scratch-resistant, and the gelcoat is prone to cracking by the action of
Table 8.13 Suitability of G.R.P. for sandwich/composite panels:

<table>
<thead>
<tr>
<th>Type of Organis.</th>
<th>Any G.R.P. exp.?</th>
<th>Satisfaction or Intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri.-arch (ANW-28)</td>
<td>no</td>
<td>yes</td>
<td>Potential for high performance, thin wall, high insulation</td>
</tr>
<tr>
<td>dist.-arch (LP-2)</td>
<td>yes</td>
<td>satisfied</td>
<td>G.R.P. met the needs in terms of the design and with insulation - the necessary U-values</td>
</tr>
<tr>
<td>pri.-arch (SP-10)</td>
<td>yes</td>
<td>satisfied</td>
<td>Advantages include whole (sandwiched) insulated panels; lightweight; tolerances in erection.</td>
</tr>
</tbody>
</table>

* For notes see Table 8.8

Table 8.14 Perceived 'impact-resistance' of G.R.P. panels

<table>
<thead>
<tr>
<th>Type of Organis.</th>
<th>Any G.R.P. exp.?</th>
<th>Satisfaction or Intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>dist.-arch (LP-19)</td>
<td>yes</td>
<td>satisfied</td>
<td>G.R.P. is fairly vandal-resistant</td>
</tr>
<tr>
<td>dist.-arch (LP-31)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>Not vandal proof</td>
</tr>
<tr>
<td>county.-arch. (LQ-17)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>G.R.P. was chosen for its resistance to impact in education projects (so far satisfactory)</td>
</tr>
<tr>
<td>dist.-arch (LNN-14)</td>
<td>no</td>
<td>yes</td>
<td>Less vandal resistant than plastics-coated steel sheet</td>
</tr>
<tr>
<td>pri.-arch (SP-9)</td>
<td>yes</td>
<td>satisfied</td>
<td>An advantage of G.R.P. is in its insitu repair</td>
</tr>
<tr>
<td>pri.-arch (SQ-1)</td>
<td>yes</td>
<td>satisfied</td>
<td>G.R.P. panels were used simulating a strip of cine film (Paris Pullman frontage etc.); fairly resistant to damage.</td>
</tr>
</tbody>
</table>

* See Notes in Table 8.8
impact energy. In comparison with brick walls and concrete surfaces, G.R.P. is obviously at a disadvantage.

Table 8.14 shows a selection of comments made in connection with various aspects of the impact resistance of G.R.P. panels.

8.7 Disadvantages of G.R.P. panels:

8.7.1 Degradation/natural weathering of exposed panels:

Over 15 per cent of specifiers with G.R.P. experience were dissatisfied with reaction-to-weathering or degradation of their exposed panels, compared to about 6 per cent who were generally pleased with the weathering behaviour of their panels (c.f. Table 8.7).

About 7 per cent of specifiers without G.R.P. experience agreed that susceptibility of G.R.P. to degradation and its 'unnatural' weathering characteristics were reasons for their decline to specify G.R.P., compared with only 2 per cent rejecting the same argument.

Overall, the specifiers with G.R.P. experience saw the above problems as the biggest disadvantage of G.R.P.; whereas the specifiers without G.R.P. experience perceived the same problems as only the third biggest disadvantage after 'increased fire risks' and 'design and jointing problems'. A possible reason for this apparent disagreement between the two groups is the lack of first hand information/experience on the part of the latter of the actual discoloration/deterioration sustained by exposed G.R.P. panels in service.

It must be stated that the past tendency has been to use more white-coloured, smooth-finished, exposed surfaces; the slightest collection of dirt on these surfaces, probably because of the electrostatic affinity of plastics materials for collecting dirt on their surfaces, can be unsightly and, in a patchy form, can cause differential UV degradation of the gelcoat. However, as has been noted, in some cases the degradation in rural areas has been reported as very significant. This is possibly due to poor quality G.R.P. being affected to a greater extent by UV radiation.

The fact that designers see 'degradation/poor weathering characteristics' of G.R.P. as the biggest disadvantage of this material is not surprising when viewed against their original motivation for using G.R.P., i.e. obtaining an architecturally pleasing surface which would require relatively little mainte-
nance. Thus, any factor which would detract from 'aesthetics' and 'freedom from maintenance' of G.R.P. panels could lead directly to dissatisfaction. This fact is adequately reflected in the special comments made by specifiers in relation to durability/natural weathering characteristics in Table 8.9.

8.7.2 Design and jointing problems:

These problems were considered as the second major disadvantage of G.R.P. by both groups of specifiers (i.e. with or without G.R.P. experience, c.f. Table 8.7); about 13 per cent of the specifiers with G.R.P. experience agreed that complexity of design and jointing techniques was one of the reasons for their dissatisfaction over the use of G.R.P., compared with approximately 6 per cent who agreed that such complexity problems did not cause any dissatisfaction in their case.

Nearly 7.5 per cent of the specifiers without G.R.P. experience saw the above problems as one of the main reasons for their not considering the use of G.R.P., compared with only 3 per cent who rejected the same argument.

There is no doubt that the complexity of design and jointing techniques for G.R.P. panels pose real problems for many designers and specifiers; this fact is proved by a study of the comments and observations contained in Table 8.15, as made by specifiers; not only do the above comments confirm the actual design problems of structural and non-structural design of G.R.P. panels/structures which have been considered in some detail in Chapter 6, but they also highlight a number of administrative, contractual and legal obstacles. Also, it is noteworthy that there still exists considerable doubt in the minds of designers about the long term performance of G.R.P.

8.7.3 Increased total costs:

About 11.5 per cent of the specifiers with G.R.P. experience were dissatisfied with G.R.P. partly because its use had proved costly and uneconomic. Similarly, about 7 per cent of all those without G.R.P. experience agreed that the high cost of G.R.P. panels was one of the reasons why they refuse to consider the use of this material in their future projects.

The economics of using purpose-made G.R.P. panels suggests that, theoretically, these may be attractive in a number of situations on a cost/performance basis (c.f. section 5.6). In practice, the economic potential has not always been realised, and
<table>
<thead>
<tr>
<th>Type of organisation</th>
<th>Any G.R.P. exp.?</th>
<th>Satisfaction or Intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri.-arch. (AP-16)</td>
<td>yes</td>
<td>satisfied</td>
<td>Finish is still a function of actual individual who carries out the work.</td>
</tr>
<tr>
<td>pri.-arch. (AQ-6)</td>
<td>yes</td>
<td>satisfied</td>
<td>There seems to be a lack of written material providing guidelines as to the capabilities of this material. Too often one has to rely on the manufacturers' expertise and this may or may not produce the correct specification for the job in mind.</td>
</tr>
<tr>
<td>pri.-arch. (AQ-18)</td>
<td>yes</td>
<td>satisfied</td>
<td>Simplified information is needed for potential users of G.R.P. in respect of its structural and fire-resisting qualities (Also thermal insulation values).</td>
</tr>
<tr>
<td>pri.-arch. (ANW-5)</td>
<td>no</td>
<td>yes</td>
<td>(1) In designing a building usually within a constricted time, it is much more conclusive to have samples of cladding material to hand i.e. Armoraclad, Escel, etc. (2) Unfortunately we do not have or know how to obtain a reasonable selection of panel types, colours, etc. (3) With better information at hand, we consider the use of G.R.P. would be more general.</td>
</tr>
<tr>
<td>consult. eng. (CP-4)</td>
<td>yes</td>
<td>satisfied</td>
<td>A study and collection of information on the design of connections would be very useful.</td>
</tr>
<tr>
<td>consult. eng. (CNW-13)</td>
<td>no</td>
<td>yes</td>
<td>G.R.P. is unlikely to become widely used until there is a B.S. or CP governing its use.</td>
</tr>
<tr>
<td>dist.-arch (LP-24)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>Design and jointing satisfactory when compared with time spent on detailing junctions, corners and returns in several other materials. The lack of adequate flexibility on tolerances is a problem which led in one case to moulding of a special unit to suit the site dimension.</td>
</tr>
<tr>
<td>consult. eng. (LP-25)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>Design and detailing require more consideration to avoid distortion.</td>
</tr>
<tr>
<td>dist.-arch (LP-29)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>More experience of performance required before further use.</td>
</tr>
<tr>
<td>dist.-arch (LQ-18)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>More information and publicity required on the subject of all production techniques for the benefit of designers.</td>
</tr>
<tr>
<td>country-arch. (LNN-6)</td>
<td>no</td>
<td>no</td>
<td>Our staff opinion favours the many alternatives which have been proved in use over a long period. Lack of familiarity with G.R.P. and its performance may determine this attitude.</td>
</tr>
<tr>
<td>pri.-arch (SP-7)</td>
<td>yes</td>
<td>satisfied</td>
<td>The production of nationally agreed standards i.e. BS/F of P etc. will do much to overcome the existing reluctance of local authority officers to accept the material more readily.</td>
</tr>
</tbody>
</table>
Table 8.15 Special comments made on problems of design and jointing of G.R.P. panels and the need for a Code of Practice

<table>
<thead>
<tr>
<th>Type of organ.</th>
<th>Any G.R.P. exp.?</th>
<th>Satisfaction or Intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri.-arch. (SP-8)</td>
<td>yes</td>
<td>satisfied</td>
<td>I would like to see a co-ordinated textbook devoted fully to G.R.P. and the construction industry, including the following basic information: (1) working examples and details; (2) technical data to assist in local authority, fire officers, etc. negotiations; (3) description of the materials, properties, jointing methods etc. aimed at the architect. Such a textbook would inevitably promote the use of this material in the construction industry.</td>
</tr>
<tr>
<td>pri.-arch. (SP-20)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>It would be useful if an authoritative design guide and Code of Practice could be made available dealing with: (i) Materials' specification and characteristics; (ii) Standard formulations and structure of different grades; and (iii) Physical properties and structure of laminate for various uses.</td>
</tr>
<tr>
<td>pri.-arch. (SP-21)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>The information required is on practical aspects i.e. the views and opinions of building inspectors relative to current regulations, the fire officers' views, methods of jointing and fixing in direct relationship to site conditions. If G.R.P. is to become a useful and generally used material, then more emphasis must be given to the practical contractual aspects.</td>
</tr>
<tr>
<td>pri.-arch. (SP-23)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>What would be useful, in order to remove the doubts that many still have about the material with respect to fire, durability etc. would be to publish reports of the sort that CONSTRADO undertake for BSC: - how to meet the London Building Acts/Building Regulations etc. - though, I suppose this is largely up to the manufacturers themselves.</td>
</tr>
<tr>
<td>consult. eng. (SQ-2)</td>
<td>yes</td>
<td>satisfied</td>
<td>The design and test-proving costs of purpose-made structural G.R.P. panels will make its costs prohibitive for practical purposes until such time as a Code of Practice for G.R.P. is prepared.</td>
</tr>
<tr>
<td>Chief.arch. B 6 C E Contractor (SNW-10)</td>
<td>no</td>
<td>yes</td>
<td>Surely lack of valid knowledge on creep excludes pure structural use of this material except for curvilinear forms.</td>
</tr>
<tr>
<td>consult. eng. (SNX-1)</td>
<td>no</td>
<td>no</td>
<td>Perhaps, the design of this material is insufficiently defined.</td>
</tr>
</tbody>
</table>

* See Table 8.8 for notes
in some cases severe cost penalties have actually been suffered by clients for a number of reasons, chiefly:
(a) shortcomings in design and jointing techniques;
(b) evaluation and test-proving problems;
(c) problems of obtaining quotations related to the quality of G.R.P.;
(d) production and quality control problems; and
(e) weathering and durability aspects.

Thus, it is probable that the majority of the 18 dissatisfied specifiers (c.f. Table 8.7) have suffered additional expenses beyond their original estimates due to one or a combination of the above factors (see also Table 8.12).

8.7.4 Increased fire risks:

As may be seen from Table 8.7, there is an apparent disagreement on 'increased fire risks' due to the use of G.R.P. between the two groups of specifiers (i.e. with and without G.R.P. experience); this disagreement is seen from the rankings of disadvantages; in the case of specifiers with G.R.P. experience the ranking is (4), whereas in the case of specifiers without G.R.P. experience the ranking is (1).

However, on a proportional basis, both groups appear to agree, i.e. in both groups about 9 per cent held the view that the use of G.R.P. had increased or could increase the fire risks of their buildings. The proportion of those rejecting this argument was approximately 10 per cent and 1 per cent for specifiers with and without G.R.P. experience respectively.

It can be seen that the specifiers with G.R.P. experience generally thought that 'increased fire risks' due to the use of G.R.P. panels were less deleterious than 'degradation and natural weathering problems'. It is probable that those without G.R.P. experience were less aware of the likely problems generally associated with 'degradation and natural weathering' of G.R.P. panels.

Limitation on applications of G.R.P. panels due to problems of fire behaviour and combustibility (B.S. 476) has been of concern to many specifiers. Table 8.16 contains a selection of comments on this, together with other aspects of the fire behaviour of G.R.P.

A study of the comments in Table 8.16 reveals the following points:
**Table 8.16 Special comments made on fire risks of G.R.P. panels**

<table>
<thead>
<tr>
<th>Type of Organis.</th>
<th>Any G.R.P. exp.?</th>
<th>Satisfaction or Intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri-arch (AP-9)</td>
<td>yes</td>
<td>satisfied</td>
<td>In one recent case, we were entirely satisfied with panels but new powers enabled fire authority to require this treatment to render the panels 'fire-resistant'. This is difficult as panels are already in place.</td>
</tr>
<tr>
<td>pri-arch (AQ-24)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>G.R.P. panels did not pass over 15 m high 'Building Regulations' G.R.C. would have passed this regulation</td>
</tr>
<tr>
<td>pri-arch (ANW-8)</td>
<td>no</td>
<td>yes</td>
<td>All applications should be practically at least fire-retardant but preferably 'fire-proof' and proofed against giving off toxic fumes when subjected to intense heat such as in a fire.</td>
</tr>
<tr>
<td>pri-arch (ANW-30)</td>
<td>no</td>
<td>yes</td>
<td>Before using G.R.P. I would want to check spread of flame characteristics and acceptance under G.L.C. Building Acts or Building Regulations</td>
</tr>
<tr>
<td>Consult Eng. (CQ-5)</td>
<td>yes</td>
<td>satisfied</td>
<td>Susceptibility to fire is a major drawback of G.R.P.</td>
</tr>
<tr>
<td>dist. arch. (LP-5)</td>
<td>yes</td>
<td>satisfied</td>
<td>The use of plastics are limited because of fire hazards and the release of noxious gases.</td>
</tr>
<tr>
<td>country-arch (LP-21)</td>
<td>yes</td>
<td>satisfied</td>
<td>Concern has been expressed regarding the spread of flame externally across G.R.P. panels.</td>
</tr>
<tr>
<td>dist. arch. (LP-22)</td>
<td>yes</td>
<td>part-satis.</td>
<td>Second thoughts are being given in the field of plastics, because of behaviour in fire, melting points, etc. Probably G.R.P. comes under this category.</td>
</tr>
<tr>
<td>country-arch (LP-26)</td>
<td>yes</td>
<td>part-satis.</td>
<td>The fire-rating requirements of certain classes of buildings limit use of G.R.P. panels e.g. on multi-storey buildings.</td>
</tr>
<tr>
<td>country-arch (LQ-17)</td>
<td>yes</td>
<td>part-satis.</td>
<td>We are concerned with the fire aspects of G.R.P.</td>
</tr>
<tr>
<td>dist. arch. (LQ-18)</td>
<td>yes</td>
<td>part-satis</td>
<td>Since you are sufficiently interested in structural use, I believe there is more scope for an inherently 'fire-resistant' material such as G.R.C.</td>
</tr>
<tr>
<td>dist. arch. (LNM-8)</td>
<td>no</td>
<td>yes</td>
<td>Difficulty in obtaining a suitable design for fire regulations, particularly in Inner London</td>
</tr>
<tr>
<td>country-arch (LNM-13)</td>
<td>no</td>
<td>yes</td>
<td>Fire-resistance is of great importance.</td>
</tr>
<tr>
<td>Type of Organ.</td>
<td>Any G.R.P. exp.?</td>
<td>Satisfaction or Intention</td>
<td>Comment(s) made</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------</td>
<td>--------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>dist-arch (LNN-27)</td>
<td>no</td>
<td>yes</td>
<td>The use of G.R.P. must be appropriate to the building function and the associated fire-risks.</td>
</tr>
<tr>
<td>dist-arch (LNN-5)</td>
<td>no</td>
<td>no</td>
<td>There are difficulties in meeting the Building Regulations, especially where the distance from boundary is short.</td>
</tr>
<tr>
<td>dist-arch (LNN-9)</td>
<td>no</td>
<td>no</td>
<td>District Surveyors would not normally allow G.R.P. except for minor buildings or temporary licence.</td>
</tr>
<tr>
<td>dist-arch (LNN-10)</td>
<td>no</td>
<td>no</td>
<td>Would be prepared to consider use of G.R.P. if it is fire-resistant.</td>
</tr>
<tr>
<td>pri-arch (SP-1)</td>
<td>yes</td>
<td>satisfied</td>
<td>Correct resins could give 'fire-resistance' but they are expensive. The public and building surveyors are now cautious about G.R.P. quite wrongly, but they are and prejudice exists. G.R.C. is rapidly becoming a competitor for G.R.P. and at the moment it is appearing to have a good performance.</td>
</tr>
<tr>
<td>G.L.C.-arch (SP-2)</td>
<td>yes</td>
<td>part-sat.</td>
<td>The G.L.C. have built four 22 Storey blocks (housing); G.R.P. cladding was used. Most of the comparatively minor in-use problems have arisen from the 'fire-proofing' i.e. use of antimony oxide in the resin. The overlay of polyurethane finish failure - not extensively but may become so. Correct knowledge of plastics behaviour is large scale fire, particularly smoke generation, would prevent the architect proposing G.R.P. again - unless the behaviour of plastics could be moderated - this seems unlikely.</td>
</tr>
<tr>
<td>pri-arch (SP-4)</td>
<td>yes</td>
<td>satisfied</td>
<td>I am presently involved in my first project involving large areas of G.R.P. external cladding. We are employing specialist consultants. The building is a Section 20, under the London Building Act. Sample panels have been subjected to 'fire-test' in the presence of various G.L.C. and L.F.B. officials. The test was successful and the panels were passed.</td>
</tr>
<tr>
<td>London Transport Chief Arch (SP-26)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>High smoke and toxic fume risk when used in enclosed spaces and when used as external cladding in large areas subjected to heat from adjacent fires. The main limitation of this material is its inherent combustibility. All anti-fire treatments so far have had some other undesirable or potentially dangerous side effects.</td>
</tr>
<tr>
<td>pri-arch (SQ-5)</td>
<td>yes</td>
<td>satisfied</td>
<td>The association of fire risks with plastics generally has proved difficult when persuading clients in its use.</td>
</tr>
</tbody>
</table>

* See Table 8.8 for notes
(a) The majority of those who had used G.R.P. panels did not underestimate the fire risks associated with the use of G.R.P. panels; as may be seen from the above Table, out of 22 comments made on this subject, 14 are from those with G.R.P. experience, and these contain some very strong remarks and observations on the fire behaviour of G.R.P.

(b) Because of the difficulties in meeting the requirements of the present and proposed building and statutory regulations, some specifiers are avoiding the use of G.R.P. panels.

(c) Persuasion of clients to approve the use of G.R.P. panels has also been difficult.

(d) Obtaining approval from building and district surveyors, fire officers, etc., has been difficult and problematic.

(e) Present regulations virtually exclude the use of G.R.P. on buildings higher than 15m.

(f) Apart from one case, the rest of the specifiers do not appear to object to the extent of control exercised by various authorities under the Building Regulations and other legislation.

8.7.5 Extra cleaning problems:

As manifested by the figures in Table 8.7, there seems to be some disagreement amongst the specifiers with G.R.P. experience on the need for regular cleaning of exposed G.R.P. surfaces; in fact, about 9 per cent of the above group agreed that this problem was one of the main reasons for dissatisfaction, whilst about 10 per cent rejected this argument.

The frequency requirements for cleaning G.R.P. surfaces are dependent on the following:

(a) degree of atmospheric pollution of the surrounding environment;

(b) roughness of the surface (i.e. glossy surfaces are relatively more self-cleansing compared with rough textured surfaces);

(c) the geometry of the panel and the angle of tilt of the exposed planes relative to the vertical projection (e.g. upper and lower planes of a pyramidal cladding panel will be washed at different rates);

(d) the electrostatical affinity of G.R.P. surfaces for attracting dirt.

As has already been noted, 'cleaning requirements', 'maintenance requirements' and 'aesthetic appearance' of G.R.P. surfaces
are interrelated, because, as has been reported by many specifiers, the tendency is for dirt to collect in patches on the surface. These patches shield the material beneath from UV radiation effects consequently, the panel does not weather evenly and its aesthetic appearance is lowered.

Because of the above interrelation, it is possible that part of the dissatisfaction on the grounds of 'aesthetic appearance' of weathered G.R.P. surfaces has resulted from dirt accumulation which has been left uncleaned for long periods of time.

Table 8.17 gives a selection of comments and observations made by specifiers on the above problem.

8.7.6 Problems associated with site erection and jointing of G.R.P. panels:

This is one of the six standard arguments put forward as a possible cause for dissatisfaction with the use of G.R.P. panels (c.f. the questionnaire, Appendix A). However, as can be seen from Table 8.7, only about 5 per cent of the specifiers with G.R.P. experience agreed that site erection/jointing problems had caused their dissatisfaction, compared to 12 per cent rejecting the same argument.

The specifiers without G.R.P. experience saw complexity of site erection/jointing of G.R.P. panels as the fifth biggest disadvantage of G.R.P. panels; about 6 per cent agreed that this was a reason for their not considering future use of G.R.P. panels, compared to about 3 per cent who thought this argument was not relevant.

Site erection problems stem to a large extent from the lack of fit of panels onto their position on site; this in turn is determined by the variations of the dimensions of panels and also by variation/inaccuracies of the corresponding site dimensions. By adopting a correct design for the panel and by ensuring maximum accuracy in the dimensions of the mould, manufacturing variations can be minimized. However, constructional variations on site are less predictable, despite use of up-to-date 'setting-out' instruments.

Timber-based components/panels are amenable to site alteration using small tools; precast concrete panels are not as flexible and lack of fit may prove problematic. G.R.P. units and panels are not amenable to site alteration due to the tendency to splitting and cracking of the laminate edges, etc.; in many cases, corner and odd units will have to be left out until all other units have
Table 8.17  Comments related to cleaning requirement of exposed G.R.P. surfaces

<table>
<thead>
<tr>
<th>Type of Organis. (ref.code)</th>
<th>Any G.R.P. exp.?</th>
<th>Satisfaction or Intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri-arch (AP-1) yes part-satisfied If a semi-glazed finish is used then it may be self washing, but surfaces simulating any rougher materials may well require more cleaning and the degree of difficulty in doing so may well relate to the area in which the building is located (i.e. atmospheric.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pri-arch (ANW-8) no yes If the material is used on a visual situation, it should be self-cleansing and anti-static.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dist-arch (LP-24) yes part-satisfied G.R.P. is not self cleansing as a surface material - a greasy film evolves on the surface requiring regular cleaning - more difficult to remove dirt than from glass or smooth sheet materials, irregular dirtying of surfaces cause differential fading through varying light transmission; surfaces must be kept absolutely clean during early stage of life of building.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dist-arch (LP-31) yes dissatisfied Dirt collection is a problem in many cases.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* See Table 8.8 for notes
been erected, so that the site dimensions may be taken and used appropriately to modify the relevant moulds prior to moulding of these corner and odd units.

Table 8.18 contains a selection of special comments on the above problem and other aspects, such as complexity of joint designs and fixing, etc., made by the specifiers with G.R.P. experience.

It must be noted that part of the complexity of site jointing/fixing of G.R.P. panels is associated with the relatively low value of the modulus of elasticity of this material; thus, if the fixings are not sufficiently close to each other, the panel edge will distort and the joint gap will increase in width; not only does this result in visual distortion of lines and planes, but it will seriously undermine the performance efficiency of the joint (see also 8.7.7 below).

8.7.7 Other disadvantages of G.R.P. panels:

8.7.7.1 Thermal movement problems:

As may be seen from the comments and observations included in Table 8.19 below, two basically different problems are caused by thermal movement of G.R.P. panels, viz:

(a) excessive linear or planar expansion: there have been numerous problems because of excessive G.R.P. expansion;

(b) warping or bowing of the panels: this problem is particularly acute when large sized sandwich panels are used, in which case the outer and inner faces expand at different rates, causing warping or core failure (if the core material is weak in shear) or debonding/delaminating (if the interfacial/interlaminar bond is weak).

Use of a dark colour, non-glazed (matt) surface and large sized and flat profiles increases the magnitude of thermal problems; panel orientation also has some effect. Thus, the worst combination is the case of a fairly flat, south-facing panel with a non-glazed black finished surface (c.f. Table 8.19 and see also 8.7.7.2 below).

8.7.7.2 Problems associated with the relatively low modulus of elasticity of G.R.P.:

Although, to a large extent, the problems of low rigidity of G.R.P. panels can be avoided by careful designing and detailing of these panels, nevertheless, it is not always possible or economical to design very stiff panels without the use of other materials
Table 8.18 Comments on problems of site erection/jointing of G.R.P. panels

<table>
<thead>
<tr>
<th>Type of Organis.</th>
<th>Any G.R.P. exp.?</th>
<th>Satisfaction or Intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri-arch (AP-1)</td>
<td>yes</td>
<td>part-satisfied</td>
<td>Use of G.R.P. panels require more complex fixings, unless they are designed and reinforced with other materials for sufficient rigidity against imposed load/thermal distation</td>
</tr>
<tr>
<td>dist-arch (LP-31)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>Manufacturing and erection problems.</td>
</tr>
<tr>
<td>country-arch (LQ-19)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>We are disturbed by discrepancies in dimensional tolerances; also disappointed by discrepancies in finish.</td>
</tr>
<tr>
<td>pri-arch (SP-9)</td>
<td>yes</td>
<td>satisfied</td>
<td>Damage of panels in transit and storage difficult to overcome; ideally the panels should be made on site. Tolerances, particularly in relation to supporting structures need careful attention. Economic justification for using G.R.P. is dependent on early consideration of jointing and fixing practicalities.</td>
</tr>
<tr>
<td>pri-arch (SP-10)</td>
<td>yes</td>
<td>satisfied</td>
<td>A disadvantage of G.R.P. is related to the jointing problems.</td>
</tr>
</tbody>
</table>

* See Table 8.8 for notes
Table 8.19† Observations on Problems of Thermal Movements of G.R.P.

<table>
<thead>
<tr>
<th>Type of organisation</th>
<th>any satisfaction or intention</th>
<th>Comments made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri. arch. (AQ - 22)</td>
<td>yes dissatisfied</td>
<td>Movements of G.R.P. panels backed with insulation are excessive due to build-up of heat. Panels had to be 're-glazed' into frames with special sealant to allow for movements of much greater size than anticipated.</td>
</tr>
<tr>
<td>dist. arch. (LP - 14)</td>
<td>yes satisfied</td>
<td>I found that thermal movements of inner and outer skins of cladding being different were a problem.</td>
</tr>
<tr>
<td>county arch. (LP - 26)</td>
<td>yes part. sat.</td>
<td>G.R.P. has limited use as a cladding material due to problems of thermal movements, particularly with dark colours.</td>
</tr>
<tr>
<td>county arch. (LQ - 17)</td>
<td>yes part. sat.</td>
<td>Black panels bowed on south elevation (thermal problems).</td>
</tr>
<tr>
<td>dist. arch. (LQ - 20)</td>
<td>yes dissatisfied</td>
<td>Excessive thermal expansion caused panels to bow outwards in the heat of the sun.</td>
</tr>
<tr>
<td>dist. arch. (LQ - 25)</td>
<td>yes dissatisfied</td>
<td>Thermal expansion can cause delamination if the panel is made up as a composite unit.</td>
</tr>
<tr>
<td>county arch. (LNN - 13)</td>
<td>no yes</td>
<td>Thermal movements in large panels affect tolerances, sizes, fixings, etc.</td>
</tr>
<tr>
<td>dist. arch. (LNN - 5)</td>
<td>no no</td>
<td>We were disappointed to observe excessive thermal movements which had occurred in the case of a G.R.P. swimming pool cover structure.</td>
</tr>
<tr>
<td>dist. arch. (LNN - 7)</td>
<td>no no</td>
<td>High thermal coefficient of expansion presents greater difficulty in designing suitable joints.</td>
</tr>
</tbody>
</table>

† - see Table 8.8 for notes.
either as struts and beams laminated on the reverse side of the panel, or as a core in a sandwich construction. Use of stiffening ribs may cause surface distortion of the panels when subjected to thermal stresses, either due to restraining of the outer skin by these stiffeners, or, if a sandwich construction is used, due to restraint of the interfacial bond between the core material and the outer skin.

Use of a stiff substrate layer or core material (such as asbestos-cement, etc.) may be considered. However, since these are usually flat, they could restrict the shaping of G.R.P. panels. The most successful way of dealing with this problem is to use some form of three dimensional shaping, such as pyramids, etc. (c.f. section 5.7).

Table 8.20 contains a selection of comments made by specifiers on the above problem (see also 8.7.2)

8.7.7.3 Miscellaneous problems:
In connection with a G.R.P. roof, used in coastal areas, incorporating translucent sections, an authority (County Architects' Department, Ref. code LP - 27) who were partially satisfied with performance of the G.R.P. observed the following problems:
(a) glare is difficult to control;
(b) seagulls tend to peck at the material and droppings become a problem;
(c) solar gain; and
(d) drumming of rainfall.

8.8 Adequacy of Production Methods; Perceived State of the G.R.P. Processing Industry and Quality Control Aspects:
As the above factors are closely interrelated, it was felt wrong to distinguish one from the others, especially since the majority of building panels are produced employing the contact-moulding process. Therefore, the following is a combined discussion of the responses of the specifiers to questions 7 and 8 of the questionnaire, which read as follows (c.f. Appendix A):

7. Would you consider the hand-lay method of production of G.R.P. for the construction industry is outdated?
8. If your answer is YES to question 7, does this imply that you consider mechanical means should be employed to manufacture G.R.P. laminate components?

The purpose of these questions was to find out to what extent
Table 8.20† Special Comments on Problems of Low Rigidity of G.R.P. Panels

<table>
<thead>
<tr>
<th>Type of organisation (Ref. code)</th>
<th>Any satisfaction of G.R.P. or intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri. arch. (AP - 1)</td>
<td>yes partial sat.</td>
<td>It is possible to make a fairly large panel robust enough to handle, but not strong enough to cope with loads without considerable extra expense - either there is need to reinforce the panel itself, which increases its weight, or it demands a more complex back-up on the building structure and the use of more complex fixings.</td>
</tr>
<tr>
<td>cons. eng. (CQ - 5)</td>
<td>yes partial sat.</td>
<td>G.R.P. has a low modulus of elasticity. In present structures, deflection problems will always govern and this is a pity, since the material has tremendous possibilities.</td>
</tr>
<tr>
<td>county arch. (LQ - 24)</td>
<td>yes dissatisfied</td>
<td>G.R.P. has too low a modulus of elasticity for use in simple load-bearing forms on its own and needs to be in complex shapes (shells) or stiffened by other materials. In either case this involves manufacturing problems.</td>
</tr>
<tr>
<td>dist. arch. (LNN -7)</td>
<td>no no</td>
<td>By the very nature of G.R.P. surfaces, even the slightest distortions can be most noticeable and objectionable.</td>
</tr>
<tr>
<td>county arch. (LNN -11)</td>
<td>no no</td>
<td>Some products show unevenness and irregularity which stems from lack of rigidity.</td>
</tr>
<tr>
<td>dist. arch. (LNN -13)</td>
<td>no no</td>
<td>Because of the relatively low modulus of elasticity, plastic deformation can be high.</td>
</tr>
<tr>
<td>GLC arch. SP - 25</td>
<td>yes partial sat.</td>
<td>Not suitable for load-bearing purposes due to creep, low modulus of elasticity, etc.</td>
</tr>
</tbody>
</table>

† - see Table 8.8 for notes.
the specifiers' intentions as to the use of G.R.P. have been affected by the production characteristics of G.R.P. panels. This information is supplemented by replies to question 9, which was aimed at discovering how far architects are prepared to trade 'quality' and 'economy' afforded by mechanically produced products against architectural parameters such as 'character' of buildings, site geometry and local conditions, etc. Thus, questions 7, 8 and 9 are interrelated.

Tables 8.21 and 8.22 illustrate the general pattern of replies to the above questions. It can be seen that about 35.6 per cent of the specifiers with G.R.P. experience agreed that the hand-lay method was outdated, compared with 30.5 per cent who rejected this argument; and 9 per cent who stated that their reply to this question would depend on the case under consideration.

The pattern of reply in the case of specifiers without G.R.P. experience was as follows: 23.5 per cent considered that the hand-lay method was outdated; 15.2 per cent disagreed; and 1.2 per cent stated that their reply would depend on the case under consideration. In short, the majority of the specifiers saw a deficiency in the hand-lay method of production. However, a more accurate picture of the specifiers' attitudes towards the production processes is obtained by study of their comments as selected and included in Table 8.23.

The fact that specifiers generally favoured the use of mechanical production means (subject to economic considerations) is beyond doubt. Nearly those with G.R.P. experience who disfavoured the hand-lay method preferred the use of mechanical means; in addition, some of those who considered that hand-lay was outdated still backed the use of mechanical means of production; only one authority rejected this idea (c.f. Table 8.21).

In the case of specifiers without G.R.P. experience, 87 per cent of those who had agreed that the hand-lay method was outdated favoured use of mechanical means of production, compared with 15 per cent rejecting the idea (c.f. Table 8.22).

Table 8.24 contains a selection of the special comments made by the specifiers on the necessity of employing mechanical production means for G.R.P. panels in the construction industry.

Summary of Tables 8.23 and 8.24: The following points may be observed:

(1) Many specifiers are sceptical of the hand-lay method, regardless of the economic implications, i.e. they view this pro-
Table 8.21 Attitudes of Group 1 Specifiers (with G.R.P. experience) on the Adequacy of Production Processes

<table>
<thead>
<tr>
<th>(I) Question Number:</th>
<th>(II) Yes</th>
<th>(III) No</th>
<th>(IV) Depends</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. %</td>
<td>No. %</td>
<td>No. %</td>
</tr>
<tr>
<td>7. Hand‐lay outdated?</td>
<td>56 35.6</td>
<td>48 30.6</td>
<td>14 9</td>
</tr>
<tr>
<td>8. Mechanical produc-</td>
<td>63 40.0</td>
<td>1 0.6</td>
<td>- -</td>
</tr>
<tr>
<td>tion means?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Use of standard</td>
<td>103 65.6</td>
<td>18 11.5</td>
<td>- -</td>
</tr>
<tr>
<td>panels/systems?</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* - Percentage of total number of specifiers in Group 1, i.e. 157.

Table 8.22 Attitudes of Group 2 Specifiers (without G.R.P experience) on the Adequacy of Production Processes

<table>
<thead>
<tr>
<th>(I) Question Number:</th>
<th>(II) yes</th>
<th>(III) No</th>
<th>(IV) Depends</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. %</td>
<td>No. %</td>
<td>No. %</td>
</tr>
<tr>
<td>7. Hand‐lay outdated?</td>
<td>38 23.2</td>
<td>25 15.2</td>
<td>2 1.2</td>
</tr>
<tr>
<td>8. Mechanical produc-</td>
<td>33 20.0</td>
<td>5 3.2</td>
<td>- -</td>
</tr>
<tr>
<td>tion means?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Use of standard</td>
<td>67 41.0</td>
<td>11 6.7</td>
<td>- -</td>
</tr>
<tr>
<td>panels/systems</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* - Percentage of total number of specifiers in Group 2, i.e. 164.
Table 8.23  A selection of comments on the adequacy of the hand-lay method/quality control and the state of the G.R.P. processing industry.

<table>
<thead>
<tr>
<th>Type of organisation (Ref. code)</th>
<th>any G.R.P. or intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri. arch. (AP - 1)</td>
<td>yes part. sat.</td>
<td>Whether or not the hand-lay method is outdated depends on what is being made. A sprayed lay-up is obviously more desirable from a manufacturing point of view, but the efficiency and cost of the equipment are still problematical for the small operator.</td>
</tr>
<tr>
<td>pri. arch. (AP - 3)</td>
<td>yes satisfied</td>
<td>G.R.P. may be used more when there are more firms available: (i) to produce; (ii) to supply and fix; and (iii) availability.</td>
</tr>
<tr>
<td>pri. arch. (AP - 9)</td>
<td>yes satisfied</td>
<td>[outdated] - mainly because of labour content; a most expensive item these days.</td>
</tr>
<tr>
<td>pri. arch. (AP - 15)</td>
<td>yes satisfied</td>
<td>Hand-lay is outdated in developed countries, but particularly applicable in emergent countries.</td>
</tr>
<tr>
<td>pri. arch. (AP - 16)</td>
<td>yes satisfied</td>
<td>Hand-lay is not outdated; for high quality, large flat surface infill panels, we found the hand-lay-up method much more successful in terms of finish. Also, at present no significant reduction in tender price is achieved by specifying the spray technique; it seems that some manufacturers prefer hand-lay-up, as there is much less wastage.</td>
</tr>
<tr>
<td>pri. arch. (AQ - 3)</td>
<td>yes satisfied</td>
<td>Whilst 'hand-lay' may be slow and expensive, I do not see a satisfactory alternative for complex shapes and therefore one must accept the cost involvement.</td>
</tr>
<tr>
<td>Type of organisation (Ref. code)</td>
<td>any G.R.P. satisfaction or intention</td>
<td>Comment(s) made</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>pri. arch. (AQ - 6)</td>
<td>yes satisfied</td>
<td>Hand-lay allows for formation of complex shapes without cost penalty of expensive dies. Seems to be a new outlet for real craftsmanship in that operatives seem to achieve considerable job satisfaction.</td>
</tr>
<tr>
<td>pri. arch. (ANW - 19)</td>
<td>no yes</td>
<td>Tactical use of hand-lay in conjunction with mass-production.</td>
</tr>
<tr>
<td>cons. eng. (CQ - 4)</td>
<td>yes part. sat.</td>
<td>Whilst the hand-lay method exists the shape and complexity of units are viable. Mechanical means might be too restrictive. There is too much financial instability among producers to have confidence in their products. There is too much change in resins, fillers, etc. by manufacturers after their own basic research is done, rendering their test results invalid.</td>
</tr>
<tr>
<td>dist. arch. (LP - 2)</td>
<td>yes satisfied</td>
<td>There is still some use for 'hand-lay', but progressively mechanical means produce economy.</td>
</tr>
<tr>
<td>dist. arch. (LP - 4)</td>
<td>yes satisfied</td>
<td>The question of production method really depends on the type and complexity of the required panels; some may well lend themselves to mechanical manufacture.</td>
</tr>
<tr>
<td>dist. arch. (LP - 6)</td>
<td>yes satisfied</td>
<td>To a degree 'hand-lay' is outdated. Consider G.R.P. work as a parallel to joinery work: maximum mechanization is used to obtain economy with fine quality in long run production of standard items, but 'hand' production (i.e. power tool assisted craftsmen remains an essential part of building joinery. Note also the R.C. precast methods - fully mechanized floor beams production, but short run cladding panels made by hand.</td>
</tr>
<tr>
<td>Type of organisation (Ref. code)</td>
<td>G.R.P.</td>
<td>satisfaction or</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------</td>
<td>----------------</td>
</tr>
<tr>
<td>dist. arch. (LP - 11)</td>
<td>yes</td>
<td>satisfied</td>
</tr>
<tr>
<td>dist. arch. (LP - 14)</td>
<td>yes</td>
<td>satisfied</td>
</tr>
<tr>
<td>dist. arch. (LP - 24)</td>
<td>yes</td>
<td>part. sat.</td>
</tr>
<tr>
<td>dist. arch. (LP - 29)</td>
<td>yes</td>
<td>dissatisfied</td>
</tr>
<tr>
<td>dist. arch. (LP - 31)</td>
<td>yes</td>
<td>dissatisfied</td>
</tr>
<tr>
<td>county arch. (LP - 33)</td>
<td>yes</td>
<td>dissatisfied</td>
</tr>
<tr>
<td>Type of organisation</td>
<td>G.R.P.</td>
<td>satisfaction or intention</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>dist. arch. (LP - 34)</td>
<td>yes</td>
<td>dissatisfied</td>
</tr>
<tr>
<td>dist. arch. (LQ - 1)</td>
<td>yes</td>
<td>satisfied</td>
</tr>
<tr>
<td>county arch. (LQ - 2)</td>
<td>yes</td>
<td>satisfied</td>
</tr>
<tr>
<td>dist. arch. (LQ - 4)</td>
<td>yes</td>
<td>satisfied</td>
</tr>
<tr>
<td>county arch. (LQ - 17)</td>
<td>yes</td>
<td>part. sat.</td>
</tr>
<tr>
<td>county arch. (LQ - 194)</td>
<td>yes</td>
<td>dissatisfied</td>
</tr>
</tbody>
</table>
Table 8.23 Contd.

<table>
<thead>
<tr>
<th>Type of organisation (Ref. code)</th>
<th>any G.R.P. satisfaction or exp.? intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>County arch. (LQ - 24)</td>
<td>yes dissatisfied</td>
<td>Use of 'hand-lay' precludes significant lowering of the costs.</td>
</tr>
<tr>
<td>dist. arch. (LQ - 25)</td>
<td>yes dissatisfied</td>
<td>Hand-lay production is subject to variations. Inadequate supervision becomes critical.</td>
</tr>
<tr>
<td>county arch. (LNW - 13)</td>
<td>no yes</td>
<td>Mould costs can be over-emphasized. Modular moulds could provide real economies [handlay is not necessarily outdated].</td>
</tr>
<tr>
<td>dist. arch. (LNW - 22)</td>
<td>no yes</td>
<td>Hand-lay is outdated - like many other things in the construction industry!!</td>
</tr>
<tr>
<td>dist. arch. (LNN - 7)</td>
<td>no no</td>
<td>The hand-lay process is slow and could give rise to variation and distortion in finished panels.</td>
</tr>
<tr>
<td>pri. arch. (SP - 2)</td>
<td>yes satisfied</td>
<td>'Hand-lay' gives better quality control.</td>
</tr>
<tr>
<td>pri. arch. (SP - 4)</td>
<td>yes satisfied</td>
<td>I am advised by certain specialists and manufacturers that 'hand-lay' is still more reliable for complex units.</td>
</tr>
<tr>
<td>pri. arch. (SP - 6)</td>
<td>yes satisfied</td>
<td>Perhaps more accurate to say we find that 'G.R.P. industry' - manufacturer - is relatively underdeveloped and unsophisticated.</td>
</tr>
<tr>
<td>Type of organisation (Ref. code)</td>
<td>G.R.P. exp.?</td>
<td>any satisfaction or intention</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>pri. arch. (SP - 7)</td>
<td>yes</td>
<td>satisfied</td>
</tr>
<tr>
<td>pri. arch. cons. eng. (SP - 12)</td>
<td>yes</td>
<td>satisfied</td>
</tr>
<tr>
<td>pri. arch. (SP - 21)</td>
<td>yes</td>
<td>part. sat.</td>
</tr>
<tr>
<td>pri. arch. (SP - 23)</td>
<td>yes</td>
<td>part. sat.</td>
</tr>
<tr>
<td>pri. arch. (SQ - 11)</td>
<td>yes</td>
<td>dissatisfied</td>
</tr>
</tbody>
</table>

+ - see Table 8.8 for notes.
Table 8.24 A selection of comments on the need for employment of mechanical means

<table>
<thead>
<tr>
<th>Type of organisation (Ref. code)</th>
<th>any satisfaction or intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri. arch. (ANW - 19)</td>
<td>no</td>
<td>Limited as all precast/prefab. work to the market. As long as there is a free market, there is a problem of standardization. We are contemplating our standard panels for 12 bays only.</td>
</tr>
<tr>
<td>dist. arch. (LQ - 4)</td>
<td>yes</td>
<td>Mechanical means are for production demand and quality control</td>
</tr>
<tr>
<td>dist. arch. (LQ - 18)</td>
<td>yes</td>
<td>If mechanical production implies loss of ability to produce complex shapes, then a major advantage of G.R.P. may well have disappeared.</td>
</tr>
<tr>
<td>dist. arch. (LQ - 21)</td>
<td>yes</td>
<td>Mechanical means should probably help to obtain a much more accurate dimensional unit for fixing to site-erected framing.</td>
</tr>
<tr>
<td>cons. eng. (CQ - 4)</td>
<td>yes</td>
<td>Mechanical means are probably too restrictive.</td>
</tr>
<tr>
<td>cons. eng. (CNW - 13)</td>
<td>no</td>
<td>Machine made components have superior quality. To realize full potential of G.R.P., use of machine fabrication is essential.</td>
</tr>
<tr>
<td>pri. arch. (SP - 18)</td>
<td>yes</td>
<td>In general, hot press and similar techniques are not viable when related to the pace of building construction.</td>
</tr>
<tr>
<td>Type of organisation (Ref. code)</td>
<td>any G.R.P. exp.?</td>
<td>satisfaction or intention</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>pri. arch. (SP - 23)</td>
<td>yes</td>
<td>part. sat.</td>
</tr>
<tr>
<td>pri. arch. (SQ - 3)</td>
<td>yes</td>
<td>satisfied</td>
</tr>
<tr>
<td>pri. arch. (SNW - 8)</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>pri. arch. (SNW - 9)</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

+ see Table 8.8 for notes
duction technique as technically inferior and not amenable to both satisfactory quality control and acceptable dimensional variations.

(2) Some specifiers with previous G.R.P. experience are unwilling to specify hand-laminated products again because they are dissatisfied with the quality control aspects of the contact-moulding process.

(3) There is ample indication that many specifiers without G.R.P. experience do not trust G.R.P. units produced by the contact-moulding process. They do not trust that there is adequate technical awareness of the building industry's requirements amongst the G.R.P. processors.

(4) Some of the specifiers who did not agree that the hand-lay method was outdated are, in fact, fully aware of the technical shortcomings of the production process. They consider that either it is the only production process which is economically viable for the comparatively low unit repetition of most G.R.P. projects, or that this process is complementary to mechanical means of production and must be retained for odd units, corners, etc.

(5) Some specifiers, however, are in favour of the contact-moulding process in general because they consider it is probably more appropriate to the speed of construction in general and gives greater flexibility in composition, size, shape, quality, etc., of G.R.P. panels. One authority observed that it could even revive real craftsmanship in the construction industry, since there is a certain degree of job satisfaction enjoyed by makers of G.R.P. units.

(6) Mechanical means of production were generally favoured because of improved quality control and dimensional accuracy. In addition, many hoped that mechanically means could eventually result in considerable lowering of the costs, especially for modular buildings.

(7) Some specifiers warned against possible design inflexibility of mechanically produced units; the failure of earlier mechanically produced precast concrete panels has been cited as an example of too restrictive design approaches.

8.9 Standard Panels/Systems:

The discussion on this subject is essentially based on the responses received to question 9 of the questionnaire, which read as follows (c.f. Appendix A):
9. Processing G.R.P. by mechanical means is not economic unless a large number of units are produced from the same mould. Would you be willing to use units which are identical to units on another construction site, and which were placed by one of your competitors?

The general pattern of replies was as follows: Nearly 65.6 per cent of the specifiers with G.R.P. experience gave positive replies to the above question and 11.5 per cent gave negative replies (c.f. Table 8.21). The corresponding figures for the specifiers without G.R.P. experience are 41 and 6.7 per cent respectively (c.f. Table 8.22). Thus, the overall response of the specifiers to the acceptability of standard panels/systems appears to be favourable. However, as with questions 7 and 8, the above question attracted a very large number of comments and qualifications, etc.; this is an indication that a mere positive or negative reply to this question is not adequate in itself to give a correct picture of the matter. In fact, some specifiers stated that it was impossible for them to generalize on this problem, since their decision would entirely depend on the case under consideration.

Table 8.25 contains a selection of a range of comments made by specifiers on the above problem.

A study of this table leads to the following observations:

(1) If it can be shown that there will be significant cost-savings associated with the use of standard G.R.P. panels/systems compared with alternative materials, then there is a market for such G.R.P. products, especially in the public sector of the construction industry; where the design and development may be undertaken in association with various local authority consortia using the accepted design module.

(2) However, the success of any standard mass-produced panel/system depends on the quality of design and flexibility in application. This implies that adequate research work must be carried out to identify optimum performance requirements derived from a range of buildings and users' needs, etc.; and also, special attention must be paid to the details of the design, including aesthetics. In addition, flexibility of incorporating individual components/units of a standard system in conventional or semi-industrialized buildings should be considered, since this will reduce the commercial risks to a large extent (c.f. Chapter 11).
<table>
<thead>
<tr>
<th>Type of organisation (Ref. code)</th>
<th>any</th>
<th>satisfaction or intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri. arch. (AP - 1)</td>
<td>yes</td>
<td>part. sat.</td>
<td>[yes]. This seems an obvious and logical progression and compares with the Theses behind both concrete and timber building systems, but lessons must be learnt in that they will never be really successful unless the initial research is done and a suitable flexible system is produced.</td>
</tr>
<tr>
<td>pri. arch. (AP - 5)</td>
<td>yes</td>
<td>satisfied</td>
<td>Very unlikely. Most attempts at standard panels are very flashy and corny in design.</td>
</tr>
<tr>
<td>pri. arch. (AP - 11)</td>
<td>yes</td>
<td>satisfied</td>
<td>[yes] - subject to copyright (of the design).</td>
</tr>
<tr>
<td>pri. arch. (ANW - 19)</td>
<td>no</td>
<td>yes</td>
<td>If they fit the bill, of course.</td>
</tr>
<tr>
<td>cons. eng. (CP - 1)</td>
<td>yes</td>
<td>dissatisfied</td>
<td>Any range of standard panels would have to offer a wide variety.</td>
</tr>
<tr>
<td>cons. eng. (CP - 10)</td>
<td>yes</td>
<td>satisfied</td>
<td>Yes - as an engineer, but most clients (and their architects) would not.</td>
</tr>
<tr>
<td>cons. eng. (CNW - 10)</td>
<td>no</td>
<td>yes</td>
<td>I would use standard panels, provided these did not create an identical effect.</td>
</tr>
<tr>
<td>dist. arch. (LP - 4)</td>
<td>yes</td>
<td>satisfied</td>
<td>I can see no reason why G.R.P. units should not be treated in a similar way to other standard type units, e.g. stainless steel, enameled, PVC, etc.</td>
</tr>
<tr>
<td>Type of organisation (Ref. code)</td>
<td>any satisfaction or intention</td>
<td>Comment(s) made</td>
<td></td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------------------------------</td>
<td>-----------------</td>
<td></td>
</tr>
<tr>
<td>dist. arch. (LP - 6)</td>
<td>yes satisfied</td>
<td>Panels would need to have a certain flexibility of application design-wise to remain acceptable (e.g. as standard windows, corrugated cladding sheets, etc., which have these characteristics).</td>
<td></td>
</tr>
<tr>
<td>dist. arch. (LP - 12)</td>
<td>yes satisfied</td>
<td>Further development should take place with G.R.P. and standardized jointing methods evolved. Standardized units should be viable, similar to the standard ranges, e.g. windows, i.e. possible use of fixed increments of, say, 300mm on width and height.</td>
<td></td>
</tr>
<tr>
<td>dist. arch. (LP - 13)</td>
<td>yes satisfied</td>
<td>The whole purpose is surely to provide individuality.</td>
<td></td>
</tr>
<tr>
<td>dist. arch. (LP - 14)</td>
<td>yes satisfied</td>
<td>Mass production of a special panel; I would say only welcome in 'industry building' and temporary structures.</td>
<td></td>
</tr>
<tr>
<td>dist. arch. (LP - 15)</td>
<td>yes satisfied</td>
<td>Some degree of mechanization appears logical if the price is to be competitive.</td>
<td></td>
</tr>
<tr>
<td>county arch. (LP - 18)</td>
<td>yes satisfied</td>
<td>We would like to say 'yes' to standardized panels, but it is still probably cheaper to assemble the components of a sandwich wall on site.</td>
<td></td>
</tr>
<tr>
<td>county arch. (LP - 24)</td>
<td>yes part. sat.</td>
<td>&quot;identical to units on another construction site&quot;: Most building solutions imply a response to particular clients or 'locale' requirements - it is unlikely that a whole unit would be relevant repeated on totally different sites unless total project economies are placed before the total architectural considerations of a site/building (which includes technology and economic considerations).</td>
<td></td>
</tr>
</tbody>
</table>
Table 8.25  Contd.

<table>
<thead>
<tr>
<th>Type of organisation (Ref. code)</th>
<th>any satisfaction or intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>dist. arch. (LP - 29)</td>
<td>yes dissatisfied</td>
<td>Yes - provided: (a) span; (b) appearance; and (c) performance were known to be satisfactory.</td>
</tr>
<tr>
<td>dist. arch. (LQ - 7)</td>
<td>yes satisfied</td>
<td>A sufficient variety of panels should be produced by different manufacturers to avoid repetition on too many sites.</td>
</tr>
<tr>
<td>county arch. (LQ - 17)</td>
<td>yes part. sat.</td>
<td>If a situation arose where units used on another building were the right answer for a building of ours, then I would see no objection. Proximity, colour, building type would have to be taken into account, e.g. school not far from a factory using same units.</td>
</tr>
<tr>
<td>county arch. (LQ - 19)</td>
<td>yes dissatisfied</td>
<td>Yes - most local authorities use a common dimensional discipline in their design work and it would not be difficult to co-ordinate requirements in this field.</td>
</tr>
<tr>
<td>county arch. (LQ - 24)</td>
<td>yes dissatisfied</td>
<td>No - mass production by mechanical means is the key to lowering costs, but mass repetition of a few basic designs would meet with strong resistance by project architects.</td>
</tr>
<tr>
<td>dist. arch. (LQ - 25)</td>
<td>yes dissatisfied</td>
<td>Yes - providing that there was a reasonably wide modular based range to choose from.</td>
</tr>
<tr>
<td>county arch. (LNW - 2)</td>
<td>no yes</td>
<td>There are opportunities for the development of G.R.P. panels both structural and cladding in association with the various local authority consortia in CLASP, SCOLA, CLAW, METHOD, etc.</td>
</tr>
</tbody>
</table>
Table 8.25  Contd.

<table>
<thead>
<tr>
<th>Type of organisation (Ref. code)</th>
<th>any satisfaction or intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>dist. arch. (LNW - 7)</td>
<td>no</td>
<td>[Yes] - As L.A. planning is now generally to a modular grid, standard panels somewhat similar in width to the standard windows with various surface textures should be acceptable for a wide range of buildings.</td>
</tr>
<tr>
<td>dist arch. (LNW - 10)</td>
<td>no</td>
<td>I am in favour of G.R.P. development for system building particularly.</td>
</tr>
<tr>
<td>county arch. (LNW - 13)</td>
<td>no</td>
<td>No - not necessarily. There is an urgent need for standardization on an effective panel to panel jointing system that deals not only with horizontal and vertical joints, but also the 'cross-over' problem. Given this, I think standard panels can become viable.</td>
</tr>
<tr>
<td>pri. arch. (SP - 11)</td>
<td>yes</td>
<td>Yes, in certain circumstances. No one wants all buildings to appear similar, but this need not happen with a sensible design approach - and there is always the economic factor to weigh.</td>
</tr>
<tr>
<td>cons. eng. (SP - 12)</td>
<td>yes</td>
<td>This is most likely in the case of load-bearing units and panels and less likely in the case of non-load-bearing and exposed units, which are unlikely to fit the individual requirements of another architect.</td>
</tr>
<tr>
<td>cons. eng. (SP - 13)</td>
<td>yes</td>
<td>I would use standard panels as an Engineer, but most architects will insist on designing their own shape. If they cannot, they will not use G.R.P.</td>
</tr>
<tr>
<td>Type of organisation (Ref. code)</td>
<td>G.R.P. or intention</td>
<td>Comment(s) made</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>---------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Brit. Rail Plastics Dev't Unit (SP - 15)</td>
<td>yes satisfied</td>
<td>We only design and develop to our clients' requests, but would consider the answer to be NO, on their behalf. Nevertheless, the idea is economically commendable.</td>
</tr>
<tr>
<td>pri. arch. (SP - 20)</td>
<td>yes part. sat.</td>
<td>[Yes]. But this presupposes a more mature approach to the design of units than seen in a great deal of work which appears over-styled and mannered.</td>
</tr>
<tr>
<td>pri. arch. (SP - 21)</td>
<td>yes part. sat.</td>
<td>[Yes]. I consider there could be a number of variations in basic units which, when joined together, could give a variety of expressions.</td>
</tr>
<tr>
<td>cons. eng. + pri. arch. (SP - 22)</td>
<td>yes part. sat.</td>
<td>It would depend on building and client. An industrial building might well use standard or repeat panels. Prestige office unlikely to - It also depends how identifiable is the panel in appearance.</td>
</tr>
<tr>
<td>pri. arch. (SP - 23)</td>
<td>yes part. sat.</td>
<td>[Yes] - provided that the appearance and performance of the panels exactly suited the job. As all buildings tend to have indiosyncrasies, this may not be possible - witness the failure of the &quot;open-component&quot; co-ordinated approaches - and the sterility of the end results in systems built schools, etc. It largely depends on the component designer/manufacturer - I would mind using Jean Prouve's panels (though they are steel).</td>
</tr>
</tbody>
</table>
Table 8.25 Contd.

<table>
<thead>
<tr>
<th>Type of organisation (Ref. code)</th>
<th>any satisfaction or intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri. arch. (SNW - 8)</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Building Contr.'s chief arch. (SNW - 10)</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

+ - see Table 8.8 for notes
Identical effects on different building projects are not generally accepted unless these are practically unidentifiable. Thus, the design calls for a variety of standard units, helped by intelligent use of colours and surface textures, etc.

The function and location of a building will affect the choice of design. For example, there is a greater chance for acceptance of a standard panel/system in an educational building than in a prestige office block.

Load-bearing and self-supporting panels/systems are more likely to be used and accepted than non-load-bearing and decorative ones, especially if the panels/systems form an integral part of a comprehensive package deal, e.g. combined with structural framing, glazing, insulation, lining, etc.

Given all the above factors, there are still some specifiers who are strongly opposed to the basic idea of standard panels/systems.

8.10 Miscellaneous Considerations:

8.10.1 Perceived competitors for G.R.P. panels:

Although there was no provision for enquiring about this aspect of G.R.P. panels, some specifiers made passing reference in their comments to competing materials; from these comments, it appears that brickwork is a current favourite and that G.R.C. is rapidly becoming a competitor.

Table 8.26 contains a selection of the relevant comments; it can be seen that some specifiers with G.R.P. experience have turned to G.R.C., though long term performance of the latter is still in question. G.R.C. has the psychological advantage of belonging to the cement and concrete family. However, there are other advantages, viz: incombustibility, higher panel stiffness and the possibility of more mechanized production techniques; these would help to reduce the resistance in the construction market (c.f. Table 8.26).

8.10.2 Perceived future of G.R.P. in the construction industry:

This is another aspect not specifically covered in the G.R.P. questionnaire, and the information for this discussion is extracted from comments/observations made by specifiers under 'general comments' at the end of the questionnaire.

Table 8.27 contains a selection of the relevant comments;
Table 8.26+  Perceived competitors for G.R.P. panels

<table>
<thead>
<tr>
<th>Type of organisation (Ref. code)</th>
<th>Type of satisfaction</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri. arch. (AQ - 24)</td>
<td>yes</td>
<td>G.R.C. would pass the building regulations for buildings higher than 15m.</td>
</tr>
<tr>
<td>dist. arch. (LQ - 18)</td>
<td>yes</td>
<td>Since you are sufficiently interested in structural use, I believe there is more scope for an inherent fire-resistant material such as G.R.C.</td>
</tr>
<tr>
<td>county arch. (LQ - 19)</td>
<td>yes</td>
<td>Brickwork cladding, both structural and non-structural, even with its problems of site labour intensivity, equals or excels G.R.P. in all the advantages claimed for G.R.P. except mouldability and light weight. Architects remain reluctant to use G.R.P. extensively under present circumstances. Although in an early stage of development, manufacturing techniques for G.R.C. products are much less labour-intensive and already seem to show a cost-saving on G.R.P. other than those resulting from cheaper materials.</td>
</tr>
<tr>
<td>county arch. (LNN - 11)</td>
<td>no</td>
<td>One turns towards G.R.C. products as the prices of G.R.P. are too high nowadays and the panel design calls for further reinforcement for adequate rigidity.</td>
</tr>
</tbody>
</table>

+ - see Table 8.8 for notes
Table 8.27 Perceived future for G.R.P. in the construction industry

<table>
<thead>
<tr>
<th>Type of organisation (Ref. code)</th>
<th>G.R.P. satisfaction or intention</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>pri. arch. (AP - 1) yes part. sat.</td>
<td>Generally speaking, there must be some future in the use of G.R.P. in building design, but it is hoped that the material is used honestly to seek a solution to design problems rather than, as with many others before (cast iron, etc.), to emulate and simulate other solutions which were arrived at honestly for that material only. Only then do I feel we will achieve true progress.</td>
<td></td>
</tr>
<tr>
<td>dist. arch. (LNW - 27) no yes</td>
<td>G.R.P. has a future, particularly when economic means have been devised to provide a sandwich with an insulation as an in-filling.</td>
<td></td>
</tr>
<tr>
<td>county arch. (LNW - 35) no yes</td>
<td>I think G.R.P. would have to be cheaper than traditional materials before its use could be considered by this authority for anything other than a one-off special building.</td>
<td></td>
</tr>
<tr>
<td>cons. eng. (CNW - 2) no yes</td>
<td>I believe G.R.P. has a good future and is potentially an extremely interesting material to the architect.</td>
<td></td>
</tr>
<tr>
<td>pri. arch. (SP - 11) yes satisfied</td>
<td>Use of G.R.P. has to be considered in relation to the actual building projects.</td>
<td></td>
</tr>
<tr>
<td>pri. arch. (SQ - 3) yes satisfied</td>
<td>I think that the building industry and the plastics industry tend to operate separately and in parallel to the detriment of both.</td>
<td></td>
</tr>
</tbody>
</table>

* see Table 8.8 for notes
from this table the following can be concluded:

(1) Direct substitution/copying of other products in G.R.P. is regarded by members of the design profession as a wrong approach for the future development of G.R.P. Thus, the design of a window frame in G.R.P. must be based on the properties and aesthetics of this material (i.e. rounded corners, etc) and not merely imitate aluminium frames, etc. In short, G.R.P. must be specified where its properties provide the most satisfactory solution to the design problem, including economic considerations.

(2) The above approach implies a natural course of development of G.R.P. applications which intrinsically places all the construction materials in a complementary order and not in a state of competition with each other.

(3) Future utilization of G.R.P. in the construction industry is to a large extent dependent on development work pursued to uncover the full potential of this material.

(4) Evidence of long term satisfactory performance of G.R.P. in service will speed up the acceptance of this material by the construction industry.

(5) Large scale future utilization of G.R.P. is not only dependent on its technical and performance attributes. It is also dependent on the economic viability of this material; G.R.P. has to show real savings on total costs of future projects in order to advance from one-off custom-designed projects to mass-produced components and units (see Chapter 13 and c.f. section 8.6.5 and Table 8.12).

8.11 Summary of the Main Points:

8.11.1 Perceived advantages and disadvantages of G.R.P. panels:

To the specifiers, G.R.P. has a number of advantages; these include qualities of visual attraction, low maintenance requirements, ease of shaping and manufacture, lightness in weight and the potential for use in sandwich and composite panels. The disadvantages are unsatisfactory natural weathering, complexity of design and jointing problems, increased fire and smoke risks, excessive thermal movements, relatively low value of creep modulus and extra cleaning requirements in service.

8.11.2 Choice of G.R.P. panels:

In choosing G.R.P. panels, the quality of design - which includes both service performance and architectural characteristics
- is often against costs, availability and degree of 'convenience' attainable.

8.11.3 Perceived economics of G.R.P. panels:

The detailed analysis of the observations on the economics of G.R.P. panels suggests that, whilst specifiers do not generally consider G.R.P. to be a cheap material, they are nevertheless conscious that there are occasions where the use of this material can be advantageous on a cost/performance basis. However, the advancement of application of G.R.P. from the rather one-off special cases to a more general use will depend on the average cost of this material relative to the alternative materials (see 13.6.3).

It was also observed that the overall economics of using G.R.P. panels had caused dissatisfaction among some specifiers. This is because, in initial feasibility studies, the use of G.R.P. panels in these cases had appeared to be economic but, in practice, severe cost penalties were probably suffered by clients for a variety of reasons; chiefly:

(a) shortcomings in design and jointing techniques;
(b) evaluation and test-proving problems;
(c) problems of obtaining prices/quotations related to the quality of G.R.P.;
(d) production and quality control problems;
(e) problems of site erection (lack of fit, etc.);
(f) weathering and durability problems.

8.11.4 Potential demand:

It is highly probable that the potential market for G.R.P. panels in the construction industry is substantially greater than the size of the present market. This potential demand has been suppressed by a number of factors; these are:

(1) Lack of sufficient design knowledge and expertise amongst specifiers/designers in the construction industry. This may be attributed to:
   (a) lack of basic training in design of plastics components;
   (b) the non-availability of design procedure and data in a form suitable for use by designers.

(2) The lack of trust by some specifiers in the quality of products produced by the contact-moulding process, and in the ability of the reinforced plastics industry to supply the correct quality product at the right price.
(3) The lack of valid knowledge related to the long term behaviour of G.R.P. panels in various exposed conditions.

(4) Lack of 'convenience' and non-availability of 'ready-to-use' design packages with proven performance in service. Many construction projects are required to be completed in a short span of time and there may not be sufficient time to pass through the routine of design, development, full scale testing, etc.; and therefore, G.R.P. as a potential construction material is disregarded in favour of other materials. An example of this situation is structural roofing systems, where there is potential for development work leading to standardized structural units with proven performance capabilities in service and a wide range of applications.

8.11.5 Adequacy of production processes:

It has been shown that the contact-moulding process was generally perceived as a technically inadequate production process. In addition, it was noted that the 'hand-lay' method was perceived as a labour-intensive and therefore economically undesirable process. However, many specifiers saw no alternative method due to the high tooling costs of moulds associated with the mechanical means of production, which are not economic for the relatively small number of repetitive units normally called for in the construction industry.

8.11.6 Standard panels/systems:

It has been noted that the general acceptability of any standard system is primarily dependent on its economic competitiveness compared with alternatives. In addition, it was found that the following factors will affect the use of such systems:

(1) Quality of design, including both service performance and aesthetics.

(2) Functional suitability of the design, especially if it is an integrated design package including structure and services.

(3) Flexibility in application, including the possibility of incorporation in full or in parts in a variety of conventional and industrialized buildings.

(4) Avoidance of identical identifiable major effects on adjacent or nearby sites.
CHAPTER 8  APPENDIX A

UNIVERSITY OF SURREY

QUESTIONNAIRE

All information given here will be treated as CONFIDENTIAL.

If you would like to qualify your answers please use the spaces provided beneath some of the questions.

1. Do you have experience in using g.r.p. load bearing panels* in the construction industry? YES/NO

*By a load bearing panel we mean one in which superimposed loads from external forces are applied to a unit. This includes snow, wind and the effects of maintenance. We include panels which form part of a space structure or infill panels to a building constructed from conventional materials.

2. If you have used g.r.p. load bearing panels, have they been erected for:
   (a) less than 2 years? YES/NO
   (b) between 2 and 6 years? YES/NO
   (c) greater than 6 years? YES/NO

3. Do you have experience in using g.r.p. non-load bearing (cladding or translucent) panels in the construction industry? YES/NO

4. If you have used g.r.p. non-load bearing panels, have they been erected for:
   (a) less than 2 years? YES/NO
   (b) between 2 and 6 years? YES/NO
   (c) greater than 6 years? YES/NO

5. Are you satisfied with the panels you have used or designed? YES/NO

If your answer to 5 is YES, is this because the panels:
   5-1 have given an attractive appearance to the building? YES/NO
   5-2 required no maintenance? YES/NO
   5-3 required less foundation and structural provision? YES/NO
   5-4 were relatively inexpensive? YES/NO
   5-5 proved easy to shape and manufacture? YES/NO
   5-6 proved easy to erect? YES/NO
   5-7 some other reasons (please specify).

If your answer to 5 is NO, is this because:
   5-8 the use of g.r.p. increased the fire risk? YES/NO
   5-9 g.r.p. material degraded significantly? YES/NO
   5-10 the design and jointing of g.r.p. panels proved too complex compared to conventional materials? YES/NO
   5-11 the use of g.r.p. panels proved costly and uneconomic? YES/NO
   5-12 the site erection of g.r.p. panels proved too complex compared to conventional materials? YES/NO
   5-13 the g.r.p. panels have required more cleaning attention compared to other facing materials? YES/NO
5-14 some other reasons (please specify)

6. If you have not used g.r.p. panels previously, would you consider using them?

If your answer to 6 is YES, is this because g.r.p. panels are:

6-1 architecturally pleasing?
6-2 light in weight?
6-3 easy to shape and manufacture?
6-4 relatively inexpensive?
6-5 resistant to corrosion?
6-6 some other reasons (please specify).

If your answer to 6 is NO, is this because:

6-7 there is a fire risk with g.r.p.?
6-8 the design of g.r.p. is insufficiently defined for you?
6-9 g.r.p. is insufficiently durable in external building application?
6-10 the site erection and the joining of g.r.p. panels is too complex compared to conventional materials?
6-11 g.r.p. is more costly than other materials?
6-12 some other reasons (please specify).

7. Would you consider the hand lay method of production of g.r.p. for the construction industry, outdated?

Further comments:

8. If your answer is YES to question 7, does this imply that you consider mechanical means should be employed to manufacture g.r.p. laminate components?

Further comments:

9. Producing g.r.p. panels by mechanical means is not economic unless a large number of units are produced from the same mould. Would you be willing to use units which were identical to units on another construction site and which were placed by one of your competitors?

Further comments:

If you would like to make any general comments on g.r.p. as a structural or cladding material please include these in the space provided hereunder.

Date.................................
Signature..............................

We thank you for your co-operation.

Would you please return the completed questionnaire in the stamped window envelope provided, to:
9.1 Application of Regulations concerned with the Health and Safety of the Buildings' Occupants and the Public:

9.1.I. General considerations:

As has already been noted (c.f. section 2.6), there are, in Britain, three modes of control in building matters:

1 - The England and Wales Building Regulations.
2 - The Scottish Building Regulations.
3 - The London Building Bye Laws (applicable in the area originally designated as London County Council).

In addition, the Fire Precautions Act; Offices, Shops and Railway Premises Act; and the Health and Safety at Work Act affect building matters, though less directly than the actual Building Regulations.

The central government have transferred the power to introduce any building regulations from Local Authorities, who had previously been able to introduce their own "Model Bye Laws", to the Secretary of State for the Environment. This centralization of power enables the government to intervene with sufficient speed in any situation in the country, e.g. to check the use of undesirable materials or permit utilization of new materials or new techniques in the construction industry. The Local Authorities are only required to administer the relevant regulations and Acts of Parliament in their own area.

In Chapters 2 and 3, it was noted that any design or alteration proposal must be approved by various local building and sanitary authorities (i.e. building and district surveyors), fire prevention officers, etc., in order to ensure that the proposal does not contravene any provisions of this legislation.

Approval of a design proposal by local authorities is generally regarded by the professional designers and specifiers as an important way of greatly reducing - but not eliminating - the designer's legal liabilities; and as means of transferring part of the total decision-making process to the relevant authorities. The building regulations are generally based on achievement of certain minimum performance levels as normally assessed by the relevant British Standards performance tests.
In the case of conventional constructional materials such as brick, concrete, steel, etc., these performance assessments need not be established by means of B.S. tests, since various Regulations carry tables or schedules of "deemed-to-satisfy" construction/combination of such materials. Furthermore, there are codes of practice which usually cover the use of a material and contain adequate guidance as to how to achieve any performance specification. Not only do these codes of practice include the latest scientific and technological advances related to the field of application, but they also reflect the experience gained from the use in service and safety aspects of materials.

In spite of this knowledge about the 'nominal' performance levels of various conventional construction materials, an authority may require independent tests to be carried out in order to assess the actual performance of a material or of a design and to ensure that the proposed design does not contravene any provisions of the statutory regulations. However, because of the relatively long-term service experience of most conventional materials in typical design situations, rarely do the authorities demand large-scale testing of these conventional materials.

Local authorities have power to waive certain regulations in some cases, though not on their own buildings (c.f. 2.6.2.). Thus, these authorities have wide ranges of power and responsibilities and are liable for their actions. They are therefore unlikely to accept any new material or new product without sufficient evidence of its performance and its conformity with the Regulations both in letter and in spirit. This attitude must not be misrepresented as conservatism, since authorities are not necessarily against innovation in general, but require concrete evidence to cover themselves against any possible liability. Thus, effectively, it is the central government who can revise the Building Regulations or issue orders for exemptions, etc., in order to facilitate acceptance and use of a desirable innovation. The government have, however, adopted a democratic view towards innovations, as may be seen from the establishment and status of the Agrément Board. The function and official association of the Board have already been described in Chapter 2 (section 2.7).

Since establishment in 1967, the Agrément Board have had considerable success and support as measured by the number of the Agrément Certificates issued. In the case of a standard product obtaining a certificate will facilitate its acceptance for the
approved uses, because certificates are issued to provide sufficient information under the Building Regulations. Furthermore, suitable certified innovations will eventually be incorporated in British Standards or Codes of Practice.

Assessment of performance of non-standard new products is covered by "Methods of Assessment and Testing" (MOAT) issued by the Agrément Board. MOAT No. 9, published in December 1973, is an example which deals with assessment of G.R.P. products for use in building. This document is in fact based on the execution of various tests for the appraisal of G.R.P. products (see Chapters 5 and 6); a thorough appraisal in accordance with MOAT No. 9 and the Building Regulations is costly and may have crippling economic effects on small to medium G.R.P. projects. Thus, whilst Agrément Certificates are considered as effective means of getting standard mass-produced products technically accepted by the construction industry, the effectiveness of MOATs in reducing the resistance to non-standard materials is open to question. MOATs would, however, serve as useful guides for users in the absence of a full Code of Practice.

9.1.2 Perceived attitudes of building or district surveyors on the use of G.R.P. panels:

At the outset of this study, it was planned to carry out a survey of the attitudes of the building or district surveyors on the use of G.R.P. panels. However, this plan was subsequently dropped for the following reasons: (a) unequivocal nature of the Building Regulations; and (b) predominance of performance tests.

9.1.2.1 Unequivocal nature of the Building Regulations:

A study of the Building Regulations revealed that in general the Regulations are expressed in the form of minimum performance requirements. These are not normally liable to varied interpretation; the only exceptions concern some clauses in Section B. For example, it is stated that any material incorporated in any form in a building shall be of a suitable quality in relation to the purposes for and conditions in which they are used. The Regulation B.3 carries a table in which examples of unfit materials for the weather-resisting parts of buildings are given. However, these listed materials are unfit for use in the exposed
parts due to their relatively short lives or drastic shortcomings in their mechanical and physical properties. The plastics industry considers that Section B does not exclude constructional applications of reinforced plastics, since these materials have satisfactory mechanical and physical properties and are of sufficient durability to be classed as materials with long lives (I).

Experience in the constructional use of G.R.P. panels in the U.K. covers a period of about 12 to 13 years, though there is adequate information from the marine and other industries which, together with extrapolation of the present trends, suggest that G.R.P. panels of correct quality may be classed as materials with long lives (i.e. in excess of 25 years (2)), suitable for exposed applications in buildings. Thus, on the strength of present evidence about the life and properties of G.R.P., it is unlikely that any authority would reject the use of G.R.P. panels because of the above considerations. In fact, the purpose of 'Section B' is to ensure that materials are used in suitable applications and not to prohibit use of any one particular material, especially if the proposed materials are approved by the Agrément Board for particular uses.

9.1.2.2 Predominance of performance tests:

G.R.P. panels are relatively new and their constructional use is not covered by any nationally agreed Code of Practice. Furthermore, variations in composition, materials combination, etc., from one G.R.P. project to another makes it necessary for an authority to insist on execution of appropriate performance tests as means of establishing whether or not the design satisfies the appropriate provisions of the relevant legislation. It would therefore be impossible for any authority to give hypothetical replies to any question concerning performance capabilities of G.R.P. panels. Thus, the question of a general survey becomes irrelevant.

The available information indicates that in most G.R.P. applications, specimens have been tested for assessing performance (i.e. to the B.S. 476) of the panels. This is not unexpected, since most applications of G.R.P. panels are either as external cladding or roofing or internal lining/partitioning. Thus, assessment of fire performance of G.R.P. panels, especially in large areas of unprotected panelling, forms the most important part of the design consideration.
The structural stability assessment of G.R.P. roofs and space structures (Section D of the Building Regulations) also requires special attention. There is evidence (3) that, in many cases, the authorities have requested that simulative tests be undertaken unless such tests had previously been carried out as part of the verification and evaluation of the design (c.f. section 6.2). Performance of proposed joints under the action of driving rain may similarly be tested by special testing equipment in the laboratory as part of the evaluation programme; the results of such tests may be requested by the district or building surveyors under 'Section C' of the Building Regulations, which deals with Weather Resistance.

In addition to these considerations, it has been reported (4) that in a recent design proposal for a recreational building in the Norfolk area, which involved extensive use of G.R.P. panels, the local council made their planning permission conditional on the provision of automatic sprinklers to protect the whole structure. Such attitudes on the part of the authorities, which have been reported to be common (4), are natural reactions to the tragic fires of 'Summerland' on the Isle of Man and the Old Peoples' Home in Northampton.

As has already been noted, obtaining permission from a local authority under the Building Regulations does not automatically ensure that the requirements of the Fire Precautions Act and the Health and Safety at Work Act are fulfilled. As these Acts are applicable throughout the time of occupancy or use of buildings, whereas the control under the Building Regulations terminates upon completion of the building. Thus, for example, it is possible that, due to change of occupancy or for other reasons, an order will be made under the 'occupancy' acts for additional provisions such as installation of automatic fire extinguishing devices, change of materials, opening of fire exits, etc.

To summarize, because of the limited experience on the use of G.R.P. panels in the construction industry and because of variations in the design of these panels, the building or district surveyors or other local officers/inspectors have, in most cases, based their judgments on the level of performances achieved in actual tests on these panels. In addition, there is evidence that the attitudes of the authorities on the use of new materials with fire hazards have hardened considerably, probably due to the greater awareness of fire and smoke hazards associated with the
use of combustible materials in general and plastics in particular. The fact that approval by the local authorities of large areas of G.R.P. panelling in high risk areas (e.g., where the risk of fire inception is high or where the public have access) is generally subject to provision of active fire protection devices (such as automatic sprinklers, etc.) is itself an indication of a move towards greater safety requirements in the design of buildings.

9.2 Planning and Aesthetic Approval:

9.2.1 General considerations:
In Chapters 5 and 6, it was generally established that because of the low modulus of elasticity of G.R.P., normal structural shapes such as post and beam constructions are not economically feasible in G.R.P.; folded plates and shells, which derive their stiffness primarily from the shape of the structure, must be employed in 'load-bearing' situations. Thus, space enclosure in G.R.P. involves use of 'unorthodox' structural forms; on certain sites, these forms may not easily blend in with the existing buildings.

The introduction of highly shaped, large G.R.P. panels on elevations of conventional buildings may also create aesthetic problems. These problems are caused by interplay of mass, void, scale, light, shade, colour and texture, etc., both in relation to the building and in relation to its surroundings. Aesthetic judgments of buildings do not finish at the drawing board; people judge buildings using their personal experience and values. They judge whether a building appears bright, shiny, cheerful, dignified, symbolic, vernacular, etc. Planning authorities must approve all design proposals; they will have to reconcile the public interest and the architect's design. Thus, the issues involved are complicated and are influenced by the training of town-planners and by the attitude of the public towards 'modern' architecture. An attempt has therefore been made to discuss some of these problems.

9.2.2 Background and training of an average town-planning officer:
The discussion on this subject is based on the following sources of information:
(a) Interviewing 3 corporate members of the Royal Town Planning Institute (RTPI).

(b) Interviewing Mr. J. Fowley, Head of the School of Town Planning, Kingston-upon-Thames Polytechnic.

(c) Recent journals and published information (see the list of references and the text below).

The majority of members of the RTPI enter the town-planning profession by means of completing a course recognized by the RTPI. These courses are organized by some universities and polytechnics. The qualifications required for admission to one of these courses typically range from the following categories:

(i) B.A. (or B.Sc.) in geography, social science, sociology, economics, statistics and similar subjects.

(ii) Completion of certain parts of the professional examinations in architecture or in quantity surveying, etc.

Town planning specialises in one of the following branches:

(a) Urban design, which is of interest to this study.

(b) Transportation planning.

(c) System analysis, which includes mathematical model building for the town, county, etc.

Subjects usually studied in a town-planning course are as follows:

(I) History of town-planning.

(2) Project work on historical and geographical aspects of a town; the basic aim is to try to explain why a given town is located in its present place and what factors have affected this and its growth.

(3) Study of the structure plan of a district, etc.

(4) Studies of various town-planning acts, official publications, current state of law as it affects the town planners, etc.

(5) Studies of economic and social aspects of town-planning.

(6) Statistical and mathematical analysis, model building, etc.

(7) Some studio work for aesthetic studies.

Thus, no studies are undertaken of the properties of materials, construction techniques and engineering considerations. The aesthetic studies of physical development covered by the course are not in great depth. Those graduates with architectural background are in a more fortunate position because of their
training in aesthetics and feasibility aspects of construction technology.

Most town-planning officers employed by local authorities to control their urban planning affairs are graduates of such town-planning courses. However, some senior officers have qualified by means of taking the RTPI's external examination which includes more emphasis on physical aspects of development. In addition, many senior staff are basically trained as architects; some of them are both district architect and planner in their districts.

9.2.3 Present town-planning organisations:

The recent local government reorganisation has drastically altered the structure of the planning control. The county authorities are now only responsible for preparation of the strategic plans for counties. Other urban planning matters are controlled by district authorities who are also responsible for preparation of district and local plans. A local plan may comprise development proposals for a certain area within the boundaries of a district plan, e.g. town centre area, etc. The local plan must contain statements specifying firm requirements as laid out within the framework of the district plan. These statements are referred to as 'planning briefs'.

A planning brief is produced in order to secure participation of developers in the execution of a development proposal; the brief is aimed at giving maximum information on those aspects of the development which the authority considers as essential, e.g. preservation of certain features, the distances to be observed from any listed building, the highest limitation, access points from a primary road, number of dwellings or area of shopping floor space or planning standards required, such as daylighting and so on. In addition, to these essential requirements, an authority may add suggestions and advice on, for example, matters of layout, massing of buildings and landscaping treatments.

It must be noted that work undertaken by any government department is not subject to planning control by local authorities.
9.2.4 Criteria for aesthetic acceptance of a design proposal:

9.2.4.1 Official guides:

There are rules governing the aesthetic evaluation of a design, and each case is judged on its own merits by planning officers (5, 6 and 7). This is because aesthetic judgments are subjective matters and are influenced to a large extent by personal opinions. Furthermore, preferences, fashions, and tastes change with time. These difficulties are acknowledged by the Department of the Environment (D.O.E.), who have issued various circulars and notes as guides for the planning authorities; the following are considered as relevant to this study:

MHLG Circular 28/66: Elevational Control.
MHLG: Development Control Policy Note 10, Design.

The actual documents have been reproduced in pages 423-427 for ease of reference.

A study of these documents reveals the following points:

(1) The government consider that planning authorities should generally seek 'architectural' advice when appearance of a development is in question.
(2) The government have stressed that development control should not be used by planning authorities to 'stifle' fresh approaches in design or to frustrate creative impulses for architectural advances.
(3) The need for careful consideration of a design in relation to surroundings has been emphasized; however, except in cases such as a Georgian square where the consistency of the architecture must be preserved, it has been stated that "there is often no reason why the new development should not be different in character. It may, indeed, be better if it is."
(4) Where the development proposal is likely to affect in any way a building or area of special architectural or historic interest, the authorities are required to publicize the matter, so that public opinion may be expressed before any decision is taken. Authorities are also reminded about the availability of the Royal Fine Art Commission as consultants to such matters.
DEVELOPMENT NEAR BUILDINGS OF SPECIAL ARCHITECTURAL OR HISTORIC INTEREST.

1. I am directed by the Minister of Housing and Local Government to refer to Circular No. 21/61 which asked planning authorities to review their arrangements for giving publicity to certain planning applications, and to say that the Minister attaches importance to the need for publicity for those applications which might affect adversely buildings of special architectural or historic interest. Your Council will be aware of the concern expressed by several Members of Parliament on this matter in the recent debate on Mr. Robert Cooke's Historic Buildings Bill (House of Commons Official Report, 22nd February, 1963, Cols. 771 -842). An undertaking was then given that the Minister would issue a circular on the subject to planning authorities.

2. Demolition or alteration of buildings of special architectural or historic interest is, of course, controlled under the provisions of Parts III and IV of the Town and Country Planning Act 1962. But, the physical protection of the buildings themselves is only one facet of the problem of preserving their essential character. It is equally important that development which may be proposed near to such buildings should be carefully considered in light of the effect which it might have on the building, or on the scene of which the building forms part. It will, of course, be borne in mind that many attractive streets and villages owe their character not so much to buildings of great individual merit as to the harmony produced by a whole range or complex of buildings. Such areas require the same careful treatment in considering proposals for redevelopment even if that redevelopment replaces only a building that is neither of great merit in itself nor immediately adjacent to any such building.

3. The Minister is well aware of the care and attention which planning authorities already devote to this end when dealing with planning applications but even an isolated decision which is held to pay insufficient regard to the surroundings of an historic building can lead to widespread criticism. In these circumstances particular importance attaches to bringing fully instructed opinion to bear on any application for development which, by its character and or location, might be held to have an adverse effect on buildings of special architectural or historic interest. In some cases authorities may feel sure that the knowledge immediately available to them will be adequate to enable them to reach a well founded decision. In specially important cases, however, it may well be advisable for authorities to consider whether they should not seek independent professional advice on the proposals before reaching a decision on them. Authorities will be aware that the advice of the Royal Fine Art Commission may be sought in such cases.

4. In whichever of these ways the matter is handled the nature of the proposal may be such, because of the degree of local interest in it, or because of its controversial character, that it will be desirable to arrange for publicity. The Minister hopes
that local authorities will not hesitate to take full advantage of this procedure in suitable cases so that public opinion has an opportunity to declare itself before decisions of importance are taken.

Assistant Secretary to the Clerk of the Authority.
ELEVATIONAL CONTROL.

1. I am directed by the Minister of Housing and Local Government to say that he has been considering the question of planning control of elevations, how far this contributes to the improvement of the external appearance of buildings and its effect on the quality of architectural designs generally. Aesthetic control of elevations, although sometimes successful in eliminating bad design, cannot by itself promote imaginative and first-class work. Many local authorities now accept that the design of a building is the special professional responsibility of the architect, and that architectural advice should be sought when the appearance of a building is a material factor in a planning decision. He believes that this is the right approach and recommends the general acceptance of this principle.

2. While, therefore, the Minister expects planning authorities to continue to reject obviously poor designs, and designs ill-suited to their surroundings, he also expects them to consider very carefully before withholding consent on aesthetic grounds for buildings designed by an architect for a particular site. If they are considering doing so, he thinks they should obtain professional architectural advice and state specific objections in clear professional terms so that these can be discussed with the applicant. Where the authority does not employ a qualified architect at the appropriate level, the architectural advisory panels can, of course, be used.

3. In his view this will always be a more appropriate way of dealing with objections, which must otherwise be largely subjective, than simple censorship by committees which may lead to a justifiable sense of grievance. Where permission is refused primarily on aesthetic grounds the planning authority would then, in the event of an appeal, be able to show that they had taken professional advice before rejection.

Under Secretary to the Clerk of the Authority.
DEVELOPMENT CONTROL POLICY NOTE 10: DESIGN

1. One of the objects of development control is to prevent bad design and encourage good. Planning is concerned with the environment in which people live and work, and this necessarily entails consideration of aesthetic qualities - those that make an environment visually pleasing or the reverse, as well as questions of practical convenience, health and safety. But there are obvious difficulties, and some dangers, in exercising control of design. One cannot lay down rules defining what is good and what is bad, for aesthetic judgments are largely subjective and opinions including expert opinions, often differ. Taste varies from person to person; and it also changes from generation to generation. Control must therefore be applied with restraint and with great discrimination.

2. It is particularly important that it should not be used to stifle initiative and experiment in design, or to favour the familiar merely because it is familiar. A design is not bad because it is new and different; it may be very good. Control should prevent design which is clearly bad; but it must also allow freedom for the creative processes that make good architecture.

3. The design of buildings is the business of the professional architect, and developers usually find it advisable to employ an architect when the appearance of the proposed development is likely to be important. Planning authorities are also usually guided by professional architectural advice in considering such proposals in order to ensure that the architectural aspects are properly appreciated. Clear and definite criticisms of a design on grounds that can be explained carry more weight than vague objections about it being 'inappropriate' or 'out of keeping with adjoining development'.

4. There may be two questions about the design of a building. The first is whether the design is bad in itself; fussy, or ill-proportioned or downright ugly. The second is whether, even if the design is not bad in itself, it would be bad on the particular site; out of scale with close neighbours, an urban design in a rural setting or a jarring design in a harmonious scene. The latter point is often overlooked: too many buildings are designed as separate entities, apparently without reference to their surroundings. The relationship between new development and its context is almost always important, and sometimes crucial. This is not to say that new development need always conform to the character of the existing development around it, for unless the place has some special architectural or other qualities that are worth preserving, there is often no reason why the new development should not be different in character. It may, indeed, be better if it is. But the setting should always be studied and taken into account, for it may well influence the design of the new.

5. This is particularly true of buildings in rural surroundings, where landscape and natural features may largely dominate the design; and in conservation areas and other places of distinct architectural or historic character. In some of these, for example the Georgian square or Regency terrace, consistency of
architectural style is the dominant feature and any new development will be expected to conform to it. Others comprise less formal groupings of buildings of different ages and styles and allow more scope for new development and greater freedom of design; but every new building should nevertheless be designed as part of the larger whole, with due regard to its special characteristics.

6. In such cases, and wherever the decision on a planning application is likely to turn on the appearance of the development, the planning authority may decide to ask for detailed plans and drawings showing the development in its setting, instead of giving permission in outline form. They are entitled to do this under Article 5(2) of the General Development Order, subject to a right of appeal to the Minister.

7. Trees are a valuable, and sometimes necessary, adjunct to new development, not to conceal but to enhance, and to soften the impact of new buildings on their setting. Trees of the right kind and in the right places can look well with modern buildings. Developers should always consider the desirability of keeping trees that are there and planting others. Permission for the development may be conditional on this being done. Section 12 of the Civic Amenities Act 1967 requires local planning authorities when granting planning permission to make sure, wherever appropriate, that adequate conditions are imposed for the protection of existing trees on the site or for planting of new ones.
9.2.4.2 The actual criteria employed by the authorities:

As was stated earlier, planning authorities consider each case on its own merits and in relation to the surrounding environment. However, it is understood (5, 6 and 7) that, in so doing, the authorities normally attach greater importance to public opinion, especially at local level, than to following the procedure laid out by the government. This is in addition to the 'public participation' for establishing objectives for development of county, district and local areas. Under the Town and Country Planning Act, 1971, planning authorities are required to formulate various development proposals and then consult the residents before adopting any of these as a basis for strategic plans. In addition, any formulated plan must be publicized and given a chance for discussion; the plans must then be modified to secure the public interest.

As has been noted in section 2.5, there are a host of other legislations which influence the development control in various locations.

The public, in reaction to many post-war developments, such as town centre redevelopments, have increased their vigilance (5, 8 and 9). It is generally known that the public see a sense of security in 'old', 'established' and even 'reproduced' objects. (8, 9, I0, I1 and I2). Experiments in design or 'synthetic' architecture may conflict with the norms and standards which the layman uses in his judgment of buildings. Thus, it is no surprise that, in some cases, the local residents have requested that the designs in redevelopments should match those of buildings which they replace, though the public are less aware of the changing needs or conditions of today's society, e.g. population densities, etc. (5 and 6).

Although local newspapers play a major role in publicizing news of development proposals, etc., the public campaign is normally initiated by local action groups who regularly receive notification of any relevant development application (5 and I2).

Whereas the average resident of a town may find it difficult to analyse the implications of the structure or local plans, he can usefully comprehend the effects of any development proposal for a particular site (5, 9, I3 and I4). This is in fact seen by residents' determination to guard local characters in their towns and prevent what they call 'mindless' destruction of the national
heritage (5 and 9). A local character may be created by buildings of special interest or by use of certain materials, such as local stone (e.g. City of Bath), brick or tiles. There is evidence, e.g. reference I5, that some planning authorities have refused planning permission on the grounds that a particular type of material had not been proposed, e.g. where a different type of roof tiles had been proposed in preference to those generally used on other local buildings. Thus, although not openly admitted by planning authorities, the local requirements, especially those related to the street or road concerned, and the relationship of that street or road to the whole town have far greater influence on the planning authorities' decision than the government policy, notes and guides. (I6 and I7). In section 2.5, it was explained that any applicant whose application for development has been rejected has a right to appeal against the decision; however, the length of time normally required for a case to be heard and decided - typically in excess of I year (I5) - and the resulting increase in costs may reverse the client's initial intention to develop altogether. Thus, architects find it particularly advantageous to discuss their client's instructions with the planning authorities concerned before committing themselves to any solution. In short, from the available evidence it appears that evaluation of aesthetic appearance is based on an 'ad hoc' approach, and very often existing features are used as a basis for such judgments; as far as possible, the character of a street must not be upset by introduction of 'wild' variations (I8). For example, use of a flat roof is unlikely to be allowed where neighbouring buildings are all of the pitched-roof type (7). The authorities may also require that, as far as possible, the new development should not overpower the existing buildings (5 and I9), for example, by attracting more visual attention which may undermine the value of adjoining properties (I9). Fig. 9.1 shows diagramatically the present planning process.

The question of success of the present planning process in preventing erection of 'ugly' buildings will be considered after a brief study of architects' current views on the aesthetics of modern buildings and whether or not their views are shared by planning authorities or by the public at large.

9.2.5 Architectural trends:

Present architectural trends in Britain are largely influ-
USE CONTINUITY MATERIALS BULK PRESENT PLANNING PROCESS

AN ATTEMPT AT RATIONAL PLANNING

THIS MEANS 'SOCIAL EVALUATION' OR PUBLIC PARTICIPATION IN THE PROCESS

DEVELOPMENT CONTROL AS PART OF THE PROCESS

THIS LEADS TO VERY CONSERVATIVE DECISION MAKING

THIS REFLECTS SOCIETY'S VIEWS AT THE PRESENT TIME

THIS WILL MEAN THAT THE FUTURE TOO MAY BE VERY 'CONSERVATIVE' AND 'INCREMENTAL':

- SHAPE AND BULK
- MATERIALS
- USE
- SCALE OF WINDOWS DOORS, ETC.

CONTINUITY

THIS SUGGESTS THAT THE VERY NEW MATERIALS COULD ONLY GAIN ACCEPTANCE IN THE 'ONE-OFF' SITUATIONS, E.G. REMOTE OR ISOLATED SITES AND ENTIRELY NEW USES, E.G. COMPUTER BUILDINGS, ETC.

FIG. 9.1

DIAGRAM SHOWING THE PRESENT PLANNING PROCESS
enced by the aesthetic innovations of the 'international functionalist' and the 'expressionist movements. These movements were pioneered during the late 1920's and early 1930's by many now famous architects such as the Swiss-French architect Le Corbusier, the German architects Walter Gropius and Ludwig Mies van der Rohe, the Dutch architect J.J.P. Oud and the Finnish architect Alvar Aalto, etc. Many innovative buildings erected before the outbreak of the war had common characteristics, for example, flat roofs, white and plain surfaces, 'liberated' interiors, cubic and other explicit forms, etc. The rate at which the 'new architecture' progressed throughout the world was a manifestation of the acceptance of the logical reasons behind its development. Criticisms of the 'soul-destroying' nature and plainness of the new architecture did not manage to check the spread of frontiers of the modern movements, though there were distinct disagreements between the doctrinaires of modern architecture.

In Britain there was a general opposition to the modern architecture; the planning authorities were reluctant to grant planning permission. However by 1950, the validity of modern movements was generally accepted and put into practice by British architects without proper discrimination. Sharp wrote in his pictorial survey of 'twentieth century' architecture that: "Social problems somehow got haphazardly mixed up with aesthetic ideals and an architecture emerged in the early 1950's that was painfully inadequate to meet the needs of the time. The 'new' town-planners were probably the worst culprits. Never having understood, even partially, the basis on which the new architecture had attained its pre-eminent position before the war, they now accepted a facile kind of modernism in conjunction with a pedestrian and almost mindless acceptance of a 'beaux-arts' kind of civic design. Municipal bodies, New Town Commissions, commercial firms and private clients were all prepared to pay lip-service to an architectural vocabulary they did not, or were unwilling to, understand. Young designers were caught up in a cleft stick during a period of fast-expanding building activity; either copying the best features of the master works and designing within the idiom of an established innovator, or establishing some kind of originality of their own."

Since the mid-1950's, many architects have begun to question the universal application of the 'international style'; whilst searching for new theories - this time based on 'social' and 'human' sciences - they have grown much more respon-
sive to the needs of an evolving society (8, 21, 22 and 23). However, the principles of 'international functionalism' are still largely followed in the majority of designs. The designers have not been able to find as yet any 'ready-to-use' solutions to their design problems (22 and 23). Moreover, the economic, technical and managerial superiority of the 'international style' have ensured the continuity of its use as a design philosophy (14); it is indeed doubtful if any other less viable design philosophy could ever be accepted in an industry which is under constant pressure to reduce its total costs (8 and 14).

Modern aesthetic ideas are based on the 'simplicity and purity' of building forms, 'honest' expression of structure and materials on the exterior and use of colour and surface relief as a means of overcoming the plainness of continuous surfaces. These ideas are not compatible with ornamentation and obscuring of building configurations by deceptive and elaborate variations, etc.

To a large extent, the development of modern aesthetics has been dependent on the availability of reinforced concrete and utilization of its inherent engineering qualities combined with its relative cheapness. Whilst concrete can be moulded into visually exciting and 'dynamic' forms, its surfaces do not readily respond to ornamentation. Thus, 'dynamic envelopes', 'plastic architecture' and similar expressions have been used to communicate the aesthetics of the new architecture. Practical limitations of the use of untextured concrete surfaces and flat roofs in Britain were recognized at an early stage. The appearance of damp patches on the weathered concrete surfaces were reported as early as the 1930's; and the performance of flat roof construction was reported as unsatisfactory, especially in climates with heavy rainfalls.

The importance of modern ideas must lie in their recognition of the economic viability of engineering and technological innovations of the present century. Not only was it necessary to use more and more standard mass-produced materials and components, but also to plan the design on a grid basis (14 and 24) so that, as far as possible, variety of components could be reduced and construction of joints, etc. simplified. Thus, it is no surprise to observe that most buildings have been planned on a rectangular grid basis and enclosed by repetitive patterns such as glass and
metal curtain wallings or cladding/patent glazing, etc. Clearly, these design tendencies are not only compatible with the mechanical properties of structural materials such as steel, reinforced concrete, brick, aluminium and timber, but also compatible with the principles of industrialization of the construction process due to the relative simplicity of the jointing and fitting of straight line based edges. Except in the case of one-off buildings of a special type, 'cuboid' spaces are considered by users to be the most functional and 'roomy' type of geometrical spaces. This attitude is partly historical, since ordinary rooms have mostly been of cuboid design (14 and 24).

9.2.6 The public's view of modern architecture:

The general dislike of 'modern architecture' by the average man is a well publicized matter (8, 22, 25, 26 and 27); it is frequently claimed - though not proved (28) - that modern buildings tend to engender a negative feeling. In addition, some modern buildings have failed to satisfy their users in terms of 'functions', etc. (26 and 27). As has already been noted, such public attitudes prompted some designers and scholars to look towards the human sciences for a remedy (22). Initially it was hoped that 'perceptualists' could come up with some interim solution by conducting controlled experiments. However, as seen from many recent publications (e.g. see references 22, 23, 29, 30 and 31), no such simple solution has been forthcoming. Broadbent wrote in his book "Design in Architecture" (22) that "whether or not we like it, people experience buildings by means of their senses. What one perceives consists of a transaction between what is 'there' physically in the 'real' world, stimulating one's sensory receptors and thoughts or ideals which one has already inherited at birth, or more particularly, learned from one's past experience. The building itself, the object of perception, is constant. But the life-time experience which, respectively, we bring to the perceiving of it, is different for each of us and this accounts for the differences in our perceptions of it."

A useful conclusion reached by Broadbent (22) in his search for 'social' architecture was that "matters of imagery, values, identity, sense of place which human sciences had only begun to tackle could not be quantified." Some of these matters have cultural and symbolic meanings; several experts in the architect-
ural profession (e.g. see references 32 to 35) see a key to the solution by bringing the designers closer to the users of the buildings as opposed to the present 'system' under which about 20 per cent of the population commission almost 100 per cent of buildings in Britain (36).

To the layman, the 'new architecture' manifests itself in such developments as the new Queen Elizabeth Hall in London’s South Bank, which in 1967 was voted as Britain's ugliest building by a group of engineers (14), Roehampton housing estate in London, which was the subject of a Thames TV programme in January 1976, the Economist Building in St. James Street, London (33), Cumbernauld New Town near Glasgow, and Park Hill and Hyde Park housing in Sheffield, etc. Many contemporary architects have claimed that the layman is illiterate (8, 14 and 33). This is a misconception of the role of the public. Design problems such as appearance, compatibility, proportion and scale, space, function, finance, materials, etc. are not the layman's concern. The average man hardly ever gets a chance to see the inside of many public buildings and has no ability to deduce the function of a building from its external appearance. What he concerns himself with is the appearance of a building, e.g. whether it looks bright, cheerful or dignified, whether it ought to look different, etc. Thus, any new building(s) will evoke a fundamental emotion inside him; 'liking' or 'disliking'. However, this response does not remain constant; the more he sees of the building/setting, the less will be the intensity of his response. Thus, there is a two-way process of interaction between the man and his environment. As Norberg-Schultz wrote in his book "Intentions of Architecture": "Generally we judge and act on the basis of a few representative phenomena, that is, we have an incomplete and superficial idea of the world of objects. We are forced to reorientate and change our existing attitude if we are to become more perceptive. We need to train our minds to understand complex and simple objects equally, and to train our eyes in such a way that they will influence our judgments in terms of patterns, shapes forms and spaces. All is not what it seems - as most perceptualists like to demonstrate. Illusion abounds."

The research on both the difference between the architect's and the layman's world of objects and the implications for design continues. Whilst many experts accept the need for more 'social'
and 'cultural' awareness on the part of architects, they doubt the wisdom of following aesthetic 'models' chosen by the public. Such 'models', it is argued, are probably based on certain aesthetic ideals previously pursued by architects themselves or those attributed to higher social classes.

The issues are complex and involved. Public pressure will continue to exert itself the more society moves towards a tighter state of social democracy. One thing, however, seems certain; there will be no return to the nineteenth century eclectic and picturesque architecture. Not only is such architecture outdated and incompatible with present day technologies, but it is also grossly uneconomic and 'unfit' for housing the many varied activities in an affluent society.

One would expect emergence of a new architecture with the following characteristics:-

(a) Maintaining and improving many of the technological and economic capabilities of the present architecture.

(b) Providing more suitable, 'pleasant' or 'comfortable' working and living environments.

(c) Paying due sympathy for, and improving the visual quality of, the environment.

(d) Becoming more conscious of its long term impact in generating various responses/feelings amongst the population (e.g. avoiding the sterile monotony of Stockholm, New York City, etc).

9.2.7. Failures of the present planning process:

Most experts agree that the 'real' benefits of aesthetic control have not been as high as those originally expected. This is manifested in a current debate on this subject amongst the members of the profession. For example, Malcolm Sowerby, a practising architect, in his letter to the Architects' Journal (21st March, 1976) stated: "The system at present does not work. It seldom stops bad design and it never brings out good design." He goes on to say that planners and architects take the easy option, i.e. "to accept the mediocre and stay clear of anything with character. This eventual outcome is more or less built into the present planning set-up. It would take a man bigger than most of us to beat it."

Ian Davison, another practising architect, confirms the above view in his letter to the Architects' Journal (4th February, 1976) in which he points out: "It is true that many development control
planners are lacking in architectural awareness and yet feel tempted to tinker with applications."

These and the views of many other contributors to the current debate, including town-planning officers (21, 37, 38 and 39), appear to confirm the following points:

(1) In some areas, there are no formulated development or 'action' plans (the Pilcher report, AJ 10th December, 1975, p1234). Thus, it must be difficult for the authorities concerned to consider any design proposal in the context of a 'planned' future environment.

(2) There is ample evidence to suggest that recent 'conservative' policies followed by many planning authorities have not produced improved visual environments and harmonious townscapes. In some instances, these policies have been inadequate and shortsighted, due to their support of a 'neutral' or 'cheapened' type of aesthetics (14).

(3) It has been confirmed by some senior town-planning officers (e.g. Clifford Walters, reference 37) that greater emphasis on the 'architectural' and 'physical' aspects of development in town-planning courses would help towards greater understanding of the aesthetic issues; this would eventually lead to improved visual environments both in urban and rural areas.

9.2.8 Actual planning obstacles to G.R.P. panels and structures:

It has been repeatedly stated that the introduction of reinforced plastics can give a new impetus to architecture (40) by enabling architects to design geometrical configurations which would be light in weight, economic to run (particularly on consumption of energy for heating/cooling purposes) and exciting in appearance.

In fact, in the span of 20 years, many architects and designers throughout the world have attempted to introduce folded plate/shell/ and other three-dimensional structures as the basis of their designs; the egg-shaped house "Casa Futura" by the Finnish designer Matti Suuronen is an example. However, these attempts have generally failed to establish a commercial production line, except for holiday homes, mainly in Europe and the U.S.A. (41).

It will be observed that these structures juxtaposed with buildings of traditional appearance would look self-conscious
and vulnerable to deprecative criticism. Also, quite apart from any possible psychological fears, - see the report of IBK on page 438 - it is arguable whether the public will accept the curvilinear or similar walls and ceilings for everyday use from a convenience point of view (41, 42 and 43) (see study by IBK). In Britain, prejudice against the use of such 'futuristic' designs in the field of housing is strong; except on very isolated sites or for temporary uses, it is unlikely that any planning authority would be prepared to grant the necessary permission. This conclusion was reached by the author after careful study of all the available evidence and discussion with a number of authorities. Makowski (41) in his review of the development of plastics houses has also confirmed that commercial success of 'unorthodox' shapes for the envelope of houses has not been forthcoming.

Sandwich panels and mixed constructions have had more success. For example, "Resiform" houses have been used on a number of council estates. The extensive use of composite panels incorporating glazing in H.M.S. Raleigh Redevelopment at Torpoint, Devon is another example.

As a general rule, it is unlikely that the use of 'flat' panels on external walls of dwelling houses, especially with tiled pitched roofs, would meet any opposition from the planning authorities. It must be noted that these designs are not aesthetically innovative since concrete-based panels, e.g. "Reema" or "Bison" or "Camus", etc., have similar aesthetic characteristics and are well accepted by both planning authorities and the public from an aesthetic point of view.

The worldwide development of plastics-based houses has been under study by the German Institute for Construction with Plastics (IBK). In 1973, they published a condensed report of their massive survey of all development projects or commercially produced houses. Some parts of this report have been translated from German, including the summary of their findings; for reasons of completeness and convenience, the English translation of this summary, which is self-explanatory, has been included below:
1. The study covered 232 examples from the years 1956-1972. There was a distinct tendency for the figure to increase as the years passed by. The examples come from many countries of the world.

2. Insofar as can be ascertained, the examples divide up as follows:

<table>
<thead>
<tr>
<th>Projects</th>
<th>46</th>
<th>19.8%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Built only once (prototypes)</td>
<td>98</td>
<td>42.2%</td>
</tr>
<tr>
<td>Built more than once</td>
<td>88</td>
<td>38.0%</td>
</tr>
</tbody>
</table>

3. The compilation (Parts A and C) covers structures made out of or with plastics. The discussion of criteria for design and profitability (Part B) is confined to pure plastics houses.

4. Of those types built more than once, only a few have achieved noteworthy production figures. The leader by far is the mixed-construction 'Polyvilla' (60/04), of which 500 have been built in the last 10 years.

5. In the G.F.R., a mixed-construction (KB-Haus 70/17) and a pure plastics house (Feierbach-Haus 68/11) only received the building supervisory board's approval in 1973.

6. 30% of the structural shapes had non-straight exterior surfaces, 58% were basically cubic in shape (with and without roof), and 12% were polyhedral in shape. The houses that sold best were those with basically cubic shapes.

7. 65% of the base areas were rectangular in shape, 13% were triangular or polygonal, 18% were round or oval and only 3% had totally free shapes. The findings in paras. 6 and 7 therefore show a pronounced inclination towards the more traditional building shapes.

8. The uses of plastics houses are in the majority of cases as dwelling houses or holiday chalets; whereas use as a dwelling cell, hotel, or motel cabin or as an office is possible.

9. For the fittings (sanitation, kitchen, furniture, heating/air conditioning) special arrangements were often planned and executed in the case of projects and prototypes. Houses built more than once tended to rely, however, on commercially available conventional fittings. The suggested special sanitary arrangements are almost without exception inadequate, even when measured against the minimum requirements of DIN 18022.

10. The predominant choice of construction method and material, independent of structural shape, was a sandwich of glass fibre laminated channel section and rigid PU foam, laminated on both sides. 65% of the houses were partially pre-assembled, and astonishingly, 23% were ready houses, house parts or finished cells.

11. As a consequence of the tendency to one-family houses, 43% of the examples could not be added to, 10% could be assembled in rows and 28% could be theoretically attached to each other in various planes. Multi-storey structures using plastics houses or room cells exist only on paper; as yet there is no knowledge of any such attempt in practice.

12. Static calculations show a substantial saving of weight in
the case of units that could be introduced into multi-storey self-supporting structures (80-90% for walls and ceilings). The effect on the structure as a whole, however, would be slight because the service loads would have to be taken by concrete ceilings, due to static and fireproofing reasons.

13. A perceptible reduction of the total load could be achieved by the use of lightweight load-supporting fire-resistant building elements for the floors of room units, which - subject to guidelines for the use of combustible building materials - could be inserted into economical skeleton or suspended structures.

14. Inasmuch as prices are ascertainable, at between DM-700 to DM-1300 (£120 - £200 approx.) per square metre of living space, they fall into the upper price bracket for conventional prefabricated houses. Prices are to be regarded with care, due to the lack of series' production experience.

15. The generally held idea of "plastics" as a complicated building and pre-production material for houses or room units is still in advance of the actual state of technology, with reference to both the examples in this study and to the foreseeable future.

16. The question of plastic houses has nothing to do with individual constructions or with small series of new-style, elegant dwelling houses. Rather, it is concerned with whether plastic houses and room cells can be produced cheaply enough and sold in quantities large enough to relieve the housing market.

17. The high price per Kg. of material as against that of more conventional building materials necessitates industrial production on a scale as yet unknown in the building industry, if convincing competitiveness is to be attained. Manual labour cannot withstand strong competition.

18. Efficient series production methods for compact laminated materials already exist; for room units, even for modest span widths, they do not. Suggestions are included in the discussion.

19. The most suitable way for plastic houses would therefore seem to be slab construction using sandwich units, for reasons of assembly. Joints next to the corners seem preferable to joints at the corners; the Feierbach-Haus is a good example.

20. Parts weighing 80 - 100 kg., e.g. 2.50 x 2.75 m. can be moved without difficulty by hand. In addition, however, the assembly required too much manpower compared with a light crane, when the size of the building elements can be doubled or trebled.

21. The development of PU foam-light concrete can make further progress in this field. This construction technique could draw more heavily from the experience of mineral-light concrete, but the weight involved would be substantially greater and the same problems concerning fireproofing would arise as for plastic constructions.

22. There are adequate positive experiences of satisfactorily long durability of structures and surfaces.

23. There are no psychological disadvantages to be feared about living in plastics houses.

24. Even if all building and plastics technology questions could be solved, as well as problems of production and building supervisory board approval, the basic problem still remains - whether the market, i.e. owners, building society investors, etc., would be prepared to take up thousands of homes all built alike.
25. The study concludes that even if technological solutions might be in sight, it is not to be assumed that the plastics house can offer an effective contribution to the rationalization of housing in the near future.
Although the above study covered 21 countries (including Britain) in five different continents, and as such cannot be taken as strictly applicable in Britain, nevertheless, it can be seen that G.R.P. houses must generally conform to conventional house shapes, i.e. be 'fashionable' and pleasing in appearance. Pitched-roof houses have higher chances of success in Britain compared with flat roofs from the aesthetic approval point of view. Another relevant finding of the IBK study is the question of psychological aspects; the report states that "there are no psychological disadvantages to be feared about living in plastics houses."

In the field of educational buildings, as has already been noted, an experimental G.R.P. classroom extension based on a modified geodesic structure, based on the Icosahedron, has been erected by the Lancashire County Council in Preston, Lancs. Educational and health buildings together with other government properties, are not, generally speaking, subject to planning control, although, in the majority of projects, the government department concerned obtain aesthetic approval from the local authority concerned.

The preference for industrialized building methods in the education and health sector of the public undertaking is very strong; the reasons for this will be discussed in a more appropriate place. However, the general observations on the designs employed indicate the predominance of modular cuboid forms with flat roofs (24); it will also be seen that these designs would generally make use of standardized components which are ordered and produced in bulk (see Chapter 11).

In recent years some 200 folded plate standard G.R.P. structures or roofs have been supplied to schools by Messrs. Anmac of Nottingham, mainly as an environmental protection for schools' swimming pools and sports halls; it appears that planning authorities are not generally opposed to such uses. It is likely that they consider these applications as temporary.

Another notable and significant example in the field of schools is the large scale structural roof of the 1200-pupil Morpeth Secondary School in East London. The architectural attraction of the G.R.P. roof has been attributed to its sculptural character; no planning problem has been reported (12 and 44), although the designer and the client in this case were both the Greater London Council. The use of G.R.P. structures,
especially folded plates, in other areas, e.g. Birmingham and Leicester, has been pioneered (see Chapter 8).

The above evidence therefore indicates the feasibility of using G.R.P. structures in the education sub-market, especially as roofs to buildings constructed from conventional materials. Furthermore, use of a polygon, circle or similar arrangements for teaching or assembly rooms is a perfectly feasible proposition which needs further research in order to establish the effects of such geometrical arrangements on the pupils, etc. (43).

Infill panels of flat design incorporating glazing have been used in conjunction with a proprietary steel frame in two schools in Northamptonshire. Other G.R.P. uses in educational buildings include standard components, mainly window surround units for CLASP systems and flat cladding panels for nursery buildings designed by MACE.

The potential of the education sub-market for G.R.P. uses is enormous, because the designs are generally less susceptible to planning and aesthetics constraints compared with housing. However, any use of G.R.P. panels/structures must prove more economical compared with alternative materials for a more substantial penetration of this sub-market. This is due to the continued emphasis on reduction of costs in the public building sector.

In the health sub-market, the use of folded plates, shells and other G.R.P. space structures is limited; the only example of such uses found by the author is a 7.5 m. diameter geodesic dome installed at Worthing Hospital in Sussex.

Folded plates and shells are suitable for roofs in clinics and large surgeries; a useful arrangement for such buildings could be a polygon or circular waiting room connected to various attached diagnosis/treatment rooms, although the author has not found any evidence of a built example in practice.

The preference for modular designs and system building in the health sub-market is best illustrated by study of the recently completed projects; for instance, the general hospitals at Bury St. Edmunds, Suffolk and at Frimley in Surrey which have, it is claimed (45), produced the maximum economy.

The use of G.R.P. for modular designs has been examined by Oxford Regional Health Authority; a prototype building has also been erected as the extension to the East Birmingham Hospital. However, this authority has abandoned the use of G.R.P. panels
because of high costs and weathering/fire problems (see section 10.1).

In the field of sports and recreational buildings, there is often no aesthetic restriction against G.R.P. structures, since such buildings are generally designed to stand out and be exciting and cheerful in appearance (14 and 19). Hyperbolic paraboloid domes and arches, folded plates and shells may be designed to satisfy these requirements. However, these buildings are one-off jobs and there is often a limitation on the structural use of G.R.P. because of the requirements of the building regulations; thus, roofs, especially those incorporating translucent sections, are more easily used than are whole G.R.P. structures.

The use of G.R.P. panels and structures in motels, hotels and similar buildings has been studied; e.g. G.R.P. units have been incorporated in the Saxon Inn Hotel, Northampton and in a 'Little Chef' restaurant.

Folded plates and shells are potentially suitable for 'resort' restaurants, cafes and similar 'out-of-town' places, especially on the sea front. However, such structures are unlikely to be permitted in built-up parts of most British towns. This comment is equally applicable to office buildings.

Market covers, exhibition centres, pavilions and bus and railway shelters are examples for which three-dimensional G.R.P. structures would be considered as acceptable by most planning authorities. In the case of market covers, there is ample evidence that planning authorities in a few cases have approved the use of unusual designs; in these cases - and also in the case of recreational buildings - three-dimensional structures are generally considered as satisfactory by planning authorities (14, 19 and 40).

9.2.9 Summary of the main points:

The following points are intended as a summary of this study:

(1) At present, the aesthetic potential of G.R.P. structures is only relevant to one-off buildings. There is little hope of G.R.P. space structures and shells being accepted for general use on a large scale in the near future, either by planning authorities or by the general public, especially in the field of housing. It is interesting to note that the same conclusion was reached by IBK (refer to pages 438-440 ) and Bouverie (42).
(2) Contrary to the assumption held within the plastics industry, the current trends in design do not necessarily favour highly shaped panels and structures from an aesthetic point of view. It is the 'flat' design which is compatible with almost wholly 'cuboid' architecture in the mass market, be it cladding/infilling to multi-storey buildings, or one to two storey developments, etc. This is because the public have not yet accepted curvilinear and similar forms as 'convenient' spaces for everyday use. In addition, almost all services/fittings/furniture, etc., are designed to suit cuboid buildings.

(3) It is the design of 'nominally' flat or locally shaped panels which presents aesthetic problems, because to design a panel which enhances the appearance of the building, satisfies the local planning restrictions and is not a copy of pre-cast concrete panels is not an easy task. Many 'stereotyped' designs which have been recommended by the G.R.P. manufacturers, probably for ease of manufacture, have miserably failed to please. The use of such designs in non-industrial zones of an average British town may produce visual havoc.

(4) The claim that the designers of G.R.P. panels and structures have virtually unlimited freedom in design is not, of course, wholly true, as the properties of G.R.P., especially its relatively low modulus of elasticity, will dictate the geometrical configuration of the panel or the structure. It is not often recognized by non-experts that aesthetic characteristics of a shaped panel are very often different from that of the whole structure; in many built-up locations, it is difficult to reconcile the two, especially where the design is subject to local planning constraints.

(5) The aesthetic potential of G.R.P. in flat or slightly shaped/relieved panels for system building has not been fully explored; more research/experiment is needed to find valid and pleasing solutions in G.R.P., so that its full contribution in terms of improvements in the visual quality of system building may be realized.


3. Interview notes with Mr. Barret of Messrs. Glasdon.


5. Interview notes with Mr. Hopkins, Planning Officer, Guildford Borough Council, 17th February, 1975.


7. Interview notes with Mr. Lewis, MRTPI, 'Estate and Planning Officer' of the University of Surrey.


10. Interview notes with Mr. Killeen, Architect, Metropolitan Architectural Consortium for Education (MACE), on 7th March, 1975.


19. Interview notes with Mr. J. Fowley, Head of School of Town Planning, Kingston-upon-Thames, Polytechnic, 13th February, 1976.
34. Taylor, D., "Absurdity of today's architecture", Letter to
the A.J., 10th March, 1976 (p463).


43. Interview notes with Mr. K. Inman, Architect previously in private practice, now with the Lancashire County Council, 22nd April, 1975.

44. Attfield, K., "London School a landmark in structural use of plastics", New Civil Engineer, 24th October, 1974 (p32 to 34).

45. The Architects' Journal's Building Study, 'Best Buy' hospital at Bury St. Edmunds, Suffolk, the A.J., 19th June, 1974 (p1273 to 1393).
CHAPTER 10 ATTITUDES OF CLIENTS AND INSURERS ON THE USE OF G.R.P. PANELS

10.1 Attitudes of Clients:

10.1.1 General considerations:

Some data on the nature, role and size of clients have already been noted in Chapter 2. The influence of clients on the total building process was outlined in Chapter 3. In these chapters, it was shown that clients are seldom individual patrons and that they were not necessarily the users of buildings. It was noted that various committees of local councils often act as clients; and, to a large extent, their architects and designers make the detailed decision on behalf of these committees. Thus, the attitudes of county and district architects on the use of G.R.P. panels, which were analysed in Chapter 8, may be considered to be representative of their clients as well.

10.1.2 Sources of data:

The following sources of information have been used for this study: a postal survey, interviews and published information.

10.1.2.1 Postal survey:

Table 10.1 shows the composition and size of the sample used in the postal survey, which was carried out in the first quarter of 1976. It can be seen that the study was necessarily short and included three major nationalized industries and one regional health authority; nearly all of the private organizations included in the survey were known to be leading financial institutions, chain stores and hotel and entertainment enterprises.

10.1.2.2 Interviews:

Four major building and civil engineering firms, who have various estate and development undertakings, have been interviewed. Two of these firms have commercial interest in the 'system building' market (see Chapter 11).

In addition, interviews and meetings have been conducted with the following organizations: British Railways, Lancashire County Council Architects' Department, Surrey County Council Architects' Department and the Metropolitan Architectural Consortium for Education (MACE).

10.1.2.3 Published information:
10.1.2.3 Published information:
This includes information from the Architects' Journal, Reinforced Plastics Monthly, Rubber and Plastics Weekly, New Civil Engineer and other journals. The study which follows is generally based on a combination of information from the above sources.

10.1.3 Type of data collected:
Appendix B shows the questionnaire used for the postal survey. Most of what was described in sections 8.3 and 8.4 regarding the qualitative nature of that survey applies equally to this questionnaire. However, questions related to production techniques and the use of standardized panels were omitted from this study.

Question 5 of the questionnaire was designed to provide some indication of the process of initiation of the use of G.R.P. panels. Question 6 relates to the perceived attitudes of clients on the future use of G.R.P. panels. Question 7 is designed to highlight the relative importance of various aspects of designs for which clients may employ services of architects and designers in private practice.

10.1.4 The general pattern of the results:
Table 10.1 shows the overall pattern of the results of the postal survey. It can be seen that 14 out of 23 (or roughly 60 per cent) of the participants had previous G.R.P. experience; 7 out of 14 (or 50 per cent) of these were generally satisfied with the overall cost and performance of their G.R.P. projects, 5 out of 14 (or nearly 35 per cent) were partially satisfied and 2 out of 14 (or about 15 per cent) were dissatisfied. The overall response rate was 45 per cent.

As may be seen from Table 10.1, there were two dissatisfied clients:

(1) A major insurance company who have used G.R.P. panels extensively in one of their offices; and

(2) British Gas Corporation who have also used G.R.P. panels on a large scale in several of their buildings. Because of the comparatively large scale use of G.R.P. panels made by these two clients, it may be assumed that their replies should carry more significance than the average. (See also 10.1.6.2).

Table 10.1 indicates that about 60 per cent of the partici-
Table 10.1 Composition of the Sample and Analysis of the Results

<table>
<thead>
<tr>
<th>Type of organization</th>
<th>(I)</th>
<th>(II) No. incl.</th>
<th>(III) No. rtnd.</th>
<th>(IV) Resp. rate (%)</th>
<th>(V) + G.R.P. exp.</th>
<th>(VI) Satisfied</th>
<th>(VII) Partly Satisfied</th>
<th>(VIII) Dissatisfied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Insurance Companies</td>
<td>21</td>
<td>9</td>
<td>43</td>
<td>3</td>
<td>33</td>
<td>2</td>
<td>67</td>
<td>0</td>
</tr>
<tr>
<td>Major Building Societies</td>
<td>12</td>
<td>4</td>
<td>33</td>
<td>3</td>
<td>75</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Major Clearing Banks</td>
<td>4</td>
<td>4</td>
<td>100</td>
<td>4</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Major Chain Stores</td>
<td>6</td>
<td>2</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>Major Hotel/entertainment chains</td>
<td>4</td>
<td>1</td>
<td>25</td>
<td>1</td>
<td>100</td>
<td>1</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>British Gas Corporation</td>
<td>1</td>
<td>1</td>
<td>100</td>
<td>1</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Central Electricity Generating Board</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>N.A.</td>
<td>-</td>
<td>N.A.</td>
<td>-</td>
<td>N.A.</td>
</tr>
<tr>
<td>British Airports Authority</td>
<td>1</td>
<td>1</td>
<td>100</td>
<td>1</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Oxford Regional Health Authority</td>
<td>1</td>
<td>1</td>
<td>100</td>
<td>1</td>
<td>100</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>51</td>
<td>23</td>
<td>45</td>
<td>14</td>
<td>61</td>
<td>7</td>
<td>50</td>
<td>5</td>
</tr>
<tr>
<td>County and District Architects, England and Wales</td>
<td>192</td>
<td>133</td>
<td>69</td>
<td>61</td>
<td>46</td>
<td>38</td>
<td>62</td>
<td>9</td>
</tr>
</tbody>
</table>

* - Reproduced from Table 8.1
N.A. = not applicable
pant clients had used G.R.P., compared with only 46 per cent of the county and district authorities. Although the fact that most metropolitan district authorities are small and are mainly concerned with housing may explain the observed difference, nevertheless, the results must be treated with care, because, as has already been noted, the sample used for the clients' survey is not truly representative.

G.R.P. has not been used for speculative housing and office buildings by any of the major contractors. From the interviews the author has carried out, it is apparent that the reasons are mainly associated with the high costs of G.R.P. and doubts in the minds of these companies concerning the fire behaviour and long term performance of this material. However, some of these companies have large interests and investments in other materials; this means that by development of G.R.P. they may, in effect, be reducing the size of their established markets and their products.

As will be seen in Chapter 11, MACE have recently begun to use G.R.P. cladding panels in their nursery buildings which are based on an industrialized system; however, sufficient time must expire before this authority can evaluate performance of their panels.

10.1.5 Perceived advantages and disadvantages of G.R.P. panels:

Table 10.2 shows ranking of the reasons for satisfaction and dissatisfaction of clients on the use of G.R.P. panels. These have been taken as advantages and disadvantages of G.R.P. panels respectively. The findings are to some extent similar to the results of the previous survey (c.f. section 8.4).

The explanation to Table 10.2 has been included beneath this table: N.T.A. and N.T.R. denote number of times accepted and number of times rejected respectively of the argument put forward in a question.

It can be seen that 'low maintenance requirement' (+11, -0) of G.R.P. panels was the most prominent advantage of this material as perceived by clients, followed in descending order by 'improved appearance' (+9, -2), 'improved overall economy' (+6, -2), 'shortening of the time' (+5, -1) and 'satisfactory technical performance' (+3, -2).

Of the disadvantages, 'extra cleaning problems' (+4, -1), was perceived as the biggest, followed in descending order by
### Table 10.2 Ranking of Perceived Advantages and Disadvantages of G.R.P. panels *

<table>
<thead>
<tr>
<th>Description</th>
<th>Reasons for satisfaction</th>
<th>Reasons for Dissatisfaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranking Order</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Arg't symbol</td>
<td>LM</td>
<td>IA</td>
</tr>
<tr>
<td>N.T.A.</td>
<td>+11</td>
<td>+9</td>
</tr>
<tr>
<td>N.T.R.</td>
<td>-0</td>
<td>-2</td>
</tr>
</tbody>
</table>

* - based on the combined results of replies to questions 3(a) to 3(e) and 4(a) to 4(e) inclusive (c.f. Appendix B)

**Explanation to Table 10.2:**

The argument symbols used in the above table have the following meaning; each symbol represents one of the questions 3(a) to 3(e) and 4(a) to 4(e) inclusive in the questionnaire.

- **3(a)** Improved appearance = IA
- **3(b)** Low maintenance = LM
- **3(c)** Shortening of the time to project completion = ST
- **3(d)** Improved overall economy = IE
- **3(e)** Satisfactory technical performance = SP
- **4(a)** Significant weathering/degradation = SD
- **4(b)** Delaying of the project completion = DC
- **4(c)** Increased overall costs = IC
- **4(d)** Increased fire risks = FR
- **4(e)** Extra cleaning problems = EC
'significant weathering/degradation' (+3, -0) and 'delaying of the completion date' (+3, -0), 'increased fire risks' (+3, -1) and 'increased costs' (+1, -1).

The above mentioned advantages and disadvantages have been discussed in some detail below.

10.1.6 Advantages of G.R.P. panels:

10.1.6.1 Low maintenance requirement:

11 out of 14 (or about 80 per cent) of the participant clients with G.R.P. experience agreed that 'low maintenance requirement' of G.R.P. was one of the reasons for their satisfaction. However, many of these users pointed to the relatively short period of service experience of this material, e.g. one large client commented: "It is too early to specify one's satisfaction."

The interdependence of 'maintenance requirements' with 'durability/natural weathering performance' of G.R.P. panels has already been noted (see e.g. 8.7.1).

It may be noted that one of the two dissatisfied clients (i.e. the insurance company) made the following comments on the weathering behaviour of their three years old G.R.P. panels, which have been used as curtain walling on six storeys of their seven storey office block: "Jointing unsatisfactory and many panels have cracked. Attempts to provide a satisfactory fire rating detracted from the durability and weathering qualities of the panels." From this comment, it is clear that the G.R.P. panels in question needed maintenance attention at an early stage.

There is also evidence that the internal use of G.R.P. in some cases may require maintenance (e.g. painting) as two clients have stated that the material has discoloured. In addition, it has been reported that damaged G.R.P. panels are difficult to repair.

The question of durability/proof of satisfactory long term weathering performance was considered by one organization as crucial; They commented: "We would require evidence of longer term 'field tests' to be assured that G.R.P. panels will perform satisfactorily." Another client stated: "We do not propose using G.R.P. as at present, because of the reasons outlined in 6(c) of the questionnaire."

10.1.6.2 Improved appearance:

9 out of 14 (or about 65 per cent) of clients with G.R.P. experience agreed that G.R.P. panels had given an attractive
appearance to their buildings, compared with 2 out of 14 (or about 15 per cent) who rejected the same argument.

One client observed that: "Appearance of G.R.P. is not quite good enough when used as substitutes or imitations of other materials, e.g. slate stone, brickwork, etc." This comment implies that many of the uses of G.R.P. are decorative/fascia applications usually to simulate certain surface textures. Statements by two other clients support the above conclusion; one of these was as follows: "As far as this organization is concerned, the material in question has no natural and obvious use, except for fascias."

Not all comments on the aesthetics of G.R.P. panels were favourable, e.g. one client observed: "G.R.P. is considered to be in the class of short term 'fairground' architecture! It is hoped that G.R.P. panels will not become generally popular on commercial projects, or they will result in the lowering of aesthetic standards."

It must be noted that the participant clients without G.R.P. experience (i.e. 9 organizations, see Table 10.1) did not generally perceive G.R.P. as a material with 'status' which could increase the prestige of their business (see 10.1.9).

10.1.6.3 Improved overall economy:

As can be seen from Table 10.2, 6 out of 14 (or about 45 per cent) of clients with G.R.P. experience agreed that the use of G.R.P. panels had proved economic in their cases, compared to only 2 out of 14 (or about 15 per cent) who rejected this argument.

The above finding suggests that as far as this group of clients are concerned, G.R.P. panels have shown some economic advantage over the more traditional materials. This view is supported by the following comment: "So long as cost comparisons are favourable and appearance is good, I see an increasing use of G.R.P. in fitting out our branch offices which, in many ways, are similar to shops. I myself can accept G.R.P. more readily where it does not pretend to be something else."

10.1.6.4 Shortening of the time to project completion:

This advantage of G.R.P. panels combines 'ease of manufacture and shaping' and 'ease of erection' (c.f. 8.6.3 and 8.6.4).

As seen from Table 10.2, 5 out of 14 (or about 35 per cent) of clients with G.R.P. experience agreed that some saving was made on the total time spent on design and construction of their projects, compared to only 1 out of 14 who disagreed.

Table 10.2 also shows (under disadvantages heading) that
three clients agreed that the use of G.R.P. panels had delayed their project completion dates due to increased difficulties related to the design and site erection of these panels. Thus, whilst it can be accepted that G.R.P. may be successfully used to shorten the overall length of time required for design and construction of some buildings, it must not be assumed that the use of this material will automatically result in a net saving in the total time. In addition, as has been pointed out by one authority, the length of time saved may be so small as to be insignificant to the client concerned.

10.1.6.5 Satisfactory technical performance:

Not all G.R.P. panels are designed to similar performance specifications; the purpose of the question was to find out how far G.R.P. panels had managed to satisfy the users in terms of various technical performance requirements such as effectiveness of joints or thermal movements or mechanical strength and rigidity, etc.

3 out of 14 (or about 20 per cent) of clients with G.R.P. experience agreed that 'satisfactory technical performance' of their G.R.P. panels in service was a reason for their satisfaction, compared to 2 out of 14 (or about 15 per cent) who rejected this argument. However, some clients stated that they could not yet evaluate the behaviour of their G.R.P. panels as these panels had been erected in the last one or two years.

The above finding implies weaknesses in the design and jointing techniques employed by the designers of some panels.

10.1.6.6 Other advantages of G.R.P. panels:

There was no other specific advantage stated by the participants under question 3(f) in the questionnaire (see Appendix B).

10.1.7 Disadvantages of G.R.P. panels:

10.1.7.1 Extra cleaning problems:

Problems of cleaning exposed surfaces of G.R.P. panels were considered to be the biggest disadvantage of this material; 4 out of 14 (or about 30 per cent) agreed with this argument, compared to 1 out of 14 who disagreed.

Two of these clients were in fact the insurance company and the British Gas Corporation, whose cases have been discussed in subsection 10.1.4. Another organization included in the above list complained about the extra cleaning and maintenance require-
10.1.7.2 Significant weathering/degradation:

3 out of 14 (or about 20 per cent) of the clients with G.R.P. experience were dissatisfied with the weathering/degradation of their panels; again, two of these clients were the insurance company and the British Gas Corporation. The comment made by the former on the weathering problems of his panels has already been noted in 10.1.6.1.

10.1.7.3 Delaying of the project completion:

Problems of design and site erection of G.R.P. panels, which may cause delaying of the project completion date, have been discussed in detail in Chapter 8. Cases of dissatisfied clients related to the delaying of the project completion date were considered in 10.1.6.4.

10.1.7.4 Increased fire risks:

The insurance company, British Gas and Oxford Regional Health Authority are the three clients who agreed that extensive use of G.R.P. panels on their projects had increased the fire risks on their buildings. The case of the insurance company is significant since the panels used by this client were, in fact, designed for a class 0 performance (i.e. to the B.S. 476:6), and the client is still dissatisfied with the fire risks of the panels. Two factors are likely to be affecting the attitude of this client: (a) the total extra damage likely to be sustained by the building in conditions of fire, due to combustibility of G.R.P.; and (b) the possibility of smoke evolution by the G.R.P. laminate, which may constitute a hazard to the occupants and the fire brigade.

British Gas consider the fire hazards of G.R.P. to be even greater; they commented: "G.R.P. panels are hazardous in intense heat and explosion." The Gas Authorities are not prepared to use G.R.P. in the same manner again.

The following comment was made by Oxford Regional Health Authority: "We have a class 0 requirement for fire propagation and have not been able to meet it and achieve a satisfactory weathering property. We had to relax the requirement to get around the problem for this experimental building."

10.1.7.5 Increased overall costs:

The Gas Corporation stated that the use of G.R.P. panels had resulted in an increase in their total costs coupled with delaying
of the project completion date. They are in fact dissatisfied with all aspects of their G.R.P. panels. However, the insurance company consider that their use of G.R.P. panels was economic; as has already been noted, this apparent disagreement between these two cases is not unique. However, it is possible that the insurance company are using the 'initial capital' as the basis of their judgment, because estimates for likely maintenance are difficult to make.

10.1.7.6 Other disadvantages of G.R.P. panels:

In reply to question 4(f) of the questionnaire, only two isolated comments were received; one client observed: "rather unsatisfactory performance of supplier"; and the second client commented: "G.R.P. has proved unsatisfactory in counter applications."

10.1.8 Methods of proposing G.R.P. panels:

Question 5 in the questionnaire was designed to give indications of the usual ways in which the G.R.P. panels had been specified. The replies to this question were as follows (Table 10.3):

Table 10.3 Analysis of Methods of Proposing G.R.P. panels

<table>
<thead>
<tr>
<th>G.R.P. panels were proposed:</th>
<th>Number</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) by the consulting architect/engineer and approved by the client</td>
<td>10</td>
<td>62.5</td>
</tr>
<tr>
<td>(b) by clients and discussed with the consulting architects</td>
<td>4*</td>
<td>25.0</td>
</tr>
<tr>
<td>(c) Architect/quantity surveyor presented clients with alternative designs/costs and clients chose G.R.P.</td>
<td>1</td>
<td>6.2</td>
</tr>
<tr>
<td>(d) client was not informed of the use of G.R.P. panels</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(e) some other way</td>
<td>1</td>
<td>6.3</td>
</tr>
<tr>
<td>Total</td>
<td>16</td>
<td>100</td>
</tr>
</tbody>
</table>
In two of these cases, G.R.P. panels were proposed by clients' architectural staff who had been responsible for the whole design; in these cases, the clients' design works are mainly carried out by 'in-house' staff and not by commissioning professional firms.

As can be seen from Table 10.3, in 10 cases, consulting architects had proposed the use of G.R.P., compared to 4 cases in which the clients had initiated the use of this material; only on one occasion was the client presented with a choice of materials coupled with estimates of costs which resulted in selection of G.R.P. by the clients.

However, the above finding must be treated with caution, since, as seen from the footnote to Table 10.3, in two cases the use of G.R.P. was proposed by clients' 'in-house' staff, who normally handled the bulk of the design work. Thus, they were in fact professional designers.

The above discussion may raise the following question: who represents these clients in negotiation with outside architects, contractors, etc? From the standpoint of this survey, an analysis of the titles of signatories revealed that in 10 cases they were architects, in 5 cases quantity surveyors and in the remaining 7 cases, the signatories could not be identified. However, it is likely that two of these latter were also architects and three were quantity surveyors. The remaining two signatories were not identifiable at all.

In short, it is obvious that professional designers, whether employed as staff or in private practice, had, in the overwhelming majority of cases, proposed the use of G.R.P. panels. This finding may not be valid universally due to effects of sampling; nevertheless, these facts coupled with independent observations confirm the importance of professional designers' advice given to their respective clients or employers on the use of any new material in the construction industry.

10.1.9 Reaction of clients to any future use of G.R.P. panels:

As can be seen from the questionnaire, four categories of 'reaction' have been defined; these are suggested as probable replies to question 6; all four categories of 'reaction', together with their respective responses, are shown in Table 10.4.

The result of this analysis indicates that G.R.P. is not generally perceived as a material with status similar, for
example, to brass or polished granite or marble slabs, etc. In one case (i.e. Concorde's Terminal in Heathrow Airport), its internal use in the form of tubular runners is intended to give a fashionable and symbolic appearance. To this part of the airport. It is worth noting that one of the two clients who reacted favourably to the future use of G.R.P. was the British Airports Authority, who commented: "We are relatively enthusiastic for the use of G.R.P. except in situations where modifications are likely, e.g. shop fitting." The second client with a favourable reaction was Trust Houses Forte, who have a number of motels and restaurants cladded or fitted with G.R.P. panels.

The two unfavourable reactions recorded in column (II) of Table 10.4 have been made by the British Gas Corporation and the insurance company whose cases have already been discussed. The only unfavourable reaction by users without G.R.P. experience, which is shown in column (III), has been made by a large chain store organization, who do not propose to use G.R.P. at all.

It should be noted that categories (b) and (d) together account for over three quarters of all the reactions; these two categories are not very much different from each other. This finding indicates the non-committal attitude of clients in the construction market.
Table 10.4 Analysis of Reaction by Clients to the Future Use of G.R.P. Panels

<table>
<thead>
<tr>
<th>Category of Reaction</th>
<th>(I)</th>
<th>(II) + G.R.P. exp.</th>
<th>(III) - G.R.P. exp.</th>
<th>(IV) Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No of cases</td>
<td>% of total</td>
<td>No of cases</td>
<td>% of total</td>
</tr>
<tr>
<td>(a) Favourable, provided G.R.P. panels are not too costly; because they can give a modern and fashionable appearance, increasing the prestige of the business</td>
<td>2*</td>
<td>14.2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(b) No special reaction, provided they are considered by architect/quantity surveyor as both economic and appropriate</td>
<td>4</td>
<td>28.5</td>
<td>3</td>
<td>33</td>
</tr>
<tr>
<td>(c) Unfavourable because of high costs, increased problems, reduced overall soundness and suspect long term performance</td>
<td>2</td>
<td>14.2</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>(d) Reaction would depend on the nature of the application and the case under consideration</td>
<td>6‡</td>
<td>43.3</td>
<td>5</td>
<td>56</td>
</tr>
<tr>
<td>Total</td>
<td>14</td>
<td>100.0</td>
<td>9</td>
<td>100</td>
</tr>
</tbody>
</table>

* - Includes one case in which, in addition to category (a), the client also specified categories (b) and (d).
‡ - Includes one case in which, in addition to category (d), the client also specified category (b).
10.1.10 Reasons for commissioning consulting architects to design of new buildings:

As was explained earlier, the purpose of this question was to find out the relative importance of the three defined 'reasons' for which the services of a consulting architect are generally employed. These reasons, together with the respective responses, are shown in Table 10.5.

Table 10.5 Analysis of the Order of Preferences recorded for each category of 'reason'.

<table>
<thead>
<tr>
<th>Type of Reason (design aspects)</th>
<th>Total cases included</th>
<th>Order of Preference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st (f) 2nd (r.f.) 3rd (f)</td>
<td></td>
</tr>
<tr>
<td>(a) Development of a functional and economic design using the most up-to-date technology</td>
<td>15 7 43.5 7 39.0 1 9.0</td>
<td></td>
</tr>
<tr>
<td>(b) Development of a design which is fashionable and attractive in appearance and can increase the prestige of the business</td>
<td>15 5 31.5 6 33.5 4 36.5</td>
<td></td>
</tr>
<tr>
<td>(c) Development of a design which can conform to the statutory requirements.</td>
<td>15 4 25.0 5 27.5 6 54.5</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>16 100 18 100 11 100</td>
<td></td>
</tr>
</tbody>
</table>

An assessment of the absolute and relative frequencies in Table 10.5 shows that economic and functional aspects of designs were perceived by the clients as the most crucial aspects, followed in descending order by aesthetics and compliance with the statutory requirements. However, as was seen from the total number of cases included, only 15 out of 23 clients found it possible to comment in this question; the remaining 8 either did not generally use services of consulting architects or considered separation of the above design aspects to be virtually impossible. Table 10.6 contains some of the comments made by various clients on this topic.
<table>
<thead>
<tr>
<th>Type of organization</th>
<th>Any G.R.P.</th>
<th>State of satisfaction</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>British Gas Corporation</td>
<td>yes</td>
<td>dissat.</td>
<td>Development of a design acceptable to environmentalists and hence planning approval.</td>
</tr>
<tr>
<td>British Airports Authority</td>
<td>yes</td>
<td>part. sat.</td>
<td>Difficult to answer Q.7; (a) and (b) are all of the same significance to us. (c) is something automatically expected whether we employ architects or do the work in-house.</td>
</tr>
<tr>
<td>Major Bank</td>
<td>yes</td>
<td>sat.</td>
<td>Q.7, all these reasons are interdependent and I cannot separate them in order of preference.</td>
</tr>
<tr>
<td>Major Bank</td>
<td>yes</td>
<td>sat.</td>
<td>We use a high proportion of 'in-house staff'.</td>
</tr>
<tr>
<td>Major Insurance Company</td>
<td>yes</td>
<td>sat.</td>
<td>Consulting architects are employed to lead a technical team and provide aesthetic guidance within their clients' briefs.</td>
</tr>
<tr>
<td>Major Insurance Company</td>
<td>no</td>
<td>-</td>
<td>Q.7: Unfortunately (c) often has to be the main reason for using other than Company's own Architectural Staff, due to the fact that Local Authorities are often more ready to accept schemes put forward by a wellknown consultant of their choosing.</td>
</tr>
<tr>
<td>Major Building Society</td>
<td>yes</td>
<td>part. sat.</td>
<td>For none of (a) to (c) reasons, especially, that kind of performance is expected automatically. Rather are outside Architects appointed to get work done.</td>
</tr>
<tr>
<td>Major Chain Store</td>
<td>no</td>
<td>-</td>
<td>Q.7: [(c) = 1st, (a) = 2nd, and (b) = 3rd]; future maintenance costs, e.g. weather proofing, decorations, etc. also important considerations.</td>
</tr>
<tr>
<td>Major Insurance Company</td>
<td>no</td>
<td>-</td>
<td>Wherever possible, attitudes of the building users should be recognized at the design stage.</td>
</tr>
</tbody>
</table>
10.1.11 Miscellaneous comments:

Table 10.7 contains miscellaneous comments made by various clients; these comments are self-explanatory.

10.2 Attitudes of the Insurers to the Use of G.R.P.:

10.2.1 Market division of the U.K. insurance industry:

The U.K. insurance market divides into the following four categories:

10.2.1.1 The tariff market:

This expression is used to define (1) those insurance firms, members of the Fire Offices' Committee (F.O.C.), who use the F.O.C. rules and tariffs for fire insurance of buildings. These companies insure virtually any type of premises and are in competition with each other and with the non-tariff companies (1). However, due to their trade agreement, they may not charge insurance rates below the common tariff set by the F.O.C. (1). The usual practice in the tariff market is for a company to set their yearly tariff in relation to the minimum rates; at the end of the year, if the company make a large profit, they will reduce their rates. Conversely, if they make a loss, they will increase their rates. On no account will an insurance company adopt rates below the minima set by the F.O.C. This system for setting the insurance (or tariffs) is termed (1) 'negative feedback' and is somewhat discretionary.

The F.O.C. are in fact the trade association of the tariff companies (1). The F.O.C. have a number of other functions, chiefly preparation of uniform rules and tariffs, fire research and testing of materials for approval purposes; these functions are discussed in more detail in the later part of this section.

The tariff companies control up to 65 per cent of the U.K. insurance market (1).

10.2.1.2 The non-tariff market:

The companies in this market also use the F.O.C. rules and tariffs but may choose to undercut these tariffs in order to increase their share of the insurance market.

10.2.1.3 Mutual companies:

These companies are owned by their shareholders. They also use a similar system for calculating the insurance tariffs, but they require a building to conform to their standard categories.
<table>
<thead>
<tr>
<th>Type of organization</th>
<th>Any G.R.P. exp.?</th>
<th>State of satisfaction</th>
<th>Comment(s) made</th>
</tr>
</thead>
<tbody>
<tr>
<td>British Gas Corporation</td>
<td>yes</td>
<td>dissat.</td>
<td>We have used G.R.P. panels quite extensively in our early building projects, i.e. over the last eight years or so, but our increasing awareness of various safety and security hazards is now precluding this type of material in the majority of applications.</td>
</tr>
<tr>
<td>Oxford Regional Health Authority</td>
<td>yes</td>
<td>part. sat.</td>
<td>We have found G.R.P. to be unsuitable for Oxford method cladding because of cost and the fire/weathering problem. However, we are investigating its use on the window panels because no fire rating is required there.</td>
</tr>
<tr>
<td>Major Bank</td>
<td>yes</td>
<td>sat.</td>
<td>We have had extremely limited applications of this material to date, but are considering its respective qualities for the future.</td>
</tr>
<tr>
<td>Major Bank</td>
<td>yes</td>
<td>sat.</td>
<td>Advice to the Architects on the use and technical problems associated with G.R.P. panels could be more widely available.</td>
</tr>
<tr>
<td>&quot; &quot;</td>
<td>Glass Reinforced Cement (Cem-Fil) would seem to have more versatility than G.R.P.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
before they are prepared to insure it (1). This type of insurance is very common in the U.S.A. (1).

10.2.1.4 Lloyds:
This market caters for special types of insurance, e.g. supertankers, etc.

In short the attitude of the F.O.C. may be assumed to represent the attitude of the majority of insurance companies, especially in relation to the fire insurance of buildings.

10.2.2 Sources of data:
The study in this section is based on the following sources of information:
(1) Interview with a 'Technical Officer of the F.O.C. (1).
(2) Published information; there are two papers specially written on the subject of plastics in buildings and fire insurance by an F.O.C. authority (2) and by a specialist insurance broker (3).
(3) Latest versions of 'Rules' for classification of buildings to the five 'Standards' (7) and/or the three 'Classes' (8); these are published by the F.O.C. and used by the 'Fire Surveyors' in order to assess the insurance premiums, etc.

10.2.3 Basic factors affecting the attitudes of insurers:
The insurance companies regard the Building Regulations as an inadequate basis for determining the insurance rates (1 and 2); they argue that these regulations are primarily intended for the safe evacuation of building occupants, whereas the insurers' attitude is affected by the high annual losses incurred due to fire (1 and 2). The latest figures available indicate (4) that in 1974, direct fire losses in Britain totalled an estimated figure of £237m. There were 1210 fires which caused damage of £15000 or more; these 1210 fires accounted for £163,336m (or 69 per cent) of the total losses. In general, there has been a continuous rise, in terms of real costs, in the total annual fire losses since 1956 (1), e.g. the total direct fire losses in 1964 were £77m (2). These figures do not include loss of life or personal injuries, nor do they include any allowance for indirect losses through interrupted production, loss of market, etc.; the indirect losses have been reckoned (1 and 2) to be considerably greater than the direct losses.
It has been estimated (2) that, of the total direct losses, something of the order of half would be in the form of buildings.

10.2.4 Theoretical considerations:

Fig. 10.1 shows how 'total costs', 'costs of provision of fire-resistance' and 'costs of fire protection' vary with the period of 'fire-resistance' (5); these curves are theoretical and relate to a given building, e.g. an office building.

Baldwin (5) assumes the following equation for the 'total costs' (T), related to the structural fire failure:

\[ T = C(R) + p \times p_o \times p_f \times D \times \phi \]

where:
- \( R \) = fire resistance of the structure; \( C(R) \) is the costs of providing this provision.
- \( p \) = annual probability of inception of a fire.
- \( p_o \) = the probability of the incepted fire growing sufficiently large as to cause damage to the building fabric.
- \( p_f \) = the probability of failure of 'fire-resistance' given a fire which has reached a stage such as to cause damage to building fabric (e.g. beyond 'flashover' point).
- \( D \) = the expected (or assumed) total loss following failure of the 'fire-resistance' system.
- \( \phi \) = the discount factor which is derived by summing the discounted annual expected damages for the building. Since, in most buildings, the assumed life is typically greater than 50-60 years, \( \phi \rightarrow 1 + \frac{1}{r} \) (\( r = \) discount rate); for \( r = 0 \), \( \phi = n = 50 \) to 60.

The derivation of the above parameters has been discussed below:

(1) Estimation of \( p_f \): There are no statistical data related to cases of real fires from which \( p_f \) can be estimated. Experimental techniques for estimation of \( p_f \) have been used by a number of authors. A summary of their works may be found in reference 5; briefly, the expression shown below has been derived by Baldwin (5):

\[ p_f = e^{-\frac{R}{\bar{S}}} \]

where:
- \( R \) = fire-resistance of the building (in minutes), and
- \( \bar{S} \) = the mean severity of fire which changes from one occupancy to another (for offices, \( \bar{S} = 25 \) minutes).
FIG. 10.1 TOTAL FIRE COSTS vs FIRE RESISTANCE
(after Baldwin (5))
$S$ is the mean value of 'fire severity' ($S$), which is a random variable experimentally related to the fire load ($L$), the total window area ($A_W$) and the total of the sum of wall and ceiling area excluding window area ($A_T$); the expression is as follows (5):

$$S = K \times \frac{L}{\sqrt{A_W \times A_T}}$$

where $K$ = constant

(2) Estimation of $p$, $p_o$, $C(R)$ and $D$: $p$ and $p_o$ may be estimated from the annual fire statistics and the number of buildings in each occupancy exposed to the same risk. North (6) has summarized the available data, e.g. annual probabilities of incepting fire in houses and offices have been derived as $(2.7 \times 10^3)$ and $(5.7 \times 10^3)$ for dwelling houses and offices respectively (5) (1965 data).

Baldwin (5) has estimated a value of 0.10 for office premises. For concrete structural frames, Baldwin gives the following formula for estimation of $C(R)$:

$$C(R) = A + B \times R$$

where: $A$ = the cost of fire protection independent of the fire-resistance afforded by the building (or its structure).

$B$ = the costs of increasing the fire-resistance of the building per unit.

Estimation of $D$ has, however, proved difficult; this is because of the lack of valid data on the total costs of 'fire-resistance' failures, including allowances for any loss of life, etc. In some cases, an incidence of failure in a building may introduce fresh requirements for the strengthening of buildings constructed to similar standards; these may incur costs of approximately two to four times that of the original building costs (10). However, this is not a 'catastrophe', which may incur losses, on average, of up to 100 to 150 times the original costs (10).

Baldwin (5), after study of the available data, has stated that $D$ must be treated as an unknown parameter requiring further research. Unfortunately, this leads to difficulties in calculating the 'optimum' value of the 'total costs' (c.f. Fig. 10.1). According to the calculations made by Baldwin (5), to justify the provision of a minimum 'fire-resistance' of 60 minutes for offices
(as generally required under the Building Regulations), the expected loss must be greater than 40 to 50 times the initial building costs. If the expected loss is small, say less than four times the initial costs, then no 'fire-resistance' is economically justified (5).

There are various uncertainties appertaining to the above analysis:

(a) Variability of 'actual' fire-resistance of a building as a function of its 'nominal' fire-resistance based on the B.S. 476 part 8.

(b) Accuracy of mathematically linking the fire severity, room characteristics (i.e. fire load, areas of ventilation, compartment dimensions, etc.) and the 'fire-resistance'.

(c) The problems of estimating the expected total damage $D$ upon the failure of the fire-resistance.

In addition, this analysis deals with the costs of structural damage to building fabrics only, whereas the total damage of any kind, including non-structural components and finishes but excluding any allowance for loss of life or personal injuries, is the concern of the insurers.

10.2.5 The criteria used in practice by the insurers:

The above discussion illustrated the difficulties of relating the fire damage to the materials of known 'fire-resistance' and to the other relevant parameters of the building. Thus, an 'ad hoc' approach which dates back to 1907 is generally used by the F.O.C. to calculate the insurance rates for any building (1 and 2). The insurance rates are claimed (1, 2 and 3) to be related to the following factors: the risk of fire inception, the risk of fire spread and the risks of smoke generation, molten droplets and many other undesirable features which may deter the extinguishing of the fire by obstructing the firemen from reaching the seat of the fire (1 and 2).

Naturally, the risk of fire inception is mainly related to the type of occupancy. However, the possibility of ignitability of a combustible material at recurring temperatures (e.g. those associated with some industrial processes) or accidental temperatures (e.g. those reached on the surfaces exposed to radiation energy from an electric fire) will also affect the risk of fire inception.
10.2.5.1 Standards and classification of constructions:

The insurance companies, members of the F.O.C., follow 'Standards I to V' (7), as published by the F.O.C., for the purpose of rating of insurance (in some industrial processes, such as manufacture, conversion and fabrication of plastics materials or reinforced plastics, the F.O.C. rules for Classes I to III (8) replace Standards I to V). Buildings complying with these Standards qualify for discounts from normal rates in the following manner. If a building complied with the requirements of Standard V (or Class III where applicable), it would be charged in accordance with the scale of charges related to the type of occupancies (1 and 2), i.e. at a no-discount, no-penalty rating. Compliance with Standard I will attract the highest discount rate, followed in descending order by Standards II, III and IV (1 and 2).

As was stated above, some industrial premises are required to be constructed in accordance with the F.O.C. rules for Classes I, II and III (8); in this system, Class I would qualify for a maximum discount and Class II for a lower discount rate. (8). Classes I and II are claimed (1) to represent equivalent periods 'fire-resistance' of approximately 2 hours and 1 hour respectively. The intention (8) is to apply the above rules for Classes I, II and III progressively to premises occupied for other trades; the main advantage of this system is reduction in the number of classifications from five to three. For the present, Standards I to V are still applicable to most buildings.

Up-to-date versions of Standards I to V may be obtained from the F.O.C. Table 10.8 gives examples of typical constructions presently specified in these Standards; it must be noted that none of these Standards specifies periods of 'fire-resistance'. In fact, Standards I to V (and Classes I to III) are mere construction specifications and are not in the form of minimum performance requirements. Periods of fire-resistance performances given in Table 10.8 are those estimated by the author.

Further, implicit in these Standards is compliance with the Building Regulations; (1 and 2); thus, where no indications of materials are given (e.g. in the case of partition and lining materials in Standards II to V), it is assumed that any proposed materials or designs will satisfy the provisions of the Building Regulations.

A study of Standards I to V (7) reveals that, because these are based on known constructional designs, their associated fire
Table 10.6  Typical Constructions currently specified in Standards I to V (source: F.O.C.)

<table>
<thead>
<tr>
<th>Standard</th>
<th>Party walls</th>
<th>Ext. walls, (1) load-bearing</th>
<th>Ext. walls, non-load-bearing (1)</th>
<th>Floors (2)</th>
<th>Roofs</th>
<th>Thickness θ of walls around flr. openings (mm)</th>
<th>Type of partition</th>
<th>Ceiling + wall lining</th>
<th>Window frames internal doors</th>
<th>% of openings in ext. walls</th>
<th>Type of rooflight accepted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F.R. (hrs)</td>
<td>Thickness θ (mm)</td>
<td>F.R. (hrs)</td>
<td>Thickness θ (mm)</td>
<td>F.R. (hrs)</td>
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<td>F.R. (hrs)</td>
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<td>F.R. (hrs)</td>
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<tr>
<td>(I)</td>
<td>&gt; 4</td>
<td>solid 230 (150)</td>
<td>&gt; 4 solid 230 (150)</td>
<td>&gt; 4 solid 230 (150)</td>
<td>&gt; 4 solid 150 (150)</td>
<td>&gt; 2 125 (230)</td>
<td>incombustible</td>
<td>N.S.</td>
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</tr>
<tr>
<td>(II)</td>
<td>&gt; 4</td>
<td>solid 230 (150)</td>
<td>&gt; 2 solid 230 (150)</td>
<td>&gt; 2 solid 230 (150)</td>
<td>&gt; 2 125 (100)</td>
<td>incombustible</td>
<td>N.S.</td>
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<tr>
<td>(III)</td>
<td>&gt; 4</td>
<td>solid 230 (150)</td>
<td>&gt; 2 solid 230 (150)</td>
<td>&gt; 2 100 (100)</td>
<td>incombustible 2</td>
<td>N.S.</td>
<td>incombustible</td>
<td>N.S.</td>
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<tr>
<td>(IV)</td>
<td>&gt; 4</td>
<td>solid 230 (150)</td>
<td>&gt; 2 solid 230 (150)</td>
<td>&gt; 2 100 (100)</td>
<td>N.S.</td>
<td>incombustible</td>
<td>N.S.</td>
<td>incombustible</td>
<td>N.S.</td>
<td>N.S.</td>
<td>N.S.</td>
</tr>
<tr>
<td>(V)</td>
<td>&gt; 4</td>
<td>solid 230 (150)</td>
<td>2 brick or block walls</td>
<td>N.S.</td>
<td>incombustible</td>
<td>N.S.</td>
<td>N.S.</td>
<td>N.S.</td>
<td>tile, st. sheet, asbestos, wood, wood wool</td>
<td>N.S.</td>
<td>N.S.</td>
</tr>
</tbody>
</table>

W - Brick or masonry (figures inside brackets indicate equivalent thickness of reinforced concrete).
D - Reinforced concrete.
(c) - Glass rooflight (normally wired glass); this is restricted to one third of the roof area in Standard I, but not specified in Standards II to V.
(d) - Translucent G.R.P. or rigid PVC rooflights, which are allowed provided (i) the approved type is used; (ii) the combined area of rooflights does not exceed 15% of the plan area of roof; (iii) area of each rooflight does not exceed 5m²; and (iv) the distance between individual rooflights is not less than 1,8m.
(e) - As (d) except that area of each rooflight may be up to 10m².

Notes: N.S. = not specified; F.R. = ’maximum fire-resistance’.
(1) - Timber-framed external walls are not allowed; structural steel or aluminium must be protected by incombustible materials.
(2) - The surface of incombustible floors may be covered with any material provided no intervening air gap is allowed.
+ - Any supporting walls or piers must be of brickwork or masonry or concrete. Structural metals to be protected by incombustible materials.
† - Asphalt must be of specified composition; bituminous felt must be either used on an incombustible frame/decking or be covered with a minimum of 12mm sand/cement mortar or 50mm dry sand. Also, a variety of trade products, some of the sandwich design, are accepted as covering materials, e.g. 'Galbestos', 'Coloursteel', 'Trimat', 'natural Black Cellactite'.

Unaccounted areas calculated in accordance with current recommendations.
risks in a given occupancy are established from past experience (l). Standard I must be regarded as providing for permanent working spaces of virtually incombustible materials with the main building elements having a 'fire-resistance' period of at least 4 hours (1,2 and 7). Standard II has less stringent rules and is equivalent to a fire-resistance period of 2 hours. In accordance with Standard III, the insurance rate for every floor could be different (2 and 7). Standards IV and V do not generally provide for protection of floor openings, though in Standard IV, if the stair steps and landings are constructed from combustible materials, protection of floor openings must be ensured by means of at least 50mm thick incombustible walls (7).

It must be noted that Standard V was originally designed to cater for suspended floors constructed using timber joints, and also pitched roofs using timber trusses and purlines; these types of construction are typical of domestic houses and other small buildings. However, timber-framed walls cladded with hardboard or similar materials will receive additional charges over and above those corresponding to Standard V; roofs constructed from timber members but not covered with incombustible materials, such as tiles or asbestos-cement sheeting, may also be charged penalty rates (c.f. Table 10.8).

Elements of construction included in the F.O.C. classification system (7 and 8) include the following:

(1) Party wall: This is a wall which is intended to separate buildings of different occupancies or parts of a building used for different purposes (e.g. storage, production, etc.); at least 230mm (9in) of solid brickwork or masonry or reinforced concrete is required without any unprotected openings. Exposed metal or timber, etc., is not allowed.

(2) External walls, load-bearing: Use of any combustible material in any form in external walls is disfavoured by the insurers (1,2,3,7 and 8). Structural metals must be protected (except in the case of Standard V, which allows use of structural steel in conjunction with brick, concrete or similar materials infilling the distances between metal stanchions).

(3) External walls, non-load-bearing: As above, except that in certain cases (e.g. Class III (8)), up to 10 per cent metal sheet cladding is allowed, provided the supporting framework is also incombustible.

(4) Floors: In order to qualify for any discount off normal
rates, floors must be constructed entirely of incombustible materials with some degree of fire-resistance; floor openings for stairs, lifts, etc., must also be protected by means of fire-resistant walls, so that any fire is confined to the floor of origin only.

(5) Roofs: Under Standard V, roofs are expected to be of either incombustible covering where timber trusses or joists are used, or bituminous felt on an incombustible deck, or bituminous felt protected by an incombustible layer of mortar, etc. Use of G.R.P. or rigid PVC rooflights is not allowed under Standards I to III (8) (c.f. Table 10.8).

Class I (7 and 8) calls for constructions somewhere between Standards I and II; under Class I, limits have been placed on the total areas of wall openings (50%). Further, the use of combustible wall and ceiling linings and partition materials is not allowed, and the total volume of any one compartment is limited to 7000m³ (the same restriction on volume applies to Classes II and III (8)).

Class II constructions fall between Standards III and IV, and Class III between Standards IV and V. Under Classes II (8) and III, floors and roofs are to be of incombustible materials. As has been pointed out, under Class III up to 10 per cent of the external walls may be constructed from steel or aluminium sheet, provided the supporting frame is also constructed from a non-combustible material.

G.R.P. and rigid PVC rooflights must be of grade AA to B.S. 476:3 (1958) and their use is confined to Class III only (8).

10.2.5.2 Insurance rating of non-standard constructions:

If a building or some part of it is constructed outside the above Standards (or Classes), the insurers (or their representative fire-surveyors) would use a tariff list for each part of the building in order to calculate the total insurance premium (1). This list contains (1) some 1000 non-standard items, each for a particular building element/part used in a particular occupancy, e.g. unprotected structural steel as wall framing to a warehouse of known size, used for storage of a certain type of goods is classed as one category of risk which carries a particular tariff. Clearly, the greater the risk of structural fire failure, the higher the charges made (1 and 2). However, other considerations such as the extent of damage likely to be caused in small fires
(i.e. those fires which do not develop sufficiently to engulf the whole building), the ease with which a damaged part can be repaired and reinstated, etc., may also affect the insurance rate (1).

It is worth noting that the insurance of privately owned houses is outside the tariff market, i.e. each insurance company, whether or not a member of the F.O.C., has its own system of insurance ratings for dwelling houses. Thus, the F.O.C. have no feedback of information on materials' performances from this sector of the market. However, as has already been noted, timber-framed houses are charged additionally over brick or block-built houses, though the rate may differ significantly from one company to another (1).

The F.O.C. rely to a large extent on their testing of new constructional materials (1 and 2). B.S. 476: part 8 is accepted for assessment of 'fire-resistance' performance, as is part 4, which is used to distinguish between combustible and non-combustible materials. Testing of materials for use in roofing, external walls, partitions, ceiling and wall linings is carried out on a much larger scale than that specified by B.S. 476: parts 3, 6 and 7. The test rig used by the F.O.C. measures approximately 27.5m x 6m x 3m high (1). Fire loads and construction methods in these tests are identical to, or representative of, those proposed for actual use. Observations are made of heat contribution, spread of flame, emission of smoke, production of molten droplets, flying embers, etc. The extent of damage sustained will then be assessed and recorded (1).

The main criticism by the F.O.C. of B.S. 476: 3, 6 and 7 tests is centred on the small scale testing philosophy as opposed to large scale testing (1 and 2). According to the F.O.C., these B.S. tests do not yield results which would characterize true fire behaviour of materials in actual (or large scale) fires (1). However, the F.O.C. admit (1) that in future they may make more use of the B.S. 476: 6: fire propagation test, though the F.O.C. will always use 'total incombustibility' as a starting point for assessment of insurance rates (1 and 2). It must be emphasized that neither the F.O.C. nor any other insurer will pioneer the use of new materials or the use of traditional materials in new situations. If no testing/trial of a new or improved material is sponsored by the manufacturers, the F.O.C. will use a contingency rating (1 and 3); this may be reduced when more information on actual behaviour of the new material is accumulated (1). Thus,
to avoid additional penalty rates, it is up to the manufacturers to sponsor testing of their new materials by the F.O.C. for the purpose of insurance rating.

However, acceptance by the F.O.C. of inherently incombustible materials (those based on inorganic materials) is generally quicker compared with combustible materials (1). Durability of materials will not influence the attitude of the F.O.C. except when it affects 'structural stability' and 'fire performance' of buildings (1 and 2). As an example (1), the F.O.C. did not initially object to the structural use of high alumina cement; however, they have banned its use since 1974, when beams made with high alumina cement collapsed in a London school. This failure was not associated with the fire behaviour of high alumina cement. Another example is the case of G.R.C.; the F.O.C. have accepted this material as an incombustible material in non-load-bearing applications (1).

The extent of conservatism on the part of the insurance companies on the use of new materials is best illustrated in the case of aluminium sheeting generally used for roofing or roof decking, etc., in industrial buildings. As is shown in Chapter 13 (see 13.3.1.3, .3.6.1 and Table 13.9), a useful fire property of this material is the early local melting of the sheeting (or decking) close to the seat of fire. This provides for early venting of the fire and results in reduced severity of temperature distribution within the compartment involved in fire; also, it allows venting of smoke and increased visibility, etc.

Although this property of aluminium sheeting was known as early as 1959 (see 13.6.1 and Table 13.9), aluminium sheeting was not accepted by the F.O.C. under Classes I to III (also Standards I to IV) for roofing purposes until recently when the results of a full scale test by the F.O.C., sponsored by the Aluminium Federation, demonstrated (11) successfully that the melting of the aluminium decking (or roofing) locally over the seat of fire had a beneficial effect on the temperature distribution within the building and that the damage caused by fire was confined to the area over the fire compartment.

After the execution of this large scale fire test, the F.O.C. accepted (11) aluminium roofing as qualifying for discount in Classes II and III buildings. Prior to this, the use of aluminium roofing carried a premium penalty which adversely affected the use of aluminium sheeting in the construction industry (c.f. 13.4.2).
10.2.6 The proposed system of insurance rating:

From the discussion included in the previous subsection, it can be seen that the 'ad hoc' system for fire insurance rating of buildings, which dates back to 1907, has the following shortcomings:

(a) It is not based on the 'performance' concept. It is also heavily biased towards established materials, thus, it may retard the acceptance of new materials or new combinations of known materials.

(b) It assumes that factories, warehouses, offices, etc., are designed for an unlimited life. The modern approach is to design the above premises for a life as low as 25 years (1), especially in the case of factories. Most users require maximum flexibility in layout, particularly to accommodate the changing need for industrial processes. They also require maximum production/useable floor space on a given site. These requirements favour use of thin walls and partitions, preferably of industrialized designs, since speed of construction is crucial in most industrial buildings. Building costs in factories tend to be roughly 20 per cent of the total investment costs including plant and machinery; (9) thus, cost differential in the external envelope of these buildings is relatively unimportant compared with the total capital costs.

(c) Because of the large number of construction materials and components, it is uneconomic to rate each one separately; architects and designers will also find it difficult to design with due regard to fire insurance premiums, because it is difficult to remember 1000 or so categories of tariff.

The F.O.C. have recognized (1) the above problems and have proposed a new system of insurance rating based on 'performance' criteria. The new system, which is currently under scrutiny by the member companies, is expected to be in operation in about 2 to 5 years' time (1). Under the proposed system, materials and components will be divided into two groups: approved and unapproved. Approved materials will be those tested by the F.O.C. and grouped into bands of differing performance levels (1).

Insurance rates will be linked to achievement of various performance levels, provided that the proposed materials are of approved types (1). Additional penalties will be imposed on the use of unapproved materials/components (1).

The F.O.C. claim (1) that the new system will bring about
some major changes in the insurance rating of materials as a more liberal attitude towards new materials will be adopted, e.g. the F.O.C. will recognize extensive use of metal sheeting for cladding applications (as has been noted, presently, Class III (8) allows up to 10 per cent steel sheet cladding; this could go up to 100 per cent in certain cases).

10.2.7 The attitude of the insurers (F.O.C.) on the use of G.R.P. panels:
The F.O.C. have generally had limited experience with G.R.P. (1). Except in the case of translucent G.R.P. sheeting and other G.R.P. rooflight products, they have not tested any other G.R.P. products for the purpose of classification (1). Present insurance rates for G.R.P. used as cladding or infill panels or as complete roofs/structures will depend on the category of occupation and the design of the G.R.P. panels/structures (1). Factors affecting the insurance rates are the fire performance of the panels (i.e. 'fire-resistance' and 'reaction-to-fire' characteristics) and the presence of any effective fire protection system such as automatic sprinklers. As an illustration, on the favourable side, assume a hypothetical case of a metalwork processing factory (a low risk process). If the complete roof is constructed from fire-retardant G.R.P. segments, it may be charged (1) an extra 5 pence per £100. For woodwork processing (higher risk) a higher rate will be charged. On the unfavourable side, for a G.R.P. structure having a Class 4 spread of flame to the B.S. 476 : 7 and a grading of DD to the B.S. 476 : part 3 (1958), the insurance rate would be substantially higher—if any company would insure it at all! It is not, in fact, possible to generalize (1); since one must first ascertain which of the thousand classifications he is dealing with. In the case of G.R.P. cladding on multi-storey buildings, the danger is that the heat flux of the combustion of a panel at a lower level can help the vertical propagation of fire. This risk is especially present when a G.R.P. laminate with a general purpose gelcoat is used, even though a fire-retardant resin may have been used in the body of the laminate (1). In a class 0 laminate, the heat flux is much lower. However, once fire is incepted, the heat flux may still be a significant factor in involving the panels positioned immediately above. This means that there would be a difference in insurance rates between a class 0 material and a totally incombustible material (1).
In addition, it has already been noted that the costs of repairing potential damage caused by small fires (which are more frequent) have an important bearing on the insurance rating. In the case of G.R.P. panels, it has been claimed (1) that such panels cannot be repaired by local builders; specialist firms must be employed for their repair. New dies or moulds may also be needed for the production of 'replacement' panels. These are costly operations compared with repair of brick and concrete structures, where local builders may be employed who can use bricks or sand-cement mortar, cement grout, etc., to carry out the repair work (1).

As a general rule, the F.O.C. and the insurance companies have been very slow in accepting plastics materials (1, 2 and 3). For example, prior to 1970 foamed plastics were generally classed as one 'fire-risk' and penalty premiums were levied on their use (1 and 2). More recently, the F.O.C. have recognized the use of isocyanurate and phenolic foams (1) for insulation purposes under Standard V or Class III construction rules.

A study of the F.O.C. Standards as set out in Table 10.8 shows that, excluding Standard I, the use of G.R.P. partition panels is accepted under the remaining Standards (1, 2, 7 and 8); similarly, no restriction has been imposed on the use of G.R.P. for ceiling and wall lining in Standards II to V inclusive, provided no air gap is allowed between these and the main construction (1, 2, 7 and 8).

Under Standard V, G.R.P. profiles may be used for floors; the structural use of G.R.P. for roofs is also feasible under this Standard, provided that the external surface of G.R.P. is covered with an incombustible hard material, e.g. slate or tile. It is quite likely that, upon further improvements in the fire behaviour of G.R.P. and upon introduction of the proposed performance-based system for insurance rating, the use of G.R.P. will become more widely accepted by the F.O.C. and the insurance companies in general (1 and 3); the possibility of improvements in the fire performance of G.R.P. in the near future will be discussed in Chapter 14.

The following is a comment which was made recently by Bryce-Smith (3) in connection with this subject: "I maintain that in a system whereby insurers examine a situation and impose restrictions, it follows therefore that those who promote the use of reinforced plastics must establish the validity of their product as a safe
material. It is now an established fact, within the U.K. anyway, that the use of large areas of reinforced plastics, particularly in public places, must be extensively protected by automatic fire fighting devices. This attitude by both insurers and local authorities has been largely brought about by tragic circumstances and a further repetition would severely damage the plastics industry in general." Bryce-Smith (3) argues that the G.R.P. industry should concentrate on discovering a true fire retarding agent and meantime the use of G.R.P. in high risk situations be avoided.

The above comment confirms the point already made, viz, lack of quantitative evidence gathered by the insurers on the actual fire behaviour of G.R.P. (1).

10.2.8 The effects of insurers' attitudes on the design:

Whereas government-owned properties are not generally insured, the properties belonging to local authorities are, though insurance rates negotiated by these authorities are normally lower than the commercial rates.

In the private sector, it is an established practice to insure all properties; in most cases, obtaining a loan or mortgage in fact requires previous insurance coverage beforehand. However, as has already been noted, in Britain insurers are prepared to insure any type of premises, provided these comply with the requirements of the Building Regulations; for example, insurance cover for a timber-framed house can be arranged with relative ease (1).

There are no data on the effect of the insurance rates on the design; however, from discussions the author has had with a number of designers, it has become evident that architects tend to pay less regard to problems of insurance premiums than to the problems of conformity with the Building Regulations and other statutory provisions. This is probably due to the relative ease with which insurance coverage can be arranged for buildings designed to meet the statutory requirements. However, in recent cases and in high-risk processes such as the manufacturing of clothing and footwear, where insurance premiums can comprise a significant proportion of the total costs, architects are forced to take the insurers' view into account at the design stage. In addition, some clients who have more knowledge of insurance charges may require their buildings to be insurable at favourable rates; in these cases, architects have to consult their clients' insurers beforehand in order
Enquiries made by the author on the insurance rates charged for a typical office block complying with the relevant clauses of the Building Regulations, the Fire Precautions Act, and the Health and Safety at Work Act (1974) revealed that the annual rates range from approximately 0.1 to 0.5 per cent of the value of the building plus its contents, depending on the design of the building (including the layout of the internal spaces as related to the uses) and the provision of fire protection installations, etc. As an illustration, for an office building costing £200,000, constructed from a reinforced concrete structure (column and beam plus suspended slab floors and roof), cladded on two sides by brick walls and in the front and rear elevations by standard-grid metal curtain walling, about 0.1 to 0.15 per cent of the total value of the building, or about £200 to £300 per annum will be the insurance premium (all risks insurance coverage). If the annual insurance payments are discounted over 50 to 60 years - assumed to be the life of the building - at a rate of 10%, they will amount to about £2000 to £3000, or about 1 to 1.5 per cent of the total value of the building. If on one elevation, the metal curtain walling is replaced by G.R.P. cladding panels with a Class 2 surface spread of flame to B.S. 476:7 (the lowest performance allowed under the Building Regulations), the total insurance payment can rise by 1.5 per cent to 3 per cent of the total value of the above building; this is still insignificant compared to the total expenditure.

The above example illustrates the effect of penalty premiums charged by the insurers on the use of combustible materials; however, one must not generalize, since the insurance coverage for buildings which carry higher risks than the above can be considerably higher than the above mentioned rates (1).

The general observations on the use of G.R.P. panels indicate that from the standpoint of insurance coverage and associated problems, the government departments have been in a more fortunate position compared with other clients; this has been confirmed in practice by the relatively large scale G.R.P. projects such as the International Telephone Service Centre in London and HMS Raleigh Redevelopment in Devon, etc.
CHAPTER 10 APPENDIX B

UNIVERSITY OF SURREY
QUESTIONNAIRE

All information given here will be treated as CONFIDENTIAL.

If you would like to qualify your answers, please use the spaces provided beneath some of the questions.

1. Have you used any G.R.P. panels externally or internally, in any of your buildings? YES/NO

   Note: If your answer to question 1 is NO, please ignore questions 2 to 5 and proceed directly to questions 6 and 7.

2. Are you satisfied with the overall cost/performance of the G.R.P. panels you have used? (please specify below):
   (a) satisfied
   (b) partially satisfied
   (c) dissatisfied

3. If you are satisfied (or partially satisfied) with the overall cost/performance of the G.R.P. panels, is this because these panels:
   (a) have given an attractive and fashionable appearance to the building? YES/NO
   (b) have required little maintenance work? YES/NO
   (c) have shortened the time taken for the design and construction of the building? YES/NO
   (d) have proved economic in terms of the total costs of the project? YES/NO
   (e) have technically performed satisfactorily under all service conditions? YES/NO
   (f) some other reason (please specify)

4. If you are dissatisfied (or partially satisfied) with the overall cost/performance of the G.R.P. panels, is this because these panels:
   (a) have weathered in an unsatisfactory manner? YES/NO
   (b) have increased difficulties related to the design and site installation, and have therefore delayed the completion date of the project? YES/NO
   (c) have increased the total costs compared with the alternative designs? YES/NO
   (d) have required more cleaning and maintenance attention compared to the other facing materials? YES/NO
   (e) some other reason (please specify)

5. In which of the following ways were G.R.P. panels specified for your project; please tick the box relevant to your situation:
   (a) proposed by the consulting architect/engineer and approved by you? YES/NO
   (b) proposed by you and discussed with the consulting architect at the initial briefing stage? YES/NO
   (c) the architect/quantity surveyor presented you with alternative designs coupled with estimates of costs, and you chose G.R.P.? YES/NO
   (d) you had no knowledge of their use? YES/NO
   (e) some other way? (please specify)

6. How would you react to the likely use of G.R.P. panels in any of your future building projects? (Please tick the box relevant to your situation):
   (a) we would react favourably provided they are not too costly, because G.R.P. panels can give a modern and fashionable appearance and can increase the prestige of the building.
   (b) we would have no special reaction, provided they are considered by the architect/quantity surveyor as both economic and appropriate proposition for the particular application.
   (c) we would react unfavourably, because G.R.P. panels are costly, problematic to use, detract from the overall soundness of the building and have suspect long term performance.
   (d) our reaction would depend on the nature of application and the case under consideration.

   Further comments:

7. Please specify below (in order of preference), the relative importance of each of the following reasons for which you employ services of a consulting architect:
   (a) development of a functional and economic design, using the most up to date technology.
   (b) development of a design which is fashionable and attractive in appearance and can increase the prestige of the business.
   (c) development of a design which can conform to the statutory requirements.

   Further comments:

If you would like to make any general comments on this subject, please use the space provided hereunder.

Date ................................................
Signature ...........................................  We thank you for your cooperation.

Would you please return the completed questionnaire in the stamped addressed envelope provided to:

Dr. L. Holloway,
Department of Civil Engineering,
University of Surrey,
GUILDFORD, Surrey, GU4 5XN
1. Interview notes with Mr. Chitty, Technical Officer of the Fire Offices Committee, on 20th February, 1976.


11. See the Architects' Journal, 16th June, 1976 (p1170).
11.1 Industrialized Building: General:

11.1.1 Definition:

The official definition (1) of industrialized buildings is as follows:

"The term industrialization as used here covers all measures needed to enable the industry to work more like a factory industry. For the industry this means not only new materials and construction techniques, the use of dry processes, increased mechanization of site processes and the manufacture of large components under factory conditions of production and quality control; but also improved management techniques, the correlation of design and production, improved control of the selection and delivery of materials, and better organization of operations on site. Not least, industrialized building entails training teams to work in an organized fashion on long runs of repetitive work, whether the men are using new skills or old. For this purpose, industrialized building can include schemes using fully rationalized traditional methods."

The above definition clearly illustrates the fact that, contrary to common assumption, a building constructed to the principles of 'industrialized methods' is not necessarily a wholly prefabricated building, though, as commonly implied, industrialized building methods involve a large degree of prefabrication. That the managerial factors, such as sequencing of site operations etc., can influence the efficiency and productivity of a scheme is less widely understood. However, assuming that these factors have been improved to maximum possible limits, it will be seen (see 11.1.3) that further efficiency and productivity or reduction of total costs can only be brought about by increased substitution of capital for labour in areas where economic justification exists.

It must be emphasized that, as has been pointed out, by White (2), prefabrication itself cannot be considered as science or a combination of known processes identifiable and quantifiable. As normally implied, the term 'prefabrication' does not apply to bricks, blocks, roof tiles, standard doors and windows, boilers and a whole range of other standard materials/components.
assembled on site, although many of these were not available in a standard form at the turn of the century.

In this study, the term 'prefabrication' is taken to signify the process of manufacturing under factory conditions large components, segments and whole buildings either for incorporation in any type of building or as part of a proprietary system.

A distinction is generally made between 'rationalized traditional' and 'industrialized' methods, though the official classification includes both of these under 'industrialized methods'.

Schmid, et al. (3) have defined 'rationalization' of building as the process of improving and streamlining individual operations on a construction site. They claim that 'rationalization' of building affects the site erection of a building and the contractor; the following are typical measures normally taken to rationalize the construction of a building (3):

(a) Employment of a suitable contractor whose managerial resources and experience are appropriate to the scale of contract;
(b) employment of modern construction machinery;
(c) reduction in variety of components and use of standardized individual components such as windows and doors, floor slabs, roof trusses, etc.; and
(d) supervision and control of the contract costs, etc.

Schmid, et al. (3) state that industrialized building involves a totally different approach. An architect or designer employs a suitable system at the outset and bases his design on this system; most systems do not employ 'wet' trades but use dry construction techniques for the assembly of prefabricated components. It may be deduced that fully industrialized methods may involve totally different types of organization than hitherto has been common in the construction industry, e.g. system designer and system sponsor or producer assume a critical role, especially in relation to the production and warehousing of the components, etc.

Industrialized systems may be divided into two categories:
(i) Light systems which generally employ materials with a density of less than 1000 kg/m³; wood, asbestos-cement, G.R.P., aluminium and steel for skeletons are examples of materials used in light systems.
(ii) Heavy systems which generally employ materials with a density greater than 1000 kg/m³; concrete, including blocks and
slabs, and bricks are materials generally used in heavy systems.

A further division may be made according to the structural principles employed by each system, i.e. whether they use load-bearing panels, cells or skeletal frames; in all, the following classification may be made:

1. heavy panel system;
2. light panel system;
3. heavy skeletal frame system;
4. light skeletal frame system;
5. heavy cellular system;
6. light cellular system; and
7. ready-made structures (3). This is a special case for houses. It is usually offered by a contractor to a private purchaser and involves fixed design at fixed price contract; it is common in the U.S.A. and Scandinavia.

A building system may be designed either as a 'closed' or an 'open' system. In a closed system, components, parts and connectors are designed exclusively for that system; thus, these are not generally suitable for use on other systems. A closed system is usually complete, i.e. all components, finishes and fixtures are selected.

In an open system, the design is based on a variety of interchangeable standardized components which may be produced in different materials by various manufacturers.

A closed system may also be designed to accommodate different components made from various materials. However, these components will have to be manufactured exclusively for the system concerned. Most systems currently in use are classified as closed systems; thus, their sponsors are able to benefit from some degree of market competition.

The advantages of open systems are numerous. For example, possibilities of more design variations, freer use of a range of interchangeable components, etc. Economically, it may be seen as the main hope for mass production and lowering costs of buildings since standardization allows mass production. However, as will be seen later, the 'open system' concept based on freely selected components each produced to the same modular discipline is still far from reality; the degree of progress in standardization of jointing and packing techniques has been remarkably slow.

There are various textbooks which deal with the technical matters related to industrialized system building; for example,
reference 3 or reference 4. The subject is also included in the National Building Specification, 1973, RIBA. Inclusion of technical matters has therefore been avoided except for those which elucidate the main subject of this study.

11.1.2 Historical background:

In subsection 11.1.4, an attempt has been made to analyse the more recent and relevant data on the economics of 'industrialization' of the building process. However, it would be useful to give a brief review of the early attempts which took place some thirty years ago. A full account of the postwar 'non-traditional' housing and school building may be found in references 2 and 5 or in various official publications.

11.1.2.1 The development of postwar non-traditional houses:

The policy of the government in the immediate postwar years was influenced by the scarcity of the key house building materials (brick and timber) and also by the scarcity of skilled labour, especially bricklayers. Thus, a search was undertaken for alternative materials and construction methods; the aim was to economize as far as possible in these scarce resources. Later, supply of steel was also restricted.

However, there was no long term commitment, on the part of the government, to non-traditional construction methods and materials, as it was decided that a return to 'normal' building methods should follow as soon as the supply of the above resources had improved. This approach led to a multiplicity of sponsored designs being approved by the government; a natural outcome of this policy was that only five sponsored systems reached sizeable production figures (i.e. greater than 2500) and even production of these did not last long after the return to the traditional materials and methods.

The majority of the sponsored systems were found to be generally more expensive compared with traditional methods (2 and 5), though it is difficult to make any meaningful comparison, partly due to the prevailing conditions in the supply of certain materials and dilution of skilled labour.

From all the schemes submitted, only 11 types were built in significant numbers; from these, only five types were built in numbers greater than 2500. The most prominent types were the 'Acron', the 'Aluminium Bungalow' and the 'Uni-Seco Structures'; their final production figures were about 40 000, 55000 and 29000
respectively (2).

There were many sponsors who claimed that, due to uncertainty on the future continuation of production, they had never had a chance to prove the economic viability of their designs (2). However, some types such as the BISF and the 'Airey' houses which sold some 30,000 and 20,000 respectively did not show reduced costs (2). There was a marked tendency (2) amongst promoters to go for the maximum 'ceiling' price set by the government, and it is likely that they did not plan for long term business in this sector, and many of the sponsors were not normally active in the construction field (2 and 5).

Many points of interest emerged from the above programme; mainly:

(1) The survival of serialized production of prefabricated houses depended critically on the support and subsidy of the central government. As soon as the government subsidy ceased in 1953, most sponsored systems declined and a few modified their designs for apartment blocks.

The high costs of plant and factory equipment in some cases meant that large production volumes were necessary in order to amortize the capital costs with a less crippling effect on the selling price of each house. Furthermore, factories generally pay rates and have to provide for proper catering and welfare facilities for their workers. In short, they incurred higher overhead charges which, when added to transportation and handling costs, made factory production more expensive compared with traditional site construction. Even for lightweight systems such as Aluminium Bungalows, exceptionally large and continuous production volumes were essential for the amortization of initial costs of equipment, etc. Clearly, such a large demand was not forthcoming (2 and 5).

(2) The prevailing conditions were not generally favourable to advancement of prefabrication. Unemployment was high and industrial output was low. Further, not only were timber and steel, materials suitable for prefabrication, in short supply, but also the temporary nature of the programme coupled with the multiplicity of schemes did not provide grounds for long term development in this direction.

(3) It was demonstrated that 'prefabrication' for its own sake did not necessarily result in lowering of the total cost or shortening of the total time per house (expressed in man-hours).
Other factors such as transportation of components, organization of site works, dimensional accuracy of prefabricated components, the need for site rectification of joints, lines and corners, etc., affected the total costs and time considerably (2).

(4) Many local authorities considered non-traditional houses as inferior to traditional types (2 and 5); they reverted to the use of the latter as soon as the market was free.

11.1.2.2 Non-traditional schools:

The development of non-traditional schools was different from that of the houses. It was, in essence, a controlled and co-ordinated operation. The architects of these schools were inspired by the 'Bauhaus' and the teaching of the German architect Walter Gropius. This architect and his followers believed in partnership between architects and industry.

Hertfordshire was the first county to mount a large scale school building programme; 175 schools were planned for construction in 15 years starting in 1946, with half required in the first 5 years (2).

The design of these and other non-traditional schools was based on modular grid lines, flexibility in layout and interchangeability of prefabricated components within each system.

In Hertfordshire, there was close co-operation between the manufacturers of components, the architect and the users, A principle feature of this operation was the placing of bulk orders for various constructional components, thus assuring the continuity of production and lowering of costs.

The success of the Hertfordshire programme coupled with the work of the Development Group at the Ministry of Education soon attracted the attention of other authorities and led to the formation of various local authority consortia. The earliest of these was the Consortium of Local Authorities Special Programmes (CLASP), which initially included Nottinghamshire, Coventry and Derby. The success of CLASP may be judged by the number of contracts it has had to date - some 2300 major contracts according to the information contained in a recent advertisement by Messrs. Brockhouse in the Architects' Journal.

The following points of interest highlight the results of the school building programme:

(1) Although individual schools varied in size and layout, the users' requirements in schools were consistent and were analysed by the Hertfordshire team and the Development Group of the
Ministry of Education. No such parallel studies were undertaken in the case of the housing programme; in fact housing needs and preferences were varied and not known sufficiently at the time.

(2) With the exception of the Aluminium Schools, the extent of prefabrication was rational and economic in relation to the size of the programme. The success of the programme was due to standardization and bulk ordering of components. Also, it was due to continuous design improvements, monitoring and cost control by the architects concerned.

(3) The lead given by, and the personal involvement of, the architects, coupled with centralized control and continuous improvements, contributed considerably to the success of industrialized school building. Such a combination of personalities and system of control was generally absent from the housing programme.

(4) The non-traditional schools were not perceived as inferior products compared with traditional ones. On the contrary, in many respects they were considered to be superior, especially in functional terms. This is because these schools were generally designed to provide for an integrated environment with higher standards of comfort; their designs embodied the results of the latest research which had been carried out by the Building Research Station (2).

11.1.3 Theoretical considerations in prefabrication:

The economic comparison between the use of large prefabricated components and the use of sub-assemblies containing a greater number of smaller units fitted on site will depend on a number of factors; chiefly: unit repetition, transportation and handling costs, design of units, locality of the site, etc. However, for every building there is a limit to the amount of prefabrication which can be economically carried out in a factory (6). This limit will depend on the relative cost of labour and construction materials (6 and 7). A comparison between a highly industrialized country and a less industrialized country illustrates this point: for example, in the U.S.A. where labour costs are higher than in Britain, the amount of prefabrication which can be economically carried out is considerably higher.

The relative movements in costs of labour, materials and construction work in any country will change the above limit of prefabrication; thus, it is likely that in the immediate postwar years, a large degree of prefabrication and serialized production
(e.g. the Aluminium Bungalow) was not economically viable. However, a point may be reached in the near future when such a degree of prefabrication and serialized production will become economically unavoidable. As is shown in subsection 11.1.4, present trends in costs will reinforce the above prediction. Nevertheless, the influence of other factors such as social and symbolic preferences, social and political considerations in retarding a 'total' state of prefabrication must not be ignored.

11.1.4 Recent trends in industrialized dwellings:

11.1.4.1 The background to current development:

The root of the present trends in industrialization of the building process must be sought in the developments which took place in the early 1960's. There are several factors which contributed to rapid progress in this field and led to Britain assuming the lead internationally by the late 1960's. Some of these factors were as follows:

1. The belief in high-rise dwellings for conservation in the use of land: It was generally believed that high-rise (taken as buildings of over four storeys) dwellings could achieve the highest population density - expressed in persons per hectare - without lowering the standards of amenities. This was seen as the only solution to check the speed with which land was being used up in and around most cities in Britain. It was also held that the placing of dwellings vertically would produce greater degrees of cross-ventilation and natural lighting; the land released between the successive blocks of dwellings could be used for landscaping and other communal purposes. It must be noted that many of these ideas stemmed directly from those of Le Corbusier.

Tables 11.1 and 11.2 and Fig. 11.1 show the trend in industrialized dwellings with correspondence to the trend in high-rise dwellings. It can be seen that up to 1970, both trends follow an approximately similar pattern; from 1970 to 1975, that for 'high-rise' dwellings continues to reduce to a negligible level, whilst the trend for industrialized dwellings continues to fluctuate about the level of 20 per cent of all dwellings (see Fig. 11.1).

It is worth noting that the average density of all local authority housing in England and Wales (excluding the G.L.C. area) in 1967 (peak time for high-rise dwellings) was 168 persons per hectare (8). The corresponding figure for 1974, when high-rise
Table 11.1 Distribution of Storey heights: Percentage of all dwellings; tenders approved for L.A. Housing (**) - England and Wales.

<table>
<thead>
<tr>
<th>Year</th>
<th>Houses</th>
<th>Flats</th>
<th>Flats</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 storey</td>
<td>2 or 3</td>
<td>1 - 4(^+)</td>
</tr>
<tr>
<td>1958</td>
<td>8.35</td>
<td>49.0</td>
<td>31.5</td>
</tr>
<tr>
<td>1959</td>
<td>10.65</td>
<td>45.0</td>
<td>31.65</td>
</tr>
<tr>
<td>1960</td>
<td>10.65</td>
<td>42.0</td>
<td>33.0</td>
</tr>
<tr>
<td>1961</td>
<td>10.50</td>
<td>40.8</td>
<td>32.3</td>
</tr>
<tr>
<td>1962</td>
<td>9.8</td>
<td>40.4</td>
<td>32.6</td>
</tr>
<tr>
<td>1963</td>
<td>8.55</td>
<td>38.2</td>
<td>31.10</td>
</tr>
<tr>
<td>1964</td>
<td>8.65</td>
<td>36.2</td>
<td>31.10</td>
</tr>
<tr>
<td>1965</td>
<td>8.1</td>
<td>40.2</td>
<td>30.2</td>
</tr>
<tr>
<td>1966</td>
<td>6.9</td>
<td>40.6</td>
<td>26.8</td>
</tr>
<tr>
<td>1967</td>
<td>8.2</td>
<td>41.8</td>
<td>27.0</td>
</tr>
<tr>
<td>1968</td>
<td>7.4</td>
<td>41.9</td>
<td>30.8</td>
</tr>
<tr>
<td>1969</td>
<td>9.7</td>
<td>40.8</td>
<td>35.9</td>
</tr>
<tr>
<td>1970</td>
<td>9.1</td>
<td>42.4</td>
<td>38.6</td>
</tr>
<tr>
<td>1971</td>
<td>10.0</td>
<td>40.0</td>
<td>41.4</td>
</tr>
<tr>
<td>1972</td>
<td>9.8</td>
<td>38.7</td>
<td>44.1</td>
</tr>
<tr>
<td>1973</td>
<td>11.3</td>
<td>43.6</td>
<td>41.7</td>
</tr>
<tr>
<td>1974</td>
<td>10.7</td>
<td>45.2</td>
<td>41.6</td>
</tr>
<tr>
<td>1975</td>
<td>9.75</td>
<td>52.45</td>
<td>37.05</td>
</tr>
</tbody>
</table>

\(\text{P}\) - Provisional figures for first half of 1975.

\(\text{\(\text{\(+\)}\}}\) - Up to 1974 figures are for 2 to 4 storey flats.

\((**)) - Excluding G.L.C. (Source: data for 1958 - 64 inclusive have been calculated from 'Housing Statistics' Great Britain, No. 14, August 1969; the remaining data are extracted from Table 22 of various issues of Housing and Construction Statistics).
Table 11.2  Industrialized dwellings (1); L.A. Housing: England and Wales.

<table>
<thead>
<tr>
<th>Year</th>
<th>Number</th>
<th>Percentage of all dwellings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1965+</td>
<td>53600</td>
<td>27.4</td>
</tr>
<tr>
<td>1966+</td>
<td>74632</td>
<td>36.6</td>
</tr>
<tr>
<td>1967</td>
<td>71465</td>
<td>42.6</td>
</tr>
<tr>
<td>1968</td>
<td>59574</td>
<td>39.4</td>
</tr>
<tr>
<td>1969</td>
<td>34766</td>
<td>30.1</td>
</tr>
<tr>
<td>1970</td>
<td>19382</td>
<td>19.4</td>
</tr>
<tr>
<td>1971</td>
<td>19320</td>
<td>20.6</td>
</tr>
<tr>
<td>1972</td>
<td>16243</td>
<td>21.0</td>
</tr>
<tr>
<td>1973</td>
<td>22430</td>
<td>24.4</td>
</tr>
<tr>
<td>1974</td>
<td>22871</td>
<td>19.0</td>
</tr>
<tr>
<td>1975P</td>
<td>21808</td>
<td>16.7</td>
</tr>
</tbody>
</table>

P - Provisional figures.
+ - Source: 'Housing Statistics' Great Britain, No. 14; these data include Scotland as well.

(1) - Tenders approved (Source: Table 23 of various issues of Housing and Construction Statistics).
Fig. 11.1 Industrial dwellings as % of all dwellings. Also flats > 5 storeys as % of all dwellings (Tables 11.1 & 11.2)
dwellings had been reduced to a mere 2.5 per cent, was 155 (9) or about 8 per cent less than in 1967. This difference might also have been influenced by the higher standards of space in 1975, since most local authorities had delayed the implementation of the Parker Morris recommendations until well into the 1970's. Thus, the claim that high-rise dwellings could facilitate unparalleled population densities was to be proved inaccurate.

(2) The need for greater productivity per construction employee: The conviction that greater industrialization of the building process was desirable was unanimous amongst the industrialists and government officials (7,10,11 and 12). It was held that the supply of labour would be restricted, whereas the demand for construction would rise. For example, Walley (10) gave a predicted figure of 50 per cent increase in the demand for new construction works during the decade 1966 to 1976, with little or no increase in the supply of labour. Cocks (13) estimated that a demand corresponding to an annual output of 500,000 dwellings required industrialized techniques to reduce the total labour input by at least 20 per cent or a minimum of 380 man-hours. In 1964, according to Cocks (13), the average labour input per dwelling was about 1990 man-hours, which was approximately 10 per cent lower than the corresponding figure for 1960; this saving in labour requirements was attributed to the greater use of industrialized building techniques (13).

The government's objective in taking the lead and encouraging the development of industrialized buildings in the early 1960's was totally different from their earlier aims. They feared (7) that, due to limitation on the supply of labour and the rising trend in demand for all sorts of construction works, the construction costs would be forced to rise without a corresponding increase in productivity. At the time the construction industry was working close to its capacity; and, in fact, later in 1965, the demand was claimed by the Minister of Public Buildings and Works (14) to have exceeded the capacity by about 2 per cent. This situation could lead to delays in some socially urgent projects. Thus, the government on the one hand encouraged the expansion of industrialized building as a means of increasing the capacity of the industry through greater productivity per employee, and on the other hand introduced the 'Building Control Act', which required licensing of certain private developments above a certain value (c.f. section 2.5). The licensing for 1966 was proposed (14) to
cover about 7 per cent of new works in order to keep the demand just below the capacity.

The government also took the lead in the direction of modular coordination and standardization of building components (15).

11.1.4.2 The actual trends in costs of industrialized dwellings:

Tables 11.3 and 11.4 and Fig. 11.3 show the relative changes in the costs of labour capital and house building materials; the relative changes in the tender prices of both traditional and industrialized dwellings are also plotted in Fig. 11.3. It can be seen that, in 1974, the tender prices for industrialized dwellings were on average lower than the corresponding figures for the traditional methods; the percentage savings per sq. m. were 6, 8 and 35.5 respectively for houses and bungalows, flats in one to four storeys and flats in five or more storeys.

The cost advantage of low-rise industrialized dwellings (i.e. below five storeys) over traditional dwellings actually started in 1968 - 69; however, in the case of high-rise dwellings, this cost advantage was evidently present in 1964, when the average tender prices for industrialized dwellings were some three per cent below the traditional ones. (7).

It must be noted that tender prices are what the contractors actually quote for carrying out the work, and as such they do not reflect land values. Furthermore, tender prices are not necessarily accurate indications of relative movements in construction costs, since, depending on the market expectations, they may include varying profit margins.

It may be seen from Figs. 11.2 and 11.3 that, whilst in the period 1968 to 1975 tender prices for industrialized dwellings showed continuous cost advantages over traditional dwellings, their relative share of the market actually fell from 39.4 per cent in 1968 to 19 per cent in 1974 (16.7 per cent in 1975, see Table 11.2). This is an economic paradox. However, there are various possible reasons for this situation; some of which are as follows:

(a) A general reversion in the late 1960's to the use of brick and traditional methods: The realization that high density housing was also possible in low-rise developments without sacrificing any standards, brought about a general tendency towards the use of brick and traditional methods, especially as, at the time, tenders for industrialized low-rise dwellings showed no
Table 11.3  
Average Unit Costs and Indices: Traditional and Industrialized Buildings (Local Authority Housing)

<table>
<thead>
<tr>
<th>Year</th>
<th>Houses and bungalows</th>
<th>Flats in 1 to 4 storeys</th>
<th>Flats in 5 or more storeys</th>
<th>All dwellings (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Traditional</td>
<td>Indust'лизed</td>
<td>Traditional</td>
<td>Indust'лизed</td>
</tr>
<tr>
<td></td>
<td>(£/m²)</td>
<td>Index</td>
<td>(£/m²)</td>
<td>Index</td>
</tr>
<tr>
<td>1967</td>
<td>34.38</td>
<td>100</td>
<td>35.00</td>
<td>100</td>
</tr>
<tr>
<td>1968</td>
<td>35.20</td>
<td>102.5</td>
<td>35.35</td>
<td>101.0</td>
</tr>
<tr>
<td>1969</td>
<td>37.35</td>
<td>108.8</td>
<td>36.06</td>
<td>103.0</td>
</tr>
<tr>
<td>1970</td>
<td>40.04</td>
<td>117.5</td>
<td>38.54</td>
<td>110.0</td>
</tr>
<tr>
<td>1971</td>
<td>46.50</td>
<td>135.2</td>
<td>42.84</td>
<td>122.5</td>
</tr>
<tr>
<td>1972</td>
<td>55.44</td>
<td>161.5</td>
<td>53.28</td>
<td>152.0</td>
</tr>
<tr>
<td>1973</td>
<td>74.16</td>
<td>216.0</td>
<td>71.37</td>
<td>204.0</td>
</tr>
<tr>
<td>1974</td>
<td>88.45</td>
<td>257.5</td>
<td>83.26</td>
<td>238.0</td>
</tr>
<tr>
<td>1975</td>
<td>92.25</td>
<td>268.2</td>
<td>86.99</td>
<td>248.2</td>
</tr>
</tbody>
</table>

P - Provisional (first quarter of 1975 only).
⊗ - These figures may include some industrialized schemes not identified as such at the time of approval of the tender.
(2) - These figures include dwellings of mixed or special types which cannot be separately classified as house or flats.
* - Figures for 1967 and 1968 include new towns and, in some other ways, are not strictly comparable to those for later periods. (Also, original data were given in £/sq. ft.)

Note: Tenders approved for L.A., England and Wales, excluding G.L.C. (Source: Table 26 of Housing and Construction Statistics.)
### Table 11.4 Indices for Bank Rate of Interest, Average Earnings and House Building Materials. 

<table>
<thead>
<tr>
<th>Year</th>
<th>Index of Bank Rate of Interest</th>
<th>Index of Av. Earnings in Construction</th>
<th>Index of House Building Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td>1968</td>
<td>112.15</td>
<td>109.0</td>
<td>105.0</td>
</tr>
<tr>
<td>1969</td>
<td>127.0</td>
<td>115.3</td>
<td>109.0</td>
</tr>
<tr>
<td>1970</td>
<td>116.8</td>
<td>126.0</td>
<td>117.7</td>
</tr>
<tr>
<td>1971</td>
<td>97.4</td>
<td>139.0</td>
<td>129.5</td>
</tr>
<tr>
<td>1972</td>
<td>101.2</td>
<td>155.2</td>
<td>139.0</td>
</tr>
<tr>
<td>1973</td>
<td>164.0</td>
<td>184.5</td>
<td>166.2</td>
</tr>
<tr>
<td>1974</td>
<td>193.0</td>
<td>224.0</td>
<td>210.0</td>
</tr>
<tr>
<td>1975&lt;sup&gt;P&lt;/sup&gt;</td>
<td>191.0</td>
<td>268.0</td>
<td>244.0</td>
</tr>
</tbody>
</table>

<sup>P</sup> - Provisional figures

<sup>+</sup> - Calculated from Housing and Construction Statistics, including the latest statistics available at the time of writing.
FIG. 11.2 INDUSTRIALIZED DWELLINGS AS A PERCENTAGE OF ALL DWELLINGS (BASED ON TABLE 11.)

FIG. 11.3 VARIOUS COST INDICES WHICH AFFECT THE COSTS OF TRADITIONAL AND INDUSTRIALIZED DWELLINGS. ALSO FLATS > 5 STOREYS AS % OF ALL DWELLINGS.
significant cost differences compared with those built by traditional methods. However, the cost optimization of industrialized dwellings was far from complete; this point was confirmed by many authors who contributed to the 1966 Symposium on "the uses of cranes for low-rise, high density industrialized housing" held at the B.R.S.

As a result of the above symposium, a working party was set up to examine the need for further research and development and for further collaboration between the contractors, the system sponsors, the designers and the crane manufacturers. The report of this working party, which was published in 1970 (8), contained many useful guidelines on the optimization of the total costs related to the use of cranes.

As has been pointed out by Seeley (16), and also described in the outline of the above report (8), the efficiency of the cranage operations on any industrialized scheme is a measure of the total costs of that scheme. This is not necessarily due to the direct cost of cranage itself, which may constitute a small proportion of the total costs, but due to its effects on related operations. Thus, by skilled programming, all the related operations must be synchronized so as to avoid mounting costs. This point is, in fact, well illustrated in the case study undertaken by the B.R.E. (17) which is known as the Finchampstead Project.

Such detailed information on the economics of industrialized buildings was not commonly understood either by architects and their clients or by the contractors.

(b) Social preferences for low-rise housing: High-rise dwellings in use highlighted a number of unforeseen problems: tall buildings were proved to be unsuitable for housing the elderly and families with young children. There was a tendency for the communal spaces to be filled with litter; and in many cases there were complaints about inadequate privacy.

In many tall blocks, it can be generally impossible to open the external windows because of the wind intensity. These factors contributed to a rapid reduction in high-rise dwellings (see Fig. 11.2).

(c) Technical problems: In May 1967, the collapse of the 22 storey building known as Ronan Point led to a comprehensive technical enquiry in 1968 which eventually resulted in the strengthening of many tower blocks at substantially greater costs than expected. The revised rules and design recommendations on
the structural engineering of such buildings greatly added to their costs, making these schemes even more expensive compared with low-rise high density housing.

(d) Fluctuation and fall in the output of the housing sector: Table 2.4 and Fig. 2.2 indicate that the total 'housing starts' has actually fallen considerably since 1967; however, prior to this year, the 'housing starts' were fluctuating - having risen to a peak in 1964, they had dropped in 1966 as a result of the government cut-backs in local authority housing and the squeeze in credit, etc.

The reduction in local authority housing from 1968 to 1974 was not compensated for by private development; the total 'housing starts' fell substantially from 1967 to 1970; they partially recovered in 1973, but have been falling since (refer Table 2.4 and Fig. 2.2).

From 1963 to 1966, there was a serious shortage of labour as measured by unfilled vacancies in the construction industry (7 and 18). However, the reduction in the output of the industry caused an increase in the total unemployment; even in 1973, when the construction industry experienced a modest boom, there was, according to the official statistics (18), a total of nearly 86000 unemployed of which 15400 were skilled men. The unfilled vacancies on the other hand stood at 31000. From 1973 to 1975 unemployment has increased; the total in 1975 stood at 157300 of which 46100 were skilled men (18).

Added to the above was the problem of stockpiles of construction materials, e.g. in 1974 there was a total of $925 \times 10^6$ bricks in stocks, which was five times the 1972 figure and could provide up to one third of the total annual needs.

The combination of falling demand for construction works, high levels of unemployment, tighter competition from the traditional builders and stockpiles of materials does not favour the use of industrialized buildings. Thus, it is likely that these factors were partly responsible for loss of market by industrialized dwellings in 1975 despite their improved cost advantage over traditional buildings (see Table 11.3 and Fig. 11.3).

In fact, from 100 or so industrialized building systems sponsored in the early 1960's, only a limited number have gained commercial success. Even in the case of these, it is likely that their costs have been reduced and productivity improved during the last decade. Most successful systems are in fact sponsored by
major contractors, e.g. No-Fines by Messrs. Wimpey.

11.1.4.3 Analysis of the industrialized systems for dwellings:

Table A1(i) of reference 8 lists all industrialized systems for which tenders for more than 200 were approved either in 1965 or 1966 in Britain; 58 systems are thus included which, both in 1965 and 1966, accounted for 91 per cent of the total industrialized dwellings in Britain. Nearly all contracts were for the public sector (8).

Of all the systems included in Table A1(i), some 30 (or approximately 50 per cent) were based on precast or in situ concrete; 8 (or approximately 15 per cent) were based on timber framing and only one system used steel framing. The remaining 19 were not specified. However, it is likely that these were basically rationalized traditional packages suitable for houses of 1 to 2 storeys (in fact, it has been specified that in the construction of 10 of these systems the use of cranes was not essential (8)).

11.1.5 Development in industrialized buildings for educational purposes:

The development in this field has continued since 1946 to the extent that, today, a large proportion of educational buildings use industrialized methods (19); both consortia systems and privately sponsored systems have found applications. However, the former systems have been used predominantly (19).

Jervis (20) has estimated that in 1973, of £373m spent on educational buildings, 42 per cent was in industrialized buildings, 20 per cent in steel or concrete-framed systems and the remaining 38 per cent was in traditional methods.

There are numerous consortia systems; a brief description of these is given below.

11.1.5.1 ASC (Anglian Standing Conference):

Based in Lincolnshire, this consortium has nine members. The system is designed on a modular grid of 300mm. It uses load-bearing brick wall and prefabricated roof, window and door components.

11.1.5.2 CLASP:

Reference has already been made to this consortium, which is formed by 19 full members. CLASP has been in production since 1956 (19) and its design has been continuously improved. The sys-
tem has a 300mm planning module; it uses light steel frame together with lattice floor and roof beams. A variety of materials are used for cladding panels. However, aggregate-faced precast concrete is generally used in combination with timber-framing and tiling. Floor construction is also prefabricated from timber. Partitions are pre-finished steel sheet panels with plasterboard backing. Most components are factory produced and finished, including glazing, etc.

The supply of components is predetermined annually by a working party of the consortium. Some measure of competition is ensured by inviting more than one manufacturer to tender for system components. Although it is basically designed as a 'closed' system, the components can be interchanged within the system, and since the size of the scheme is large, it may be assumed as being close to an 'open' system with its undoubted economic benefits stemming from bulk production of components.

CLASP is by far the most successful industrialized system of its kind. It has also been used for a variety of non-educational buildings such as offices, computer buildings, clubs, etc. It has been adopted in a number of other countries, including Germany, France, Switzerland and Italy.

11.1.5.3 CLAW (Consortium of Local Authorities in Wales):

This consortium, which was established in 1963, has 14 members. The aims of CLAW may be described as attempts to rationalize the building process and provide for the interchangeability of building components. However, development of building methods which would introduce economy and save professional time, together with an extensive technical information service are the other objectives of CLAW.

11.1.5.4 Method (Consortium for Method Building):

This consortium, which is based in Taunton, has 15 members. However, annual programmes undertaken include a variety of private projects under standard conditions of agreement. This is because the range of components with varying performance capabilities makes 'Method' suitable for many commercial developments.

'Method' is an 'open' system based on a planning module of 300mm both horizontally and vertically; the system is capable of being utilized in a variety of localities and projects with varying budget limitations.
11.1.5.5 **ONWARD (Organization of North West Authorities for Rationalized Design):**

This consortium is based in Preston and has 19 members. It was established in 1966. The planning grid adopted by ONWARD is 4 ft. Load-bearing walls of concrete, brick and timber are spanned by prefabricated roof components. The consortium also handles the bulk ordering of standardized components.

11.1.5.6 **SCOLA (Second Consortium of Local Authorities):**

With 27 members, SCOLA constitutes one of the largest of its kind. This consortium operates from Gloucester. The planning module adopted by SCOLA is 300mm. The structure is a light steel frame with lightweight concrete cladding or brickwork on a separate foundation as an alternative.

The roof construction is felt-covered wood wool units enclosed in steel channels. Ceilings are asbestos or mineral boards in a lay-in suspension grid. Internal partitioning is dry construction based on plasterboard. As with previous consortia, this consortium enters into arrangements for bulk supply of components, some of which are on a supply and fix basis.

11.1.5.7 **SEAC (South Eastern Architects' Collaboration):**

Based in Epping, Essex, this consortium was established in 1963 and has 5 full and 10 associated members. The aims of SEAC are to develop modular building systems using various structural methods for housing, schools, etc. (e.g. SEAC Mark 2). The costs are kept within the permitted limits and use is made of a variety of cladding and roofing materials, including concrete, metal panels, tiles, wooden panels or bricks.

SEAC Mark 2 uses a light steel frame (in part wooden supports) and has a structural module of 1200mm (planning module 300mm).

11.1.5.8 **MACE (The Metropolitan Architectural Consortium for Education):**

Based at Surbiton, Surrey, this consortium was initiated by Surrey County Council in association with a number of Outer London Boroughs. The aims of MACE are to design building systems for fast erection within the cost limits; two systems have been developed:

1. **Schools' system:** Based on a planning grid of one metre, the system uses light steel framing in conjunction with concrete cladding panels and brickwork panels; G.R.P. is used for fascia panels in this system.
(2) Nursery system: This system was originally developed for nursery buildings; however, it is also suitable for other functions, e.g. clubs, libraries, etc. The planning module is 900mm and the structure is based on a light steel frame. Cladding panels are timber-framed with an outer skin of G.R.P. and an inner skin of plasterboard. The roof uses a large unit of purpose-made G.R.P. rooflight.

The nursery system has been made available for use by other local authorities.

11.1.5.9 Non-consortia systems:

A number of proprietary systems have also been adopted successfully for educational buildings; Derwent Type 6, Laingspan II, Bison, Intergrid Mark 5 and Swiftplan are examples which have been used. However, these have also been used for housing, offices, hospitals, etc.

11.1.6 Development in hospital building:

As has already been noted, a variety of proprietary systems such as Laingspan II and Intergrid have been successfully adopted for hospital buildings throughout the country. However, industrialized systems for hospital buildings are generally designed by the Regional Health Authorities or the Department of Health and Social Security (DHSS). Two notable modular systems are 'Harness' by Oxford Regional Health Authority and 'Best Buy' by the DHSS (21). The former uses a light steel frame cladded by light materials, including G.R.P. in the East Birmingham Hospital Extension project. The latter uses precast concrete frame and aerated concrete cladding panels (21).

It is worth noting that hospitals are generally complex projects, and the design of their components must be checked rigorously against performance/users' requirements (see, for example, reference 21, which describes in detail the development of 'Best Buy'). Thus, it is unlikely that any development can be successful other than those carried out in association with the Regional Health Authorities or the DHSS. However, as indicated in reference 21, there is a continuous drive to reduce the costs without lowering the essential standards; the use of precast concrete for the structural framing in preference to structural steel has resulted in some cost savings. The use of 200mm (8in) thick precast aerated concrete panels for walling is intended to provide a high degree of heat insulation. Overall, 'Best Buy' is the
backbone for future developments in the hospital building field (21) and, incidentally, the system is capable of further developments and refinements. For example, the whole system is heavy and inflexible for future alterations.

11.1.7 Advantages of industrialized building methods:

11.1.7.1 Long term advantages:

There are various fundamental reasons for assuming an eventual domination of industrialized buildings; chiefly:

1. The efficiency of labour versus machine: The average capacity of a human being is about 0.05 horsepower over long periods, though for brief spells his capacity can increase up to 0.5 horsepower. The efficiency of a human being is 1 per cent, which is very low compared with a minimum of 20 per cent for a machine. (22).

Thus, in the long run, this inherent inefficiency of labour force will come to be reflected in the total costs of labour, making labour-intensive building methods uneconomic.

This point may be illustrated by the study of the labour and materials inputs necessary for a unit production of one m² of floor area. In a conventional building, the ratio of labour input to that of materials input is approximately 1:1. In an industrialized system, it may be as low as 1:4, and in the U.S.A., according to Schmid (3), it is around 1:8.

The example given by Schmid (3) is noteworthy; he concludes that an increase of 50 per cent in the cost of labour would increase the costs of a labour-intensive building by a minimum of 25 per cent. The corresponding increase in an industrialized system in the U.S.A. would be about 7 per cent; which, when viewed against the general increase in the cost of living, etc., would actually make industrialized buildings cheaper relative to other goods and services.

2. The long term increase in the demand: Meyer-Bohe (22) states that, up to the year 2000, the stock of existing buildings will have to be doubled to cope with the potential demand; the increase in the world population from the present figure of 4 billion to a predicted 6.5 billion, the increase in urbanization (up to 90 per cent of the above population is expected to live in cities (22)) and the need for replacement and upgrading of the existing stocks are but some factors generating the worldwide demand for building.
Although the population in the U.K. is not expected to increase proportionate to the world population, the long term demand for buildings is not expected to be very much less since, according to a figure by Mr. Peter Shore (23), the D.O.E. have estimated that, despite a stable population, there will be an increase of 2 million households in Britain between 1974 and 1986. The 1973 housing output in the U.K. was approximately 300,000 (18); this is less than half the potential demand (28), which leads to an accumulation in demand (7).

As was demonstrated in the 1960's, the traditional methods are not capable of meeting high levels of demand; this means that the industrialized methods would have to be introduced.

11.1.7.2 Present advantages of industrialized building methods:

For a prospective client, employment of industrialized building methods and systems in appropriate situations may result in the following gains:

(1) Saving of time on design and development (i.e. pre-contract period): By choosing a well tried and tested industrialized system, the design stage may be shortened considerably; thus, the designer is able to concentrate his attention on clarifying the brief, analysing users' requirements, achieving better planning arrangements and possibly saving space, improving the quality without increasing the costs or the overall time scale. All of these would give the client better value for money.

(2) Saving of time on construction and completion: In an industrialized system, the production of components can be arranged to suit the pace of construction regardless of the conditions of the weather. Quick assembly of the external shell of a building would also assure better working conditions for site operatives.

Quicker completion of a building may have the following benefits:

(a) reduced interest charges: Private developers pay as much as 20 per cent on short term loans in order to finance a project (20); the corresponding rate for public authorities is about 15 per cent (7 and 20).

(b) protection from the effects of inflationary cost increases: In rapid inflationary periods, prices for materials and hiring of labour are subject to continuous increases. The longer the length of the
construction, the higher are these inflationary costs.

(c) earlier return on capital: An early occupation or use of a building may bring income (in the form of a lease, rent, etc.) which can be set against the costs.

(3) Lowering of costs per square metre: There are numerous situations in which careful application of industrialized building systems may result in lowering of first costs, running costs, users' costs and maintenance charges. Not only can wastages in materials and labour be eliminated in an industrialized method, but also the amount of non-productive work such as scaffolding can be minimized.

(4) Higher standards of quality and performance: In terms of both quality and performance, an industrialized building such as CLASP may prove superior to a traditional building, because the former is subject to continuous improvements as a result of feedback of information from sites. Furthermore, the components used by the former are factory produced and are therefore of a superior quality.

11.1.8 Disadvantages of industrialized buildings:

Industrialization of the building process has had its own problems; the majority of these problems have stemmed from the practical difficulties of applying a novel concept and from market resistance to change. The following are a brief description of the main problems which have affected the progress of industrialization:

11.1.8.1 Problems of joint design and its satisfactory functioning:

As has been pointed out by Testa (3), the transition from proprietary systems to buildings with mass-produced, dimensionally co-ordinated components requires a large degree of research and development in jointing techniques. In the case of proprietary systems, joint design is usually worked out for known components in conformity with the local/national building regulations, and often without preserving the 'modular' principle of the design. Modular grids are used only as an aid for planning and dimensioning of the building.

Further, the development of joints between elements of wall and foundation or roof has been insufficiently researched (3);
these problems are often left to be overcome by users of the sys-
tems.

11.1.8.2 Problems related to the scale of production, trans-
portation and handling:

The tendency in the past has been towards large and heavy
concrete-panel systems, with the components weighing from 2.5 to
10 tonnes (8). As a general rule, the heavier the components, the
higher the total capital investment required for the production
and handling equipment in the factory and the higher the charges
for transportation and assembly on site (3 and 8).

Transportation charges in heavy systems may constitute up to
one third of the total costs of the components delivered on site
(16); there are also practical and safety restrictions imposed on
the transportation and assembly of heavy components (3, 8 and 22).

However, the present day trend is towards light frames of
steel or timber with components weighing in the range of 50 to 100
kg, or occasionally up to 250 kg, which may require a light crane
for their erection (8 and 17).

Given these fixed and variable costs, it can be deduced that
long runs of production are needed in order to amortize these costs
in a satisfactory manner. This, in turn, implies that building
clients have to pool their requirements with those of others in
order to arrive at an economic unit production. Clearly, such a
systematic and disciplined approach has not been forthcoming on the
part of large private and public clients (17) and, as a result, too
many firms have tried to share the market, with few really having
any chance to develop to any great extent (17).

11.1.8.3 Design restrictions:

Most heavy load-bearing concrete systems designed mainly by
builders and engineers as 'closed' systems have tended to be
inflexible in application (3 and 16). In addition, architectural
parameters such as proportion, surface texture, colour, etc., have
been overlooked by many system sponsors. However, there is evi-
dence (e.g. reference 3) that this situation has been changing for
some time, especially as newer and lighter materials with improved
aesthetic characteristics have found applications. Nevertheless,
system building must be developed further to respond to the many
varied demands which the present traditional methods can largely
satisfy (see comments contained in Table 8.25).
11.2 Relationships between G.R.P. panels and Industrialized Building Methods:

11.2.1 Present use of G.R.P. panels in industrialized buildings:

From the official definition given in 11.1.1, it may be noted that custom-moulded G.R.P. panels can be classified as an industrialized method of construction, since these panels are produced in a factory and assembled on site, employing 'dry construction' techniques in general.

Assuming a diagram which would show the gradual progress from 'craftsmen-based' building to 'component-based' building (in which all components are freely selected from mass-produced interchangeable components and assembled on site with a minimum of site labour), it will be seen that 'custom-moulded' G.R.P. panels occupy an intermediate position on this diagram. In other words, the use of G.R.P. panels involves some degree of industrialization and is probably representative of the current state of development in this direction (i.e. standardization and reduction of variety as related to individual projects).

The following examples of the use of G.R.P. panels probably go one step further in the direction of industrialization:

(1) The modular range of buildings designed and produced by British Rail for use as ticket offices, cafes, waiting rooms, etc. Storey-height panels are made of G.R.P. with a timber frame moulded on to their backs. Roof is made up of modular segments moulded in G.R.P. and bolted together via their flanges. British Rail intend, subject to satisfactory performance and minor modification, to manufacture this system on a continuous basis using the contact moulding process (24). Panels and segments in this system are light in weight and can be erected with the help of a light crane.

(2) Resiform industrialized building system: Originally developed for housing in 1965 by Messrs. William Old and approved in 1967 by both the National Building Agency and the National House Builders' Registration Council, this system is based on a planning module of 300mm. Storey-height components are made from G.R.P. with timber-framing fixed onto their backs.

(3) Prefabricated modular folded plate G.R.P. structure by Messrs. Anmac of Nottingham: A brief description of this system, which is suitable for covering swimming pools and a variety of other applications such as sports halls, warehouses, etc., has
been given in preceding chapters.

(4) MACE Nursery system: As has been referred to previously this system is a modular design which utilizes G.R.P. cladding and moulded-in timber framing; 30 of such nurseries have been planned for the next five years.

(5) Various components supplied to consortia systems: This includes window units moulded by Messrs. Bourne Plastics for CLASP at the rate of 200 units per annum.

(6) The experimental use of G.R.P. panels on the 'Harness' system for the extension of East Birmingham Hospital: Although the use of G.R.P. did not develop on a continuous basis, the health authority are investigating development of G.R.P. window units for use on a continuous basis (see 10.1).

(7) Miscellaneous experimental attempts: For example, the prototype G.R.P. house designed by Pierre Botschi and Dereck Walker (25) for Milton Keynes Development Corporation may prove to be a real breakthrough in the field of industrialized low cost G.R.P. dwellings (see 11.2.3 for discussion on this innovation).

Industrialized G.R.P.-based houses have had some success in other countries, notably Germany and the U.S.A.; these developments are no doubt influenced by the conviction that G.R.P. is an ideal material for industrialized building due to its light weight and aesthetic characteristics and its ability to be moulded into large panels and structures.

It must also be noted that timber-framed G.R.P. components can be considered as a natural development in the field of timber-framed system building in which G.R.P. outer skin replaces board materials such as plywood, fibreboard, asbestos-cement, etc. The advantages of this substitution include ease of manufacturing with reduction of site labour, enhanced appearance/durability, etc.

11.2.2 Comparison between G.R.P. panels and industrialized systems in general:

11.2.2.1 Design capabilities:

Custom-moulded G.R.P. panels offer improved design freedom; such a freedom is not secured in most industrialized systems available in the market.

Furthermore, being versatile, G.R.P. can be successfully utilized in mixed constructions, e.g. as fully finished and glazed infill panels between walls of traditional construction.
It can be seen that the above use of G.R.P. panels bears some resemblance to the earlier use of patent glazing and metal curtain walling which used to be fabricated to architects' requirements. Today, for reasons of economy, architects and engineers specify fully standardized proprietary patent glazing or metal curtain walling (27). The majority of these are, in fact, erected by specialist sub-contractors connected with the manufacture of these systems (27).

In the case of G.R.P. panels, it is likely that a parallel situation will develop in the future.

11.2.2.2 **Production and quality control:**

Hand laminated G.R.P. panels are broadly comparable to table or floor cast concrete units.

Most concrete factories in the U.K. employ mechanical means for mixing concrete, for pouring and compacting it into the moulds and for handling the cast units. Some modern factories have equipment for the finishing of the concrete surfaces, e.g. the machinery used by Messrs. Laings for printing various surface reliefs on freshly cast panels from 'Faircrete' (see section 4.5).

Thus, production of concrete units, whilst not entirely manual, permits a certain degree of flexibility, e.g. for incorporation of window frames, etc.

The fundamental difference between production of G.R.P. and concrete units stems from the degree of quality control required in every stage of production and curing. Generally speaking, the quality of concrete is less critically dependent on the skill of operators. Furthermore, testing procedures for concrete are comparatively easy; most defects can be detected by eye or by use of non-destructive tests.

In the case of G.R.P., many defects could show up several months after site installations, which would incur high remedial costs. As is evident, press moulded G.R.P. panels are more uniform in quality, but still dependent on the production and environmental factors, though research in this direction is in progress (24).

11.2.2.3 **Transportation:**

G.R.P. panels enjoy a considerable advantage over concrete and other systems as they are the lightest material in weight known to the construction industry; thus, a G.R.P. factory can effectively serve a regional, national or even international market.
11.2.2.4 Site handling and erection:

The light weight property of G.R.P. is a valuable asset in reducing the handling and site erection costs compared with heavier systems. Also, being fairly resistant to the action of impact, and especially resistant to shattering, it has superior site handling capabilities compared with asbestos-cement based components.

11.2.2.5 Economics:

It has been said (26) that it is only in competition with on-site constructed building components (e.g. walls) that G.R.P. panels have a chance. Prefabricated concrete and wooden-based panels are cheaper than G.R.P. panels because of lower materials' costs.

Although this claim has some degree of truth in it, it is not necessarily universally applicable. A generalized comparison between costs of contact-moulded G.R.P. panels and factory produced concrete panels shows that in both processes the overhead charges are roughly similar.

The cost of materials for reinforced concrete panels depends on the design of the panels. However, it is likely to be significantly less than the cost of materials in a G.R.P. panel of equivalent performance (c.f. section 5.6 and Table 5.20).

The cost of labour is higher in hand laminated G.R.P. panels because all operations are performed by hand labour. In the case of 'spray-up' moulding, the labour input is potentially capable of reduction and it may become comparable with that of concrete panels. Transportation and erection costs of G.R.P. panels are considerably lower than those of concrete panels. Also, production of concrete units involves higher capital investment, especially for lifting devices in the factory.

In appropriate cases there are other savings associated with the use of G.R.P. panels, e.g. when, due to the light weight property of this material, the costs of structural and foundation provisions may be reduced, as well as fuel and maintenance costs.

This analysis shows that in certain circumstances the use of G.R.P. panels may be economically advantageous compared with concrete-based panels. However, as has already been discussed, (c.f. sections 5.6 and 14.2) and seen from the above analysis, because of high labour costs, there is little economic potential for contact-moulded industrialized G.R.P. units in competition with concrete.
However, with large runs of production when it may be possible to utilize mechanical means of production, G.R.P. panels may prove economically advantageous. This means that future penetration of G.R.P. into the industrialized building field is dependent upon employment of capital-intensive production machinery, probably in association with large corporate clients, consortia, etc.

Furthermore, G.R.P. is a novel material and it may be possible to see cheaper resins with improved properties as substitutes for polyesters; also, improved design of composites may reduce the cost of materials input; these aspects are further discussed in Chapter 14.

11.2.2.6 Technical aspects:

Concrete panels possess good 'fire-resistance' and 'sound insulation' performance; if aerated concrete is used, an adequate degree of thermal insulation may also be obtained. However, heavy structures have different thermal behaviour compared with light structures; the former structures absorb a considerable amount of heat before 'warming up', whereas the latter structures warm up in a shorter period. This difference is important when a building is heated intermittently; the fuel consumption of a light building of an appropriate design (e.g. a sandwich panel with an adequate degree of thermal insulation) is considerably less than that of heavy structures.

Although 'fire-resistance' and 'sound insulation' performances of G.R.P. are poor, these can be improved by composite designs.

Another basic difference between G.R.P. and concrete concerns the imperviousness of the surface; G.R.P. is non-porous and, unlike concrete, reduces the risk of moisture penetration.

11.2.3 Future implications of G.R.P. development for system building:

As has been noted in the preceding chapters and confirmed by the findings of IBK (see pages 438-440), the technical problems of manufacturing large G.R.P. (e.g. room-sized) units by mechanical means for incorporation in industrialized building systems have not been solved entirely. However, developments such as large presses (see page 205) or the manufacture of the plastics house WG 2000 in Germany (28) provide significant advances in this direction.

Design and development of G.R.P. systems for standardized
curtain walling is not only a technical and economic possibility, but is also in line with current design trends, e.g. reduction of window areas and higher degrees of heat insulation for heat conservation, the use of reflective surfaces for minimization of solar heat gain (hence reduction of the load on the air-conditioning system), the preference for large-sized panels in order to reduce the number of joints and sub-assemblies, etc. However, introduction of such systems with sufficient degrees of flexibility in application is currently beyond the resources and experience of the majority of G.R.P. processors (see section 7.2).

Thus, the future development in industrialized G.R.P. systems depends on the sporadic and often unco-ordinated efforts such as the G.R.P. house experimentally erected at Milton Keynes (25). This development, which represents a large degree of industrialization, is very significant in that, according to the designers' estimate (25), it can be built within the cost yardsticks and that 2 to 3 houses per week, initially, can be produced by each fabricator. This example shows the potential of G.R.P in the field of industrialization which has been largely overlooked by the major G.R.P. processors (see section 7.2).

It should be noted that the successful and continuous development of all composite materials such as G.R.P, G.R.C., etc., is in fact a recognition of the need for lightweight and versatile materials suitable for industrialized building techniques. Before G.R.P. can be assured of any leading position, a number of technical and production improvements will have to be made; these are discussed in Chapter 14 under the general heading: "The Need for Further Research and Development."
9. Table 22 of Housing and Construction Statistics, No. 16, 4th quarter 1975, HMSO, June 1976 (average figure has been estimated by the author using the data in Table 22).

18. Department of the Environment: Annual and Monthly Bulletins of Construction Statistics up to 1972. (Now replaced by Housing and Construction Statistics Quarterly; Tables 12 and 13 of this publication contain statistics on employment).


20. Jervis, R., "Quick returns and saving on interest and labour costs", The Times, Wednesday, January 8th, 1975 (p25). Mr. Jervis is the Principal Quantity Surveyor with the National Building Agency.


24. Rubber and Plastics Weekly, May 7th, 1976 (p30 and 31). Also meeting and correspondence with the R and D unit of British Railways.


12.1 Current Trends in the Consumption of Basic Engineering Materials in the U.K. Economy and the Dependence on Overseas Supplies:

It is a common practice to divide materials into the following classes: non-renewable and renewable materials.

Non-renewable materials include non-metallic minerals such as sand and gravel, stone, clay, etc., as well as metals, synthetic polymers and allied materials.

Renewable materials include timber and wood-based materials, natural rubber and various natural fibres.

Although mineral fuels are also non-renewable resources, they are not generally classed as materials since they are primarily utilized as fuel resources.

Table 12.1 shows that minerals used in the U.K. construction industry are mainly derived from indigenous sources. This is because these minerals are not only heavy in weight and costly to transport, but they are also the most common materials generally occurring everywhere in the world (see also Table 12.4).

Table 12.2 and Fig. 12.1 show the U.K. consumption of certain common metals in the decade 1964 to 1974 and the corresponding data for population and 'index of industrial production'. It can be seen from Fig. 12.1 that whilst the index of industrial production rose by approximately one quarter, the consumption of iron and steel fluctuated around the same level. The consumption of copper, lead and softwood timber declined significantly in the same period.

In contrast to these, the consumption of aluminium showed a significant increase; this increase is not unexpected since, as will be seen later, the relative economic competitiveness of this material has been improving, especially since 1970 (1 and 2) (see Chapter 13).

The consumption of synthetic resins showed an even higher rate of growth relative to the other materials, to population increase or to industrial production increases. It can be seen that in modern economics, newer materials occupy important positions alongside such old-established materials as iron and steel, copper and lead, etc.

Table 12.3 shows that the U.K. must import most of her metal
Table 12.1 Production of Bulk Construction Minerals (including Cement) in the U.K. in 1974.

<table>
<thead>
<tr>
<th>Material</th>
<th>Unit</th>
<th>Production figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>$10^3 \times$ tonnes</td>
<td>17781</td>
</tr>
<tr>
<td>Building sand</td>
<td>&quot;</td>
<td>20405</td>
</tr>
<tr>
<td>Concreting sand</td>
<td>&quot;</td>
<td>32428</td>
</tr>
<tr>
<td>Gravel</td>
<td>&quot;</td>
<td>59959</td>
</tr>
<tr>
<td>Manufactured lightweight</td>
<td>aggregates</td>
<td>1012</td>
</tr>
<tr>
<td>Silica + refractory and</td>
<td>moulding sand</td>
<td>6384</td>
</tr>
<tr>
<td>Gypsum and plaster</td>
<td>&quot;</td>
<td>4153</td>
</tr>
<tr>
<td>Building bricks +</td>
<td>$10^6n$</td>
<td>7183</td>
</tr>
</tbody>
</table>

- Source: Annual Abs. of Statistics, 1975, HMSO.
+ - 1973 figures.

needs directly from foreign suppliers either in the form of ores or processed metals. The same is also true in the case of timber and wood-based products (Table 12.4). However, with the exception of asbestos, the U.K. foreign trade in other constructional materials is either in surplus or is a relatively small scale trade (by value) compared with that in metals, timber and asbestos.

In addition, as mentioned earlier, the U.K, is mainly self-sufficient in all major constructional materials such as cement, brick, etc.

12.2 The World Reserves of the Essential Materials:

Table 12.5, which is taken from reference 3, indicates the world reserves of the most extensively used elements. It also shows the resource-to-demand ratio R/D in 1968.

As the demand grows, R/D is reduced. However, according to Goeller and Weinberg (3), the world population must finally level off; this will eventually result in a levelling off of the world demand for energy and non-renewable resources.

Goeller, et al. (3), in a survey of all minerals and metals used worldwide, concluded that only extractable hydrocarbons,
Table 12.2  U.K. Consumption of Selected Materials (Source: Annual Abs. of Statistics, 1975)

<table>
<thead>
<tr>
<th>Year</th>
<th>U.K. Population (x 10^6)</th>
<th>Index of Ind. Prod.</th>
<th>Total iron and steel (x 10^6 T)</th>
<th>Aluminium (x 10^3 T)</th>
<th>Lead (x 10^3 T)</th>
<th>Copper (x 10^6 m^3)</th>
<th>Softwood timber index</th>
<th>All synthetic resins (x 10^3 T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1964</td>
<td>53.885</td>
<td>100</td>
<td>23.465</td>
<td>440.663</td>
<td>427.4</td>
<td>789.4</td>
<td>9.355</td>
<td>883.4</td>
</tr>
<tr>
<td>1965</td>
<td>54.218</td>
<td>100.8</td>
<td>23.369</td>
<td>450.189</td>
<td>435.1</td>
<td>814.0</td>
<td>8.879</td>
<td>957.3</td>
</tr>
<tr>
<td>1966</td>
<td>54.500</td>
<td>101.2</td>
<td>22.680</td>
<td>453.649</td>
<td>413.9</td>
<td>742.5</td>
<td>8.479</td>
<td>1017.0</td>
</tr>
<tr>
<td>1967</td>
<td>54.800</td>
<td>101.8</td>
<td>21.870</td>
<td>444.171</td>
<td>393.3</td>
<td>655.9</td>
<td>8.973</td>
<td>1108.3</td>
</tr>
<tr>
<td>1968</td>
<td>55.049</td>
<td>102</td>
<td>21.360</td>
<td>483.306</td>
<td>394.3</td>
<td>679.6</td>
<td>9.238</td>
<td>1233.6</td>
</tr>
<tr>
<td>1969</td>
<td>55.263</td>
<td>102.7</td>
<td>23.214</td>
<td>504.884</td>
<td>387.0</td>
<td>690.5</td>
<td>8.453</td>
<td>1319.0</td>
</tr>
<tr>
<td>1970</td>
<td>55.421</td>
<td>103</td>
<td>24.521</td>
<td>491.600</td>
<td>350.3</td>
<td>673.6</td>
<td>8.510</td>
<td>1468.0</td>
</tr>
<tr>
<td>1971</td>
<td>55.610</td>
<td>103.2</td>
<td>22.400</td>
<td>449.190</td>
<td>366.4</td>
<td>645.1</td>
<td>8.565</td>
<td>1446.9</td>
</tr>
<tr>
<td>1972</td>
<td>55.793</td>
<td>103.6</td>
<td>22.240</td>
<td>488.437</td>
<td>354.9</td>
<td>667.8</td>
<td>8.922</td>
<td>1607.6</td>
</tr>
<tr>
<td>1973</td>
<td>55.933</td>
<td>104</td>
<td>24.190</td>
<td>575.103</td>
<td>364.1</td>
<td>717.7</td>
<td>10.077</td>
<td>2398.6</td>
</tr>
<tr>
<td>1974</td>
<td>56.056</td>
<td>104.1</td>
<td>23.244</td>
<td>591.269</td>
<td>325.3</td>
<td>659.8</td>
<td>7.893</td>
<td>2334.9</td>
</tr>
</tbody>
</table>

+  - Source: OECD
+  - Production figures
All synthetic resins (production)
Aluminium
Index of industrial production
Population index
Iron & steel
Timber
Lead
Copper

FIG. 12.1. U.K. CONSUMPTION OF SELECTED MATERIALS; THE POPULATION AND THE INDEX OF INDUSTRIAL PRODUCTION
reduced carbons and phosphorus are practically exhaustible resources. A study of the world demand for materials in 1968 showed (3) that extractable hydrocarbons constitute about 67 per cent of the world demand (80 per cent of the U.S.A. demand) for non-renewable resources. Iron, steel and aluminium together accounted for 94 per cent of the world demand for metals (3).

The extraction of these metals from their oxides (or ores) requires energy either in the form of fossil fuels or from other sources. In fact, the lower the grade of ores (recoverable metal content), the higher the quantity of energy required for their extraction. Thus, future availability and cost of metals will depend on the availability and cost of energy. This is seen from Table 12.6, which shows the ratio of energy required to extract the abundant metals as well as copper from the lowest grade resources to those of highest grade resources. A point worth noting is that this ratio \( E^L/E_H \) is generally below 2; in other words, the future energy requirements for processing these metals is not expected to exceed the present total energy input by a large proportion. (Note that with the coal reserves lasting for upward of 150 years, the production of iron and steel will not change significantly; thus, the total energy input for processing metals will not increase by more than one fifth.)

In 1968, 95 per cent of the world demand on metals consisted of iron, aluminium, silicon, magnesium and titanium (3). However, these metals, which accounted for 80 per cent of the value of all metals used in the world, consumed 95 per cent of the total energy used in 1968 for extracting all metals.

The remaining metals were mainly Cu, Zn, Cr, Pb, Ni and Sn, which together accounted for 20 per cent of the value of the world demand for metals. The cost of energy used for processing these metals was equivalent to approximately one half of the total value of these metals (3).

It must be noted that the energy input for processing recycled metals is considerably less than the virgin metals. It ranges from 3 to 30 per cent of the virgin metals, depending on the type of metal: for example, for the aluminium alloys the remelt energy is approximately 3 to 4 per cent of the original input (3).

One of the useful conclusions reached by Goeller, et al. (3), is that, given plentiful and cheap sources of energy and the range of possibility for materials' substitution, there are, practically,
Table 12.3 U.K. Dependence on Foreign Supplies of Metals and/or Ores+ (1974).

<table>
<thead>
<tr>
<th>Material type</th>
<th>Unit</th>
<th>Quantity</th>
<th>Major Supplier of Metal and/or Ore (1974)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bauxite Production</td>
<td>(x 10^3T)</td>
<td>--</td>
<td>Norway, Ghana,</td>
</tr>
<tr>
<td>Bauxite Imports</td>
<td>&quot;</td>
<td>324</td>
<td>Canada, Greece,</td>
</tr>
<tr>
<td>Metal Production</td>
<td>&quot;</td>
<td>251.6</td>
<td>Switzerland, Holland.</td>
</tr>
<tr>
<td>Metal Consumption</td>
<td>&quot;</td>
<td>487.8</td>
<td></td>
</tr>
<tr>
<td>Lead</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mine Production</td>
<td>&quot;</td>
<td>4.0</td>
<td>Australia, Canada,</td>
</tr>
<tr>
<td>Refined Production</td>
<td>&quot;</td>
<td>276.9</td>
<td>S.W. Africa.</td>
</tr>
<tr>
<td>Total Consumption</td>
<td>&quot;</td>
<td>266.4</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mine Production</td>
<td>&quot;</td>
<td>--</td>
<td>Zambia, Canada,</td>
</tr>
<tr>
<td>Smelter Production</td>
<td>&quot;</td>
<td>--</td>
<td>Chile, U.S.S.R., W.</td>
</tr>
<tr>
<td>Refined Production</td>
<td>&quot;</td>
<td>160.1</td>
<td>Germany, Zaire, S.</td>
</tr>
<tr>
<td>Metal Consumption</td>
<td>&quot;</td>
<td>496.9</td>
<td>Africa, U.S.A., Australia.</td>
</tr>
<tr>
<td>Zinc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mine Production</td>
<td>&quot;</td>
<td>3.0</td>
<td>Australia, Peru,</td>
</tr>
<tr>
<td>Smelter Production</td>
<td>&quot;</td>
<td>84.4</td>
<td>Irish Rep., Canada,</td>
</tr>
<tr>
<td>Metal Consumption</td>
<td>&quot;</td>
<td>268.5</td>
<td>Morocco, Iran.</td>
</tr>
<tr>
<td>Tin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mine Production</td>
<td>&quot;</td>
<td>3.2</td>
<td>Malaysia, Nigeria,</td>
</tr>
<tr>
<td>Smelter Production</td>
<td>&quot;</td>
<td>11.8</td>
<td>U.S.A.</td>
</tr>
<tr>
<td>Metal Consumption</td>
<td>&quot;</td>
<td>16.7</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mine Production</td>
<td>&quot;</td>
<td>--</td>
<td>Canada, Norway.</td>
</tr>
<tr>
<td>Smelter Production</td>
<td>&quot;</td>
<td>35.7</td>
<td></td>
</tr>
<tr>
<td>Metal Consumption</td>
<td>&quot;</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td>Iron + Steel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ore Production</td>
<td>(x 10^6T)</td>
<td>3.951</td>
<td>Various countries</td>
</tr>
<tr>
<td>Ore Imports</td>
<td>&quot;</td>
<td>18.269</td>
<td></td>
</tr>
<tr>
<td>Total Production</td>
<td>&quot;</td>
<td>23.419</td>
<td></td>
</tr>
<tr>
<td>Total Consumption</td>
<td>&quot;</td>
<td>23.244</td>
<td></td>
</tr>
</tbody>
</table>


= - Source: Annual Abs. of Statistics, 1975, HMSO.
Table 12.4  Imports - Exports of Building Materials and Components* in 1974

<table>
<thead>
<tr>
<th>Material</th>
<th>Imports Value (c.i.f.) (£ x 10^3)</th>
<th>Exports Value (f.o.b.) (£ x 10^3)</th>
<th>Net Imports (--) (£ x 10^3)</th>
<th>Possibility for U.K. self sufficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conifer timber</td>
<td>505224</td>
<td>NIL</td>
<td>- 505224</td>
<td>Remote</td>
</tr>
<tr>
<td>Other wood products</td>
<td>215873</td>
<td>16570</td>
<td>- 201303</td>
<td>Remote</td>
</tr>
<tr>
<td>Asbestos and asbestos-cement</td>
<td>22620</td>
<td>2890</td>
<td>- 19730</td>
<td>Remote</td>
</tr>
<tr>
<td>Gypsum, plaster, etc.</td>
<td>2374</td>
<td>1200</td>
<td>- 1179</td>
<td>Good</td>
</tr>
<tr>
<td>Sand, gravel and crushed stone</td>
<td>2742</td>
<td>4970</td>
<td>+ 2228</td>
<td>Not known (probably good)</td>
</tr>
<tr>
<td>Natural and manufactured bitumenous products</td>
<td>2664</td>
<td>5376</td>
<td>+ 2712</td>
<td>Not known</td>
</tr>
<tr>
<td>Glass products, excluding glass fibre</td>
<td>9146</td>
<td>22060</td>
<td>+ 12914</td>
<td>Good</td>
</tr>
<tr>
<td>Cement</td>
<td>2980</td>
<td>9786</td>
<td>+ 6806</td>
<td>Good</td>
</tr>
<tr>
<td>Clay bricks, tiles, etc.</td>
<td>298</td>
<td>737</td>
<td>+ 439</td>
<td>Good</td>
</tr>
<tr>
<td>Glazed and unglazed tiles</td>
<td>4437</td>
<td>9578</td>
<td>+ 5141</td>
<td>Good</td>
</tr>
<tr>
<td>Building stone and slate</td>
<td>4956</td>
<td>964</td>
<td>- 3992</td>
<td>Moderate (expensive materials)</td>
</tr>
<tr>
<td>Mineral insulating materials</td>
<td>6193</td>
<td>3246</td>
<td>- 2949</td>
<td>Good</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>Resource:</th>
<th>Max., in best resource (%)</th>
<th>World Resources (tons)</th>
<th>R/D (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH&lt;sub&gt;x&lt;/sub&gt; (extractable)</td>
<td>Coal, oil, gas</td>
<td>&lt;75</td>
<td>1 x 10&lt;sup&gt;13&lt;/sup&gt;</td>
<td>2500</td>
</tr>
<tr>
<td>C (oxidised)</td>
<td>Limestone</td>
<td>12</td>
<td>2 x 10&lt;sup&gt;15&lt;/sup&gt;</td>
<td>4 x 10&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
<tr>
<td>Si</td>
<td>Sand, sandstone</td>
<td>45</td>
<td>1.2 x 10&lt;sup&gt;16&lt;/sup&gt;</td>
<td>5 x 10&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ca</td>
<td>Limestone</td>
<td>40</td>
<td>5 x 10&lt;sup&gt;15&lt;/sup&gt;</td>
<td>4 x 10&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
<tr>
<td>H</td>
<td>Water</td>
<td>11</td>
<td>1.7 x 10&lt;sup&gt;17&lt;/sup&gt;</td>
<td>~ 10&lt;sup&gt;10&lt;/sup&gt;</td>
</tr>
<tr>
<td>Fe</td>
<td>Basalt&lt;sup&gt;+&lt;/sup&gt;, Laterite</td>
<td>10</td>
<td>1.8 x 10&lt;sup&gt;15&lt;/sup&gt;</td>
<td>4.5 x 10&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
<tr>
<td>N</td>
<td>Air</td>
<td>80</td>
<td>4.5 x 10&lt;sup&gt;15&lt;/sup&gt;</td>
<td>1 x 10&lt;sup&gt;8&lt;/sup&gt;</td>
</tr>
<tr>
<td>Na</td>
<td>Rock salt, Seawater</td>
<td>39</td>
<td>1.6 x 10&lt;sup&gt;16&lt;/sup&gt;</td>
<td>3 x 10&lt;sup&gt;8&lt;/sup&gt;</td>
</tr>
<tr>
<td>O</td>
<td>Air</td>
<td>20</td>
<td>1.1 x 10&lt;sup&gt;15&lt;/sup&gt;</td>
<td>3.5 x 10&lt;sup&gt;7&lt;/sup&gt;</td>
</tr>
<tr>
<td>S</td>
<td>Gypsum, Seawater</td>
<td>23</td>
<td>1.1 x 10&lt;sup&gt;15&lt;/sup&gt;</td>
<td>3 x 10&lt;sup&gt;7&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cl</td>
<td>Rock salt, Seawater</td>
<td>61</td>
<td>2.9 x 10&lt;sup&gt;16&lt;/sup&gt;</td>
<td>4 x 10&lt;sup&gt;8&lt;/sup&gt;</td>
</tr>
<tr>
<td>P</td>
<td>Phosphate rock</td>
<td>14</td>
<td>1.6 x 10&lt;sup&gt;10&lt;/sup&gt;</td>
<td>1300</td>
</tr>
<tr>
<td>K</td>
<td>Sylvite, Seawater</td>
<td>52</td>
<td>5.7 x 10&lt;sup&gt;14&lt;/sup&gt;</td>
<td>4 x 10&lt;sup&gt;7&lt;/sup&gt;</td>
</tr>
<tr>
<td>Al</td>
<td>Clay (Kaolin)</td>
<td>21</td>
<td>1.7 x 10&lt;sup&gt;15&lt;/sup&gt;</td>
<td>2 x 10&lt;sup&gt;8&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mg</td>
<td>Seawater</td>
<td>0.012</td>
<td>2 x 10&lt;sup&gt;15&lt;/sup&gt;</td>
<td>4 x 10&lt;sup&gt;8&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mn</td>
<td>Seafloor nodules</td>
<td>30</td>
<td>1 x 10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>13000</td>
</tr>
<tr>
<td>Ar</td>
<td>Air</td>
<td>1</td>
<td>5 x 10&lt;sup&gt;13&lt;/sup&gt;</td>
<td>2 x 10&lt;sup&gt;8&lt;/sup&gt;</td>
</tr>
<tr>
<td>Br</td>
<td>Seawater</td>
<td>--</td>
<td>1 x 10&lt;sup&gt;14&lt;/sup&gt;</td>
<td>6 x 10&lt;sup&gt;8&lt;/sup&gt;</td>
</tr>
<tr>
<td>Ni</td>
<td>Peridotite&lt;sup&gt;+&lt;/sup&gt;</td>
<td>0.2</td>
<td>6 x 10&lt;sup&gt;11&lt;/sup&gt;</td>
<td>1.4 x 10&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>+</sup> Although there are no processes for extracting iron from basalt or nickel from ultrabasic rock peridotite, it is reasonable to assume that, in the long term, these processes can be developed successfully (Reference 3).
Table 12.6 Energy Input for Extraction of the Abundant Metals and Copper
(Reference 3)

<table>
<thead>
<tr>
<th>Metal</th>
<th>Source</th>
<th>Gross Energy(^+) (kWh/ton)</th>
<th>(E_L/E_H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium ingot</td>
<td>Seawater</td>
<td>100000</td>
<td>1</td>
</tr>
<tr>
<td>Aluminium ingot</td>
<td>Bauxite</td>
<td>56000</td>
<td>1</td>
</tr>
<tr>
<td>Aluminium ingot</td>
<td>Clay</td>
<td>72000</td>
<td>1.28</td>
</tr>
<tr>
<td>Raw steel</td>
<td>Magnetic taconites</td>
<td>10100</td>
<td>1</td>
</tr>
<tr>
<td>Raw steel</td>
<td>Iron laterites</td>
<td>11900</td>
<td>1.17 (with carbon)</td>
</tr>
<tr>
<td>Titanium ingot</td>
<td>Rutile</td>
<td>138900</td>
<td>1</td>
</tr>
<tr>
<td>Titanium ingot</td>
<td>Ilmenite</td>
<td>164700</td>
<td>1.18</td>
</tr>
<tr>
<td>Titanium ingot</td>
<td>Tit'm-rich soils</td>
<td>227000</td>
<td>1.163</td>
</tr>
<tr>
<td>Refined copper</td>
<td>Prophyry ore</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(1 per cent Cu)</td>
<td>14000</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Prophyry ore</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.3 per cent Cu)</td>
<td>27300</td>
<td>1.95</td>
</tr>
</tbody>
</table>

\(^+\) For the estimation of gross energy, it is assumed that the thermal efficiency for the generation of electricity is 40 per cent.
no limits to the world supply of most essential elements, including metals. Thus, processing and availability of most materials will in the long term become 'energy-limited' as opposed to 'resource-limited'.

12.3 International Trade of Industrial Materials:

In section 2.2, when discussing the rapid increases in the price of construction materials, it was mentioned that market prices in the U.K. are very sensitive to international movements in prices; it is proposed here to examine the nature of this dependency in some detail.

Table 12.7 shows the composition of the world exports trade in 1973. It can be seen that primary commodities accounted for approximately one third of the total world trade in that year. The primary commodities do not include the processed metals; however, it is estimated (1) that inclusion of these would not alter the above proportion significantly.

An examination of the data in Table 12.7 shows that only in the case of fuels do the developing countries have a dominant position in the world market. In other words, some industrialized countries are not only major consumers of materials and foods but also major producers and exporters of the same as well.

Furthermore, the total world export of ores and minerals, which in 1973 stood at $13.9 \times 10^9$ U.S. dollars, was relatively small in value compared with the trade in food, fuels or agricultural raw materials, which were respectively $80.9$, $62.5$ and $30.4 \times 10^9$ U.S. dollars (see Table 12.7).

According to data given by Fried (4), the world exports of non-renewable materials, including ores and metals, in 1973 totalled $13 \times 10^9$ U.S. dollars; the seven largest items in these were copper, cotton, iron ore, wool, rubber, tin and phosphate rock, which together accounted for approximately one half of the total.

The other half consisted of some 25 to 30 additional commodities; the world trade in each of these commodities was generally below $0.5 \times 10^9$ U.S. dollars.

Fried (4) has given the following four conditions as necessary stimuli for establishment of a cartel for the manipulation of the international market by producing countries:

(1) Involvement of a relatively small number of producing countries.
Table 12.7 The Composition of the World Exports (f.o.b.), 1973. (Original Source: United Nations)

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Advanced Market Economies</th>
<th>Centrally Planned Economies</th>
<th>Developing Countries</th>
<th>Total World Exports</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($ x 10^9)</td>
<td>(%)</td>
<td>($ x 10^9)</td>
<td>(%)</td>
</tr>
<tr>
<td>Manufactured and processed products+</td>
<td>296</td>
<td>82.2</td>
<td>36.6</td>
<td>10.3</td>
</tr>
<tr>
<td><strong>Primary Commodities:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Food</td>
<td>51.2</td>
<td>63.2</td>
<td>6.9</td>
<td>8.5</td>
</tr>
<tr>
<td>Fuels</td>
<td>13.7</td>
<td>21.7</td>
<td>5.8</td>
<td>9.3</td>
</tr>
<tr>
<td>Agricultural raw materials</td>
<td>17.4</td>
<td>57.2</td>
<td>3.8</td>
<td>12.5</td>
</tr>
<tr>
<td>Ores and Minerals</td>
<td>7.1</td>
<td>51.0</td>
<td>1.7</td>
<td>12.3</td>
</tr>
<tr>
<td>Residue</td>
<td>6.9</td>
<td>60.0</td>
<td>3.1</td>
<td>27.0</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td>392.3</td>
<td>70.2</td>
<td>57.9</td>
<td>10.3</td>
</tr>
</tbody>
</table>

+ - Includes metals but not ores.

= - Figures may not add to totals due to rounding.
(2) Inelastic demand for the commodity concerned.
(3) Inelastic supply of the commodity or of its close substitutes from sources outside the cartel.
(4) Alignment of the exporting policies of the producing countries in order to regulate the supply and maintain the prices. This implies that the producing countries must be able to build up surplus stocks without crippling effects on their economies or foreign trade.

The conditions set forth by Fried (4) are fulfilled in one commodity only and that is fuels (1 and 4) (which consist mainly of oil).

For example, the production of certain commodities such as copper, etc., is concentrated among a few countries. However, the financial weakness of these exporting countries, the sharp competition from substitutes (such as aluminium alloys in the case of copper), and the slow growth of the market have effectively prevented the establishment of a cartel similar to OPEC.

Furthermore, as has been pointed out by Goeller (3), et al., and confirmed by Radcliffe (1), even very substantial rises in the prices of metals other than iron, steel and aluminium could have isolated and limited effects on the total industrial production or other activities within the world economies.

The closest international to that of OPEC was the relatively high taxation imposed in 1974 by the Government of Jamaica on bauxite, which was followed in varying degrees by other producers. However, two special factors were responsible for the success of the above policy (1 and 2):

(1) The trade in bauxite is within integrated companies and not in the international markets.
(2) The importing companies have purpose-made plant and machinery which suits a particular type of ore only. Also, their large investments in concentrating, smelting, refining, etc., equipment situated in producing countries are hostage to the producing governments.

In short, the international commodity price cycle of 1972 to 1975 is not attributable to restricted supply policies; it is a natural reaction to the market forces, especially demand (4). The world economy as a whole experienced high growth rates in 1972 and 1973 (some 30 per cent above the trend (4)); this, coupled with unfounded fears about the likelihood of permanent shortages in the supply of certain industrial materials, especially expensive metals, and also the unusually high levels of stock buildings
triggered off the 1972 to 1974 boom in prices (5).

For Britain, the situation was worsened by the fall in the value of sterling and the unusually high rates of domestic inflation.

The short term supply difficulties experienced in 1972 to 1974 brought about unusual fears for the future state of supply of industrial materials including timber (6), especially in the light of increasing dependence of Western Europe and Japan on the developing countries (these countries import some three quarters of their raw materials requirements (1), with Japan as the largest single importer of a number of industrial materials, accounting for approximately 20 per cent of the world imports of these materials (4)).

The fears of supply shortages have to a large extent disappeared since the world's worst postwar recession began in 1975, when the prices of many materials such as copper, tin and rubber collapsed. The view expressed by some experts (e.g. those given in reference 4) is that the medium term situation may be very close to that of the past two decades, when demand for most primary commodities grew slowly. Thus, reduction of surplus stock-piles and support of prices in the international markets received much of the attention of the producers of these commodities.

Nevertheless, such developments in international trade as the control of prices and/or accessibility of certain critical commodities are stimulating research in the advanced countries for technological innovations in processing materials from indigenous resources (7) or developing close substitutes (1,8,9 and 10).

In short, as far as the U.K. is concerned, there are a number of issues which must be studied carefully in the light of the new conditions created in the 1970's in the international trading scene; the main issues are:

(1) The growing dependence of many countries, including the U.S.A., on imported sources of supply, partly as a result of implementing the environmental protection regulations which have tended to constrain the availability and increase the cost of industrial materials (11), and partly due to depletion of indigenous rich resources (12).

(2) The future uncertainty surrounding the prices of these commodities, exacerbated by their dependence on the availability and supply of cheap energy resources. (The energy implications
of industrial materials are considered in more detail in 12.5.)

(3) The increased tendency among producing countries (whether industrialized or developing) to take over the management and control of production facilities for these commodities and to try to maximize the export of locally processed products in preference to the sale of raw materials (hence added value of exports).

(4) The tendency discussed earlier among some exporting countries to manipulate the prices and/or availability of certain commodities for economic or political gains.

Whilst all sectors of the U.K. manufacturing and construction industries are dependent on the supply of industrial materials, especially metals, the vulnerability of the construction industry to any likely restriction on the supply of timber is of the greatest importance to this study; thus, in the following section attention has been paid to the future availability of timber in the U.K.

12.4 The Future Availability and Supply of Timber in the U.K.:

Being a renewable resource, the importance of timber and associated products has been largely neglected by potential producers such as the U.S.A. (Despite her large forested lands, the U.S.A. has been a net importer of timber since 1914; the proportion of the U.S. consumption supplied from imports has increased (13) from 0 in 1914 to 12.2 per cent in 1971.)

For Britain, the current situation is characterized by the statistics given by Groves (14): U.K. production of timber is small — 8 per cent of the total consumption, with hardwoods as the biggest home source (by volume). Hardwood production is about 20 to 25 per cent of the hardwood consumption. The corresponding figures for chipboard and softwood are 15 and 4 per cent respectively (14).

The total home production in the medium term (year 2000) is expected to rise to about 12 per cent of consumption (14); thus, Britain will remain a major importer of timber products.

In the last decade, the average annual imports of timber (which is taken here to include both solid and sheet materials) has been of the order of $10.5 \times 10^6$ cubic metres; imports have grown by an average of 1 per cent per annum on a volume basis. As may be seen from Table 12.8, the consumption of sheet materials has grown rapidly, so that the share of these materials from the
total volume of imports has doubled in the span of ten years, 1962 to 1974.

Chipboard has shown the highest growth rate, followed in descending order by veneers and plywood. The use of fibreboard has remained virtually unchanged.

Table 12.8 Composition of Imports of Timber Products (Source: Reference 14):

<table>
<thead>
<tr>
<th>Class of Product</th>
<th>Type</th>
<th>Average 1960-64 (%)</th>
<th>1972 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>breakdown</td>
<td>class total</td>
<td>breakdown</td>
</tr>
<tr>
<td>Solid</td>
<td>softwood</td>
<td>78</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>hardwood</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Sheet</td>
<td>plywood</td>
<td>6.5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>chipboard</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fibreboard</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>veneers</td>
<td>0.25</td>
<td></td>
</tr>
</tbody>
</table>

The above data do not reveal the whole picture of the substitution pattern within the timber-based products; not only have sheet materials been replacing solid timbers, especially hardwoods (14), but also, the cheaper sheet products such as chipboard and lower priced plywoods have been increasing their market share at the expense of more expensive products such as fibreboard (14).

In short, greater degrees of utilization of sheet materials, coupled with an overall reduction in the cross-sectional areas of solid timber in most constructional applications implies that the demand for timber has grown more than the apparent rise in the volume of imports. In other words, due to technological innovations in products, the increased demand for timber has been accommodated with a less crippling effect on the imports bill; the trend in this direction is still continuing (9 and 14).

With the substantial increase in the price of timber in the 1970's and the correspondingly large increases in the U.K.'s imports bill, the current drive in this country is to develop
indigenous alternative materials (9 and 10). However, from a global point of view, this approach may result in a net economic loss, owing to the many economic and potential energy saving advantages of this material (these aspects have been discussed in 12.5).

From the standpoint of availability, there is a clear division of opinion amongst experts. Some, like Wood (6), believe that a radical shift of policy towards the long term provision of timber is necessary on a world scale; they argue (6) that the worldwide production of timber must be increased by better management and more efficient forestry practices, especially in the tropics and the U.S.A.

The opponents to the above group see no urgent need for any radical action (15), as it is considered that the resources of tropical forests are practically inexhaustible, and that the U.S.S.R. and Canada, who have vast forests, are able to double the harvesting of their forests without exceeding the biological limits.

Another argument put forward by the latter group of experts (e.g. Bene, reference 15) is that the new plantations undertaken by many countries could produce up to one third of the world consumption by the year 2000 (for a summary of the countries who have undertaken new plantations see Table 13 of reference 6; the combined area of such plantations is about 29.17 x 10^6 hectare, which is less than one per cent of the world forest areas, though the yield per hectare of the man-made forests will be expected to be considerably greater than the average world yield; this is partly due to intensive management and choice of more suitable tree species, and partly due to favourable climates in which the greater part of the new plantations are located.).

As far as this study is concerned, the survey of the world resources of timber carried out by Wood (6) and the accompanying conclusions have been used for the limited general discussion undertaken below.

Most producers of timber, especially in the tropics, are 'mining' timber without adequate concern over reforestation; in some countries, notably Brazil, South East Asia and Africa, the natural forests are destroyed for agriculture or other uses (6), thus reducing the future potential of these sources. The influence of factors such as projected population increases in these countries, the rise of timber consumption with fises in per capita
income, the increased use of timber as a fuel source in developing countries and the increased demand for land for production of food, etc., will mean that supply potential of the tropical sources of natural forests will dwindle (6 and 13). According to Wood (6), only a radical shift in policy towards more replantation and higher levels of investment in terms of both money and manpower can avert the long term scarcity of hardwoods.

In the case of softwoods, the long term situation is dependent on Canada, the U.S.S.R. and Scandinavia.

Canada is a major supplier of softwoods, though most of the Canadian exports go to the U.S.A. (13). Canada is currently exploiting half the quantity which is considered to be biologically permissible; she is expected to increase production significantly; however, the U.S.A. is expected to increase its imports from Canada as well, so that by the year 2000 its imports will equal a figure equivalent to the whole Canadian production in 1970 (13).

The U.S.S.R. has vast forests of softwood species; however, the forests in her European sector are reported to be near depletion with no exportable surplus for at least the next 50 years. Siberian forests, mostly larch on the permafrost soils, are costly to harvest due to the severity of the climate and lack of accessibility. Furthermore, not only are the growth rates low in these areas, but the amount supplied to the Western markets will depend on factors which may be dictated from within the U.S.S.R.

Scandinavia and Finland are likely to continue to supply the European markets, especially the EEC. However, the forests of these countries are presently managed on an intensive basis and the potential increase in output is limited.

Wood (6), in conclusion to his survey, stated that for the next 20 years the tropical sources are likely to be able to supply the U.K. with mixed hardwoods, though the prices will be dependent on the world demand for timber.

In Britain, Sweden is the main supplier of softwood timber (14).

Overall, most experts agree (14) that in the foreseeable future timber will be available. However, its level of utilization will depend upon the economic competitiveness of this material in various applications (see also Chapter 13).
12.5 The Energy Implications of Engineering Materials:

As has been pointed out by Hayes (16), owing to the high cost-expectation of energy in the intermediate future (up to the year 2000), the industrialized countries need to re-examine the entire pattern of their energy uses.

The energy intensiveness of a material in the intermediate run is expected to reflect the economic competitiveness of that material, other things being equal. However, the complete pattern of energy consumption for processing of engineering materials is important from a national energy accounting point of view. The example given by Chapman (17) will serve to illustrate this point. Smelting of copper by thermal-fired and electrically heated methods is compared; on the basis of terminal heat input electricity is favoured by 2 to 1. However, if the total energy, including energy losses in the stages of generation and transmission of electricity are taken into account, the electrically heated methods will be twice as energy intensive compared with the direct thermal-fired methods (17).

Theoretically, one kilowatt-hour (kWh) of electrical energy is equivalent to some $4.44 \times 10^6$ Joules. In practice, to generate and transmit one kWh of electricity, $13.5 \times 10^6$ Joules, or more than three times that amount must be used. (16)

Extraction, processing and transportation of other forms of energy also incur losses; the losses are 3, 17 and 7 per cent respectively for coal, oil and natural gas. (16). The relatively high losses of energy in the case of oil are due to the enormous quantity of energy used in the process of refining this type of fuel.

Thus, in any analysis of the energy input for materials and products, account must be taken of the above losses. Gross energy inputs must be assigned to the flow charts representing the processing of industrial materials (16).

Determination of the energy intensiveness of materials is further complicated by the influence of factors such as differences in materials' bulk densities, differences in materials' properties, the energy captive in some materials (e.g. wood and plastics), etc. Also, the performance in service of an apparently energy-intensive material may have an overriding influence on its selection. However, with the available data, it is possible to make certain general observations on the energy implications of materials and finished products.
It can be seen from Table 12.9 that U.K. industry (other than agriculture and transport) accounts for approximately 41 per cent of total consumption by final users, with the iron and steel industry being responsible for roughly one fourth of this total. The figures in Table 12.9 do not reflect the energy used by fuel producers and losses in conversion and distribution, which in 1974 totalled approximately $25 \times 10^9$ therms, or approximately 43 per cent of the total consumption by final users.

Tables 12.10 and 12.11 contain data on energy inputs per unit weight and volume of selected metals and minerals; these data give indications of the energy requirements of materials in general including allowances for energy losses where appropriate (16).

Table 12.12 shows the energy requirements for processing and manufacture of selected timber-based products (18).

Table 12.9 Analysis of the Total Inland Energy Consumption in 1974. (Source: Annual Abs. of Statistics)

<table>
<thead>
<tr>
<th>Class of Consumer</th>
<th>Energy share (x $10^9$ therms)</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron and steel industry</td>
<td>5.481</td>
<td>9.37</td>
</tr>
<tr>
<td>Other industries</td>
<td>18.455</td>
<td>31.58</td>
</tr>
<tr>
<td>Agriculture</td>
<td>.747</td>
<td>1.28</td>
</tr>
<tr>
<td>Railways</td>
<td>.528</td>
<td>.90</td>
</tr>
<tr>
<td>Road Transport</td>
<td>9.712</td>
<td>16.62</td>
</tr>
<tr>
<td>Water Transport</td>
<td>.496</td>
<td>.85</td>
</tr>
<tr>
<td>Air Transport</td>
<td>1.675</td>
<td>2.86</td>
</tr>
<tr>
<td>Domestic</td>
<td>15.051</td>
<td>25.76</td>
</tr>
<tr>
<td>Public services</td>
<td>3.317</td>
<td>5.65</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>3.026</td>
<td>5.14</td>
</tr>
<tr>
<td>Total consumption by</td>
<td></td>
<td></td>
</tr>
<tr>
<td>final users</td>
<td>58.488</td>
<td>100(^+)</td>
</tr>
</tbody>
</table>

\(^+\) - Because of rounding, the figures may not add up to 100.

Table 12.13 shows the gross energy input, including feedstocks for manufacturing a selected number of plastic materials.
Table 12.10 Gross Energy Inputs for Selected Metals (Source: Hayes, Reference 16)

<table>
<thead>
<tr>
<th>Type of Metal</th>
<th>Type of Product</th>
<th>Energy Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>per net tonne (x 10^9 J)</td>
</tr>
<tr>
<td>Iron and steel</td>
<td>Steel slabs</td>
<td>34.5^+</td>
</tr>
<tr>
<td>Iron and steel</td>
<td>Gray iron castings</td>
<td>48.7</td>
</tr>
<tr>
<td>Iron and steel</td>
<td>Carbon steel castings</td>
<td>60.0</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Ingot</td>
<td>292.0</td>
</tr>
<tr>
<td>Zinc</td>
<td>Ingot</td>
<td>83.5</td>
</tr>
<tr>
<td>Lead</td>
<td>Ingot</td>
<td>38.7</td>
</tr>
<tr>
<td>Copper</td>
<td>Cement copper</td>
<td>125.0</td>
</tr>
<tr>
<td>Copper</td>
<td>Refined copper</td>
<td>160.5</td>
</tr>
<tr>
<td>Chromium</td>
<td>High carbon ferroalloy</td>
<td>87.7</td>
</tr>
<tr>
<td>Chromium</td>
<td>Low carbon ferroalloy</td>
<td>185.5</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Metal</td>
<td>514.0</td>
</tr>
<tr>
<td>Manganese</td>
<td>Ferromanganese</td>
<td>71.0</td>
</tr>
<tr>
<td>Manganese</td>
<td>Blast furnace</td>
<td>66.0</td>
</tr>
<tr>
<td>Manganese</td>
<td>Electric furnace</td>
<td>75.0</td>
</tr>
<tr>
<td>Titanium</td>
<td>Metal</td>
<td>690.0</td>
</tr>
</tbody>
</table>

^+ - If it is assumed that the energy losses are 10 per cent, it can be seen that in 1974, each tonne of iron and steel produced in the U.K. took an average of 34 G J gross energy to produce; this figure is comparable to the above figure given by Hayes (16).

= - For the calculation of this figure, if it is assumed that up to 40 per cent of the energy is hydro-electric power; if all energy is produced from fossil fuels, this figure will rise to 348 G J.
Table 12.11 Gross Energy Inputs for Selected Non-metallic Minerals
(Reference 16)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Product</th>
<th>Energy requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>per net tonne (x 10^9 J)</td>
</tr>
<tr>
<td>Glass</td>
<td>Glass containers</td>
<td>25</td>
</tr>
<tr>
<td>Cement</td>
<td>Portland cement</td>
<td>11 - 18</td>
</tr>
<tr>
<td>Ceramics</td>
<td>Common brick</td>
<td>5</td>
</tr>
<tr>
<td>Lime</td>
<td>Quick lime</td>
<td>12.2</td>
</tr>
<tr>
<td>Refractories</td>
<td>Basic brick</td>
<td>38.7</td>
</tr>
<tr>
<td>Refractories</td>
<td>Fireclay brick</td>
<td>6</td>
</tr>
<tr>
<td>Gypsum</td>
<td>Calcined gypsum</td>
<td>2.15</td>
</tr>
<tr>
<td>Sand and gravel</td>
<td>Sand and gravel</td>
<td>0.08</td>
</tr>
<tr>
<td>Clays</td>
<td>Kaolin</td>
<td>4</td>
</tr>
<tr>
<td>Clays</td>
<td>Other clays</td>
<td>0.14 - 7.6</td>
</tr>
</tbody>
</table>

- These figures do not agree with the figure given in reference 18, which is approximately 12 G J/tonne of brick; the corresponding value for m^3 is 26.5 G J. Also note that production of Flettons requires 40% less energy compared with other types of fired clay products.
Table 12.12 Analysis of Energy Requirements for Selected Wood-based Products (Reference 18)

<table>
<thead>
<tr>
<th>Product</th>
<th>Energy requirements (dry)</th>
<th>Energy available from wood residues (GJ/tonne)</th>
<th>Supplemenary requirements for manufacture (GJ/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Softwood lumber</td>
<td>6.95</td>
<td>4 - 5</td>
<td>0.5</td>
</tr>
<tr>
<td>Laminated lumber</td>
<td>9.45</td>
<td>9.5</td>
<td>5.3</td>
</tr>
<tr>
<td>Softwood plywood</td>
<td>9.85</td>
<td>10.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Medium-density fibreboard</td>
<td>13.3</td>
<td>14.4</td>
<td>3.9</td>
</tr>
<tr>
<td>Insulation board</td>
<td>11.45</td>
<td>16.1</td>
<td>9.4</td>
</tr>
<tr>
<td>Hardwood plywood</td>
<td>14.7</td>
<td>16.2</td>
<td>14.2</td>
</tr>
<tr>
<td>Wet-formed hardboard</td>
<td>28.2</td>
<td>29.2</td>
<td>15.2</td>
</tr>
</tbody>
</table>

*The energy available from processing residues is assumed to be utilized in the manufacture of products only; the surplus energy from the wood-residues is shown inside brackets.*
Table 12.13  Gross Energy for Selected Common Thermoplastics and Unsaturated Polyester Resins

<table>
<thead>
<tr>
<th>Material</th>
<th>Energy requirements</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Feedstock (GJ/tonne)</td>
<td>Process (GJ/tonne)</td>
<td>Total (GJ/tonne)</td>
<td>Total (GJ/m³)</td>
<td></td>
</tr>
<tr>
<td>Ethylene+</td>
<td>113.2</td>
<td>40.3</td>
<td>153.5</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Low density polyethylene+ (.92 g/cm³)</td>
<td>153.5</td>
<td>193.5</td>
<td>347.0</td>
<td>320</td>
<td></td>
</tr>
<tr>
<td>Low density polyethylene= (.92 g/cm³)</td>
<td>170.0</td>
<td>173.0</td>
<td>343.0</td>
<td>316</td>
<td></td>
</tr>
<tr>
<td>High density polyethylene= (.96 g/cm³)</td>
<td>63.0</td>
<td>67.0</td>
<td>130.0</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>Styrene monomer+</td>
<td>30.0</td>
<td>50.5</td>
<td>80.5</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Polystyrene+ (density = 1.07 g/cm³)</td>
<td>80.5</td>
<td>26.5</td>
<td>107-121.5</td>
<td>115-130</td>
<td></td>
</tr>
<tr>
<td>Polystyrene= (density = 1.07 g/cm³)</td>
<td>71.5</td>
<td>103.5</td>
<td>175.0</td>
<td>187</td>
<td></td>
</tr>
<tr>
<td>PVC polymer= (density = 1.38 g/cm³)</td>
<td>29.8</td>
<td>75.7</td>
<td>105.5</td>
<td>142.5</td>
<td></td>
</tr>
<tr>
<td>Polypropylene= (density = .90 g/cm³)</td>
<td>64.0</td>
<td>75.0</td>
<td>139.0</td>
<td>154</td>
<td></td>
</tr>
<tr>
<td>Unsaturated polyester= (density = 1.22 g/cm³)</td>
<td>-</td>
<td>-</td>
<td>70.8</td>
<td>86</td>
<td></td>
</tr>
</tbody>
</table>

+ - Based on data given in reference 16, which are mainly relevant to the U.S.A.
= - Based on data given in Ref. 17, Ch. 4, which are provided by Messrs. ICI Ltd.
* - Based on data supplied by Messrs. Scott Bader and Co. Ltd., which include an allowance of up to 25 per cent from net to gross energy input.
A study of Tables 12.9 to 12.13 shows that timber and allied products are by far the least energy-intensive engineering materials available, followed on a rising scale by non-metallic minerals, plastics and metals.

It can be seen that non-metallic minerals, which form the bulk of construction materials, require, on average, less energy than metal or plastics-based materials. It must be emphasized that the processing of non-metallic constructional materials does not generally involve the breakdown of chemical bonds or heavy energy losses in extraction and concentration of these minerals. However, these materials are generally used on a large scale, and being dense, their transportation is also energy-intensive. Thus, such comparisons based on energy per unit weight (or volume) can be grossly misleading.

Studies based on energy input per unit weight or volume of materials, although useful, are not always relevant to the problems facing the specifiers of materials; a more relevant analysis must aim at giving energy input data for finished alternative constructional products; this analysis has been included in Table 12.14.

An examination of the data in Table 12.14 will reveal striking differences between the products as opposed to unit weight or volume of materials. For example, it can be seen that single skin 0.7mm thick corrugated aluminium sheet is approximately 50 per cent more energy-intensive compared with a sandwich panel comprising an outer skin of 3.5mm G.R.P., an inner skin of 9mm thick plasterboard and a rigid core of 20mm thick expanded PVC (see entries 5 and 17 of Table 12.14). The energy input for a sandwich panel constructed from 0.9mm corrugated aluminium sheeting outer face, 9mm thick aluminium foil-backed plasterboard inner face and a rigid core of 20mm thick expanded polystyrene exceeds that of the above G.R.P. sandwich panel by a factor greater than 2.7 (see entries 15 and 17; it must be noted that these two products are of approximately equal structural, fire-resistance and thermal insulation performance).

An interesting point seen from Table 12.14 concerns the energy intensiveness of precast concrete slab or brick walling compared with G.R.P. cladding; an aerated steel-mesh reinforced concrete as entry 13 in Table 12.14 and a cavity wall as entry 22 require respectively 4.5 and 2.5 times more energy than a G.R.P. sandwich panel/timber framing built to the specification given in entry 19.
<table>
<thead>
<tr>
<th>Entry No.</th>
<th>Product description</th>
<th>Approximate Energy-content (MJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>plasterboard, 9mm thick, aluminium foiled</td>
<td>170</td>
</tr>
<tr>
<td>2</td>
<td>hardboard, 3mm thick</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>softwood plywood, 6mm thick</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>corrugated asbestos-cement sheet, (6mm thick, 150mm pitch, 13.3 kg/m²)</td>
<td>160</td>
</tr>
<tr>
<td>5</td>
<td>corrugated aluminium sheet 0.7mm, (≈ 3 kg/m², 292 GJ/tonne of metal)</td>
<td>1000</td>
</tr>
<tr>
<td>6</td>
<td>corrugated steel sheet, 0.7mm, galvanized, PVC coated (8.35 kg/m² and 3/4 GJ/tonne)</td>
<td>350</td>
</tr>
<tr>
<td>7</td>
<td>corrugated G.R.P. sheet 1mm thick, (50 GJ/tonne of glass fibre, 70.8 GJ/tonne of UPR)</td>
<td>140</td>
</tr>
<tr>
<td>8</td>
<td>corrugated rigid PVC sheet, 1.5mm thick, (2.1 kg/m², 105.5 GJ/tonne of PVC polymer)</td>
<td>230</td>
</tr>
<tr>
<td>9</td>
<td>Glasswool, 2 kg/m², (30 GJ/tonne of wool)</td>
<td>60</td>
</tr>
<tr>
<td>10</td>
<td>Expanded polystyrene slab, 20mm thick, (Density = 24 kg/m³, 175 GJ/tonne of PS)</td>
<td>87</td>
</tr>
<tr>
<td>11</td>
<td>Rigid expanded PVC, 20mm thick, (Density = 32 kg/m³, 105.5 GJ/tonne)</td>
<td>70</td>
</tr>
<tr>
<td>12</td>
<td>Aerated mesh-reinforced precast concrete slab, 100mm thick, (Density = 1800 kg/m³ and 4.34 kg/m² steel mesh; assumed energy data are 11.5 and 34 GJ/tonne for concrete and steel respectively, 0.2mm polyethylene membrane)</td>
<td>2350</td>
</tr>
<tr>
<td>13</td>
<td>Ditto, but 150mm thick, 1600 kg/m³ and 6.16 kg/m² steel reinforcement</td>
<td>3450</td>
</tr>
<tr>
<td>14</td>
<td>single skin G.R.P. panel, 6mm thick with ribbing and edge beams, 25mm glasswool quilt and 9mm thick asbestos-board lining (20 kg/m²)</td>
<td>1100</td>
</tr>
<tr>
<td>15</td>
<td>Sandwich panel of 0.9mm thick corrugated aluminium sheet, 20mm rigid expanded PS core and 9mm thick plasterboard inner lining, etc.</td>
<td>1800</td>
</tr>
<tr>
<td>16</td>
<td>Sandwich panel of 0.7mm corrugated steel sheet, galvanized and PVC coated, 20mm thick rigid expanded PS core and 9mm thick plasterboard lining, etc.</td>
<td>650</td>
</tr>
<tr>
<td>Entry No.</td>
<td>Product description</td>
<td>Approximate Energy-content (MJ/m(^2))</td>
</tr>
<tr>
<td>-----------</td>
<td>---------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>17</td>
<td>Sandwich panel of 3.5mm G.R.P. skin, 20mm rigid expanded PVC and 9mm plasterboard</td>
<td>660</td>
</tr>
<tr>
<td>18</td>
<td>Ditto, but with 2 x 9mm thick inner leaf of plasterboard</td>
<td>730</td>
</tr>
<tr>
<td>19</td>
<td>As 18 plus softwood structural framing for load-bearing purposes</td>
<td>750</td>
</tr>
<tr>
<td>20</td>
<td>Half brick leaf, using Flettons, sand/cement mortar (1000 brick = 1900 kg)</td>
<td>1200</td>
</tr>
<tr>
<td>21</td>
<td>Half brick leaf as above plus an inner leaf of aerated concrete blocks, 75mm thick (concrete block at 1000 kg/m(^3) and at 8.5 GJ/tonne)</td>
<td>1850</td>
</tr>
<tr>
<td>22</td>
<td>Ditto plus 20mm rigid expanded PS board</td>
<td>1940</td>
</tr>
<tr>
<td>23</td>
<td>Half brick, non-Fletton (1000 brick = 2.25 to 3 tonnes)</td>
<td>1750 - 2150</td>
</tr>
<tr>
<td>24</td>
<td>Ditto plus 75mm aerated concrete block inner leaf</td>
<td>2400 - 2800</td>
</tr>
<tr>
<td>25</td>
<td>12mm thick exterior grade plywood with exposed surface coated with resin and textured on 225 x 75mm timber-framing, lined with 9mm thick foil-backed plasterboard and filled with 25mm glasswool</td>
<td>400</td>
</tr>
</tbody>
</table>

+ Data are calculated using many references, in particular those given previously for Tables 12.9 to 12.13.
On an approximate energy input/performance basis, timber, wood-based products, gypsum plaster and asbestos-cement sheet products are the least energy-intensive products; these may be classed as class A energy-intensive materials.

Glass, G.R.P., plastics and thin steel sheet products are the second group of energy-intensive products; they require significantly more energy compared with the previous products; they may be classed as class B energy-intensive products.

Aluminium, brick and concrete are products which require significantly more energy compared with class B products; they may be classed as class C energy-intensive products.

The above classification is also relevant to structural members such as columns and beams; as may be deduced from data in Tables 12.10 and 12.12, timber is less energy-intensive compared, in particular, with either aluminium, steel or concrete.

The low energy intensiveness of timber and its allied products means that from a global point of view, if the maximization of the total energy resources is desired, the use of timber for both structures and cladding must be maximized. The same conclusion has been reached in the study undertaken by the Committee on Renewable Resources for Industrial Materials (CORRIM) (19); this study revealed that for light buildings of mainly residential nature, timber was the least energy-intensive construction material, as seen from the following examples (19):

(1) Steel floor joists are 50 times more energy-intensive compared with timber joists of similar structural performance.

(2) The use of aluminium framing for external walls is approximately 20 times more energy-intensive compared with timber framing.

(3) Steel and aluminium internal studs require 8 and 12 times more energy respectively compared with their timber counterparts.

(4) Roof rafters made from steel are 7 times more energy-intensive compared with timber trusses of equivalent structural performance.

(5) Aluminium cladding requires approximately 5 times more energy compared with plywood or fibreboard sheathing.

(6) Brick cladding exceeds plywood sheathing by a factor of 25 in energy requirements.

The above conclusions were generally confirmed by Bingham (20) in his recent study of light commercial buildings.
As was pointed out previously (see 12.4), this finding is of great importance from the global standpoint of energy conservation. However, it is of lesser importance to the U.K. construction industry, since the bulk of timber used in the U.K. is imported from overseas. In fact, as was reported in Chapter 2 (see 2.2), a useful criterion employed by Banks (21) when examining 'energy-intensiveness' and 'import-content' of timber versus other structural materials, was that, provided the total project costs did not increase significantly, it would pay the U.K. to substitute the materials with lower 'import-contents' for those with higher 'import-contents'. Thus, for example, the use of timber-framed walling may involve an additional import bill of £82 per residential house as compared with a cavity wall, constructed from brick and block works (21). Although the total costs per house when using timber-framed walls may be lowered by about £40 (21), it has been suggested that brick/block construction may be more desirable from the standpoint of the country's external trade. (In fact, if it is assumed that 20 per cent of houses are built annually using timber-framing, the corresponding increase in the nation's imports bill is of the order of £5m; see Table 2.10).

Referring back to Table 12.14, it can be seen that plastics-based products have a potential of energy conservation compared with both metals and/or traditional forms of construction. This implies that, other things being equal, the future competitiveness of plastics products (including G.R.P.) will be improved with future increases in the average cost of energy.

The above analysis, though useful, cannot by itself provide a guide to future prices of materials, for the following reasons:

(1) Different forms of energy have different commercial values, even though their calorific values may be of the same order. For example, aluminium reduction plants are traditionally placed in areas where the supply of energy greatly exceeds the demand generated by the accessible markets; this condition is fulfilled in remote parts of Norway, Canada, the U.S.A. and the U.S.S.R. where hydroelectric energy is utilized to obtain aluminium from bauxite.

(2) Energy costs account for a proportion of the total costs of producing materials; other cost components such as those attributable to plant and equipment, labour, etc., must also be taken into consideration. Such cost comparisons were included in the CORRIM study (19); the result showed no consistent cost
differences between systems based on timber and those based on alternative materials.

It must be noted that the manufacturing of timber-based products generally requires less heavy equipment compared with either concrete or metal-based components (see Chapter 11).

The labour input for timber-based constructional components has also been reduced considerably by the application of suitable machinery. For example, Reece (22) reported that the labour cost of timber-based roof trusses has been reduced from 60 per cent in the case of traditional construction to a mere 10 per cent in the case of machine-produced standardized trusses.

Also, as has been shown in detail in previous chapters, the processing of plastics in general and G.R.P. in particular is less costly in terms of charges attributable to plant and machinery compared with the processing of metals; the same applies to labour costs, provided the processing method is not inherently labour-intensive, such as the contact-moulding process (see 5.4).

(3) Market prices of commodities are determined by the prevailing market conditions and not by the long term cost expectations. This point has clearly been illustrated in the preceding sections of this chapter; it is further confirmed by the study of the price data contained in Table 12.15; the relatively large fall in the prices of major non-ferrous metals in 1975 has been primarily attributed to the worldwide reduction in demand for these materials and the build-up of costly stockpiles. For example, despite considerable production cutbacks started in the autumn of 1974, aluminium stocks, including those of integrated fabricating plants, in June 1975 stood at about 3.2 million tonnes or about 23 per cent of worldwide consumption in 1974. In June 1975, about 20 per cent of world production capacity of primary aluminium was idle (see Metal Statistics, 62nd. ed., 1975).

12.6 The Supply of Petrochemical Feedstocks:

Having established that plastics-based materials are generally less energy-intensive than metals, it is still necessary to examine their future supply situation, because the raw materials for plastics are almost entirely derived from oil and natural gas resources, and the competition for these materials, especially for use as fuels, is increasing.

The recent multifold increase in the cost of oil revived the interest in coal-based chemical processes. Traditionally, production of coal chemicals has been on utilization of by-products
Table 12.15  Metal Prices on the London Metal Exchange (Cash-terms;  Source: Metal Statistics, 62nd ed.)

<table>
<thead>
<tr>
<th>Metal</th>
<th>1974 highs</th>
<th>1975 lows</th>
<th>Percentage changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Date</td>
<td>£/tonne</td>
<td>DM/100 kg</td>
</tr>
<tr>
<td>Lead</td>
<td>27/2</td>
<td>324</td>
<td>200</td>
</tr>
<tr>
<td>Zinc</td>
<td>6/5</td>
<td>875</td>
<td>520</td>
</tr>
<tr>
<td>Copper</td>
<td>1/4</td>
<td>1400</td>
<td>852</td>
</tr>
<tr>
<td>Tin</td>
<td>4/9</td>
<td>4250</td>
<td>2616</td>
</tr>
<tr>
<td>Aluminium+</td>
<td>14 -</td>
<td>470</td>
<td>282</td>
</tr>
</tbody>
</table>

+ - Based on free market prices as published in the "Metal Bulletin".
(coal tar) generated by two major carbonization processes (23); these are as follows:

1. Manufacture of coke for the iron and steel industry.

Although the production of coal-based chemicals continued well into the postwar years, the production unit sizes remained so small that, in comparison with today's giant petrochemical plants they may be considered as insignificant (24).

The tendency in recent years has been to convert the heavier fractions of oil to products with higher economic value, such as motor gasoline or chemical compounds. For example, upward of 90 per cent of crude oil in the U.S.A. is turned into products with higher economic value as compared with an average of 50 per cent of refineries in other parts of the world (24). However, the trend is for these refineries to add additional installations to increase the proportion of lighter products extracted from each barrel of crude oil (24).

Added to the above is the fact that most oil and gas producing countries have embarked upon production of petrochemicals on a relatively large scale; these countries are able to use well-proven and competitive technologies, so that even after adding shipment costs their products will be cheaper than the chemicals derived from coal (24).

The conclusion to be drawn is that there would be little prospect for the development of large plants to produce organic chemicals from coal. However, there is a demand for a clean fuel to replace the diminishing supplies of heavy industrial fuels in the U.S.A. and in Europe. This situation offers coal a chance to fill the industrial fuel gap, at least for the next two decades, and proposals have already advanced for the most promising conversion processes (24).

As has been pointed out by Squires (24), the substitution of coal-based fuels for heavy industrial fuels does not only release large amounts of oil and natural gas for use as chemical feedstocks or other valuable uses. It also allows conversion of coal by-products into a variety of chemicals. (The quantities of coal which need be converted into industrial fuels will be much greater than those obtained in the production of coke or town gas.)

It must be noted that conversion of natural gas and petroleum derivants into petrochemical compounds is inherently less difficult
and more economic compared with the conversion of coal derivants, i.e. petroleum derivants and natural gas are much cleaner than coal, and as they are in the form of liquid or gas, the petrochemical plants based on these feedstocks can easily be increased in scale. These are the basic reasons for advocating the conversion of coal into clean industrial fuels (as opposed to chemical compounds), using well established technologies plus the results of up-to-date R and D undertaken in recent years by leading institutions in the West (25).

The general observations on the extent of efforts already allocated to the development of new technologies for relieving the petrochemical market (e.g. the development of 'Flash Pyrolysis' reported by Adam, et al. (26)), indicate that petrochemical feedstocks would continue to be available at least in the intermediate run.

In Britain, the supply of chemical feedstocks is further ensured by the government's commitment to expansion of the petrochemical industries (27); based on the information available to date of the government's industrial strategy and their overall energy policy, it can be expected that the government will make major concessions to the petrochemical industry over gas feedstocks and for higher investments in petrochemical plants (27).

The NEDC's main recommendations for the petrochemical industry were as follows (27):

"1. There should be a comprehensive development policy embracing the fullest possible use within the U.K. of North Sea oil and gas feedstocks. This should have as its object the creation of new high added value industries designed to regain the share of the U.K. and EEC markets lost to producers elsewhere.

2. The government should clarify North Sea development and pricing policies and also its overall energy policy.

3. The government should streamline planning procedures to encourage large scale petrochemical developments, particularly ethylene plants, early decisions on pipelines to provide appropriate feedstocks, and should also create an attractive fiscal and financial climate to encourage large scale investment in this sector."

The long term prospects (21st century and beyond) of either petrochemicals or plastics industries is less certain. There are elements of technological research in the field of energy which may bear fruit; for example, newer generations of nuclear reactors
may be introduced or natural sources of energy such as solar, geothermal, etc., may be utilized; these technological innovations are inevitable, and, seen against man's history of ingenuity for adaption, survival and advancement, are both perfectly feasible and economically viable. It is therefore beyond the scope of this brief essay to consider the long term future of petrochemicals and plastics industries. It is sufficient to mention here that society, having valued the usefulness and relative utility of a material, will continue to discover new sources for continuation of production and supply of that material until such time as more efficient and cheaper substitutes have been introduced, or when the cost of using that material will become greater than its perceived utility. These remarks imply that in any field which involves long term technological forecasting, there is always a danger of falling into the trap of false assumption that technological innovations will remain constant or that the rate of progress will continue to be as in the past. New discoveries are beyond prediction, but may change the basis of the whole economy; new industries may be born and old industries may die even sooner than anticipated by doomwatchers.

It is perhaps more appropriate to end this chapter by stressing the fact that man's best assets for survival in the long term are his ingenuity for invention and his remarkable ability for change and adaption.


22. See page 40 of "Discussion on Papers 3, 4 and 5" of the conference: "The Future Usage of Timber in the U.K." (reference 6).
13.1 Introduction and Methodology:

The purpose of this chapter is to try to predict the progress of G.R.P. in the construction industry in the remaining part of this century. However, the further the target year is from the base year, the greater the degree of caution which must be exercised in interpreting the results; as mentioned earlier, these are many unknown factors whose influence may distort the future picture considerably.

Though the term G.R.P. has been used, the meaning to be assigned to this term in this section is extended considerably: it will include all composites with a plastics-based matrix and fibrous reinforcement. This assumption implies possible future innovations within the G.R.P. industry itself, e.g. in response to the statutory requirements or for possible structural performance improvements etc. The need for performance improvements, implicit in this chapter, will be discussed in the next chapter; however, it has not been assumed that any of the probable innovations will be of such a revolutionary nature as to make the future predictions totally invalid. This is not to say that revolutionary innovations will never occur; indeed they may do and revolutionize the whole G.R.P. industry. However, being unknown, their effects cannot be taken into consideration in this study.

Input data for quantitative analysis of any resource will traditionally include market research data and reliable and consistent past statistics.

In the case of G.R.P., as was shown in section 7.1, statistical data are not consistent. Not only are their reliability and accuracy in doubt, but also the basis of their compilation is unknown and suspect. The only useful information these data convey is the existence of a trend in various applications of G.R.P. in the construction industry.

Although, the surveys on the perceived advantages, disadvantages, etc. of G.R.P. included in chapter 8 and section 10.1 contained information relevant to the market research they did not include information on quantitative aspects of future intention of the specifiers and/or clients on the use of G.R.P.
A useful method of forecasting the future progress of G.R.P. in the construction industry which is proposed by the author is that of studying the postwar progress of aluminium in the construction industry; this would provide a useful basis for comparison with G.R.P., bearing in mind the effects of stimuli and/or constraints brought about by the influence of the following:

1. Differences in properties of the two materials.
2. Differences in the economic and technological conditions at the times of introduction of the two materials.
3. Differences in the capabilities of the two industries manufacturing aluminium and G.R.P. products respectively.
4. Factors connected with the users' satisfaction, perceived advantages and disadvantages of G.R.P. and aluminium.
5. Factors associated with external circumstances such as the need for energy conservation, security of future supplies, the relation to the imports bill, etc; these were discussed in chapter 12 for all common engineering materials.

Properties of aluminium alloys are outlined in 13.3. It will be seen that despite some significant differences in the technical attributes of aluminium alloys and G.R.P. composites aluminium alloys are incombustible, also specific flexural modulus of aluminium alloys is approximately 60 per cent greater than that of unidirectional G.R.P. composites with 70 per cent glass content the two material are substitutes for each other in many applications. For example, cast aluminium panels may be substituted for contact-moulded or press-moulded G.R.P. panels, or pultruded G.R.P. profiles may be substituted for extruded aluminium sections. The same argument applies to G.R.P. and aluminium sheeting.

13.2 The Introduction of Aluminium into the Construction Industry:
Aluminium alloys were initially developed prior to the second world war by the aircraft manufacturers for aircraft structures. Although, during the 1930's a few buildings incorporated aluminium window frames, it was not until the postwar years that aluminium became generally known, especially in connection with the aluminium bungalows, houses
and schools to which reference has already been made (Chapter 11). The government programme of non-traditional house and school building provided a temporary market for the use of aluminium as a structural material. The design and development work was undertaken by the aluminium industry; the structures erected subsequently demonstrated satisfactorily the durability and structural behaviour of aluminium alloys. However, they were not economically competitive and as soon as the government subsidy was removed, the extensive use of aluminium alloys for house building declined. For example, as reported by Bowley, by 1953, the total consumption of aluminium in the construction industry had been reduced to about one-fifth of the 1948 figure.

There were several factors which contributed to the rapid decline of aluminium houses and schools, viz:

1. Whole aluminium buildings were more expensive compared with traditional forms of construction or other non-traditional packages (see chapter 11).

2. They were disliked and looked upon with suspicion by local authorities in many parts of the country; objections made concerned 'inferior' aesthetics of the structures and the possibility of high costs for their future maintenance. Some authorities did not accept the evidence presented to them by the aluminium industry on the 'corrosion-resistance' and durability aspects of aluminium alloys; some even insisted on painting the exposed surfaces.

3. The renewed demand for aircraft diverted the attention of the manufacturers away from the construction market.

Nevertheless, the non-traditional aluminium structures successfully demonstrated the potential of aluminium alloys and accelerated greatly the process of learning and acceptance of this material. Thus, other applications of this material, such as curtain walling, sheeting, enjoy an established position in the construction industry and are considered as essential structural and architectural materials.
13.3 Brief Description of Properties of Aluminium Alloys:

There are various alloys commercially available with different properties and end-uses; however, from the standpoint of this study, these will be considered under the same headings and will be summarized as 'advantages' and 'disadvantages' of aluminium alloys.

13.3.1 Advantages of aluminium alloys:

The following six advantages of aluminium alloys will be considered briefly; for more detailed information reference may be made to the B.S.I. publications or to various other references a list of which appears in the National Specification.

13.3.1.1 Lightweight:

Density of aluminium alloys is typically 2.7g/cm³ as compared with 7.8 for mild steel, 7.1 for zinc, 8.95 for copper and 11.3 for lead. A tonne of steel occupies approximately one-third the volume occupied by a tonne of aluminium.

Density of G.R.P. ranges from approximately 1.45g/cm³ for hand-laid laminates to approximately 2g/cm³ for unidirectionally reinforced profiles; these densities are about half and three quarters those of aluminium alloys respectively.

13.3.1.2 High strength to weight ratio:

Although the specific modulus of aluminium alloys is typically of the same order as mild steel, its specific tensile strength is more than three times that of mild steel; however, its specific compressive strength is marginally lower than that of mild steel.

G.R.P. has lower specific tensile or flexural strength but higher specific tensile or compressive strength compared with aluminium alloys (see Table 5.13).

It must be noted that in the majority of constructional applications, a higher specific flexural modulus is of greater importance compared with higher specific tensile and/or compressive strength (c.f. chapter 6).
13.3.1.3 'Reaction-to-fire' characteristics:

Being an inorganic material, aluminium is classed as incombustible and its presence in any fire does not contribute to the fire load.

Aluminium structures begin to lose their stability at temperatures around 225°C as compared with about 450°C for steel structures. The thickness of protective covering for aluminium structural members for a given period of 'fire-resistance' performance is greater than the corresponding one in steel members. (e.g. 25 per cent for half an hour 'fire-resistance').

The major fire advantage of aluminium sheeting or cladding is the early melting of the aluminium alloy locally at the spot adjacent to the seat of fire; this would provide for early ventilation of a fire and reduce the severity of the internal temperatures. The damage sustained by the aluminium cladding or roofing would be confined to the area in direct contact with fire (see also F.O.C.'s current acceptance of aluminium sheeting described in 10.2)

13.3.1.4 Durability and resistance to corrosion:

Alluminium alloys used in the construction industry are generally durable and their resistance to corrosion is adequate unless they are exposed to very aggressive pollutants.

BS CP 118 contains guidance on the need for protection of various aluminium alloys in a variety of atmospheric conditions. Aluminium profiles can be anodised for greater resistances to weathering. However, anodising is a costly process. Plastics coating, especially acrylics or PVC is of more general use than anodising; these give a more cheerful appearance to the aluminium surfaces.

The relatively negligible maintenance requirements of aluminium makes it particularly suitable for use in curtain walling and similar applications.

13.1.3.5 The ease of shaping and manufacture:

Aluminium alloys can be manufactured into a variety of constructional products using a variety of processes; the most important processes are as follows:

1. Extrusion: Cost of equipment for the extrusion process is high. A figure of £3 m, 1967 prices has been given in
reference 4 for a press handling 175mm diameter billets with an output of about 2000 tons per annum producing extruded profiles with cross-sections smaller than 125mm diameter circle.

In order to amortise the costs of plant and dies it is essential to secure long runs of standard profiles; this is the reason for standardization of extruded aluminium profiles from the time of their introduction into the construction industry.

2. Rolling mills for sheet, plate and strip production: Cost of equipment can be many times greater than that of extrusion, e.g. production of a continuous strip, lm wide, at the rate of 20,000 tons per annum may require an investment of the order of £20m at 1967 prices.

3. Casting: Although, the melting temperature of aluminium alloys is low, die casting of aluminium units is expensive.

Casting will include sand, gravity die and pressure die casting.

Die casting of aluminium panels is costly and requires very long runs of production to justify the initial capital costs of die.

A relatively new process for cast aluminium storey-height panels of three dimensional character has been introduced into Europe from Japan; the process which is called 'Alcast' is claimed to produce purpose-made units economically viable for a range of buildings; typical unit numbers so far undertaken in Europe are 2300 in the case of the BMW building in Munich and 4200 in the case of the Bureau International du Travail in Geneva.

It is interesting to note that the architectural profession is fairly enthusiastic about the 'Alcast' process since the aesthetics of using cast aluminium panels are generally superior to other forms of construction such as curtain walling.

Traditionally, die casting is used in the U.K. to produce door handles and other similar accessories.

4. Cold rolling: Not a particularly economical process compared with the extrusion process. However, cold rolling of aluminium profiles may be undertaken in a manner similar to that of steel profiles.
5. Press forming: This process may be undertaken to
produce profiled sheets or panels from flat sheets; press-
formed glazing mullions or cills may also be produced from
flat sheets using this process.\(^5\)

A recently publicized two-part process for producing
three-dimensionally curved components from flat aluminium
sheet is noteworthy; it has been developed after 7 years
of research and development by Messrs. Tubes Investment
(Holding) who have the worldwide patent rights.

The first stage of the process involves heating a flat
sheet and whilst still hot, it is transferred into a
mould. The second stage involves sucking-by negative
or blowing by positive air pressure - the heated sheet
into the mould; the sheet is capable of stretching to 10
times its original size.

The complete process is capable of producing very
complicated shapes, it is particularly suitable for mass
production of standard shells and components. The information
on the economic viability of this process of not available;
however, it has been suggested that car body shells, exhaust
forms and similar repetitive products may be produced
economically employing this process. Thus, the process must
be highly capital intensive and the tooling costs must be
of the same order as the hot press-moulding of G.R.P.

13.1.3.6 Availability:

During the last 30 years, the aluminium industries
throughout the world have been concerned with the development
of new markets for aluminium in order to reduce the costly
burden of high stock piles.

The aluminium industry has expanded considerably world­
wide e.g. production of primarily aluminium has risen
approximately by a factor of 4 between 1958 and 1974.\(^6\)

The relatively gigantic sums invested in the provision
of plant and equipment, etc for processing, smelting and
semi fabrication of aluminium alloys mean, in effect, that
the continuation and/or expansion of large markets are vital
for the economic survival of the industry. Added to these, are
the greater sums invested in the provision of hydroelectric
energy in remote zones of large producing countries such as
Canada and Norway. (Note that the fixed costs in this case
may be very high, so every effort must be made to maximize the
per centage of capacity utilized).
13.3.2 Disadvantages of aluminium alloys:

13.3.2.1 Costs:
In terms of cost per cubic metre; aluminium alloys have been, and still are, more expensive compared with steel or timber, though the ratio of the price of aluminium to steel or timber has fallen considerably (see 13.4,5)

13.3.2.2 Thermal properties:
The coefficient of linear thermal expansion of aluminium alloys exceeds that of steel by a factor of 2; however, it is less than hand laminated G.R.P.

13.3.2.3 Problems of design and jointing:
In the case of proprietary curtain-walling and patent glazing, the design is usually undertaken by the manufacturers and is normally based on a standardized system which has been perfected over many years.

However, if a custom-designed system is undertaken, there will be a risk of performance failure due to minor design or manufacturing imperfections; this is because the number of sub-assemblies in these systems is usually high.

For the basic principles of design in aluminium alloys, there are, in addition to the information and design data published by the Aluminium Federation, a comprehensive range of B.S. Specifications, Codes of Practice, etc. which cover all technical aspects of design. Furthermore there are numerous text books, manuals, etc; a list of which has been given in reference 3. Therefore as far as the availability of information is concerned, aluminium alloys are well covered.

Problems may be experienced with aluminium alloys and dissimilar metals in contact, or between aluminium and alkaline materials such as concrete, cement mortar etc.

Also, aluminium alloys may be attacked by acid-containing woods. However, all of these problems are covered by the BS codes of practice or by the Aluminium Federation publications.

13.3.2.4 Fire-risks:
As has been noted (see 13.3.1.3) load-bearing aluminium members must be protected by 'fire-insulating' materials, otherwise, its 'fire-resistance' performance will be
There are numerous guides on the method of protection for a given period of 'fire-resistance' performance (see for instance the Structural Sections' Data Book published by the Alum. Fed.)

**13.3.2.5 Poor heat and sound insulation performances:**

The 'heat-conductivity' of aluminium alloys is higher than steel; it is approximately 64 per cent of that of copper. With no thermal 'break' between the outer and inner halves of metal framing members, the heat loss through the frame is high. Some designs provide for independent outer and inner members so that the possibility of a 'cold-bridge' forming is avoided.

Aluminium surfaces especially that of foil, have good heat reflectivity; this property will minimize the solar gain. In common with all lightweight materials, thin-walled aluminium panels, curtain-walling, roofing etc. have poor air borne sound insulation performance, unless advantage is taken of the composite designs generally developed for aircraft structures.

**13.3.2.6 Problems related to the aesthetic acceptability of aluminium structures and/or panels:**

Mill-finished aluminium surfaces turn into a greyish dull colour which is not pleasing, particularly when it is the dominant colour.

However, in normal curtain-walling systems, aesthetic problems do not arise, because aluminium is not the dominant material.

A variety of shades can be imparted to the aluminium surfaces in the process of anodising (i.e. orange, gold, brown, etc.) However, as was stated earlier, anodising is itself an expensive process and is used sparingly. The painting of aluminium surfaces is another option but it is not generally favoured due to the need for frequent renewal and maintenance etc.

Mill-finished surfaces are nowadays considered acceptable; however, if pastel colours are desired, a thin coat of plastics may be used; this has been very popular, especially with acrylic coating; in this way the aesthetic appearance of
aluminium has been greatly improved.

The plastic coated metals tend to reduce the risk of a 'cold-bridge' forming; though with dark colours, the solar heat gain is increased.

The latter is not considered to be a significant factor in cladding and roofing applications of occupied buildings (generally industrial buildings), because, the interior is insulated by use of a layer of heat insulation sandwiched between the corrugated sheet and the lining material).

13.4 End-uses of Aluminium Alloys:

The relatively high cost of aluminium limits the use of this material to curtain-walling, patent-glazing, door and window casements, corrugated and troughed sheeting (both for roof decking, roof sheeting and vertical cladding) and structures in which the self weight is high relative to the service load (e.g. in roofs of large spans or top storeys or footbridges, etc. this is basically similar to G.R.P. structures in respect of self supporting structures).

Apart from costs, as has already been noted, some applications are not technically advisable, for example, reinforcement of concrete by aluminium bars is not recommended owing to the interaction between released alkali in the concrete mass and the metal.

There are three fairly large scale application sectors for aluminium products:

1. Aluminium curtain-walling including patent glazing, door and window casement.
2. Aluminium sheeting, roof decking and vertical cladding.
3. Aluminium structures including beams and struts.

There are also numerous other end uses, for example, aluminium casting of door handles and related accessories, or the use of extruded aluminium profiles as framing for interior cladding, suspended (false) ceiling, etc. or aluminium roof guttering, or aluminium foil as an insulation/moisture barrier, etc. However, for the sake of brevity, an outline description of the above mentioned application sectors only will be given.
Aluminium curtain-walling including patent glazing, door and window casement:

Aluminium alloys can be extruded to form deep profiles of relatively thin thicknesses, owing to their lightness in weight, their high flexural resistance and their negligible maintenance requirements, these profiles are invariably more suitable for the manufacture of mullions, glazing bars, etc. and have captured a considerable portion of this market.

As a process, extrusion is superior to press forming or cold rolling of steel. Moreover, aluminium alloys are generally easier to machine compared with steel.

Transport, handling and erection of aluminium curtain-walling (and other components) is less costly compared with steel or even wooden systems.

Being generally resistant to corrosion, aluminium frames exposed to weathering require less maintenance compared with either wood or steel. Other advantages of aluminium windows are their resistance to fungi and their resistance to distortion and warping due to moisture movements.

Though, by volume aluminium has been more costly than either wood or steel, the cost of finished aluminium curtain-walling has in recent years compared more favourably with alternatives, especially if the maintenance costs are taken into consideration. For example, as may seen from reference 11, in 1975, the cost of galvanized steel standard grid curtain-walling excluding glazing and infill panels has been quoted in the region of £45/m²; the cost of anodised aluminium is given as £51/m². If stainless steel covers are used, the cost of steel-based curtain-walling will exceed that of anodised aluminium. If stainless steel cover sheets are used the cost of steel-based curtain-walling will exceed that of anodised aluminium system.

Table 13.1 and Fig. 13.1 indicate that between 1954 and 1974, the use of aluminium for curtain-walls, patent glazing and door and window casement rose by a factor of more than 17; in the same period, the use of steel for the above purpose contracted by more than 60 per cent. The corresponding data for wood are not published by the D.O.E.

The adjusted 1975 data show that between 1954 and 1975
Table 13.1 Production of Metal Curtain-walling, window and door casement, in Aluminium and Steel (Ann. Abs. of St.'s).

<table>
<thead>
<tr>
<th>Year</th>
<th>Aluminium (Thous-tonnes)</th>
<th>index</th>
<th>Steel (Thous-tonnes)</th>
<th>index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1954</td>
<td>.915</td>
<td>100.0</td>
<td>89.3</td>
<td>100.0</td>
</tr>
<tr>
<td>1955</td>
<td>1.539</td>
<td>168.1</td>
<td>94.15</td>
<td>105.4</td>
</tr>
<tr>
<td>1956</td>
<td>2.209</td>
<td>241.6</td>
<td>89.0</td>
<td>99.7</td>
</tr>
<tr>
<td>1957</td>
<td>2.209</td>
<td>241.6</td>
<td>79.25</td>
<td>88.8</td>
</tr>
<tr>
<td>1958</td>
<td>1.957</td>
<td>214</td>
<td>71.35</td>
<td>80</td>
</tr>
<tr>
<td>1959</td>
<td>2.356</td>
<td>258</td>
<td>77.0</td>
<td>86.2</td>
</tr>
<tr>
<td>1960</td>
<td>3.042</td>
<td>333</td>
<td>74.3</td>
<td>83.2</td>
</tr>
<tr>
<td>1961</td>
<td>4.605</td>
<td>503.5</td>
<td>72.8</td>
<td>81.5</td>
</tr>
<tr>
<td>1962</td>
<td>4.22</td>
<td>461.6</td>
<td>68.7</td>
<td>77.0</td>
</tr>
<tr>
<td>1963</td>
<td>4.563</td>
<td>498</td>
<td>64.366</td>
<td>72.0</td>
</tr>
<tr>
<td>1964</td>
<td>5.812</td>
<td>636</td>
<td>72.285</td>
<td>81.0</td>
</tr>
<tr>
<td>1965</td>
<td>6.789</td>
<td>742</td>
<td>68.380</td>
<td>76.6</td>
</tr>
<tr>
<td>1966</td>
<td>7.531</td>
<td>823.5</td>
<td>59.940</td>
<td>67.2</td>
</tr>
<tr>
<td>1967</td>
<td>6.944</td>
<td>758</td>
<td>55.836</td>
<td>62.5</td>
</tr>
<tr>
<td>1968</td>
<td>7.315</td>
<td>800</td>
<td>52.307</td>
<td>58.6</td>
</tr>
<tr>
<td>1969</td>
<td>7.400</td>
<td>808.5</td>
<td>44.176</td>
<td>49.5</td>
</tr>
<tr>
<td>1970</td>
<td>7.785</td>
<td>851</td>
<td>45.060</td>
<td>50.5</td>
</tr>
<tr>
<td>1971</td>
<td>8.391</td>
<td>917</td>
<td>40.99</td>
<td>46.0</td>
</tr>
<tr>
<td>1972</td>
<td>14.092</td>
<td>1540</td>
<td>41.670</td>
<td>46.7</td>
</tr>
<tr>
<td>1973</td>
<td>15.085</td>
<td>1649</td>
<td>40.115</td>
<td>45.0</td>
</tr>
<tr>
<td>1974</td>
<td>17.540</td>
<td>1920</td>
<td>33.203</td>
<td>37.2</td>
</tr>
<tr>
<td>1975</td>
<td>27.464*</td>
<td>(2760)</td>
<td>27.061*</td>
<td>30.3*</td>
</tr>
</tbody>
</table>

* Figures for 1975 have been adjusted to include additional sites. The effect has been to increase the total production by an average of 12.6 per cent. The figure inside bracket show the value of index in 1975 without the addition of new sites (Source: Housing and Construction Statistics)
Production of steel windows, etc.

(Aluminium windows, etc.)

Production of steel windows, etc.
the use of aluminium for the same purposes grew by a factor of more than 27 compared with a contraction of approximately 70 per cent by steel.

The greatest annual rises recorded in the consumption of aluminium alloys for the above purposes were between 1971 and 1975. Clearly, the fall in the consumption of steel in the same period, whether calculated in absolute or in relative terms cannot explain the phenomenal growth in the use of aluminium. This is seen from Table 13.1; the drop in steel consumption between 1971 and 1975 was roughly 14 thousand tonnes; the corresponding increase in aluminium was approximately 19 thousand tonnes. However, a tonne of steel occupies approximately one-third of the volume occupied by a tonne of aluminium. This means that 14 thousand tonnes of steel is roughly equivalent to 4.85 thousand tonnes of aluminium or about one forth the rise in consumption of aluminium in the period 1971-75. The remaining three-forths are therefore still unaccounted for.

In fact, it is likely that aluminium has captured a share of the market held by wooden windows, doors, curtain-walling etc. (See also Table 13.4 which indicates that the construction output between 1971-73 rose by approximately 5 per cent; it has subsequently fallen by about 9.5 per cent; thus, it is unlikely that the overall modest expansion of the construction output in 1972 and 1973 has had any dramatic effect on the size of the total glazing market).

The fact that aluminium has captured a share of the market previously held by wood is further also implied by study of the movement in prices of both materials as set out in Table 13.2

Table 13.2 Price Movements in 1971-75 for Selected Materials*

<table>
<thead>
<tr>
<th>Material</th>
<th>% increase (1971-75)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium sheet, strip and plate</td>
<td>62</td>
</tr>
<tr>
<td>Steel sheet and plate</td>
<td>111</td>
</tr>
<tr>
<td>Softwood (Imported)</td>
<td>129</td>
</tr>
<tr>
<td>Copper sheet, strip etc. (1971-74)</td>
<td>72</td>
</tr>
<tr>
<td>Index of Const. Mat. Prices</td>
<td>89</td>
</tr>
</tbody>
</table>

* Based on the data included in Housing and Construction Statistics.
It can be seen from Table 13.2 that semi-fabricated aluminium alloys recorded the lowest price rises compared with softwood, steel and copper. In fact, aluminium price increases were below the index of constructional materials’ prices, competitive position relative to their alternatives and also relative to the average rise in all constructional materials.

It is worth noting that aluminium alloys are not generally used for manufacturing fire doors, shutters and similar applications, since these alloys tend to lose their stability at temperatures above 225°C compared with steel which can withstand up to 580°C before being distorted. However, with the correct choice of 'fire-resistant' core materials such as asbestos-cement or G.R.G., G.R.C. etc. faced with aluminium sheets, 'fire-resistant' doors may be constructed; nevertheless, steel is widely used for fire doors and shutters, etc. often with a core of solid wood or asbestos-cement for greater periods of fire-resistance performances. One reason for this approach is the lower cost of steel coupled with the fact that fire doors, shutters, etc. are generally required for internal separation of various compartments, especially in industrial buildings where satisfactory technical performance is of greater importance compared with aesthetics.

13.4.2 Aluminium sheeting, roof decking and vertical cladding:

The use of corrugated or troughed aluminium sheeting in Britain dates back to 1946 although, the earlier uses were associated with the post war non-traditional structures. Subsequent shortages of steel facilitated the greater use of aluminium sheeting in the place of steel sheet.

Bridgwater estimated that between 1946 and 1958 about one million square metres of aluminium sheeting had been specified; in addition to non-traditional aluminium structures, the uses appear to have been for industrial and marine buildings located in polluted environments. Gas and steel works and power stations were examples of buildings which used corrugated and troughed aluminium sheeting. This is because the risk of corrosion in these cases was high.
Corrugated and troughed aluminium sheets are in direct competition with both plastics-coated steel sheet and asbestos-cement sheet.

An estimate for the annual consumption of roof decking materials is given in reference 9, though the data have not been defined. In addition, the year to which the estimate refers has not been specified; it is probable that the estimate refers to current years (See Table 13.3) According to a figure given in reference 9, the total aluminium building sheet in the U.K. is about 8500 tons; this is roughly 7.5 per cent of the total U.K. production of aluminium sheet production in 1974 10.

These data suggest that the use of aluminium sheet for roofing and vertical cladding has not expanded as fast as curtain-walling and similar applications.

Table 13.3 The Consumption of Roof Decking Materials in the Construction Industry (Ref. 9)

<table>
<thead>
<tr>
<th>Product</th>
<th>Annual usage</th>
<th>% of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>0.80 (x10^6 m^2)</td>
<td>2.7</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.95</td>
<td>3.2</td>
</tr>
<tr>
<td>Coated Steel</td>
<td>5.20</td>
<td>17.5</td>
</tr>
<tr>
<td>Asbestos-cement</td>
<td>5.74</td>
<td>19.3</td>
</tr>
<tr>
<td>Roof tiles</td>
<td>17.0</td>
<td>57.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>29.69</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

There are various possible reasons; chiefly:

1. The relative price: The price per square metre of aluminium sheeting has been higher than asbestos-cement sheet or plastics-coated steel sheet; it has however, been lower than translucent G.R.P. sheeting.

The latest prices' guide available 11 indicates that the price advantage of asbestos-cement and plastics-coated galvanized steel sheet has been reduced considerably. Today, pricewise, there is very little to choose between plastics coated aluminium or plastics-coated galvanized steel sheet 12.
2. The penalty premiums imposed until recently by the insurers on the use of aluminium sheetings: The information on the fire behaviour of aluminium sheeting when used as roofing or cladding has been available for a considerable length of time (see for examples, discussion on this matter recorded in 1959 which in an edited form has been reported in Page 226 of reference 5); however, as has already been noted (see 10.2) it was not until recently\(^ {13}\) that the F.O.C. rules were modified to allow the use of aluminium roofing materials for Classes II and III buildings.

Thus, it is likely that architects and engineers specified corrugated or troughed aluminium sheeting sparingly, for example in areas of high corrosion risks (Note that roof sheeting materials are generally considered as functional materials; therefore, they are highly price-sensitive).

A comparatively recent development in the use of aluminium sheet is the introduction of aluminium weatherboarding (shiplap) products for domestic and light commercial buildings; the designs are based on 'snap-joint' interlocking between successive preformed and coated sheets of approximately 150 to 200 mm wide. Current proprietaty products use attractive coatings of stove-enamelled white or plastics and are backed by various types of insulating materials such as polyurethane. Though these products are generally less labour-intensive than tiles and require virtually no maintenance compared with wood-based products, they are in competition with a variety of other products made from PVC coated steel sheet, extruded UPVC and continuously produced G.R.P.

Finally, mention must be made of sandwich panels with exterior face of troughed or flat aluminium sheets and the interior face selected from a variety of materials. The core is usually of cellular plastics such as expanded polystyrene, rigid polyurethane foam and rigid phenolic foam; the latter is more advisable because of reduced fire and smoke risks; however, most manufacturers of standardized sandwich/composite products are tied up with the use of rigid polyurethane foams; this is due to the fact that good quality phenolic foams have not been available in the U.K. until fairly recently (see Chapter 14)
PVC-coated troughed steel sheet is an alternative to aluminium, especially if higher distances are required to be spanned by each sheet. A variety of proprietary products exist both in aluminium and in steel which are suitable for use in industrial, commercial, agricultural, etc. buildings.

13.4.3 Aluminium structures including beams and struts:

It has already been noted that aluminium structures are considered to be economic where their lightweight, high specific strength, and corrosion-resistance properties can be utilized with maximum efficiency. This reasoning implies that aluminium is a particularly suitable material for structural members which are subjected to tensile stresses.

The high cost of aluminium alloys means that in normal static load-bearing conditions such as columns and beams in multi-storey structures, it is more economical to use reinforced concrete or steel; the use of the latter materials will result in more rigid and stable structures. In addition reinforced concrete is a 'fire-resistant' material; and steel has a higher heat-distortion temperature and requires less 'fire-resistance' protection.

Aluminium structures are generally in the form of trusses, domes, space frames, folded plates and shells.

The structural use of aluminium alloys is covered by CP 118; structures designed in accordance with this code will be accepted under the Building Regulations (i.e. Regulation D 10).

Though the tendency in the past has been for structures to be constructed of standardized aluminium sections (e.g. those to BS 1161), it is possible to fabricate self supporting continuous structures of configurations similar to those described for G.R.P. panels and structures (Chapter 6). The range of structures is usually limited to those which can be fabricated from commercially available aluminium sheets and plates; however, thick plates are not structurally efficient compared with structures made with discrete members (i.e. those formed by assembly of pin-jointed members, for reasons, see 6.4). Furthermore, analytical methods for the latter structures are generally better defined.
A variety of proprietary structural systems are available in aluminium, e.g. double layer grids with 'Triodetic' jointing method which was developed in Canada but is available in Britain\(^3\), or the Roper IBG International Super Dome System used recently in the Swindon Leisure Centre or 'Geodesic' Domes by Temcor of California or the widely used British design called 'Hamman' etc.

A general observation on all types of structural systems in aluminium shows that for reasons of economy, the overall stiffness of the structures is mainly derived from its geometry; this is apparently similar to G.R.P. structures. However, it must be remembered that the specific flexural modulus of aluminium is higher than that of G.R.P. and unlike G.R.P., it is not time and temperature dependent (i.e. excluding elevated temperatures). The combination of these qualities means that aluminium is inherently a more efficient structural material compared with G.R.P.

As was discussed in Chapter 9 and has been confirmed by Oosterhoff\(^{14}\), the use of structural systems with unorthodox geometrical configurations is limited. The use of double layer grids has been more acceptable; however, here too the traditional designs have normally proved more competitive except for very large spans. The reason has been attributed\(^3,^{14}\) to the relatively high labour-input generally required for the connection and installation of these grid-systems.

In Britain, the tendency has been for proprietary portal frames and arches to be fabricated from steel for use on industrial projects. However, light-duty aluminium frames for swimming pools and similar applications are commercially available. In the case of double-grid, the use of steel is more widespread than aluminium.

In short, the market for aluminium structures is limited, because aluminium beams, struts, portal frames, etc. are uneconomic compared with steel or wooden members of equivalent performance and because the market for structures of unusual shapes is limited.
13.5 Specification of a Quantitative Model for the Apparent Consumption of Total Aluminium in the U.K. Construction Industry:

13.5.1 Choice of explanatory variables:

From the review carried out of the end-uses of aluminium alloys in the construction industry, it can be concluded that steel, wood, asbestos-cement and to a limited extent copper and plastics are the main competitors for aluminium products.

Official price index numbers for corrugated and troughed asbestos-cement sheet are not published; these data are in fact of confidential nature because there are only two major suppliers of asbestos-cement goods.

There is an officially compiled price index numbers for 'plastics building materials', however, this index is heavily biased towards the major tonnage uses of plastics such as pipework and plumbing, floor covering, insulation etc. (see Tables 4.7 and 4.8 on page 120). It was therefore considered inappropriate to accept this price index for representing the price movements of rigid extruded PVC window casement and weatherboarding products - both of which are fairly new and have not as yet seriously challenged the market held by aluminium alloys and wood.

In short, it was decided to exclude the above price indices (i.e. for asbestos-cement sheet and for PVC). The effect of excluding the former index is unknown, however, the effect of omitting the latter index is expected to be insignificant.

The model initially proposed is as follows:

\[ Y = f(0, P_A, P_S, P_W, P_C) \]  
- (13.1)

where:

\( Y \) = index of total apparent consumption of aluminium in the construction industry (apparent consumption = production - exports + imports ± changes in stocks).

\( O \) = index for output of the construction industry.

\( P_A \) = index for aluminium prices (semi-fabricated).

\( P_S \) = index for steel prices (sheet and plate).

\( P_W \) = index for wood prices (i.e. softwood, hardwood and plywood price indices combined in a weighted pattern which reflects the relative consumption of these materials in the
construction industry).

\[ P_c = \text{index for copper prices (sheet and strip)} \]

### 13.5.2 Sources of data and their validity:

Table 13.4 shows the data as calculated initially for the purpose of an econometric analysis. Fig. 13.2 shows the same price indices plotted; Fig. 13.3 shows indices for consumption of aluminium in the U.K. construction industry and in all sectors of the U.K. economy, together with index numbers for the construction output and production indices for aluminium and steel curtain-walling etc. (These production indices were in fact given previously in Table 13.1 and Fig. 13.1; they are repeated here for comparison purposes and for ease of reference).

There are ample notes beneath Table 13.4 on the sources of data and methods used for deriving these indices; it can be seen that consumption data for aluminium are based on the statistics published by OECD; price indices and the index number for the construction output are based on the D.O.E. statistics published in "Housing and Construction Statistics".

An alternative set of price indices for aluminium and copper may be considered to be those of ingots as published in various periodicals, e.g. those published in "Metal Statistics". The use and relevance of these indices will be discussed in a more appropriate place.

It is generally beyond the scope of this project to establish the validity or consistency of the data included in Table 13.4. However, caution must be exercised about the accuracy of these figures, especially of those representing the total (apparent) consumption of aluminium alloys in the construction industry \((Y)\). It is generally difficult to arrive at a very accurate figure for \(Y\), since there are various small uses of aluminium which are difficult to classify or quantify, e.g. aluminium trimming and framing profiles used in conversion and renovation of old houses, offices, etc.
Table 13.4 Calculation of various indices for use on a Quantitative Model (for sources see below)

<table>
<thead>
<tr>
<th>Year</th>
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Sources: Columns II and III: Annual Absrt. of Stat's Col's IV and V: Metal statistics 55th-62nd. Ed. (Data originate OECD); Col. VI: Housing of Const. Stat's (Tables I and II, p 1 and 70, Issue 16 for 4th qtr. 1975); Columns VII to XI extracted from various issues of H & C St's and from data especially supplied by the D.O.E.; the following definitions are used:

- PA = Index of price for aluminium plates sheets and strips (H & C S)
- IC = Index of construction Materials' Prices (H & C S)
- PS = Average of two indices for steel sheet and steel plate both individually shown in H & C St's
- PW = 0.8 x P + 0.1 x P + 0.1 x P ; where P softwood, P hardwood, and P plywood are indices given in the H & C St.'s respectively for imported softwood, hardwood and plywood (Weights reflect the approximate pattern of consumption).
- PC = Index of Price for Copper Sheet and Strip. (H & C St.'s)
FIG. 13.2 PRICE INDICES OF VARIOUS STRUCTURAL MATERIALS AND INDEX OF CONSTRUCTION MATERIALS' PRICES. (1959=100) (1975=PROVISIONAL)
Aluminium windows & casement doors

Total consumption of Al. in the const. indus.

Construction output of Alum. in all U.K. industries

Steel windows and casement doors

FIG. 13.3
Price indices are based on the price index numbers of material purchases by individual industries and broad industry sectors in the Department of Trade's wholesale Price Index Series.

The individual prices indices of all materials used in the construction industry are combined in a weighting pattern which reflects the relative value of the purchases of these materials by the construction industry in 1968; the resulting index is called: "The index of construction materials' prices" ($I_C$). All material price indices are expressed net of VAT.

As can be seen from Table 2.3 (which is an extract from the National Output-Input Table for 1968), there are many construction materials which are not in direct competition with aluminium alloys, but would influence $I_C$ to varying degrees (see 2.2); the effect of these may be such as to distort the explanatory value of this index (See 13.5.3)

The index for construction output at constant prices is given by the Department of the Environment. The figures for 1963 to 1974 include estimates of unrecorded output by small firms and self-employed workers; for the period prior to 1963, the figures do not include the above estimates and are not therefore strictly comparable to the data for 1963-74.

A study of curves in Fig. 13.3 shows that in 1971-74, the total aluminium consumption in the construction industry rose proportionately faster than in all other industries; by far, the fastest growing sub-market has been curtain-walling, window and door casements etc.

A particular point of interest is the rise in 1974, of aluminium consumption in the construction industry despite a fall in the construction output; this is not unexpected since aluminium alloys recorded the lowest price rises in 1970's compared with alternative materials (see 13.5.3)

It is worth noting that relative to $I_C$, aluminium has become progressively cheaper in the last 14 years (see Table 13.4 and Fig. 13.2)
13.5.3 Input data for computer analysis and the results:

Table 13.5 contains the indices for both the dependent (Y) and 'independent' (or explanatory) variables which were used as input for a computer analysis. As can be seen, the data prior to 1963 have been omitted; this is expected to have increased the reliability of the analysis (see the discussion regarding the consistency of construction output indices).

Further, it can be seen that 1970 has been taken as the base year. This is because all of the D.O.E. indices used for this analysis are currently published using 1970 as the base year; these figures can be used without any arithmetic transformation.

It can be seen that price variables have been divided by $I_C$ and the new variable entered in columns IX to XII (Table 13.5)

Columns XIII to XV contain the ratio of $P_A$ to $P_S$, $P_W$ and $P_C$ respectively, and finally column XVI contains index numbers for construction output at factor cost, 1970 prices, which have been extracted from the 1975 issue of National Income & Expenditure. These index numbers do not agree with the corresponding numbers published by the D.O.E. ($O_1$); it is likely that the difference ($O_1-O_2$) which is higher for the pre-1970 data, is a direct result of the omission of the estimate of the output by small firms and self-employed persons, etc. which previously were not calculated and added to the figures derived from the quarterly and annual enquiries (see notes given beneath Table II of issue 10, Housing and Construction Statistics).

The computer programme used for the analysis of the above data is the standard "Multiple Regression Analysis" (MREG) available through the Multi-Access system of the University of Surrey Computing Unit.

This programme allows for experiments using a selection of the explanatory variables from Table 13.5

It has also the facility of transforming the original data into logarithmic numbers and then using these as input data for multiple regression analysis; alternatively one could calculate logarithmic numbers manually for a selected
Table 13.5  Input Data for Computer Analysis

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* As defined previously.  † Index of construction output @ factor cost, 1970 prices: Nat. & Income & Exp. 1975.
Table 13.6 Alternative Set of Input Data for Computer Analysis

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(1) - Average Prices of Aluminium 99.5% ingots expressed in index numbers (Source: Metal Statistics, 62nd. Ed.)

(2) - Average Prices of Copper (electrolytic, wirebars) expressed in index numbers (Source: as above)

(3) - Index numbers of imported softwood (Source: H & C. St.'s)
variable and use these as input data in combination with non-logarithmic data for other variables. This latter procedure would allow non-linear mathematical models to be tested—however, for the sake of simplicity and ability to interpret the resulting regression coefficients, such non-logarithmic and logarithmic combination of variables have been omitted from this analysis.

In short, the models tested are of the following general forms:

\[ Y = a + b_1 x_1 + b_2 x_2 + b_3 x_3 + \ldots + U \quad (13.2) \]
or the first differences of the same. (This is identified as Row Data analysis in the programme and is signified by 'R/D' in Table 13.7)

\[ \log Y = \log a + \beta_1 \log x_1 + \beta_2 \log x_2 + \ldots + u \quad (13.3) \]
or the first differences of the same (this is identified as Logarithmic analysis in the programme and is signified by 'Log' in Table 13.7)

Equation 13.3 is of special value since it would yield the calculated values of \( \beta_1, \beta_2, \ldots \) which, subject to correct sign, etc. may be taken as estimates of elasticities of the sort usually needed in econometric analysis.\(^{15}\)

A variety of models were tested assuming \( Y \) (column II, Table 13.5) as the dependent variable and a selection of explanatory or independent variables from columns III to XVI of Table 13.5. The results are summarized in Table 13.7. It can be seen that both \( P_S \) and \( P_C \) proved to be insignificant variables; omission of these two variables from the originally proposed model (eqn. 13.1) gave a better result as can be seen by study of models 6 and 12 in Table 13.7)

Comparisons of models 13 and 14 with 15 and 16 respectively show that the price of aluminium alloys relative to the index of construction materials' prices (\( P_A/I_C \)) is not as good an explanatory variable as \( P_A/P_W \); this may also be seen by reference to Fig. 13.4 and Fig. 13.5 which show in a plotted form, the goodness of fit for models 14 and 15 respectively. This is probably justified since, as was noted before, \( I_C \) is influenced by prices of many materials which are not indirect competition with aluminium products in the construction industry; however, wooden products such as curtain-
Walling, window and door casement, etc. are in direct competition with aluminium products.

Table 13.7 includes a number of experimental models such as model number 4. The purpose was to see if one could develop a combined relative price variable i.e. $P_A/I$, in which $I$ could be a combination of $P_S$, $P_W$ and $P_C$ using a pattern of weighting as was given by an appropriate experimental model; this price variable $(P_A/I)$ could then be used in conjunction with $Q_1$ to give a good fit thus, avoiding problems of multi-collinearity, etc. However, as a general rule, these efforts failed because the weights suggested by regression co-efficients of the above experimental models were of the wrong sign.

In short, with the input data selected from columns III to XV of Table 13.5, the best possible result was model 16 (see Fig. 13.5). However, the negative autocorrelation test at 5 per cent level of significance is inconclusive i.e. we have:

At 5 per cent level of significance $d_u = 1.54$

and with $k' = 2$, $N = 12$

calculated $d = 2.55 > d_u > d_L$ : no evidence of positive autocorrelation

$4 - d = 1.45 < d_L < 4 - d < d_u$ : The test for negative autocorrelation is inconclusive.

The first differencing technique for reducing any likely autocorrelation did not prove successful (see models 17 and 18, Table 13.7).

Three possible courses of action were therefore considered; these are as follows:

1. Introduction of new variables, e.g. introduction of a variable to represent the effects of advertising and promotional measures undertaken for marketing aluminium products. A possible simple variable would be derived by dividing the annual advertising expenditure on aluminium products by the advertising expenditure on all other alternative products; more complicated analysis is also possible.

Inclusion of an advertising variable was not possible due to the lack of data on advertising expenditure for aluminium relative to other products. Random checks made by the author on a trade journal (e.g. the Architects' Journal)
did not show any evidence of disproportionate advertising and promotional efforts by the aluminium industry.

In short, the effects of advertising and promotional expenditure on the consumption of aluminium products cannot be isolated chiefly because of the lack of data.

2. The use of lagged variables: This course of action was not considered to be appropriate since nearly all of the aluminium products used in the construction industry are of standardized types; although, the preliminary design of buildings is normally carried out in advance of their construction, detailed designs are generally produced nearer the time of construction. Also, as has been noted previously (see chapter 3) the architect has the power to order substitution of various construction components if the price or non-availability, etc. justifies his action.

Referring to Table 13.1 it can be seen that in 1974, curtain-walling and allied applications required 17540 tonnes of aluminium alloys; this figure is approximately 28 per cent of the total aluminium alloys consumed in 1974 in the construction industry. In the same year, according to the official statistics (H & C. St's. No. 16), the deliveries totalled 18310 tonnes, the production deficit in 1974 was therefore 700 tonnes which was compensated for by deliveries from stocks. Furthermore, the stock piling of some 4168 tonnes of aluminium curtain-walling etc. indicates that most products in this category are standardized proprietary products. These are added reasons for which the above course of action was not pursued.

3. The use of different data for the same variables: Model 16 (Table 13.7) indicates that the t-statistic for $O^1$ is approximately 3.69; this is rather low compared with a value of approximately 10.69 for $P^A/P^W$; it was therefore decided to substitute $O^2$ (column XVI, Table 13.5) for $O^1$.

As it may be seen from Table 13.7 (models 19 to 22) and from fig. 13.6 which shows a plotted line representing model 20, the substitution of $O^2$ for $O^1$ did not eliminate the problem of negative auto-correlation; the Dubin-Watson Statistics ($d$) increased from 2.55 in the case of model 16 to 2.72 in the case of model 20. This shows that $d$ has moved towards 4 and hence it has increased the possibility of negative auto-correlation.
As was pointed out at the beginning of this section, it is possible to use ingot prices for aluminium and copper. Table 13.6 contains new price variables for aluminium \(P'_A\), for electrolytic copper \(P'_C\), for imported softwood \(P'_W\) and finally new price ratios which were calculated in a manner similar to Table 13.5.

The results are shown in Table 13.7 (see models 23 to 25) and Fig. 13.7, which shows model 24 plotted; it can be seen that, although problems of negative auto-correlation have been eliminated altogether, the resulting models are less accurate compared with model 16. This point is well illustrated by direct comparison of plotted lines in Fig. 13.5 and Fig. 13.7 which represent models 16 and 24 respectively; the increased residuals for 1973 and 1974 in model 24 is a major drawback of this model compared with model 16.
<table>
<thead>
<tr>
<th>Model No.</th>
<th>Independent Variables</th>
<th>(1) R/D or Log</th>
<th>T-statistics</th>
<th>R² - 3 (x10^-3)</th>
<th>Test for A/C</th>
<th>Any Possibility of M/C?</th>
<th>Identification problems?</th>
<th>Comment on the model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$O_1$, $P_A$, $P_S$, $P_W$ and $P_C$</td>
<td>R/D</td>
<td>insig. T for $P_A$, $P_S$ and $P_C$. Low T for $O_1$ ($T = 1.252$)</td>
<td>971</td>
<td>6.022</td>
<td>No. posit. A/C incon. neg. A/C</td>
<td>No</td>
<td>wrong sign for $P_A$, $P_S$ and $P_C$</td>
</tr>
<tr>
<td>2</td>
<td>Ditto but in F/D</td>
<td>R/D</td>
<td>T is insig. for all but $P_W$ ($T = 2.21$)</td>
<td>826</td>
<td>9.212</td>
<td>As above</td>
<td>No</td>
<td>As above</td>
</tr>
<tr>
<td>3</td>
<td>$O_1$, $P_A$, $P_S$, $P_W$ and $P_C$</td>
<td>R/D</td>
<td>insig. T for $P_A$, $P_S$, $P_C$ and $P_C$, Low T for $O_1$</td>
<td>957</td>
<td>7.3753</td>
<td>As above</td>
<td>Yes</td>
<td>wrong sign for $P_C$</td>
</tr>
<tr>
<td>4</td>
<td>$O_1$, $P_A$, $P_S$, $P_W$ and $P_C$</td>
<td>R/D</td>
<td>insig. T for $P_A$, $P_S$ and $P_A$, Low T for $O_1$</td>
<td>960</td>
<td>6.592</td>
<td>As above</td>
<td>Yes</td>
<td>wrong sign for $P_A$</td>
</tr>
<tr>
<td>5</td>
<td>Ditto but in F/D</td>
<td>R/D</td>
<td>Sig. T only for $P_A/P_W$</td>
<td>706</td>
<td>10.953</td>
<td>No A/C</td>
<td>Yes</td>
<td>wrong signs for $P_A$, $P_S$ and $P_C$</td>
</tr>
<tr>
<td>6</td>
<td>$O_1$, $P_A$ and $P_W$</td>
<td>R/D</td>
<td>$T = 1.79$, -1.57 &amp; 5.95 respect.</td>
<td>966</td>
<td>5.697</td>
<td>No.post Incen. neg. (4-d = 1.69 &lt; du = 1.8)</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>7</td>
<td>Ditto but in F/D</td>
<td>R/D</td>
<td>Insig. T for $P_A$ ($T = 0.179$)</td>
<td>811</td>
<td>8.12</td>
<td>As above (4-d = 1.754 &lt; du = 1.80)</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>8</td>
<td>$O_1$, $P_A$, $P_S$, $P_W$ and $P_C$</td>
<td>R/D</td>
<td>$T = 1.73$, -1.547 &amp; 4.846</td>
<td>947</td>
<td>7.08</td>
<td>No post. A/C Incen. neg.</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>9</td>
<td>Ditto</td>
<td>Log</td>
<td>$T = 2.25$, -1.61 &amp; 3.92</td>
<td>937</td>
<td>(0.0623)</td>
<td>As above</td>
<td>Yes</td>
<td>None</td>
</tr>
<tr>
<td>10</td>
<td>As Model 8 but in F/D</td>
<td>R/D</td>
<td>Insig. T for $O_1$ and $P_A$, $P_S$</td>
<td>690</td>
<td>10.873</td>
<td>Incon. post A/C No negative A/C</td>
<td>No</td>
<td>N/A</td>
</tr>
<tr>
<td>11</td>
<td>As model 9 but in F/D</td>
<td>Log</td>
<td>Insig. T for $O_1$ and $P_A$, $P_S$</td>
<td>540</td>
<td>(0.0873)</td>
<td>Incon. for post. No neg. A/C (d = 1.764 &lt; du = 1.80)</td>
<td>No</td>
<td>N/A</td>
</tr>
<tr>
<td>12</td>
<td>$O_1$, $P_A$ and $P_W$</td>
<td>Log</td>
<td>$T = 1.3$, -1.63 &amp; 4.897</td>
<td>943</td>
<td>(0.0589)</td>
<td>No positt. A/C Incen. neg. A/C (4-d = 1.7 &lt; du = 1.8)</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>13</td>
<td>$O_1$ and $P_A$</td>
<td>R/D</td>
<td>Sig. T for both</td>
<td>769</td>
<td>13.933</td>
<td>No A/C</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>14</td>
<td>Ditto</td>
<td>Log</td>
<td>Sig. T for both</td>
<td>800</td>
<td>(0.1031)</td>
<td>No A/C</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>-----</td>
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</tr>
<tr>
<td>15</td>
<td>$O_1$ &amp; $P_A/V_W$</td>
<td>R/D</td>
<td>$T = 2.95$ and $-12.51$</td>
<td>960</td>
<td>5.8494</td>
<td>No posit. A/C</td>
<td>Incon. neg. A/C</td>
<td>No</td>
</tr>
<tr>
<td>16</td>
<td>Ditto</td>
<td>Log</td>
<td>$T = 3.69$ and $-10.69$</td>
<td>947</td>
<td>(0.05359)</td>
<td>As above, 4-d = 1.45 &lt; du = 1.53</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>17</td>
<td>As Model 15 but in F/D</td>
<td>R/D</td>
<td>$T = 0.5668$ &amp; $-4.26$ insig. T for $O_1$</td>
<td>703</td>
<td>9.535</td>
<td>No A/C</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>18</td>
<td>As Model 15 but in F/D</td>
<td>Log</td>
<td>$T = 1$ and $-3$ (Low for $O_1$)</td>
<td>534</td>
<td>(0.08223)</td>
<td>No A/C</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>19</td>
<td>$P/A/P_W$ &amp; $O_2$</td>
<td>R/D</td>
<td>$T = -13.14$ &amp; $2.975$</td>
<td>960</td>
<td>5.82213</td>
<td>No posit. A/C</td>
<td>Incon. neg. A/C (4-d = 1.067 &lt; du = 1.8)</td>
<td>No</td>
</tr>
<tr>
<td>20</td>
<td>Ditto</td>
<td>Log</td>
<td>$T = -11.29$ &amp; $3.884$</td>
<td>950</td>
<td>(0.05186)</td>
<td>As above (4-d = 1.28 &lt; du = 1.8)</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>21</td>
<td>$P_A/I_C$ &amp; $O_2$</td>
<td>R/D</td>
<td>$T = -4.79$ &amp; $3.20$</td>
<td>771</td>
<td>13.8766</td>
<td>Incon. posit A/C</td>
<td>No neg. A/C (4-d = 1.52 &lt; du = 1.8)</td>
<td>No</td>
</tr>
<tr>
<td>22</td>
<td>As above</td>
<td>Log</td>
<td>$T = -4.96$ &amp; $3.84$</td>
<td>798</td>
<td>(0.10471)</td>
<td>No A/C</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>23</td>
<td>$P_A/P_{SW}$ &amp; $O_2$</td>
<td>R/D</td>
<td>$T = -8.54$ &amp; $1.543$</td>
<td>911</td>
<td>8.667</td>
<td>No A/C</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>24</td>
<td>As above</td>
<td>Log</td>
<td>$T = -8.534$ &amp; $2.383$</td>
<td>917</td>
<td>(0.0671)</td>
<td>No A/C</td>
<td>No</td>
<td>None</td>
</tr>
<tr>
<td>25</td>
<td>$O_2$, $P_A/I_C$</td>
<td>R/D</td>
<td>$T = 1.534$ &amp; $-3.356$</td>
<td>639</td>
<td>17.431</td>
<td>Incon. for both pos. &amp; neg. A/C</td>
<td>No</td>
<td>None</td>
</tr>
</tbody>
</table>

Notes: * This summary is compiled for the purpose of discussion; it does not therefore include a large number of models with essentially different variables or different combinations which were also tried out.

(1) - R/D refers to Raw Data; Log refers to Logarithematic data. (2) - Figures in brackets are Log Y - Log Y'; the antilog of the same is therefore equivalent to Y for example for a figure of 0.0515 the ratio is 1.055 or the error is about 5.5 per cent of Y'. A/C = auto-correlation; M = multicollinearity.
$R^2 \approx 0.800$

$d = 1.6$ - No evidence of A/G

FIG. 13.4 MODEL NO. 14
\[ \log_e Y = 5.17916 + 0.679387 \log_e 0.1 - 0.803407 \log_e (P_A/P_W) \]

\[ R^2 = 0.9472 \]

\[ d = 2.55 (d_L=1.54, d_H=0.86) \]

**FIG. 13.5 MODEL NO. 16**
\[ \log_e Y = 4.28722 + 0.881678 \log_e O_2 - 0.813664 \log_e \left( \frac{P}{P_w} \right) \]

\[ R^2 = 0.95 \]

\[ d = 2.72(d_1 = 1.54, d_2 = 0.86) \]

FIG. 13.6: MODEL NO. 20
\[ \log Y = 4.53978 + 0.71234 \times \log \theta - 0.705173 \times \log \left( \frac{P}{P_n} \right) \]

\[ R^2 = 0.917 \]

\[ d = 2.353 \text{ : No evidence of A/C} \]
Another drawback of the above approach stems from the use of ingot prices in the analysis. In fact, the starting material for aluminium products is generally in the form of semi-fabricated products e.g. billets, strips, etc; this consideration implies that a more appropriate price measure is the price index numbers for these semi-fabricated products (i.e. $P_A$) in preference to those of ingots' (i.e. $P_A'$).

Nevertheless, the above substitution exercise clearly indicates that, whatever set of data is used for the analysis, the effectiveness of $P_A/P_W$ in explaining the total apparent consumption of aluminium alloys in the construction industry ($Y$) is unaltered. In other words on the basis of the available data, steel and copper prices appear to be insignificant. It must be noted that with each new set of data, a range of possible models were tested; however, the analysis did not produce results substantially different from those obtained using the original set of data; in order to keep Table 13.7 concise, only the results relevant to a selected number of models have been reported.

The fact that the variable representing the movements in prices of steel products ($P_S$), proved insignificant is unexpected; not only is plastic-coated or mill-finished profiled aluminium sheet a close substitute for plastics-coated galvanised profiled steel sheet, but also (as was noted in 13.4.3) many extruded aluminium profiles are substitutes for their steel counterparts as well. In fact, whole steel structures may be designed in aluminium using the normal structural engineering techniques.

The above reasoning implies that the explanatory power of $P_S$ is open to question; this point is well illustrated in the case of the following two products:

1. Roofing and vertical cladding products: Nowadays, there are a range of proprietary composite products of large dimensions, especially for use on industrial buildings; these products incorporate a variety of materials such as different insulation and lining materials etc.

   In the case of vertical cladding, troughed sheets of either aluminium or steel are bonded to a rigid core of foamed-plastics such as polystyrene, polyurethane, phenolics isocynaurates, etc. The inner lining material is generally a sheet of metal, plasterboard or asbestos building.
board or fibreboard etc.

Roof decking systems are based on corrugated metal as a decking material (i.e. secondary load-bearing material transfers the imposed loads including self-weight to the structural frame etc); the insulation, waterproof membrane, weather resisting finish, etc. are bonded in the factory onto the troughed metal.

The above discussion shows that the price of these products is only partially influenced by the cost of the metal sheet.

2. Curtain-walling and allied products: As was shown in 13.4.1 aluminium alloys have steadily captured most of this market from galvanized steel during the last thirty years; the present market for prestige projects is divided between aluminium and stainless steel exterior curtain walling, where either exposed galvanised steel frames are covered by a thin sheet of stainless steel or frames are manufactured wholly from stainless steel. In such cases the cost of raw steel as a proportion of the cost of the finished products is likely to be less significant compared with the high costs of manufacturing and rust-proofing operations (i.e. galvanizing and coverage with stainless steel, etc.); thus, it is probable that the price of raw steel alone cannot reflect the true cost of steel curtain-walling products, except in the fields of heavy-duty applications such as fire doors, load-bearing frames etc.

In addition to steel, the price of semi-fabricated (or ingot) copper also proved a highly insignificant variable. It is difficult to find examples of aluminium alloys having substituted copper in the construction industry; the case of copper pipes for domestic hot water and copper cylinders for domestic storage of hot water is a good example where there is no evidence to suggest that aluminium has been used; the ease of cold shaping and welding of copper is a major advantage of this material over aluminium alloys.

Other applications such as cast copper or brass panels, copper-sheet roofing, etc. where aluminium alloys could be substituted for copper, are generally rare; these applications were mainly phased out after the war; furthermore, as has been noted, G.R.P. has been used in a decorative manner in place of cast copper or brass features.
13.6 Some Observations on the Progress of Aluminium Alloys in the Construction Industry:

13.6.1 Introductory and trial period:

As was stated previously, the introduction of aluminium into the construction industry coincided with the shortages of timber, brick and steel coupled with a greatly diluted war-stricken labour force.

The aluminium industry was aware of the need for developing new outlets for its greatly expanded war-time output; the industry was conscious of the fact that the demand for military aircraft would drop immediately after the war. Thus in 1944, the Aluminium Development Association (ADA, now called the Aluminium Federation) was established by primary and secondary aluminium producers. A function of this organization was to further research into the uses of aluminium and encourage their development; the ADA was also responsible for collection and processing of technical information and for the provision of design data, publicity etc.

The ADA subsequently played a major role in the development of the constructional applications and distribution of the related information including provision, publication and up-dating of numerous British Standards Specifications and Codes of Practice (today, there are some 37 BS Specifications and 5 Codes of Practice mainly or partly dealing with properties, method of manufacture, testing etc. of the uses of aluminium in the construction industry; in addition, there are 25 simplified publications by the ADA or the Aluminium Federation, which generally deal with the same problems).

In short, although the post war non-traditional bungalows, houses and schools constructed from aluminium elements provided an ideal opportunity for the development of this material, it was, in fact, the positive approach on the part of the industry which secured development of more permanent outlets for aluminium products in the construction industry.

It must not be assumed that the advent of aluminium structures alone managed to remove doubts which existed in the minds of architects, specifiers and local authorities on the durability, structural performance etc. of this material; studies of the proceedings of various symposia, seminars etc.
undertaken by the author showed documentary evidence of this fact.

The most detailed discussion on the durability, technical performance and aesthetics of aluminium-based components were recorded by the A.D.A. in 1959, when a symposium convened by the same organization was held at the Royal Institute of British Architects in London (see reference 5); Tables 13.8 to 13.12 contain a sample of comments and/or statements made by various participants at the above symposium; the main points of interests are summarized below:

13.6.1.1 Perceived 'corrosion-resistance' (durability aspects):

There are various indications of previous performance failures as shown in Table 13.8, probably as a result of wrong alloys being used, e.g. one user (architect, p 36, reference 5) stated: "In the last five or six years, we found that some of the post-war applications of aluminium as substitutes for other materials were completely unsatisfactory. In many cases it had not done the job, and that I think militated against the later introduction of aluminium on a larger scale".

Thus, even with the vast knowledge being then available as a result of pre-and war time aluminium uses in other industries, and with the great care exercised by the aluminium manufacturers in trying to follow a steady development programme for constructional products, mistakes on applications were inevitable; these had a retarding effect on the general acceptance of this material by architects and engineers.

The approach of the aluminium industry at the outset, according to one manufacturer (see page 155 of reference 5), was that of considerable caution and an endeavor to follow developments based on sound principles as opposed to a rush to flood the material-hungry market with every type of aluminium product.

However, there were also smaller firms, and stockists who probably did not hold a long term view but were active in the market.

It must also be remembered that practising architects and professional designers, at the time, were not familiar with aluminium alloys, as it is likely that they had not been trained to handle the design of aluminium components and structures.
13.6.1.2 Perceived fire behaviour:

There is considerable evidence that the requirement for a two-hour 'fire-resistant' wall under the 'Building By-Laws' was technically unnecessary in 'unprotected' areas on building elevations. The direct and indirect cost of this wall had a crippling economic effect on the use of metal curtain-walling. Although, it was generally known that the provision of a two-hour 'fire-resistant' wall across the elevation was unnecessary, there was no lead on the part of architects or engineers for getting the regulations changed; this was understandable in view of the complexity of the issues involved in assessing the fire-risks.

In the case of aluminium cladding and roofing applications, it is interesting to note that the question of early melting of aluminium sheet at the spot closest to the seat of fire was discussed both in the text and during the discussion time (see Table 13.9). However, it took almost another 17 years (1959-76) for this property to be accepted by the insurers as a useful attribute, and this change of attitude was brought about only after a positive demonstration of the same in a full scale trial (see 10.2).

Table 13.8 Comments made on corrosion-resistance/durability aspects

<table>
<thead>
<tr>
<th>Page</th>
<th>Comment by:</th>
<th>Actual comment or extracts:</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Pri-Arch.</td>
<td>For more than 30 years an effective whispering campaign has been conducted against aluminium on the theme, &quot;Yes we know it doesn't rust: but it corrodes&quot;. Scientifically the corrosion of aluminium cannot be denied and fortunately, for the whisperers, the most damaging overtones: rodents gawing away at the rotting timbers. Having had in honesty to admit that it corrodes one goes on to add that, like that of copper, the corrosion of aluminium is self-stifling. But that carries no conviction; the word has been admitted and the qualification makes no impression.</td>
</tr>
<tr>
<td>Page</td>
<td>Comment by:</td>
<td>Actual comment or extracts</td>
</tr>
<tr>
<td>------</td>
<td>----------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>38</td>
<td>Pri-Arch.</td>
<td>For public understanding, and for proper use of aluminium by designers, this is the industry's biggest problem: to get across the idea that, except in atmospheres where salt and sulphur combine to make a vicious poultice, if you do not mind what it looks like aluminium may be let alone and forgotten. Are we assured that corrosion on aluminium is self-sealing? You have suggested that a little corrosion is a good thing. Yes, if it stops at a little; corrosion often occurs where you cannot see it, and where it can be dangerous. Can we, as architects, using your material, be assured that corrosion will go only so far as to improve the stability of the building and no farther?</td>
</tr>
<tr>
<td>39</td>
<td>Manufactures of Aluminium windows etc.</td>
<td>Only yesterday I was with a borough engineer who said: &quot;I cannot buy your windows because I have had a number of aluminium clothes-line posts topple over during the past six months&quot;. He maintained that this was due to the inability of aluminium to resist atmospheric corrosion. The company that supplied the posts is replacing them, and undoubtedly this time it will use the right alloy; surely it always comes back to that.</td>
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<tr>
<td>132</td>
<td>Alum. Manufacturer</td>
<td>The fire-resistance regulations are hard to understand. Apparently, the need for a back-up wall does not apply to schools. Is it that in their immaculate wisdom, the authorities have decided that, unlike most of us here today, the young are able to run fast?</td>
</tr>
<tr>
<td>134</td>
<td>Not known</td>
<td>We have had the depressing experience of two large fires in curtain-walling installations: one was a large fire at Brussels airport and the other was at the factory in Bristol. In both cases, the report of the local fire authorities has been that the damage done to the buildings was very much less than it would have been with what we call traditional walling.</td>
</tr>
<tr>
<td>145</td>
<td>Private Arch.</td>
<td>Much of discussion has dealt with fire resistance. This is a vital topic to the curtain wall industry, because if back-up walls can be done away with, the economic case for curtain walling will be vastly strengthened. It has been interesting to hear the views and experience of several continental speakers as well as those of Fire Research Station; without exception, the feeling has been that our present regulations, which insist on back-up walls or fins, are too strict.</td>
</tr>
<tr>
<td>226</td>
<td>Aluminium Manuf.</td>
<td>During the morning session we were given evidence of the value of aluminium cladding for buildings vis-à-vis problems concerning fire risk. It should be emphasized that aluminium is not combustible in anyway. Furthermore, due to its relatively low melting point aluminium melts in areas adjacent to the seat of a serious fire and thereby permits the release of hot gases and fumes - a most important factor the virtues of which are only now being realized. In this way it assists in localizing a fire - which is of considerable importance when considering fire risk: indeed this (early venting of a fire) has been recognised in the Model By-Laws and also by the London County Council.</td>
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13.6.1.3 Perceived aesthetics:

Considerable concern was expressed at the conference about the discoloration (oxidation) of aluminium surfaces on exposure to the natural environmental agencies (see Table 13.10). An examination of the available evidence shows that anxieties expressed about the weathered aluminium surfaces were partly psychological, stemming from an expectation that new materials ought to look similar to old materials both in appearance and character. These objections were to subside as more and more aluminium products were used and the weathered aluminium surfaces became familiar scenes in everyday life.

Today architects and the public generally accept that weathered aluminium surfaces look like nothing on earth but 'aluminium' i.e. aluminium has established an identity of its own along side the so-called 'old' materials; it is also interesting that the old 'snags' of aluminium have generally become a part of its natural characteristics.

There were also widespread fears on the probable monotony created by repetitive curtain-walling of basically similar design patterns, especially because the choice of architects at the time was focused on a typical design (see Table 13.10) Despite such fears, the aluminium curtain walling continued to grow in popularity, probably because, as was stated by one of the authors at the symposium (Table 13.10), the curtain-walling building was perceived as an expression of the spirit of the time and served as a status symbol.

13.6.1.4 Perceived economics:

Table 13.11 shows a sample of comments made on the economics of using aluminium curtain-walling relative to alternative forms of construction; it can be seen that high costs of aluminium constituted a major disadvantage which effectively constrained the greater utilization of this material. There was also an indication by one authority that, because the long term service performance of aluminium was still to be proved, and because its costs exceeded those of alternatives, there was little incentive for specifying aluminium products.
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<tr>
<td>9</td>
<td>Private Arch.</td>
<td>The oxidation of copper makes attractive coloration, but not so that of aluminium.</td>
</tr>
<tr>
<td>49</td>
<td>Arch.A.D.A.</td>
<td>Some architectural critics have expressed dismay at the advent of the curtain wall which would, they fear, result in buildings losing their architectural character and all looking alike. If the architectural expressions of curtain-walling do begin to look similar in appearance, it will be from the architects' and designers' choice, and not as a result of technical limitations.</td>
</tr>
<tr>
<td>89</td>
<td>Eng.</td>
<td>The real reasons why architects and their public enjoy curtain walling are less tangible. The new construction expresses the spirit of our times, both in its appearance and in the very idea that to clothe a building in factory made units is right. In the past weight was regarded as good in itself, it stood for value. We are now moving towards a time when weight no longer matters and it is inevitable that in this transition aluminium should play a leading part.</td>
</tr>
<tr>
<td>92</td>
<td>Eng.</td>
<td>The weathered aluminium has been described as &quot;looking like nothing on earth&quot;. What it does look like is weathered Portland stone, and there is no logical reason why, at close view, weathered aluminium should be thought more displeasing than stone; from street level, the facade will look much the same whether the aluminium members are weathered or new.</td>
</tr>
<tr>
<td>172</td>
<td>Not known</td>
<td>I am told that on stone dirt is acceptable architecturally, but if so, I wonder how it is that so many stone cleaning companies have sprung up in recent years to wash the face of London.</td>
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<td>238</td>
<td>Arch. (Private)</td>
<td>I join issue on the question of appearance and the comparison made with asbestos-cement; as an architect, I hold no brief for either. Also, I believe that plain uncoloured texture of aluminium is preferable to some of the strong colours that one might adopt. I do not like dyed anodised finishes, nor do I like stove enamelling but if the surface had a 'hallowed' effect it would be ideal for large structures.</td>
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<td>239</td>
<td>Local authority architect</td>
<td>I am concerned principally with public buildings. It was easy to persuade people that they could use aluminium in buildings when there was nothing else to get. Aluminium had a wonderful chance when there was a shortage of steel and we had aluminium roofing, cladding, trusses and all sorts of things. Aluminium windows replaced steel windows for example. The point being made now is that we can have all sorts of wonderful things if we can afford them. If we cannot afford to pay for them now, we are told to think of the money we will save in years to come. There is, however, still a very great resistance to be overcome by people who are not convinced that aluminium will stand up to the weathering when it necessarily must be used in conjunction with other materials. Therefore, where cost is at all a problem, people usually finish up by saying: &quot;It might be alright, but we shall be safer with something else&quot;.</td>
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<tr>
<td>134</td>
<td>Alum. Manuf.</td>
<td>Why is it that the full and proper exploitation of curtain-walling had lagged in this country behind? I believe the real answer is one of the cost.</td>
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<tr>
<td>39</td>
<td>Alum. Manuf.</td>
<td>We have the greatest difficulty in competing on price with similar components in other materials. As someone just said about vitreous enamelled aluminium, the more we use the more the price should come down.</td>
</tr>
<tr>
<td>247</td>
<td>Not known</td>
<td>Price is one of the criteria, and a big one. In the old days - 1947 - we had relatively cheap extrusions; they are now twice more expensive. British steel was going at roughly £100 a ton and when that was short we paid an extra £15 for continental steel. Now the situation is completely reversed. Reinforced concrete has become a</td>
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<tr>
<td>247</td>
<td>Not known (con'td)</td>
<td>building medium in the large blocks of flats or offices, and it is ousting steel. Consequently, the steel people are short of work and have cut their price, sometimes supplying fabricated steel work at a loss. It is therefore, difficult at this stage to envisage aluminium being used for simple structures such as sheds. Nevertheless, I feel there will be cases where, even taking that into account, aluminium is the economical solution.</td>
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</table>
Another interesting point, which was brought up at the symposium, is the question of 'first cost' vis-a-vis total cost; it was stated that, though the 'total cost' was a logical criterion for economic comparison, there were, in many public and private projects, budgetary limitations which did not allow the products with higher initial costs to be specified.

Evidently, this problem is still prevailing in the construction market with even more force than ever before.

13.6.1.5 The general state of acceptance of aluminium alloys:

Table 13.12 shows that even though the curtain-walling form of construction was an architectural design cliche of the post-war years, there was still considerable apparent 'indifference' displayed by some architects towards aluminium curtain-walling; this had bewildered the aluminium industry whose intensive marketing policies were not paying off as were initially hoped for. In fact, the evidence in Table 13.12 shows that the architects, and their clients had responded faster and more favourably to initially lower aluminium curtain-walling prices than to the high salesmanship efforts by the industry with emphasis being placed mainly on technical attributes of the material such as low density, high tensile strength, etc.

Table 13.12 also indicates that there are, amongst architects, a number who are prepared to take more risk for the sake of general progress in the construction industry or for other less obvious reasons such as the creation of architectural sensation, etc.

One striking point which emerges from the above review is that it appears that the use of aluminium alloys for curtain-walling, patent-glazing, window and door casements dominated the symposium and the minds of most contributors. This implies that the use of aluminium for primary structural applications such as skeletal frames etc. was not perceived to be either technically efficient or economically viable; the industry also appeared to be more concerned with the successful marketing of the above products compared with aluminium sheeting or structural applications, etc. The industry was
Table 13.12 Comments on general acceptance of aluminium

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<td>36</td>
<td>Aluminium sheet manuf.</td>
<td>Great scope for manufacturers lies in better design for the use of aluminium, but it is also up to the architects to be slightly more receptive to new ideas, so that some of the conventional methods may be discarded when a new material comes along.</td>
</tr>
<tr>
<td>36</td>
<td>Public authority architect</td>
<td>The use of aluminium is of interest to me as an architect concerned with the development of new constructional methods; housing is my primary concern. In this connection, a review of various materials has shown that aluminium in sheet form for low-pitched roofs and external cladding has attractive performance/cost ratios by comparison with other materials. The possible use of this material has been suggested to various local authorities for such purposes, and I should like to mention one of the main reactions: namely, there is still prejudice against certain lightweight materials, such as aluminium. I think this is inevitable, but there is, nevertheless, a general trend towards the use of lighter weight construction, and the inherent advantages that it offers has set in motion a development that seems likely to continue.</td>
</tr>
<tr>
<td>142</td>
<td>Alum. Manuf.</td>
<td>The aluminium industry, in association with the curtain-walling manufacturers, can provide the answers to most of the problems concerned in the development of an efficient curtain-walling system, but we cannot cope with the fire regulations. I would like to make a plea that if there is a chance of reducing the regulations for fire-resistant back-up walls, let us make sure that these are brought into force as quickly as possible, as it will make an enormous difference to the cost and the extent to which curtain-walling will be used in this country.</td>
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<td>144</td>
<td>Insurance Broker</td>
<td>There have been in the past, failures due to colour fading and, more serious failures of the anodic film itself whether coloured or not. It is agreed that, if the most up-to-date technical processes are properly applied such failures need not occur today. Previous shortcomings, however infrequent may cause some architects and/or their clients to seek to secure guarantees, or guarantees may have to be offered to secure business in competition with other materials. (The recorded service experience is so much more satisfying than any guarantee).</td>
</tr>
<tr>
<td>240</td>
<td>Local authority</td>
<td>For a large school contract some years ago we sent out to eleven firms for prices of steel windows. When the prices came in, they were all identical. One of the eleven firms who had quoted said: &quot;Let us quote in aluminium and we shall beat it&quot;. We went out again to the same firms and the price came in cheaper. Today, however, if I went to obtain a price for aluminium windows, they are dearer than steel windows. I am wondering whether that is one of the reasons why aluminium is dearer today and we cannot use it as much as we would like. Is there in fact a 'ring' governing the price?</td>
</tr>
<tr>
<td>247</td>
<td>Not known (ex-manuf)</td>
<td>I have been out of the aluminium industry for four years and I am, therefore, unbiased. I feel, however, that the use of aluminium was largely due to the people who worked with me and to the architects with whom we worked. On the comet flight shed, for example, the architect had the courage to use a brand new material, entrust it to a team of very young engineers, and allow us to build a hanger of 200 ft span. It was built at a moderate cost and was completed on time.</td>
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</table>
probably aware of the fact that where aesthetics are not a prime consideration, the chances of selling a higher priced material (such as aluminium sheeting compared with asbestos-cement or plastics-coated steel sheets) are reduced.

Having briefly examined the state of progress of aluminium alloys in the construction industry up to 1959, attention must now be focused on the original problem, i.e. whether it is possible to estimate the length of time taken up by the so-called "introductory and trial" phase of aluminium products in the construction industry.

It is impossible to separate the effects of postwar shortages of other materials and the stimuli given to the development of aluminium by investment grants and subsidized market provided by the government of the time for bungalows, houses, and schools. Not only did these make the material known across the country, but they also demonstrated alloys in practice - a factor which is of paramount importance in the construction industry.

It is therefore possible that by 1950 every practising architect and engineer must have learnt about the aluminium structures and by a decade later, i.e. roughly the time the A.D.A. symposium was convened in London, sufficient information on the service behaviour of the earliest structures must have been available.

The above reasonings imply that there ought to be a differential rate of growth for periods pre 1954 and post 1954. This year is taken as the basis for comparison, because in 1954, the construction market became totally free from the central government's postwar restrictions, see 2.2. However, the data available do not support this view. Thus, the data on the curtain-walling and allied applications already studied in 13.4.1 show that between 1945 and 1954, the production of aluminium-based systems grew from virtually nil to 915 tonnes; assuming that the first year of commercial production was 1946 in which some 320 tonnes (hypothetical figure) of aluminium curtain-walling etc. was produced; the average annual compound growth rate would be about 14 per cent for 1946-54.
From 1954 to 1971 the average annual compound growth rate was also about 14 per cent; the tonnage grew from 915 tonnes in 1954 to 8391 tonnes in 1974 or approximately by a factor of 9. Clearly, it is impossible to label any portion of the 1945-71 period as the "introductory and trial period" since the average growth rate was fairly uniform over the whole period.

13.6.2 Rapid growth period:

The economies of scale will lead us to believe that as the market demand for a manufactured product increases, it provides an opportunity for the production scale to be increased. Past experience has been that larger production scales tend to bring down the unit costs and the market prices.

Clearly, the extent to which the scale of production can be economically increased is also related to the type of manufacturing process; for a given process, there is a limit to the increase in the scale of production after which diminishing returns will set in.

The phenomenal rise in the production and consumption of aluminium curtain-walling, window and door casement, etc. between 1971 and 1975 cannot be attributed solely to the effects of economies of scale; as has been shown in 13.5, the price ratio \( P_A/P_W \) is the most significant variable in explaining the rapid growth of total aluminium alloys utilized in the construction market; the fall in \( P_A/P_W \) was partly due to 'below-average' rises in the price of aluminium ingots, and partly due to substantial rises in the price of timber (see \( P_{AW} \), \( P'_{AW} \), \( P_W \), and \( P'_{SW} \), Tables 13.5 and 13.6).

In short, as is shown in 13.6.3, the definition of an S-shaped growth curve with a high degree of confidence is not possible, because the construction market appears to be highly competitive.
13.6.3 A concept for materials' substitution:

Based on the observations of the progress of aluminium in the construction market, the following generalization may be noted:

1. A material must be technically suitable for a given application; this condition includes both satisfactory service performance and acceptable aesthetic qualities.

   The latter implies that aesthetic attributes of a given material must be compatible with the design tendencies in architecture.

   The technical attributes of the same material should facilitate a greater degree of industrialization in the building process.

2. Having fulfilled the above condition, the unit cost of the material relative to its alternatives will determine the extent of its utilization in the construction industry; in other words, the ratio of its price per unit effect (e.g. per m² of exterior cladding, see Table 5.2) to those of substitutes is the most significant variable. A relatively modest rise in the price of substitutes may have the effect of changing the balance of economics in favour of the given material in a range of constructional projects.

   It must be emphasized that, in the past, the short-term evidence of satisfactory service performance was often inadequate to specifiers. However, since the second world war, there has been a marked change in the attitudes of specifiers towards innovation; nowadays, short-term evidence of satisfactory service performance backed by scientific data (such as accelerated laboratory tests etc.) are generally accepted by some architects (see chapter 8). The main problem will then be centered on the rewards associated with taking a higher degree of risk. This reward may be connected with the ability to do one's own thing (idiosyncratic designs) or to build to a tight timetable under the pressure from clients or to save space (maximization of the space for letting). More generally, the rewards may be associated with a net cost-saving on an already-established architectural fashion. The latter may also be extended to include the speculative housing market where cost is crucial. The case of PVC plumbing and rainwater goods serves to illustrate this point; in just under 15 years, these
products captured the bulk of the house building market from cast-iron and clayware products.

13.7 **Comparison between the Introduction of Aluminium alloys and G.R.P. composites into the Constructional Industry:**

A comparison between the two materials will be carried out under the five headings already noted in 13.1; these are as follows:

13.7.1 **Differences in properties of the two materials:**

As must be clear to the reader (see Chapters 5 and 13.3) the mechanical properties of G.R.P. composites are inferior to those of aluminium alloys; the same generalized comment applies to the fire properties of the two materials.

However, as far as aesthetic qualities are concerned, G.R.P. panels are superior to corrugated and troughed aluminium cladding or roofings.

G.R.P. composites have the potential of enhancing the aesthetics of industrialized buildings, because components can be moulded into intricate designs and thus cater for architectural initiative and greater variations.

Overall, given the current state of development, and other things being equal, one would expect that the rate of acceptance of G.R.P. would be lower than that of aluminium, unless design and aesthetics potential of G.R.P. are utilized (Note that the use of G.R.P. panels has mainly been confined to custom-designed projects).

13.7.2 **Differences in the economic and technological conditions at the times of introduction of the two materials:**

If we assume that the real marketing of aluminium products started after 1954, it can be seen that after this year the construction industry was expanding (see 2.2); the time of introduction was fortunate especially for aluminium curtain-walling and similar products which symbolized the modern trends in architecture (see 9.2), and were in high demand for most of the time.

As has been moted, the introduction of G.R.P. panels in the late sixties was at a less fortunate time, because of the subsequent recession in the construction industry in 1970 followed by the 1975 depression from which the industry has not yet recovered.
The effects of falling output and the depression on the plight of industrialized building systems were studied in Chapter 11; it was stated that expanding output and rising demand for buildings would create favourable conditions for the use of new materials and construction techniques, especially when the traditional resources (i.e. both materials and labour) are in short supply; conversely, it was seen that the falling demand for construction works coupled with high levels of unemployment and stock-piles of materials would adversely affect the use of new materials, particularly due to increased competition from established materials, and because of political and social pressures against less labour-intensive processes etc.

It must be remembered that the construction market experienced a modest boom in 1972 and 1973; however, it was generally too short-lived to have had a long term stimulating effect on the development and use of G.R.P. products in the construction industry.

From the standpoint of technological differences, it is difficult to make any meaningful comparisons. The construction technology has generally progressed considerably in the last 30 years; the greater use of machines on construction sites, the development of new design concepts and refined structural engineering techniques etc. are but some of the manifestations of this progress. However, as far G.R.P. and aluminium are concerned, this progress is of less relevance, except in relation to the changes in architectural concepts, e.g. 'partnership between architect and the industry' or 'international functionalism' were generally sympathetic to the use of aluminium curtain-walling and other products in the 1950's.

Although, the early drive in the 1960's for greater industrialization of the building process was potentially sympathetic to the use of G.R.P. panels, it did not actually lead to the development of building systems based on G.R.P. composites; the advent of G.R.P. panels was too late (about 1968) to have left any impact on the development of industrialized building systems.
Nevertheless, the gradual recognition of the advantages of construction technologies based on dry assembly of factory finished large panels of lightweight materials has been beneficial to the use of G.R.P. panels.

13.7.3 Differences in the capabilities of the two industries manufacturing aluminium and G.R.P. products respectively:

Production of plastic resins and glass-fibre are both an order of magnitude less capital-intensive compared with the production of primary and secondary aluminium. (If the production of hydroelectric energy is also included, it can be seen that capital investment will be colossal).

The aluminium fabrication industry (i.e. extruders, and operators of presses, diecasting processes, etc.) is relatively more capital-intensive compared with the mechanized processors of G.R.P. products; however, if a comparison is made with the contact-moulding part of the industry, the aluminium industry will show an order of magnitude more capital-intensive.

As was noted, the approach of the aluminium industry to the construction industry has been based on a programme of steady developments based on sound principles taking into account the changing needs of the users etc; this approach contrasts with the sporadic and unco-ordinated developments noted in the case of G.R.P. processors active in the construction market (see 7.2).

Thus, other things being equal, a lower rate of growth would be expected for the future sales of G.R.P. products in the construction industry compared with the growth rates enjoyed by aluminium products, due to the lack of concerted R & D, marketing, etc. by the G.R.P. processors for the construction industry.

13.7.4 Factors connected with the users' satisfaction, perceived advantages and disadvantages of G.R.P. and aluminium products:

As far as the specifiers, clients and insurance companies are concerned, it can be said that both materials were initially received with almost similar responses; e.g. the back-up 'fire-resistant' wall in the case of aluminium curtain-walling constituted a major economic obstacle to the wider uses of this product. Similarly, there is evidence (see 8.7.4 and 10.2)
that there are unjustified fears associated with the use of G.R.P. panels solely on the ground that G.R.P. contains combustible materials; such fears are less apparent in the case of wholly combustible familiar materials such as timber.

Another interesting similar response to aluminium alloys and G.R.P. composites centres on the weathering behaviour and durability aspects of the two materials; it was noted that many architects viewed the surface discolouration (oxidation) of aluminium alloys with suspicion in spite of the evidence presented to them by the aluminium industry which indicated the changes in surface appearance did not significantly affect the structural performance of this material.

Similar responses were recorded in connection with the surface discolouration in the case of G.R.P. panels; it is bewildering to note that the use of plastics-coating on metals for weather protection and aesthetic improvements, is generally accepted but not so that of plastics components (see 8.7.1)

13.7.5 Factors connected with external circumstances such as the need for energy conservation, security of future supplies, the relation to the imports' bill etc.

During the twenty years from 1950 to 1970, the world production of natural gas and petroleum resources expanded substantially and the real cost of energy declined significantly\(^{18}\). The abundant supply of petroleum and natural gas in the above period played a major role in the development of petrochemical and plastics industries; the prices of plastics products fell progressively as the production scales were increased\(^ {19}\).

The low cost of energy also played a major role in the development of the aluminium industry, i.e. it was economic to produce electricity from coal, oil or natural gas in power stations and use it for extraction of the metal in the primary processing for aluminium (see also the footnote in Table 12.10; it can be seen that up to 60 per cent of electrical energy used for the production of aluminium in the U.S.A. is provided from sources other than hydroelectricity).
From the stand point of availability, both aluminium alloys and plastics including G.R.P. were, at the times of their introduction, in a similar position, i.e. both materials were in search of new outlets in the construction market; in both cases, the respective industries were able to cope with rising demands by utilizing their spare capacities of by double shift work, etc.

As far as the external trade is concerned, the production of plastics and G.R.P. is, and has always been, more favourable compared to production of aluminium, because the latter requires importation of bauxite as well as oil for provision of electrical energy. Furthermore, as may be seen from Table 13.13, imports have traditionally accounted for the bulk of the U.K. consumption of aluminium until 1970; from 1970 to 1974, the home smelter production has increased to about 60 per cent of the home consumption; in short, the imported sources have always accounted for a relatively high proportion of the U.K. market.

There is no evidence to suggest that the government have at any time, directly intervened to reduce the quantities of aluminium used in the U.K. construction industry. (See also Table 13.4 which indicates that in 1974, the construction market accounted for approximately 10.5 per cent of the total U.K. consumption of aluminium alloys).

**Table 13.13 U.K. Consumption, Production and Imports of Primary Aluminium in Thousand Tonnes**

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<td>Consumption</td>
<td>235.3</td>
<td>285.4</td>
<td>362.9</td>
<td>404.2</td>
<td>325.6</td>
<td>492.1</td>
</tr>
<tr>
<td>Smelter-Production</td>
<td>26.8</td>
<td>34.6</td>
<td>37.1</td>
<td>39.6</td>
<td>119.0</td>
<td>293.1</td>
</tr>
<tr>
<td>Net imports of crude metal</td>
<td>208.5</td>
<td>250.8</td>
<td>325.8</td>
<td>364.6</td>
<td>206.6</td>
<td>199.0</td>
</tr>
<tr>
<td>Imports as % of consumption</td>
<td>88.7</td>
<td>88.0</td>
<td>89.7</td>
<td>90.3</td>
<td>63.5</td>
<td>40.5</td>
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(Source: Metal statistics 55th - 62nd.edns).
13.8 Forecasting of the Future Trends for the Growth of G.R.P. Products in the Construction Market:

13.8.1 General considerations:

There are various independent evidences which indicate that the demand for G.R.P. products in all industries (including the construction) is cyclic and is closely linked with the state of economic activities as a whole. The above observations on the demand for G.R.P. panels in the past imply that the experience of aluminium alloys may be unrelated to the fate of G.R.P. after all; however, as will be seen later there is some explanation for this apparent disagreement between factors determining the progress of aluminium and G.R.P. in the construction industry.

13.8.2 Statistical analysis of the past trends:

Table 13.14 contains calculations of the index numbers for the total consumption of G.R.P. in the construction industry (Y); this Table also shows calculations of the index numbers for the price of flame-retardant unsaturated polyester resins (P), which, in the absence of more accurate data, is taken as a measure of G.R.P. prices. It will be remembered that this resin is generally specified for the main body of G.R.P. laminates proposed for use on buildings (see 5.2, 5.3, 5.4 and 7.1).

It must be re-emphasized that the statistical analysis of these data cannot be expected to yield any accurate picture of the demand for G.R.P. products in the construction market, since, as must be already clear to the reader, the basis, accuracy and relevance of these data are open to question.

Table 13.15 shows the set of data used as input for the computer analysis using the same programme (MREG), the results obtained are not reported because, all the models tested exhibited wrong elasticity of demand on price. However, in all the analytical models, the index of construction output (O) proved a significant variable though, the correlation coefficients derived from analysing the actual indices or their logarithms were unusually low. The correlation coefficients showed marked improvements when the data were transformed into the first differences. (The same applies to the multiple correlation coefficient R and also to R^2)
Table 13.14  Calculations for Price (P) and Consumption Variable (Y)

<table>
<thead>
<tr>
<th>Year</th>
<th>Total G.R.P. in* the construction (Y) x 10^3 tonnes</th>
<th>Price of UPR - + F.R. (P) £/tonne index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>9.8</td>
<td>220</td>
</tr>
<tr>
<td>1969</td>
<td>11.0</td>
<td>220</td>
</tr>
<tr>
<td>1970</td>
<td>11.5</td>
<td>295</td>
</tr>
<tr>
<td>1971</td>
<td>12.0</td>
<td>300</td>
</tr>
<tr>
<td>1972</td>
<td>13.3</td>
<td>300</td>
</tr>
<tr>
<td>1973</td>
<td>15.7</td>
<td>370</td>
</tr>
<tr>
<td>1974</td>
<td>14.2</td>
<td>600</td>
</tr>
<tr>
<td>1975</td>
<td>12.2</td>
<td>640</td>
</tr>
</tbody>
</table>

* Data based on the following: 1968-72 Table 7.2; 1973-75 Table 7.8
+ Flame-Retardant UPR prices are based on Table 5.9

Table 13.15  Data Used for the Computer Analysis

<table>
<thead>
<tr>
<th>Year</th>
<th>Y</th>
<th>O(1)</th>
<th>P_{UPR-FR}</th>
<th>I_{C}(1)</th>
<th>P/IC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100.0</td>
</tr>
<tr>
<td>1969</td>
<td>112.2</td>
<td>99.5</td>
<td>100</td>
<td>103.5</td>
<td>96.5</td>
</tr>
<tr>
<td>1970</td>
<td>117.3</td>
<td>97.7</td>
<td>134</td>
<td>112.2</td>
<td>119.4</td>
</tr>
<tr>
<td>1971</td>
<td>122.5</td>
<td>100.4</td>
<td>136.2</td>
<td>122.2</td>
<td>111.5</td>
</tr>
<tr>
<td>1972</td>
<td>135.8</td>
<td>102</td>
<td>136.2</td>
<td>130</td>
<td>105</td>
</tr>
<tr>
<td>1973</td>
<td>160.2</td>
<td>105.3</td>
<td>168</td>
<td>153.8</td>
<td>109</td>
</tr>
<tr>
<td>1974</td>
<td>145</td>
<td>96.5</td>
<td>272.6</td>
<td>196.4</td>
<td>139</td>
</tr>
<tr>
<td>1975</td>
<td>124.5</td>
<td>90.7</td>
<td>291</td>
<td>231</td>
<td>126</td>
</tr>
</tbody>
</table>

(1) - Based on O_{I} and I_{C} in Table 13.5.
Finally, the relationship between Y and 0 without any other independent variable was tested; the results showed for the first differences of the data, the model was approximately equivalent to the previous models (where some other variables were also taken into consideration).

It was felt that all of the resulting mathematical models were inadequate for forecasting purposes, because they did not include the effects of price variables in the consumption function; omission of the price variable may be acceptable in the short term for a material such as G.R.P. whose varied end-uses are still dependent on applications where the special attributes of this material are needed (e.g. its ease of shaping in custom-moulded panels, its light-weight property or its low maintenance-requirement, etc.)

However, in the long run, as was demonstrated in the case of aluminium alloys, the demand for G.R.P. products must be a function of the price of these products relative to their alternatives.

The fact that the demand for G.R.P. products in the past was found to be statistically related to the first differences of 0 is in line with the independent observations reported in 13.8.1, whether this relationship will continue to persist in the next 10 or 20 years is open to question, because of the reasons given in 13.8.3

13.8.3 Explanation for the disagreement between G.R.P. and aluminium alloys:

Several likely reasons may be suggested for the different patterns of demand for G.R.P. and aluminium products; some of these are as follows:

13.8.3.1 Data inaccuracies:

It has already been noted that the data used for analysing the demand for G.R.P. are not reliable. In addition, the price of flame-retardant unsaturated polyester resin may be an insufficient measure of the prices of G.R.P. products.

13.8.3.2 Heterogeneity of G.R.P. products:

As was noted in 7.1, the uses of G.R.P. cannot be identified except in so far as the standard products such as G.R.P. sheeting and G.R.P. bathroom components may be
separated from the custom-moulded panels.

In fact, the price for standard products such as G.R.P. sheeting is a highly significant variable (Note the static or contraction nature of the market for G.R.P. sheeting, partly because of the price competition from rigid P.V.C. sheeting as discussed in 7.1)

The data analysed for the uses of aluminium alloys related to 1963-74. In this period, it can be assumed that the bulk of the market consisted of standardized products; hence the consumption was found to be highly related to the price of this material.

In short, the consumption of custom-moulded G.R.P. panels is less price-sensitive compared with standard-products; this point was in fact well established in chapter 8 when the specifiers', reasons for the use of G.R.P. panels were analysed. It was in essence, demonstrated that in the majority of cases, the prime motives for specifying G.R.P. panels were not necessarily associated with cost savings.

The above discussion indicates that the future use of custom-moulded G.R.P. panels cannot be assumed to expand as a function of the increase in volume of construction works, because the latter increases would not necessarily generate a proportionately greater number of projects which would use custom-designed G.R.P. panels. Clearly, the number of projects which could use custom-moulded G.R.P. panels is limited, and is a function of the average cost per m² of these panels. Moreover the architectural fashions may change in favour of other forms of construction such as tinted-glass vertical flush cladding which is the current favourite in the U.S.A. and in the U.K.²³.

13.8.3.3 Stimuli and or constraints due to the expanding or contracting volume of construction works:

As was mentioned previously (e.g. 13.7.2) the introduction of products, which are in competition with established products, is facilitated by an expanding demand for these products; conversely, it can be constrained by a falling demand for these materials because of a combinations of economic, political and social factors already noted.

In effect, because of the limitations, in the short term, in expansion of the output of traditional materials and in the supply of skilled and unskilled labour, the
use of alternative materials can rise faster than the expansion rate in the volume of the construction works; conversely its rate of utilization can fall faster than those of traditional materials because of greater competition and influence of political and social considerations.

Thus, the fact that past consumption data for G.R.P. products used in the construction industry show greater rates of fluctuation than the output of the construction industry itself—and these were found to be sensitive to the changes in the construction output rather than being dependent on its magnitude—is justified.

13.8.4 Forecasting of the future consumption of G.R.P. as a function of the changes in construction output:

Substantial rises in the cost of energy, especially those compounds which are also used as petrochemical feedstocks, initially put the G.R.P. industry in an uncompetitive situation (see Table 5.8; it can be seen that UPR prices in 1973-74 rose substantially).

However, by 1975 when the effects of higher energy costs had been passed on to the prices of traditional materials such as steel, cement, brick, etc. the competitive position of the G.R.P. industry was partially improved. Precise comparison of costs in the case of G.R.P. and traditional materials is impossible, partly due to lack of data on the former, and partly as a result of the idiosyncratic nature of present G.R.P. applications.

However, assuming that with the full costs of energy inputs passed on to the prices of traditional materials, the economic competitiveness of G.R.P. products relative to that of the traditional materials will have reverted to that prevailing in 1968-73, and further assuming that this relative position will not change significantly up to the year 2000, it can be said that the growth of G.R.P. products may be assumed to depend on the changes in the output of the construction industry, provided there will be no major product innovation such as the introduction of standardized G.R.P. panels and units, etc. (see below for a discussion on the validity of the assumption that relative economics of custom-moulded G.R.P. units will remain unchanged with future increases in the cost of energy).
Although, different types of energy command different prices on the market, it is reasonable to assume that up to the year 2000, the costs of all forms of energy will rise in parallel; thus, other things being equal, those products based on lower quantities of energy will be expected to improve their relative economic competitiveness compared with the more energy-intensive products (see Table 12.14). This reasoning implies that G.R.P. will be expected to improve its economic competitiveness compared to brick, concrete, aluminium, etc.

It is therefore probable that the growth of G.R.P. consumption in the construction market will be facilitated and it may experience high growth rates as was seen in the case of aluminium. However, such price effects cannot be predicted partly due to the lack of valid past data and partly because the future cost and availability of various types of materials are extremely uncertain.

To avoid complexity in view of the available data it was therefore decided to dwell on the assumption that relative economics or applications of G.R.P. products will not change significantly in the intermediate run.

The equation used for forecasting is as follows:

\[ \Delta Y = 7.67 + 3.14 \times \Delta O \]

\[ t - \text{statistic} = 4.28 \]

\[ \text{correl. coeff.} = 0.89 \]

\[ \text{S.E. of Est.} = 8.116% \]

\[ \text{Durban-Watson, } d = 1.796 \]

Where:

\( \Delta Y \) = change in the consumption of G.R.P. in the construction industry.

\( \Delta O \) = change in output of the construction industry

Various other models tried showed that the regression coefficient of \( \Delta Y \) on \( \Delta O \) was of the same order as the above.

Using the above equation, the future consumption of G.R.P. has been worked out using three average annual compound growth rates of 1.5, 2.5 and 3.5 for the construction output (see Table 13.16 and Fig. 13.8)
Table 13.16 Forecast Data for Future Consumption of G.R.P. products

<table>
<thead>
<tr>
<th>Year</th>
<th>Actual (x10³ T)</th>
<th>Actual index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>9.8</td>
<td>100</td>
</tr>
<tr>
<td>1973</td>
<td>15.7</td>
<td>160.2</td>
</tr>
<tr>
<td>1975</td>
<td>12.2</td>
<td>124.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>Forecast (1) (x10³ T)</th>
<th>Forecast (1) index</th>
<th>Forecast (2) (x10³ T)</th>
<th>Forecast (2) index</th>
<th>Forecast (3) (x10³ T)</th>
<th>Forecast (3) index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>15.1</td>
<td>154</td>
<td>16.75</td>
<td>171</td>
<td>18.15</td>
<td>186</td>
</tr>
<tr>
<td>1985</td>
<td>17.85</td>
<td>182</td>
<td>21.1</td>
<td>215</td>
<td>24.5</td>
<td>250</td>
</tr>
<tr>
<td>1990</td>
<td>20.6</td>
<td>210</td>
<td>26.0</td>
<td>265</td>
<td>32.0</td>
<td>326</td>
</tr>
<tr>
<td>1995</td>
<td>23.5</td>
<td>240</td>
<td>31.4</td>
<td>320</td>
<td>39.5</td>
<td>403</td>
</tr>
<tr>
<td>2000</td>
<td>26.8</td>
<td>274</td>
<td>37.8</td>
<td>384</td>
<td>51.3</td>
<td>523</td>
</tr>
</tbody>
</table>

NOTES:
Forecast (1): Assumest 1.5 compound % p.a. growth in the Construction output
Forecast (2): Assumest 2.5 compound % p.a. growth in the Construction output
Forecast (3): Assumest 3.5 compound % p.a. growth in the Construction output

The equations used is as follows: \( \Delta Y = 7.67 + 3.14 \times \Delta O \)

The assumed growth rates for the construction output are not high, because, in the decade 1963-73, the actual average annual compound growth rate was approximately 2.1 percent (see Table 2.4).

Forecasts (1), (2) and (3) represent average annual compound growth rates of approximately 2.3, 3.2 and 4.2 percent respectively corresponding to the above three rates assumed for the construction output (c.f. 7.1)

A word of warning must be delivered regarding the validity of the results especially those which are for 1990-2000; this is because of the greater degrees of uncertainty which are associated with the assumption used for the above forecast.
1.5 Compound % p.a. Growth in Construction Output

(2) Ditto, but @ 2.5 Compound %

(3) Ditto, but @ 3.5 Compound %
6. The production figures have been taken from 55th and 62nd. Editions of Metal Statictics, Metallgesellschaft A.G. these were 3546.7 and 13910.6 thousand tonnes in 1958 and 1974 respectively.
8. See page 8 of reference 5.
17. See pages 37 to 40 of reference 4


22. Notes of interviews the author has held with several G.R.P. processors, consultants and UPR resin manufacturer.

14.1 The Need for Applied Research:

14.1.1 The shortcoming in mechanical properties:

In chapter 9, it was concluded that the use of nominally flat G.R.P. panels in mixed systems, is in line with the current design tendencies in architecture and that the future of G.R.P. panels whether standardized modular units or other types, appears to lie in further developing aesthetics of 'flat' designs with shades, textures, etc. compatible with, and expressive of G.R.P. composites.

Given the above objectives, it can be seen that for constructions involving large segment/panels whether suspended vertically on facades where the wind loading intensity is high, or suspended horizontally as roof elements, etc. the relatively low specific creep flexural modulus of G.R.P. is a serious disadvantage. Apart from matters associated with the structural engineering and safety aspects of these constructions, it is generally recognised that excessive deflection or sagging of panels or structural elements visible to the eyes is aesthetically unacceptable and may cause psychological distress to building occupants (see 6.2, Tables 8.15 and 8.20).

Improvements to the specific flexural modulus of G.R.P. may be brought about by adopting one, or a combination of the following methods:

(a) The use of a stiffer matrix in the place of polyesters.
(b) Inclusion of higher proportions of glass fibre and stiffening fillers than normally used.
(c) Employment of stiffer fibres as substitutes for glass fibre.

The possibility of achieving any of the above improvements is discussed below.

14.1.2 The use of a stiffer matrix in the place of polyesters:

Judged by properties of common plastics, discussed in 4.1, substitution of any other plastic resins for polyesters does not offer the prospect of substantial improvement in the composite stiffness of G.R.P. This is seen by reference to Table 4.2 and 4.6 and also from theoretical considerations of properties of composites in 4.2.2 where it may be seen that the
composite stiffness ($E_c$) is principally influenced by the stiffness of the reinforcing fibres. Thus, the composite stiffness of an unidirectionally reinforced glass fibre/polyester resin composite containing 70 per cent glass by weight is three times that of random G.R.P. containing about 30 per cent glass by weight (see Table 5.13).

Current interest is centred on the use of 'cold-setting' phenol-formaldehyde resins for low pressure moulding in association with glass fibre. The main reason for developing this technological innovation is not, however, linked with improving the composite stiffness of G.R.P.; any slight improvements which will result from substitution of phenolic resins for polyesters will be incidental (see also 14.1.7 for a discussion on reactions-to-fire properties of phenolic resins etc).

It must also be observed that as far as the author is aware, there are not, so far, any other plastics under commercial development which would be potentially capable of substituting polyester resins for greater stiffness.

14.1.3 Inclusion of higher proportions of glass fibre and stiffening fillers:

As was noted in detail (see 5.5), the proportion of glass-fibre and fillers which can be incorporated in a G.R.P. composite is dependent upon the production process. Glass fibre contents in excess of 40 per cent by weight can be incorporated into the G.R.P. composites processed by the cold-press and/or resin injection moulding techniques. In the former process, the proportion of inert fillers such as calcium carbonate may also be high. These processes can produce much stiffer mouldings compared with the contact-moulding process (see 5.5).

The use of the press-moulding process calls for production volumes many times greater than those normally required in the case of the contact-moulding process (see 5.5); thus, their employment involves product innovation (standardization etc), which will be considered in section 14.2. However, it must be emphasized that G.R.P. composites with glass fibre contents of up to 70 per cent - the highest possible limit - still have lower values of specific flexural modulus compared with mild steel or aluminium alloys. As Table 4.6 shows, the specific tensile modulus of a polyester/glass cloth containing 55 per cent
by weight glass fibre in approximately 36 per cent of that of aluminium or mild steel; therefore, other means of improving the composite stiffness of G.R.P. should be considered.

14.1.4 Employment of stiffer fibres as substitutes for glass-fibre:

Table 4.1 contains information on two fibres which are stiffer than glass; these are:

(a) asbestos fibre, and
(b) carbon fibres.

14.1.4.1 Asbestos fibres:

The modulus of elasticity of asbestos fibre is typically three times that of glass fibre; further, this fibre is relatively inexpensive (see Table 4.16). However, asbestos fibre is not considered a candidate for substitution of glass fibre because of the following reasons:

1. Health hazards associated with the handling, using or processing of asbestos - reinforced polyester resins, especially in the contact-moulding process (see 4.5.3.2.)

2. Asbestos fibres do not exhibit good wetting properties when used in conjunction with polyester resins. This means that the use of asbestos fibres is limited to those processes in which the resin is cured under pressure, e.g. compression moulding.

3. In addition to 1 and 2 above, considerable reluctance is being displayed by most corporate clients and the public for using asbestos-based products. Thus, British Railway Board have banned the use of asbestos products; therefore, the use of asbestos fibres does not offer a commercial prospect for G.R.P.

14.1.4.2 Carbon fibres:

As was noted previously, carbon fibres are technically very desirable as their modulus of elasticity is typically 4 to 6 times greater than that of E-glass fibre. However, the phenomenal price of this material at the present time prohibits the general application of this material for constructional uses (c.f. Table 4.16)

The future prospect for price reduction of carbon fibres is encouraging. Hilling reports that the price of this material may fall from about §60 per pound to §10 per pound, assuming that £1 = §1.63, the corresponding prices are £82/kg and £13.5/kg respectively.
It can be seen that both in terms of current and future prices per unit weight or volume, carbon fibres are highly uneconomic (the price of E-glass fibre is currently about £1/kg.)

The technology of polymeric fibres has recently received a major boost by the successful development of a new generation of high strength/high modulus (HS/HM) fibres; the polymer used is polyaromatic-amide (aramide); this polymer has a geometric molecular structure which prevents the polymer chain from coiling. Thus, most of the fibre strength and stiffness are derived from the stretching action of the C-C bond rather than from uncoiling and flexing actions in normal polymeric fibres which usually account for the relatively low modulus of these fibres.

Du Pont and Monsanto independently developed the process of producing HS/HM aramide fibres and both firms have undertaken commercial production of these fibres. Current prices are reported to range from $3.5 to $8.5 per pound (i.e. £4.5 to £11.5 per kg); however, it is expected that prices will fall as the production volume is increased.

HS/HM aramide fibres are presently produced by spinning from a liquid crystal solution. The modulus of these fibres range from 60GN/m² for fibres used as tyre cord, to about 135GN/m² for those suitable for use as reinforcement for rigid matrices. No reference has been made to the potential of the latter type fibres for reinforcing viscoelastic matrices.

HS/HM fibres are light in weight (specific gravity = 1.4); they are light in colour (thus better than carbon fibres) and are resistant to moisture and water. Although based on organic materials, they have been claimed to improve the resistance to burning characteristics of the composites made from them, compared with those made with inorganic fibres, such as glass fibre. This is because, these fibres are not heat-conductive. The trade names of high modulus fibres which are of interest in the construction industry are 'Kevlar - 49' from Du Pont and 'X-500-G' by Monsanto.

Other developments in the field of composites may also reach commercial exploitation. The recent discovery of one-component polyethylene composite in an example. The extrusion of polyethylene under very high pressure (2500 atmosphere) at a temperature of about 734°C resulted in fibres consisting of
parallel crystalline polymer fibrils. These fibrils have been used as reinforcement in a matrix of normal polyethylene hence a one-component composite. The polyethylene fibrils are claimed to have a modulus close to that of E-glass fibre.

One distinct property of HS/HM aramide fibres is reported to be their weakness in compression. This means that the high modulus type HS/HM fibres are particularly good candidates for reinforcing rigid and brittle type matrices such as hydraulic cement paste.

No test results have as yet been reported on incorporating these fibres in either a rigid or a plastic matrix; it is not therefore possible to arrive at any meaningful conclusion on these remarkable fibres which hold the potential of revolutionizing the future of composites in the construction industry especially in association with Portland cement (c.f. 15.3).

There is a need for concerted efforts to explore the new possibilities which have been opened up by the new generation of polymeric fibres; there is every reason to believe that the future designers/users of composite materials will be able to tailor the composite properties to suit their performance specifications; this may be done by suitable choice of fibres and matrix and also by variation of the fibre volume fraction (c.f. chapter 4).

14.1.5 The shortcomings in the 'reaction-to-fire' characteristics and the 'fire-resistance' performance of G.R.P. composites:

It has already been noted that in the absence of flame-retardant additives, general-purpose polyesters burn with relative ease; G.R.P. mouldings produced from these resins cannot satisfy either class 0 or classes 1 and 2 requirements when tested to BS 476 parts 6 and 7 respectively (see 4.2.10 and 5.4.3).

As was noted in 4.2.10 both Het-acid resin and antimony trioxide/chlorinated-wax filled resins are more resistant to molecular decomposition in conditions of fire and when used offer improved reaction-to-fire characteristics. However, substitution of flame-retardant polyester resins for general-purpose resins in G.R.P. composites cannot improve the 'fire-resistance' performance (to BS 476:8) significantly.

The methods of imparting flame-retardancy outlined above are based on the generation of large volumes of dense smoke which would restrict oxygen from reaching the seat of combustion; the result is a slow, smouldering, mode of combustion.
As was seen in Chapters 8 and 10 (see 8.7.4 and 10.1.7.4) both specifiers and clients are very concerned about the smoke hazards associated with the use of G.R.P. panels in the construction industry. It has already been shown (see 5.4.3) that smoke and released gases can create both physiological hazards due to toxicity and irritancy effects, and psychological hazards due to reduced visibility through smoke, state of panic, etc.

Not only do flame-retardant polyesters emit large volumes of smoke, but they also release highly noxious fumes such as hydrogen chloride etc.

There is considerable evidence\(^5,\)\(^6,\)\(^7\) that the resin manufacturers are conscious of the fire and smoke problems of polyester resins; as will be seen below, they are engaged on various scientific research for overcoming these problems.

There are three ways of reducing or eliminating the fire and smoke hazards of G.R.P. mouldings:

(a) Development of truly effective 'fire-retardant' additives with substantially reduced volumes of smoke and noxious gases.

(b) Substitution of plastics, with superior 'reaction-to-fire' characteristics for polyesters.

(c) The use of an incombustible matrix reinforced by either inorganic fibres or by polymeric fibres.

The future possibility of achieving the required minimum fire-retardancy and fire-resistance standards by employment of one, or a combination of the above methods, is considered below.

### 14.1.6 Development of truly effective 'fire-retardant' fillers with substantially reduced volumes of smoke and noxious gases:

Additives are generally of two types: chemically active such as antimony-trioxide/chlorinated-wax fillers, and chemically inert fillers such as calcium carbonate powder, alumina-hydrates, etc.

As was noted previously (see 5.4.3), current interest is focused on solutions based on the latter types of additives such as alumina-trihydrate. However, there is a limit to the amount of inorganic fillers which can be incorporated into a resin; this limit is not only dependent on the type of production process. It is also dictated by durability considerations (i.e. satisfactory...
Based on current knowledge, the probability of success is generally higher with the use of inorganic fillers of the following characteristics:

(a) To be chemically inert: at normal temperatures; there should be no chemical reaction between the filler and the resin or glass fibre.

(b) To react to the rise in temperature: the filler should react to the fire at an early stage and should protect the organic materials from combustion.

(c) The above characteristics should be effective at a low level of filler content (i.e. approximately below 20 per cent of the weight of the resin).

The use of phosphate glass fibre developed recently (1976) by ICI can be seen as an approach which fulfils the above criteria.

Phosphate glass consists of the following inorganic materials: \( \text{P}_2\text{O}_5 \) 58-76 moles\%, \( \text{ZnO} \) 5-30 moles\%, \( \text{Li}_2\text{O} \) 5-25 moles\% and one or more alkaline earth metal oxides 0-10 moles\%. The resulting glass is claimed to be resistant to water. Transformation temperature of phosphate glass is in the range of 140-280°C depending on the molecular water content.

It is claimed that the phosphate glass melts at an early stage of exposure to fire forming a protective layer of fused glass which prevents oxygen from reaching the resin behind it. If a blowing agent capable of decomposing on heating is also included in the composite, it will foam the fused glass, thus extending the fire protection action.

The use of phosphate glass fibre has been claimed to have no associated adverse effects i.e. neither will they reduce the mechanical properties of the composite relative to E-glass fibre, nor will they lose their effectiveness on aging and exposure to natural environment. The organic fillers tend to leach out from the body of the composite and lose their effectiveness on aging.

No reference has been made to the smoke abatement performance of phosphate glass fibre/polyester resin composites; however, it is likely that the smoke emission will be considerably reduced, especially in the early stage of fire, because the resin will be prevented from combustion by a protective layer of fused or foamed glass. Further, the general-purpose polyesters which will be used in these composites will produce less smoke compared with
the flame-retardant resins. (It will be seen that the effect of phosphate glass on the combustion of gel coat will be negligible since it is not generally present in the gel coat).

ICI Ltd. claim\(^7\) that the use of phosphate glass-fibre confers a high degree of fire retardancy; however, no results have been published of tests in accordance with BS 476 parts 6 and 7.

In addition, no indications are available of the likely cost of phosphate glass fibre and the required fibre volume in normal G.R.P. panels. There is as yet no commercial production of phosphate glass fibre.

A major production advantage of phosphate glass fibre is associated with its low melting point; thus, its production may be less energy-intensive compared with E-glass fibre. However, the main constituents of phosphate glass which are \(P_2O_5\), ZnO and \(Li_2O\), are more costly per tonne than the corresponding materials in E or A glass fibre, because \(P_2O_5\), ZnO and \(Li_2O\) occur less commonly in nature.

Another cost advantage of phosphate glass fibre/polyester resin composites is associated with the use of general-purpose resins; these are less costly compared with the flame-retardant grades. (see Table 5.9)

As may be observed this innovation is in its infancy and it may prove to be an effective solution to the fire and smoke hazards associated with the present G.R.P. applications in the construction industry.

14.1.7 Substitution of plastics with superior 'reaction-to-fire' characteristics for polyesters:

Phenolic resins, especially phenol-formaldehyde (PF) formulations have improved 'reaction-to-fire' characteristics and in conjunction with other materials they exhibit improved 'fire-resistance' performance compared with polyester resins (see Table 14.1); they are also the cheapest of all thermosetting resins (see Table 4.4).

As was noted in 4.2.9, the use of phenolic resins in the place of polyesters has not been possible because the curing of these resins had, until recently, been carried out under high pressure and temperature; the processing of these resins is incompatible with glass fibre since, the fibres receive severe damage under the pressure.
The recent breakthrough\textsuperscript{6, 13} in the technology of phenolic resins has made it possible to use these resins in practically all familiar processing techniques employed for polyester/glass fibre composites except in the hand-lay-up method. The curing of the new types of phenolic resins is at low temperature and is carried out under influence of catalysts and initiators in a manner similar to polyester resins\textsuperscript{6, 13}.

The viscosity of phenolic resins is higher than polyesters; as a result, they do not wet out glass fibre surfaces in the hand-lay-up method\textsuperscript{13}.

However, spray-up equipment basically similar to advanced commercial equipment have been used successfully\textsuperscript{13} for depositing phenolic resin/glass fibre systems; the mould temperature is required to be kept at above $40^\circ$C, otherwise the process is similar to polyester/glass fibre systems\textsuperscript{13}.

It must be noted that the fire-retardancy of phenolic resins is an inherent property of these materials; they generally contain no additives and their fire properties do not alter on aging\textsuperscript{13}.

If the quality is controlled, there will be virtually no free phenol or formaldehyde, thus no risks of corrosion in contact with metals\textsuperscript{13}.

It is generally understood\textsuperscript{13} that attempts have been made to develop phenolic gel coats, with characteristics of uniform and controlled discoloration; the choice of colour has been limited to pastel red, brown, rustic and similar shades. Considerable success has apparently been made in this direction\textsuperscript{13}.

The commercial introduction of new phenolic resins has not been forthcoming. The reason for relative caution on the part of developer of these resins is attributed to his existing involvement in polyester resins and the capital investments etc. already committed to polyesters. The market for polyesters would be adversely affected if phenolic resins were introduced without due caution. Also, the producer has long term contracts for supplying polyester resins to some major users.

From an overall commercial point of view, it may be in the interest of the G.R.P. industry that the improved resin systems are put into use without undue delay. The industry should also plan for a large tonnage market in order to ensure that resin prices will fall quickly as the production volume develops;
Table 14.1 Fire properties of phenolic-based laminates or phenolic foams (References 5, 9)

<table>
<thead>
<tr>
<th>Property</th>
<th>Test method</th>
<th>Performance</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface flame spread</td>
<td>BS 476:7</td>
<td>Class 1, nil spread</td>
<td>phenolic resins char in the vicinity of flame</td>
</tr>
<tr>
<td>Fire-Propagation</td>
<td>BS 476:6</td>
<td>Class 0 possible</td>
<td>With selected facing materials (see performance data contained in references 5, 9 and 10)</td>
</tr>
<tr>
<td>Optical transmission</td>
<td>BS DD36/74</td>
<td>Over 95% Optical transmission</td>
<td>(c.f. &lt; 50 polyesters) Tests have shown that the toxicity of emitted gases is similar to those of mineralized boards (reference 11). Products of combustion are: crystalline carbon char, CO₂ and water vapour; see references 9 and 12).</td>
</tr>
<tr>
<td>Fire-resistance</td>
<td>BS 476:8</td>
<td>&gt; ½ hour</td>
<td>(c.f. &lt; 10 minutes for polyesters). Phenolic foams used as rigid cores in sandwich constructions can achieve 'fire-resistance' performances in excess of one hour (references 5 and 9).</td>
</tr>
</tbody>
</table>
fortunately, this is possible, because the same resins are used for producing closed-cell rigid phenolic foams\textsuperscript{13}, which is currently being marketed in Britain in the place of polyurethanes, isocyanurates, polystyrene, etc. in situations where fire and smoke hazards of these groups of insulating materials are high.

Phenolic foams exhibit remarkable resistance to the penetration of fire; when used as the core materials in sandwich panels with selected facings such as aluminium and steel sheet, G.R.P., plaster-board, etc. they can register 'fire-resistance' performance in excess of one hour for metal/plaster board facing\textsuperscript{5, 9, 13} and half hour in the case of G.R.P. facing\textsuperscript{5, 9, 11}.

It is interesting to note that the market for the new type of phenolic foam\textsuperscript{9} is growing by 100 per cent per annum\textsuperscript{13} and the market size is expected\textsuperscript{13} to be of the order of 10,000 tonnes in 1980.

The adoption and development of phenolic resins/glass fibre composites has an additional benefit in that very small moulders will have to close down, because they cannot produce hand laminated panels using phenolic resins.

Also, the use of phenolic resins is reported\textsuperscript{13} to suit the resin-injection technique which is more capital-intensive compared with the spray-up technique.

Lightweight sandwich panels may be developed using glass-fibre reinforced phenolic facing, a core of rigid phenolic foam and an inner lining of plaster-board (or G.R.G.); the exterior may be coated with attractive and durable coatings, e.g. PVF, alternatively phenolic gel coats may be sprayed etc.

Products of this nature will have vastly superior thermal insulation performances compared with traditional forms of construction and will be expected to have 'fire-resistance' performances in excess of one hour or if desired one and a half hours with increased thickness of G.R.G. inner face; they are particularly ideal for production of standardized panels for use on a variety of buildings.

14.1.8 The use of an incombustible matrix reinforced by either inorganic fibres or by polymeric fibres:

This option is not of interest to the plastics industry except when the use of a polymeric fibre is involved.

However, from the stand point of the construction industry,
the efficiency of the finished product in the given task at a competitive price is the criterion for choice of materials. It may be argued that the use of hydraulic cement paste in the place of polyesters will change the aesthetics and visual quality of products so drastically that architects and engineers would no longer be interested in its use. The evidence from the use of G.R.C. does not support this argument, e.g. G.R.C. cladding panels have been used extensively on the new Crédit Lyonnais building in the City of London. The architect in charge of this project is reported\(^{14}\) to have said this "I don't think you should compare G.R.C. with concrete. It is a material of its own right. I would like to recommend it to other architects". Each panel in the above project, which weighed approximately 250 kg, has a protective silicone coating and is mounted on an outward lean of about 5\(^{\circ}\) to reduce the maintenance requirements\(^{14}\). A review of the mechanical, fire, durability and other properties of G.R.C. was given in sections 4.3 and 4.4. In particular it was noted (see 4.3.1) that the modulus of elasticity of glass fibre is generally inadequate for reinforcing the cement paste. The substitution of HS/HM polymeric fibres for alkali-resistant glass fibre (Cem-Fil) appears to produce ideal composites provided the interfacial band will prove to be satisfactory. The advantages of these fibres as reinforcement for hydraulic cement paste are likely to be numerous chiefly:

1. The elastic modulus exceeds glass fibre by a factor of 2; this will mean that the fibres will come under load at an early stage relative to glass fibre.

On an equal weight basis the stiffness of HS/HM fibres exceeds that of 'Cem-Fil' by a factor of approximately 3.33

2. The tensile strength of HS/HM fibres is greater than both E and S-glass fibre (on an equal weight basis, it is greater than 'Cem-Fil' fibres by a factor of about 2, on a volume basis it is about the same).

3. The HS/HM are approximately 40 percent lighter than glass fibres.

4. The HS/HM fibres are resistant to water-alkaline solutions etc. There will be little or no concern about the durability
of composites produced from these fibres (c.f. G.R.C. 4.4.3).

5. The 'fire-resistance' performance of composites made from the above fibres and Portland cement matrix is not expected to be significantly lower than G.R.C.; this is because polymeric fibres are non-conductive of heat; therefore, unlike glass fibre, they do not dissipate heat to other parts of the composite. (Fibres which conduct heat can expand when exposed to high temperatures; this phenomenon causes scaling and disintegration of the composite).

In short, the future prospect for HS/HM/cement composites appears to be good; further research should therefore be undertaken to advance the knowledge on the properties, methods of fabrication, etc. of these composites.

14.1.9 The need for basic research to improve the reaction-to-weathering characteristics of G.R.P. composites:

As was noted in 8.6.2 (Table 8.9), 10.1.6.1 and 10.1.7.2, there is ample evidence that a large number of specifiers and their clients are dissatisfied with the reaction-to-weathering characteristics of G.R.P. panels.

In a quality-sensitive material such as G.R.P. there is always a risk of poor quality products being sold to customers, especially when the quality procedure is not rigidly adhered to. Other factors may also contribute to the poor weathering reaction and discolouration of G.R.P. surfaces e.g. the use of highly filled fire-retardant gel coats, or the wrong-type of resin. Unsuitable colours may also fade fast.

As far as the basic research on the resins is concerned, the objective must be to develop resins with higher degrees of resistance to solar radiation, and other environmental effects such as moisture and temperature. Alternatively, gel coats should be omitted altogether and in their place a more durable but thinner coating of plastics applied, e.g. the use of polyvinyl fluoride (PVF) coating or high quality polyurethane coating are preferable to a gel coat of polyester resin.

The main body of mouldings may be produced from a fire-retardant fire-resistant composite and sprayed with a durable and pleasing coat from one of the above formulations. Another advantage of using a separate finishing coat is in the improved uniformity of the colour and appearance of the mouldings.
The reaction-to-weathering of G.R.P. is not only controlled by the type of protective coating used, it is also dependent on the surface roughness, panel orientation, geographical location, etc. These factors concern the design and use of the panels.

14.2 The Need for Development:

14.2.1 The need for reduction of unit costs of G.R.P. products:

In order to increase its competitive position, the G.R.P. industry must try to bring down the unit costs of its products; this can be done by one or a combination of the following methods:

(a) Substitution of cheaper resins for fire-retardant polyesters.
(b) Improvement in the design of products for maximum economy.
(c) Mechanization of the production process.
(d) Mechanization of the production process coupled with standardization of products.

The possibility of achieving a greater degree of economy together with performance improvements is considered below.

14.2.2 Substitution of cheaper resins for fire-retardant polyesters:

Based on present day prices, it appears that the new generation of phenolic resins are the best candidates; their suitability on technical grounds have already been noted (see 14.1.2 and 14.1.7); their suitability on economic grounds is due to the following:

1. The price of phenol-formaldehyde resins of laminating quality is approximately £400/tonne; this is about half the fire-retardant polyesters.
2. Unlike polyesters, phenolic resins do not need expensive initiators and catalysts.
3. Based on two chemicals (e.g. phenol and formaldehyde), phenolic resins require less processing compared with polyesters which require three stages of processing, ie. first, to produce chemicals such as naphtha and benzene; second to produce styrene, glycols, anhydrides etc. and finally to produce unsaturated polyester resins. Thus, it is likely that phenolic resins will remain cheaper than polyesters.
14.2.3 Improvement in the design of products for maximum economy:

In sections 5.6 and 5.7 and also in chapter 6 it was shown that the design of a panel had a significant effect on its total costs. It was noted that for maximum economy the weight of materials input must be kept to an absolute minimum.

In order to achieve this objective, structural configurations should be devised which would be highly compatible with the properties of G.R.P. i.e. they should derive their stiffness primarily from the shape of the structure. Shells, folded-plates, and similar geometrical configurations were shown to be very suitable in fulfilling the above requirements; however, as was noted subsequently (chapter 9) the applications of these structures were found to be limited.

The tendency for architectural facades to be 'flush' means that G.R.P. panels must be designed as nominally flat and that each panel must show sufficient resistance to buckling and distortion individually. This is not compatible with the mechanical properties of G.R.P. unless G.R.P. is used in composite with other materials such as sandwich constructions.

The technology of manufacturing large load bearing sandwich panels is not very advanced; there are numerous economic and technical factors to be resolved e.g. the bond between the facing and the core of a sandwich panel may be a problem, and, as was shown in 6.5.3, it can render theoretical considerations invalid. Development of economic and efficient methods for producing room-sized panels and/or cells in sandwich constructions will be of paramount importance.

A point to be emphasized is the fact that it is generally uneconomic to undertake R & D for small projects using structural sandwich constructions. This is not only due to the need to prove the structural performance of each design by means of full scale load bearing tests. It is also due to the need to prove the ability of the given design to satisfy other performance requirements such as fire, thermal, acoustic, jointing, fixings, etc.

The concept of sandwich and/or composite designs lends itself very well to standardization of products and employment of mechanized production processes which will be noted later. It also allows gradual developments of designs with thermal-insulation and moisture-resistance performances vastly superior to traditional forms of constructions (provision of a high standard of thermal insulation without the risk of moisture
penetration has not always been successful in the case of traditional cavity-filled masonry or concrete structures).

In short, the design and production of sandwich panels must be optimized in respect of both costs and performance capacities. There is also a need for development of a fault-proof jointing system; development of these may be undertaken within an integrated framework of product planning, marketing, production and warehousing, distribution and site erection, maintenance and customers' services, etc. of a proprietary building system (see 14.2.5).

14.2.4 Mechanization of the production process:

Assuming that there will be no standardization of G.R.P. panels and G.R.P. processors will continue to rely on custom-designed projects as the principle method of obtaining business orders, it will be seen that there is little scope for introducing mechanization, because, as was seen in 7.2.2.9, the unit repetition of a typical custom-designed G.R.P. project is below 500.

In such cases, as has been illustrated by Ives et al.\textsuperscript{15}, the optimum mechanization is limited to the use of standard hand held G.R.P. spray-up equipment. Only in exceptional cases where products of higher quality and performance are required or where the unit repetition is of the order of thousands is it possible to employ more mechanized production processes such as press-moulding, resin injection, etc.

Clearly, the spray-up technique is not the ultimate in labour-saving techniques\textsuperscript{5,15} and will improve the economics of G.R.P. processing by a marginal amount. A more fundamental process innovation would involve product innovation and standardization on the scale which would have serious repercussion on the organisation of the G.R.P. processing industry.

14.2.5 Mechanization of the process coupled with standardization of products:

Production of G.R.P. units may be mechanized if the unit repetition is such that the finished cost of producing one unit will be less or equal to the cost of producing the same unit manually. Under present day economic conditions, a unit repetition in excess of 5000 to 10,000 is required depending on the size, design and quality of the unit (see 5.5.2).

The economic advantage of mechanical production techniques is that with the maximum volume of production being in the range of 50,000 to 200,000 for a set of matched metal dies made of mild steel and chrome-plated hardened steel respectively, it is possible
to bring down the unit costs of products significantly, because of the influence of the following factors:

(i) The tooling costs will be amortized over a larger production volume

(ii) The same argument applied to the fixed costs such as overheads etc.

(iii) The labour input per unit production is low; thus, it is possible to increase the productivity per employee.

Production of repetitive units of the above order (greater than 5,000 - 10,000) requires the following efforts:

1. Market research: the objectives must be: firstly to identify the range of projects e.g. if house building market is desired, the range of residential units, the frequency of occurrence and the past trend in these should be investigated; secondly to see which components or segments in these units can be standardized along with their associated performance requirements, and thirdly to record the range of opinion expressed by corporate clients regarding the possibility of combining their requirements with those of others in order to narrow the range of requirements, etc.

2. Design and development: The above information must be used by a team of designers comprising an architect, a civil/structural engineer, a G.R.P. (composite materials) production engineer, and others (if required) to produce design details and performance specifications for a range of units produced by a few basic tools. The possibilities of surface variations such as embossment, recessing, texturing, etc. must be provided by bolting of additional metal plates onto the moulds' surfaces using concealed fixings or similar arrangements. Furthermore, modular dimensional variation in units must be provided by adding intermediate pieces of metals, etc; thus, whilst keeping the tooling costs to an absolute minimum, it must be possible to cater for a range of designs. Account must also be taken of the possibility for incorporating glazing sheets, louvre, ventilation grilles, etc. Jointing, curvature, guttering and other visible features should be designed to express the 'plastic' quality of this material and not designs in other materials. Special attention must be paid to ensure that functional efficiency of internal spaces are not affected by the geometry of the structure. In short, maximum flexibility in application
must be aimed for with a high standard of quality and finish.

3. Marketing: It is preferable to carry out design and development of standardized units in association with various corporate clients who could use the resultant components on their buildings. However, intensified marketing should start concurrently to market the products: this should include the following:

(a) Identification of the potential markets and means of selling: Association with private developers, building contractors, etc. should be explored on a mutually profitable basis. Also, direct selling of components/units for incorporation in various other projects should be investigated in co-operation with builders' merchants.

To keep the initial prices down, large final production volumes should be planned for at the outset.

(b) Advertising: Advertising should be in the technical journals serving the construction industry.

Advertisements should be designed to convey the major advantages of the products, especially its potential for direct and indirect cost-saving; in addition, they should emphasize the aesthetics and high standards of finish, etc. of the products. Promotion of the image of the company and its products should also be taken into consideration.

(c) The provision of information: Technical data sheet, design manuals, etc. should contain details of performance tests relevant to the product; this information should assist in obtaining approval under the building regulation.

(d) The effectiveness of sales polices should be reviewed regularly and modified as necessary.

(e) Continuous product improvement: It must be ensured that the performance of the given product is improved and its costs reduced. This means that the changing needs of clients in the construction industry must be taken into consideration; the R & D effort must be directed towards identifying the intricacies of the requirements in the construction industry and modifying the products to reflect the same.
CHAPTER 14. References


7. ICI Ltd. "Fire-retardant compositions", Brit. Pat. 1404 621

8. ICI Ltd. "Phosphate glass", Brit. Pat. 1404 622


11. Hollaway, L. and Partington, R. "The Analysis and design of a G.R.P. space structure prototype classroom" Paper 56, 2nd, Int. Conf. on Space Structure, Department of Civil Engineering, University of Surrey, Sept. 1975 (p 487)

12. QMC Industrial Research Ltd. "Comparative fire testing of 'Phenex pan' and isocyanurate foam", Author of the report: Dr. R.J.S. Green, 25th November 1975 (project 00/440).

13. Interview notes with Mr. Eddy Norman. Technical Director of APA Foam Products Ltd., on 11th November 1976

14. See page 8 of New Civil Engineer, 29th April 1976

15.1 Process of Acceptance of a New Material in the Construction Industry:

15.1.1 Process of selection of materials:

As been noted in the preceding chapters, decisions to incorporate materials or components into construction projects are generally taken by architects and engineers. Thus, unlike oligopolistic industries, there is no centralized control over the adoption of potentially useful innovations. Moreover, as was seen in chapters 2 and 3, there is no competition between the specifiers and hence no urgency to adopt those innovations which are potentially capable of reducing the unit cost, or improving the efficiency of construction projects, especially if the adoption of the given innovation carries a high degree of risk.

The only cost competition which may exist is in the field of speculative housing, office or factory development undertaken by property companies who may use the 'all-inclusive' package deals (or system buildings) offered by the major contractors.

Lack of centralized control over the choice of materials or construction techniques, the heterogeneous nature of demand and the scattered locations of construction sites have resulted in the industry functioning in a haphazard manner, especially given the localized nature of the market demand and the protection from competition brought about by the comparatively high costs of transporting bulky and dense materials. The only control exercised over the choice of materials is that of specifiers. These specifiers, by nature of their numbers and differences in training do not exhibit a unified pattern of control over the adoption of new materials or construction techniques. There are, however, certain common tendencies which are characteristic of architects and engineers: the strong influence of fashion in architecture or the strong tendency to follow established methods of construction, etc. Furthermore, the choices of specifiers are generally constrained by conformity with the current planning/aesthetic control and approval under the current building regulations or with the 'cost-yardsticks'
or overall budgetary limitations (see Fig. 15.1).

To some extent, some clients have control over the cost and efficiency of their buildings, because they are able to choose the most efficient professional designer and/or consultant. This means that professional designers and consultants must endeavour to build up their reputations for greater efficiency in design, cost control and management of their construction project. Otherwise, their workload may be affected adversely.

Professional firms of designers and consultants are liable for faulty designs; they are generally cautious towards the use of unproven and risky innovations (because as was noted above, they should ensure that their buildings will function with maximum efficiency, and that they be trouble free).

As was noted in 9.1.1, the central government has the power to allow utilization of certain desirable innovations or prohibit the use of undesirable materials by amending the building regulations; this will have a significant effect on the acceptance of new materials (see also 2.7, for the influence of the British Standards and the Agrément certificates, etc.)

The flow chart in Fig. 15.1 incorporates the findings of the surveys on the use of G.R.P. panels in the construction industry. It can be seen that the starting point in the process of selecting materials is whether or not the material under consideration is combustible and also whether or not components made from it can comply with the current building regulations both in letter and in spirit.

The conformity with the fire regulations is generally at the forefront of any feasibility study (see 8.7.4, Table 8.16, 10.1.7.4 and Table 13.9); thus, other things being equal, the order of preference for materials will be as follows:-

1st - Non-combustible and fire-resistant, e.g. reinforced concrete, brick.
2nd - Non-combustible e.g. steel, aluminium, glass.
3rd - Combustible, e.g. timber, G.R.P.

Equally important are durability, structural, thermal and sound insulation performances which must be satisfactory and comply with the building regulations.
Is the new material (NM) combustible? (BS 476:4)

Can the proposed unit be made from NM to comply with the Building Regulations? (structural performance, fire, thermal insulation, etc.)

Technical information, BS, design data and charts, advertisements, case histories, etc. on the actual and potential uses of NM, its advs and disadvs.

Is the new material (NM) combustible? (BS 476:4)

Can the proposed unit be made from NM to comply with the Building Regulations? (structural performance, fire, thermal insulation, etc.)

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Technical information, BS, design data and charts, advertisements, case histories, etc. on the actual and potential uses of NM, its advs and disadvs.
However, fulfillment of the above conditions does not necessarily mean that new materials will automatically be accepted. There must be reasons (or stimuli) for specifiers to use a new material. (The tendency to use established products and materials has already been noted); conversely, there are constraints against its use due to many factors; these are considered below (see 15.1.2 and 15.1.3)

15.1.2 Stimuli for the use of new materials:

Blocks 4 to 10 in the flow chart (Fig. 15.1) show the stimuli which will usually influence the choice of new materials (c.f. Tables 8.7 and 10.2) In addition, there are other stimuli, such as rising demand for construction works, availability of manufacturing facilities and/or availability of manufactured components and sub-contracting facilities, availability of technical information including results of performance tests, design guides, codes of design practice, detailed information on methods of jointing and fixings, etc; these have been considered in more detail below.

15.1.2.1 High performance capabilities:

1. Mechanical properties which include specific strength, specific modulus, impact strength, resistance to creep and fatigue. Other things being equal, the higher the mechanical properties of a new material are the higher the chances for its acceptance as a structural and as an architectural material (c.f. Tables 8.14, 8.20, subsections 4.2.3, 5.4.1, 6.2.1 and 6.2.2)

2. Fire properties (see the order of preference discussed in 15.1.1)

3. Durability: Other things being equal, the higher the length of time is for a given material in service, the higher the degree of confidence is amongst specifiers for its use (c.f. Tables 8.9 and 13.8)

However, scientific evidence e.g. on the nature of a material, together with results of accelerated weathering and wear tests, etc. are being increasingly accepted by architects.

4. Thermal and sound insulation: If the material alone does not provide for high standards of thermal and sound insulation, its ability to provide the same in composite constructions will be an important stimulus for its acceptance
and utilization (e.g. G.R.P. has a massive potential for use in sandwich constructions with very high standards of thermal insulation coupled with a low heat-absorbing capacity and high resistance to moisture penetration; see Tables 8.11 and 8.13)

5. Resistance to moisture penetration: This is especially important in conjunction with the above i.e. risks of moisture forming a 'bridge' through a given composite construction; the lower this risk is the higher will be the chances of its acceptance.

15.1.2.2 Potential cost-savings:
The quantitative analysis of the use of aluminium alloys in the construction industry and the comments by specifiers included in Tables 8.12, 10.5, 13.11 and 13.12 show that other things being equal, the economic competitiveness of a given material will determine the extent of penetration of a material into the construction market relative to its alternatives (c.f. 8.6.5, 13.6.3 and 13.8.3). It must be noted that the potential for cost-savings, especially savings in the first cost, serves as the most effective stimulus for the acceptance and utilization of a new material in the construction industry. This means that there is little or no likelihood for acceptance and widespread use of high performance but costly materials such as carbonfibre reinforced plastics (CFRP).

15.1.2.3 Aesthetics and architectural characteristics:
These include shape, appearance, colour, mouldability and reaction-to-weathering characteristics. The evidence in the case of custom-moulded G.R.P. panels suggests that aesthetics and architectural characteristics constitute strong stimuli for the use of new facing materials (c.f. Tables 8.7, 8.8, 10.2, 10.5 and 13.10)

Architectural fashions and tastes will play a major role in the use of versatile and attractive materials such as G.R.P. (The G.R.P. moulders rely heavily on these qualities of G.R.P. panels for selling their services to architects, see 7.2)
15.1.2.4 Low-maintenance requirements:

The increasing importance of this characteristic for facing and lining materials was proved in the case of G.R.P. panels and aluminium alloys; this is especially applicable to high-rise buildings and other situations where access for maintenance is difficult or maintenance costs are high etc. (c.f. Tables 8.7, 8.9, 10.2 and 13.10)

In short, the chances for acceptance and utilization of materials requiring frequent and costly maintenance are remote.

15.1.2.5 Light Weight, ease of shaping and manufacture—speed of construction:

These characteristics are highly interrelated (see 8.6.4); their combined effects may result in speedy construction using both industrialized and rationalized traditional methods of construction (c.f. Tables 8.11, 8.25, also see subsections 11.1.7 and 11.1.8)

It must be emphasized that new materials should be capable of enhancing the existing trend to greater industrialization of the building process. If building brick were not known and were developed in modern times as a new material, the chances for its acceptance would have been remote. Architects and engineers would have almost certainly criticized it as being too small a building component, involving a wet and messy construction method, requiring lining/finishing operations and affording low standards of finish, etc.

15.1.2.6 Degree of convenience:

The degree of convenience attainable in using a given material is dependent upon the following:

(a) Availability of technical information for designing components or using these, etc.

(b) The length of time required for, and the complexity of design.

(c) Availability of manufacturing and sub-contracting facilities for production, transportation and erection of units.

(d) Ease of obtaining planning and aesthetic approval.

The higher the degree of convenience attainable in using a new material; the greater are the chances of its wider acceptance and use in the construction industry (see below)
15.1.2.6.1 Availability of technical information for designing components or using these, etc:

Tables 8.15, 8.18 and 8.20 show that the availability of technical information serves as a major stimulus in acceptance and use of new materials. The information required is: BS specifications and codes of practice, information on methods of manufacture and potential uses, range of performance capabilities, cost comparisons, case histories, details of site jointing and fixings, guides for obtaining approval under the building regulations, etc.

15.1.2.6.2 The length of time required for, and the complexity of design:

Chapter 6 in particular illustrated the design difficulties facing potential users of complex structural configurations (see also Table 8.15)

Some of these problems can be overcome if the design is carried out for a standardized set of structural systems. As was noted in chapter 6, this has been carried out successfully in the case of standardized double layer steel grids such as the NODUS system developed and marketed by the British Steel Corporation. There are various manuals for NODUS such as computer programme for structural analysis, design of members and joints, guidance for obtaining approval from G.L.C. and under the building regulations and so on. These facilities have greatly facilitated the use of NODUS both in the U.K. and abroad.

15.1.2.6.3 Availability of manufacturing and sub-contracting facilities for production, transportation and site erection of units:

Availability of standard products must be ensured through stockists and distributors of construction materials.

In the case of units manufactured to customers requirements, availability of adequate production facilities must be ensured. Provision for the subsequent erection of units must also be made in association with experienced sub-contractors (see 8.7.2 and Table 8.15)

It must be noted that many construction projects are required to be designed and constructed in a relatively short period of time; thus, the ability to manufacture,
supply and fix units manufactured from a given material in a short span of time plays a major role in its wider acceptance and utilization.

15.1.2.6.4 Ease of obtaining planning and aesthetic approval:

As was noted in Chapter 9, there are design and planning restrictions applicable to building projects, especially in built-up areas, e.g. town centres.

For housing estates, schools, factories and their adjoining offices and similar projects as was observed in Chapters 9 and 11, the chances of obtaining planning permission for a given design proposal based on industrialized building methods, are generally dependent on the building's shape appearance, colour, scale, mass, voids, the ability to blend with the surroundings, etc. Thus, if the new material is capable of being used efficiently in cuboid forms of not too unorthodox appearance, its acceptance will be facilitated.

The development of an industrialized system for the mass market offers an opportunity for continuous design improvement on the lines suggested in Chapter 9 (see the summary of points in 9.2.6; an example is the successful building system 'REEMA' which has been subject to continuous design and construction refinements since its introduction; see also 8.11)

15.1.2.7 Rising demand for construction works:

As has been noted repeatedly (see Chapters 7, 11 and 13), this factor acts as a critical stimulus to the use of new materials especially when they are capable of cutting the design and construction time short or when the traditional resources (i.e. materials and both skilled and unskilled labour) are in short supply (c.f. 11.1.7.2)

It must be noted that the short to medium-term supply for some of the traditional resources is inelastic e.g. the total number of skilled workers cannot be increased immediately by increasing wages nationally.
15.1.3 Constraints against the use of new materials:

Constraints are usually dictated by the statutory requirements and by clients' requirements and for those of their insurance companies (i.e. the F.O.C., see 10.2). There are also other types of constraints such as lack of valid knowledge by the specifiers, etc. The constraints identified in the case of G.R.P. and, to a lesser extent, aluminium alloys have been summarized under the following headings:

15.1.3.1 Inherent weaknesses in the properties of the material or shortcomings in the performances of components made from it: These are as follows:

1. Mechanical properties: If the mechanical properties of a new material fall short of its existing alternatives already in general use or when the performances of components made from it fall short of the minima specified under the building regulations, then the acceptance of that material will be constrained, especially when the costs of its use will exceed those of superior alternatives (c.f. Tables 8.14 and 8.20, see also chapters 6 and 10)

2. Combustibility, poor 'fire-resistance' performance and susceptibility to emission of smoke and noxious gases: As has been studied in the case of G.R.P. and aluminium alloys, the fire properties of a given material and/or the fire performances made from it will have to conform to the statutory requirements.

However, from the standpoint of both building inspectors and insurers the use of combustible materials is less acceptable. This is so even though the components made from these may have 'fire-resistance' performances comparable to those made from incombustible materials when tested to BS 476:8 (c.f. 4.2.10, 4.3, 8.7.4, Table 8.16, 10.1.7.4 and Table 13.9)

3. Unproven durability: If the durability of a material has not been proved in service it use will be limited. This is because buildings are generally designed for a life span of 50 to 60 years and sometimes more. However, factories especially those housing light manufacturing processes are usually designed for a life span of about 25 to 30 years.

As was mentioned earlier, other evidence indicating a satisfactory life span for a material may in certain cases be acceptable to some architects.
In the absence of this information, the likelihood of acceptance for a completely new material will be very remote, especially for load-bearing applications. Thus G.R.C. is not used for long term load bearing applications pending further evidence of its long term durability (see 4.4.3).

4. Poor thermal and sound insulation: The current trend is for development of more relevant and sophisticated methods for evaluating thermal insulation: performances including heat absorbing capacities of existing and proposed buildings; this is due to the rising costs of energy.

Also, the sound insulation performances of various constructions are increasingly being brought under control, especially where the buildings are situated close to sources of noise such as airports, motorways or trunk routes.

Generally speaking, thermal insulation is provided by the use of insulating materials, especially cellular plastics, sandwiched between an outer and an inner leaf of other materials. Thus, the ability of a given material to form, in combination with other materials, composite constructions of high thermal and sound insulating standards and of low heat-absorbing capacities with very low risks of moisture penetration and at an acceptable cost, will be a critical factor in its acceptance and use, especially in conjunction with industrialized building systems. The combination of these factors once proved by experience can provide, however, a very strong stimulus to the acceptance and use of the industrialized building systems themselves (c.f. Tables 8.11 and 8.13).

However, if a material is incapable of providing the above qualities at an acceptable price, it would be difficult to persuade architects, engineers and their clients to its use.

5. Poor resistance to the penetration of moisture: If the components made from a given materials (or their joints) are not highly resistant to the penetration of moisture, especially in conditions of driving rain, architects and engineers will be reluctant to specify the same. The weather-resistance of external walls and roofs of buildings is controlled by the building regulations, though these regulations do not make reference to any particular performance test; in practice the performance of components and their joints is assessed by subjecting a representative
construction of the same to simulated rain and wind, which represent the most severe driving rain conditions experienced in service.

The risk of moisture penetrating through joints in non-porous materials is usually greater than the corresponding risk for the penetration of moisture through the main body of the components; thus, the efficiency of jointing and fixing methods should be checked more rigorously.

**15.1.3.2 High unit costs:**

Traditionally, construction materials have been cheaper than those used in other industries. This is so even when the cost per unit volume of materials are compared.

Assuming that a material is capable of meeting the required technical criteria in a given application. The extent of penetration for this material in that application will be dependent on its average finished cost relative to those of its alternatives; this is particularly applicable to standardized products (c.f. 13.8.3).

This fact means that the use of a very expensive high performance material is generally confined to applications where no other material is capable of satisfying the required performance specifications such as the use of polytetrafluoride (PTTF) in the bridge bearing due to its very low friction coefficient. These specialised applications are usually rare and constitute an insignificant part of the construction market (c.f. Tables 8.12 and 10.2, see also 13.8.3 and 15.1.2.2)

As was noted repeatedly in the previous chapters, there is evidence that the importance of economics in design and construction of building is growing, with more emphasis being placed on the cost/performance ratio of various construction designs.

**15.1.3.3 Lack of flexibility in shape, size, appearance, colour, texture, etc. - low aesthetic appeal and poor reaction-to-weathering characteristics:**

There is architectural and planning resistance to the use of a new material possessing the above attributes. It is worth noting that pure asbestos-cement sheeting, used either as cladding or roofing, has rarely been specified by architects on non-industrial buildings.
As was discussed in 15.1.2.3, materials or components which are visually exposed should not engender dull or negative feeling; in addition, they should not weather in an unpleasant manner (c.f. chapter 9)

15.1.3.4 Heavy Weight:

As was illustrated in chapter 11 (see 11.1.8.2), heavy weight components are at a disadvantage compared with lightweight components; this is because of the higher manufacturing, handling, transportation and site erection costs and also higher costs of foundation and structural provisions mostly associated with the use of heavy-weight components; in addition, there are stringent safety regulations for handling and transportation of large and heavy components.

It is to be noted that the weight of the finished component/unit is the correct criterion for the purpose of weight comparisons and not the density of the constituent materials (see also 15.1.2.5)

15.1.3.5 Delays and inconveniences:

The factors controlling the degree of convenience in using a new or established material were considered in 15.1.2.6; generally speaking, the lower the degree of convenience attainable in using a given material, the lower the probability of its widespread use (assuming other things being equal); this is especially true if the material is relatively new.

15.1.3.6 Falling demand for construction works:

As was noted previously, the state of activities within the construction industry is a highly significant factor in the use of new materials or construction techniques. There is little chance for acceptance of a new material in the construction industry at times of falling demand for construction works unless the material in question offers substantial benefits over its alternatives. The reasons for this are tighter cost competition from traditional materials, the presence of political and social influences and the reluctance of specifiers to take more risk than absolutely necessary.
15.1.3.7 Special requirements:

Sometimes, there is a call for special performance requirements, e.g. resistance to various vapour chemicals in certain parts of a building housing a particular chemical engineering process or, as more commonly encountered in the design of buildings, is the requirement for a high degree of resistance to corrosion in coastal areas (c.f. 10.1)

Other restrictions on the choice of materials or designs may be imposed by the insurance companies (i.e. the F.O.C. rules, etc.)

Finally, restrictions may stem from the newly enacted "Health and Safety at Work", e.g. the use of asbestos-based products in certain circumstances may be against the requirements of this Act.

In addition to the above technical restrictions, there are, in the majority of cases, economic restrictions either in the form of cost yardsticks (mostly occurring in the public projects) or other forms of budgetary limitations.

15.1.4 Conclusions on the mechanism of acceptance of materials in the construction industry:

It may be concluded that in choosing and accepting a new material or components made from it, the quality of the resulting products, which includes both service performance and architectural characteristics, is often traded against the costs and the degree of convenience attainable in the given material.

The degree of convenience attainable in a given material was seen to depend on the following:

(a) Availability of technical data for designing and/or specifying the proposed components, including the familiarity of designers with the given material.

(b) The length of time required for, and the complexity of designing components, structures, etc. in the given material.

(c) Availability of manufacturing and sub-contracting facilities for production, transportation and erection of components/panels, etc. including avoidance of delays in completion of construction projects.
15. Ease of obtaining planning and aesthetic approval.

The interplay of factors considered in 15.1 are shown in Fig. 15.2. The diagram in Fig. 15.2 exhibits the complex interrelation of the factors affecting acceptance and use of new materials in the construction industry which have been discussed in the preceding parts of this section.

15.2 Estimation of the Length of Time Required for a New Material to reach the "Traditional Status":

15.2.1 Basis for defining the 'traditional status':

Throughout this work the term 'traditional' has been used loosely to refer to familiar materials commonly used for constructional purposes, some of which have been known from the times of antiquities such as iron, brick and stone.

The author has found no reference to a scientific definition for the concept of 'traditional' (or conventional or established) material; it was therefore decided to explore the possibility of arriving at a satisfactory definition by using one of the following concepts:

(a) Sales or consumption curve for a given material in the construction industry.
(b) The consumption or sales growth rate of the material relative to that of construction output.
(c) The availability of technical data and literature on the material.
(d) The size of the present market relative to the size of the potential market.

It is proposed to examine each of these concepts and see whether or not with the experience of G.R.P. and aluminium alloys it is possible to arrive at a meaningful estimate of the time-scale required for a new material to reach the 'traditional' status.

15.2.2 Sales or consumption curve for a given material in the construction market:

Generally speaking, the end-uses found within the construction market for a given material are numerous. Take the example of aluminium alloys which are used in curtain-walling, patent-glazing, window and door casements, double glazing, corrugated and troughed roofing, troughed roof decking, troughed cladding, sandwich construction, roof structures, space frames, double layer grids, rainwater goods,
FIG. 15.2 DIAGRAMMATIC REPRESENTATION OF FACTORS AFFECTING THE ACCEPTANCE OF NEW MATERIALS IN THE CONSTRUCTION INDUSTRY
handrails, balustrading and many more varied applications. This consideration implies that it is difficult to assume any saturation level and fit a logistic or similar curve to the data. Clearly, if one were to fit a logistic or S-shaped curve to the scatter diagram in Fig. 13.3 representing the total consumption of aluminium alloys in the construction market, it would suggest that aluminium products had, up to 1972, been faced with 'resistance', because of the process of "learning and acceptance" on the part of specifiers; this would give the impression that it has taken over a quarter of a century for the potential benefits of aluminium alloys and their products to be widely known within the construction industry. However, according to the quantitative analysis undertaken earlier, the sharp rise in the consumption of this material in 1971-74 is attributable to its increased price advantage over the alternative materials.

Furthermore, as must be clear to the reader, aluminium alloys were introduced initially on a large scale during the course of the non-traditional house and school building programmes. At about the same time, the commercial developments for curtain-walling and allied products as well as sheeting and structural uses took place. Thus, for all practical purposes, it can be assumed that by 1960 the majority of specifiers were familiar with the potential benefits and associated costs of using aluminium products and were able to obtain first hand information on service performance of the earlier post-war aluminium structures.

The above discussion shows that a sales or consumption curve of a given material in the construction industry/the length of time taken up in the process of 'learning and acceptance'.

15.2.3 The growth rate for sales or consumption of a given material relative to the construction output:

It has been shown (see 7.1.2.3) that the growth usually consists of the following two components:

(a) existing growth which is a function of growth of the construction industry; and

(b) penetration growth which is a function of the continuation of the process of substitution of the given
Conceptually, it is possible to state that if the rate of growth of sales or consumption for a given material is not greater than the growth rate in the construction output, it may be classed as a traditional material, i.e. its growth is not of the penetration type; this concept is, however, incomplete since it ignores the possibility of sudden growth due to a change in the relative prices or other economic factors; this growth may continue for some years until the market equilibrium is re-established. For a number of competing materials in a given application, the equilibrium point may be assumed to be reached when the actual market share of each material approaches its potential market size. The latter is a function of its relative price, its quality, its advertising expenditure, etc. Any change in relative prices will upset the market equilibrium and it may take some time before the equilibrium is re-established; during this time some materials may experience growth whilst others may lose part of their market share (c.f. 13.4.1, Tables 13.1 and Fig. 13.1)

In short, the above concept is also inadequate as a basis for estimating the length of time taken up in the process of "learning and acceptance".

15.2.4 The availability of technical data and literature on the material:

The first step in introducing a new material is usually in the form of publication of an article in a scientific or technical journal giving information on mechanical and physical properties obtained in the laboratory.

As the potential of the commercial development is evaluated, many performance tests are undertaken; for example in conjunction with its proposed use for some development. Construction technical journals usually carry reports of these scattered developments, this coupled with advertisements by the producers will help to dissipate initial knowledge of the material and its potential uses.

The experience from the development of aluminium alloys and to a lesser extent that of G.R.P. in the construction industry indicate that the amount of published information subsequently tends to increase rapidly as research workers
try to provide information needed for economic design and resolution of constructional problems and as more information is gathered from trials, other industrial applications, etc.

Finally, a time comes when the progress of knowledge and the accumulated experience permit provision and publication of BS specifications and codes of practice.

The publication of a BS design code of practice may be taken as the point beyond which a material is no longer defined as new. This is because, the designers and specifiers are generally able to use this code, and the resulting designs are generally accepted by the building inspectors for compliance with the building regulations (c.f. Table 8.15)

The first code of practice for constructional use of aluminium corrugated and troughed sheets was part 1 of CP 143 which was published in 1958. However, publications in 1951 of BS 1161 which dealt with dimensions and section properties of a range of angle, channel, I and T sections was highly significant.

In 1962, the Institution of Structural Engineers (ISE) published a report dealing with the structural use of aluminium alloys; this publication served as a code of practice whose recommendations were widely used by designers (see also ISE Proceedings: Aluminium in Structural Engineering, Sym. 1963)

The ISE report was superseded by CP 118 which was published in 1969 as an integrated document dealing with all aspects of stress and strain analysis, design, testing, manufacture, fire and environmental protection, etc.

The use of aluminium windows and patent-glazing is not normally subject to control under the building regulations, because, these parts are generally non-load-bearing and their instability or collapse does not affect the stability of the structures to which they are fitted. Furthermore, as far as could be ascertained, it appeared that the back-up 'fire-resistant' wall which used to be required in every floor with aluminium curtain-wallings was also required in the case of steel curtain-wall. (The use of wooden curtain-wall was not generally permitted under the old Building By-Laws).

The above review implies that as far as aluminium curtain-wall, patent-glazing, window casement, roof sheeting,
roof decking, vertical cladding and other 'non-structural' uses are concerned, by 1960, their use must have been considered as conventional. By 1963, all the technical information for structural use of aluminium had become available. Therefore, it is likely that aluminium had reached the so-called 'traditional status' within 18 years of their introduction into the construction industry i.e. 1945-1963.

In the case of G.R.P., as has been noted in detail in chapter 6, there are no national codes of practice. Taking 1967 as the origin when G.R.P. cladding panels were introduced one could conclude that within 20 years (or by 1987) G.R.P. will have reached the 'traditional status'. Clearly, this is not a satisfactory way of estimating the time-scale involved for a material to reach the established status, because of the following reasons:

1. In the case of aluminium alloys, the research and development efforts by the Aluminium Development Association, the Aluminium Window Association and individual aluminium companies have been both well-planned and intensive. This has not been happening in the case of G.R.P.

   The greater the extent of efforts spent on R & D, the shorter the length of time required for provision and publication of a design code, etc.

2. The Institution of Structural Engineers took an active interest in the preparation of a code of practice for the structural use of aluminium; no similar attempts have been observed in the case of G.R.P. composites.

   The length of time required for preparation and publication of a code of practice for a material may therefore be dependent on the interest taken in the material by influential institutions and/or research establishments (c.f. the involvement of the BRE in the development of G.R.C., section 4.4)

3. In normal structural applications, mechanical properties of aluminium alloys are independent of the effects of loading duration and temperature. As was seen in previous chapters (see 4.2.3, 4.2.8 and 6.2), mechanical properties of G.R.P. are both time and temperature dependent.
Thus, because of the complexity of structural analysis and design in G.R.P. composites, it may take considerably longer for the relevant information to be collected, processed and formulated for the purpose of a national code of practice.

The above consideration may be generalized, i.e. the length of time required for collection and processing of scientific data on the constructional uses of a new material is dependent upon the complexity of the properties of this material and whether or not they can be quantified using the established engineering practices.

In short, although the above concept is by itself useful in that it has an explanatory power when looking back and reviewing the period of 'learning and acceptance', it is not universally applicable.

Nevertheless, the above analysis gives indications of the sort of 'time-scale' involved for the structural use of a material to be covered by a national design code of practice.

Generally speaking, if a structure is designed in accordance with the recommendations of the relevant code of practice, it will be considered by the building inspectors as complying with the requirements of the building regulations; thus, many costly loading and other performance tests, etc. are avoided and the constructional uses of a material is greatly facilitated.

15.2.5 The size of the present market relative to the potential market:

Suppose that for a new material a potential market is forecast based on its advantages and disadvantages relative to those of present alternatives and including an allowance for probable price falls corresponding to probable increased volumes of consumption (e.g. because of possibility of introducing economies of scale, etc.)

The time taken for the size of the market for a given material to increase from nil (year of introduction), to its potential size may be defined as the time taken for that material to reach the 'traditional status'.

The above concept presupposes that it is possible to forecast the potential size of the market for a new material with a reasonable degree of accuracy; as was seen in the case of G.R.P. (see 13.8), it is not always possible
to do this even though the experience of other materials is available.

The reasons for the market size of a given material being substantially less than its potential market size may be attributed to the lack of valid knowledge on the material and its potential benefits amongst specifiers, clients and local authorities; in particular lack of detailed knowledge on the following:

1. The properties of the material including physical, composition, mechanical and fire, durability, potential for shaping, appearance, colour etc.
2. Methods of making constructional components, elements, etc. from it.
3. Economics of the use of the given material in various applications compared with those of alternatives.
4. Methods of obtaining approval under planning and building regulations and other statutory requirements.

In the case of G.R.P. panels, it was observed (see Table 8.1) that about half the specifiers who took part in the G.R.P. survey, had not used G.R.P. panels. There are many reasons for this, viz:

(a) Lack of valid knowledge of G.R.P. (see 1 to 4 above)
(b) Avoidance of its use because of perceived shortcomings in performances of G.R.P. panels, especially 'fire-resistance' performance.
(c) Avoidance of its use due to perceived costs of G.R.P. panels being higher than those of alternatives.
(d) Lack of opportunity to specify G.R.P. panels, i.e. non occurrence of projects which the respondent considered to be suitable for the use of G.R.P. panels.

It can be seen from column (VIII) of Table 15.1 that a large percentage of the specifiers in the postal survey without G.R.P. experience, stated that they would consider its use in their future projects. The reasons for their not specifying G.R.P. are not therefore associated with cost/performance aspects of this material but with the lack of valid knowledge and/or lack of opportunity. (i.e. items a and d above). This fact is confirmed by a study of the comments by specifiers contained in Table 8.15.
Table 15.1 Analysis of the intentions of specifiers on the future use of G.R.P. (see the text and note 1)

<table>
<thead>
<tr>
<th>(I) Sample designation</th>
<th>(II) Sample size (n)</th>
<th>(III) No. of returns (n)</th>
<th>(IV) Response rate (%)</th>
<th>(V) Without G.R.P. exp (n)</th>
<th>(VI) (V) as % of (III) (%)</th>
<th>(VII) Would consider G.R.P. (n)</th>
<th>(VIII) (VII) as % of V (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>192</td>
<td>133</td>
<td>69</td>
<td>72</td>
<td>54</td>
<td>58</td>
<td>80.5</td>
</tr>
<tr>
<td>A</td>
<td>192</td>
<td>91</td>
<td>47.5</td>
<td>50</td>
<td>55</td>
<td>41</td>
<td>82</td>
</tr>
<tr>
<td>C</td>
<td>90</td>
<td>46</td>
<td>51</td>
<td>29</td>
<td>63</td>
<td>27</td>
<td>93</td>
</tr>
<tr>
<td>S</td>
<td>73*</td>
<td>51*</td>
<td>70</td>
<td>13</td>
<td>25.5</td>
<td>12</td>
<td>92</td>
</tr>
<tr>
<td>L + A + C + S</td>
<td>547</td>
<td>321</td>
<td>58.5</td>
<td>164</td>
<td>51</td>
<td>138</td>
<td>84</td>
</tr>
</tbody>
</table>

* - includes 19 questionnaire from the pilot survey
+ - includes 18 returns from the pilot survey

Note: for source see chapter 8, specially Table 8.1
In short, it can be seen that the higher the extent of dissemination of relevant technical information on a new material amongst specifiers, the higher is the probability of its utilization in constructional projects.

The above discussion suggests that it may be possible to calculate a rate for dissemination of information for one particular material based on data collected, for example, from surveying annually a sample of specifiers and plotting with time, the cumulative percentage of those who have learnt sufficiently about the material so that if the circumstance was to arise they could use it with confidence.

However, there is no evidence that the rate of dissemination of information calculated for a given material will be applicable to others as well. In fact, undertaken by each industry and also depending on the perceived utility of their products, each industry may experience a different pattern of reaction (or response) to its products.

Nonetheless, the above analysis for G.R.P. is useful in that it suggests that between 1967 and 1975, i.e. in the span of about 8 years, approximately one half of specifiers had gained first-hand experience of this material. Clearly it should not take long before the majority of specifiers learn about, or gain first-hand experience of using, this material; thus, it appears that the estimation of a time scale of about 18 years in the case of aluminium alloys has some relevance to that of G.R.P. However, beyond this point it is not possible to generalize any further.

15.3 Transfer of Experience from G.R.P. and Aluminium alloys to other Composites or New Materials:

15.3.1 Diagrammatic representation of the process for development of new materials or composites:

Fig. 15.3 shows the process which was found to be appropriate for the development of new materials or products aimed at the construction industry. The following is a brief description of each step required for successful development and marketing of constructional products from a given material, e.g. composites made with high strength/high modulus polymeric fibres embedded in a hydraulic cement matrix (c.f. chapter 14)
Fig. 15.3. Diagrammatical representation of the process recommended for the development of new materials/products for the construction market.
15.3.2 Identification of the properties of the material:
Properties normally required include the following:

1. Nature of materials: That is information on chemical composition and nature of constituents, density or specific gravity, physical form, colour and texture, chemical reactivity, toxicity, etc.

2. Mechanical properties: Tensile and compressive strength, modulus of elasticity and flexural modulus, shear strength, ultimate elongation, visco-elasticity (if any) impact strength, creep and fatigue behaviour, range and directionality of the above properties (not required in the case of isotropic/homogeneous materials).

3. Physical properties: These are thermal insulation and thermal expansion characteristics, heat-distortion temperature, opacity, resistance to air borne and impact sounds, resistance to moisture and resistance to solar radiation.

4. Fire-behaviour: Reaction-to-fire characteristics and 'fire-resistance' properties to be assessed in accordance with the relevant parts of BS 476.

5. Long term durability: Results of exposure tests to be supplemented if necessary with accelerated weathering and wear tests.

All of the properties under items 1 to 5 above, must be determined in accordance with the relevant BS tests.

15.3.3 Identification of architectural characteristics:
These include the possibility of shaping, appearance, texture, colour etc. Also, it includes the characteristics of weathered surfaces.

15.3.4 Identification of potential applications:
This is a logical way of product planning; it involves determining the potential products, their range, and more important, methods of manufacturing these, e.g. whether or not flexible production techniques, such as the labour-intensive contact-moulding process in the case of G.R.P. are advisable or more capital-intensive processes are preferable.

To a large extent, the type of production process for a given product is dependent on the volume of demand for that product; however, the demand itself is dependent on the unit cost or price of the product. Thus, it is vital
to decide at the outset what type of production process is desired since each production process usually yields a different unit cost for the finished product; this in turn implies a different market demand.

Alternatively, a number of potential processes may be chosen for investigation; however, caution must be exercised with the labour-intensive processes, since their economics are critically dependent on the wages of operatives. The tendency in the past has been for the wages to rise proportionately faster than either the cost of capital or cost of materials.

15.3.5 Design and development of the proposed products:

As has been noted previously constructional components are designed against a number of performance or users' requirements. These requirements may vary according to the type of occupancy of the building.

Having decided which products to produce, the next step should be to undertake research into the users' requirements, preferably in conjunction with corporate clients such as the G.L.C., large housing authorities, regional health authorities, education consortia, etc. A range of performance requirements may be compiled, e.g. for components used on residential houses, offices, schools, etc; the proposed components must be designed to satisfy this range so as to increase the chances of its incorporation into a range of buildings. This is especially applicable to standardized products; the performances of these should ideally surpass those of existing alternatives, e.g. its thermal-insulation/heat-absorbing performances should exceed the minimum standards by a large margin.

It must also be emphasized that the choice and design of the products' range, scale, size, shape, colour, texture, etc. must be entrusted to a professional architect and that maximum flexibility in appearance and in application must be aimed for at an acceptable tooling cost.

Practical and functional considerations must be put before the need for material (c.f. chapters 6 and 9).

Joints, fixings and lifting eyes must be designed for maximum efficiency and simplicity so that they can be handled by unskilled labour on site.
Prototypes must be manufactured and subjected to all the relevant performance tests and if necessary, the design must be modified for maximum economy.

The diagram in Fig. 15.3 shows that stages 4, 4.1 and 4.2 are interrelated; this is because, in addition to research and development work, the R & D department is usually responsible for other technical aspects of the proposed product; a fully staffed technical team should ensure provision of technical literature on the product, criteria for its selection and methods of obtaining approval under the statutory regulations.

For example, an Agrément Certificate or MOAT may be contemplated (see 2.7); however, provision of BS specifications and codes of practice should be planned from the outset.

The product should eventually be included in the 'deemed-to-satisfy' schedules of the building regulations, because, as was studied in 2.6 these schedules are widely used by specifiers and designers for reasons of pure convenience, decreased legal liability and ease of obtaining approval from the local authorities.

Also, the technical/R & D department should arrange for a feed-back of information from users (architects or clients) on the service performance of the product and undertake regular cost/performance analysis in relation to both changing needs of the users and the threats from alternative products; major or minor modifications or product improvement should be carried out on a regular basis (see also 15.3.8)

15.3.6 Appraisal of the potential of a proposed product:

This stage is the most critical part of the whole development process, because it involves making a decision as to whether or not to go ahead with the production of a proposed product.

The potential advantages and disadvantages of the proposed product must be compared with those of existing alternatives. Price of the proposed product should be estimated; this should be based on the desired production processes and should include an allowance for invisible cost items.

The resulting prices (or the installed costs, see Table 5.20) should be compared with those of alternatives; a final decision on the economic viability of the proposed product
should be made after careful evaluation of its cost/performance ratio compared with those of alternatives, in doing this, it must be borne in mind that products which have lower first costs (i.e. design and construction costs excluding running and maintenance costs) can be incorporated into a wide range of low to medium cost projects; thus, these products are likely to be accepted sooner, compared with the high-cost materials.

Having decided to proceed with the production of the proposed product, the major advantages should be identified and selected for inclusion in advertisements, product's data sheet etc.

15.3.7 Production, warehousing and distribution:

If the proposed product is standardized, it may be advisable to enter into arrangements with builders' merchants; however, if the product involves standardized building systems or forms part of a comprehensive building system, it may be advisable to explore possibilities of co-operating with construction companies (i.e. main-contractors or sub-contractors depending on the nature of works involved); alternatively both methods may be employed, i.e. parts of an 'all-inclusive' building system may be marketed for use on consortia systems or on any normal building through a network of builders' merchants etc.

For products manufactured to customers' requirements, it is difficult to plan this stage, however, provision for trained operatives, raw materials and production spaces should be made; also, means of transporting the manufactured products should be provided.

15.3.8 Advertising and product promotion:

As has been generally noted throughout this study (see, for example, chapters 8 and 10), architects, engineers and quantity surveyors whether employed directly by their clients or acting as consultants, normally make decisions on behalf of their clients.

Unlike members of the general public making decisions freely on, for example, the choice of a consumer durable, a specifier's choice is normally constrained because of the statutory requirements and due to the special requirements by clients, etc.
In addition, a specifier would normally be inclined more towards the use of materials/components with known durability and service performances unless he sees a major reward/inducement for taking greater degrees of risk (see Figures 15.1 and 15.2).

The above consideration implies that advertising of new materials or products must give convincing and quantitative information on the cost/performance advantage of these materials; special emphasis must be placed on the potential for saving in first costs and total costs by use of new materials; in addition, superior performances attainable by the use of these materials should be conveyed; these data should be based on comparison between the new and the established material.

Advertisements should be placed in the technical construction journals (see 2.6 for the effectiveness of this method of dissipation of information; it was found to be generally the cheapest and most effective method of conveying information to specifiers).

Advertisements should give brief reference to the results of performance tests carried out by recognized authorities; it should be ensured that all the technical data needed for the use of the proposed product are correctly compiled and copies are supplied on request to specifiers.

Advertisements should also give a clear indication of the fact that provisions have been made for speedy supply or supply and site installation service; the emphasis must be placed on the potential of the material/product in reducing the length of construction time and the ease of incorporating mechanical, electrical and plumbing services without the need for employment of 'wet-processes' on site either to finish the surfaces or to rectify the joint lines, corners, etc.

Information on dimensional accuracy of the product and its compatibility with the normal tolerances attainable on site should be included in the product data sheet, etc.

Aesthetics and architectural qualities should be given special attention; in particular, advertisements should refer to the design possibilities, give information on the range of sizes, surface textures, colours, etc.
If custom-designed products are also offered, information on their approximate costs vis-a-vis standardized products should be included in the relevant data sheet.

In short, for advertising to be effective, heavy emphasis must be placed on the cost/performance advantages of the new material/product; the potential for savings in the first costs of projects should be stressed. The advertisements should also convey the aesthetic qualities, the degree of convenience and the flexibility in application which are attainable in the given material/product.

15.3.9 Customers' services and feedback of information:

The manufacturer's involvement should not end at the completion of a project; provision should be provided for dealing with customers' complaints and replacement or repair of faulty products; also, customers' enquiries about methods of cleaning, maintenance and renovation of products should be handled in a proper manner. Advice should be given on future conversion, extension or demolition of buildings constructed mainly from a new material/components.

Finally, as has already been pointed out, it is important to arrange for information on actual performance of products in service to reach the manufacturers on a continuous basis; this information may be supplemented by new users' requirements etc.

15.3.10 Observation on the manufacturer's required resources:

A general observation on stages 1 to 8 shown in Fig. 15.3 and as were discussed in 15.3.2 to 15.3.9 inclusive, indicate that it requires a manufacturer with sufficient resources and a high degree of managerial experience to introduce a new material or new products in the construction market; this is because, it may take a long period of time and money for an innovatory idea to be generally accepted within the construction industry; in fact, the tendency in the past has been for very large manufacturing companies to sponsor the general development of a material up to the point of manufacturing specific components; the latter task is usually passed on to smaller companies, etc. under licensing arrangements.

As an illustration, Pilkingtons have financed the development of G.R.C. However, the scientific development of this material and the process of making constructional products from G.R.C. have been undertaken by the Building
Research Establishment; BRE have in fact followed stages 1 to 5 in Fig. 15.3 (excluding planning of direct commercial production).

Without the financial backing by Pilkingtons and the intensive R & D undertaken by BRE, the rapid development of this material would have been impossible.

The production techniques developed by BRE for making G.R.C. components constitute significant advances in the construction technology which may be utilized for manufacturing other rigid composites, namely, HS/HM fibres/hydraulic cement composites. (see 4.3)