CABLE-NET SUPPORTED GLASS FACADE SYSTEMS

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ABSTRACT

Cable-net supported glass facade systems that comprise of pre-stressed cable-net, glass panes and glass support attachments; are commonly used in airport terminals, hotel lobbies, and trade centres. Glass used in building facade presents an aesthetic feature as well as contributes to the structural stiffness of the whole structural system of the building. In this research, the performance of cable-net supported glass facade systems was investigated via experiments and finite element analysis using the Abaqus v6.9 software. Two generic configurations of cable-net system were considered, namely flat and curved cable-net system, both with and without glass panes. For the curved cable-nets, two different curvatures were considered. Each system was subjected to three tests: static, impact and cable anchorage failure test. The results indicated that the glass panes made significant contributions to the stiffness of the whole structural system. The glass stiffness contribution for flat cable-net system was high at the early stage of loading (approximately 30%) but reduced when the load was increased. However, the glass stiffness contribution for curved cable-net increased gradually as the load was increased. For both configurations, the glass stiffness contribution remained steady at about 20% of the whole structural stiffness as the cables in the cable-net stiffened until the maximum load was applied to the system. Based on the static tests, the pre-stress force in the cables in the cable-net systems can possibly be reduced by approximately 50% of the initial pre-stress force; should the glass be considered in the analysis design of cable-net structure. Moreover, the curved cable-net could be designed to have lower pre-stress force in cables compared to that of flat cable-net to meet the deflection criterion of the cable-net structure. Consequently, in the impact test, the glass supported by cable-net structure was deflected at the same level as the cable-net when subjected to impact force. Although the deflection of cable-net is large, the deflection of individual glass was very shallow compared to the allowable deflection of glass pane. Despite the cable-net structure having the capability in reducing the impact force on the glass pane, it has no capability to prevent glass breakage.
when the impact hit the glass at its edge. Another effect of impact test was the corner node of the cable-net structure had almost the same deflection when the ball bearing hit the glass at the centre of glass facade; although it was found to be very stiff in the static test. The corner node was deflected excessively although the impact was farther from the node. The sudden failure of cable anchorage had no dramatic effects such as progressive collapse or glass breakage even though the cable forces in the curved cable-net oscillated about ±20% of the initial pre-stressed force. Finite element (FE) models were developed for flat cable-nets with and without glass panes using the Abaqus v6.9 software. The FE results were in good agreement with the experimental results with only 1% difference between the two sets of results.
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<tr>
<td>EEIPS</td>
<td>Extra extra improved plow steel</td>
</tr>
<tr>
<td>EIPS</td>
<td>Extra improved plow steel</td>
</tr>
<tr>
<td>FC</td>
<td>Fibre core</td>
</tr>
<tr>
<td>FE</td>
<td>Finite element</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element method</td>
</tr>
<tr>
<td>GSA</td>
<td>Glass support attachment</td>
</tr>
<tr>
<td>GSC</td>
<td>Glass stiffness contribution</td>
</tr>
<tr>
<td>IGU</td>
<td>Insulated glass unit</td>
</tr>
<tr>
<td>IPS</td>
<td>Improved plow steel</td>
</tr>
<tr>
<td>IWRC</td>
<td>Independent wire rope core</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear variable differential transformer</td>
</tr>
<tr>
<td>MBL</td>
<td>Minimum breaking load</td>
</tr>
<tr>
<td>NiS</td>
<td>Nickel sulphide</td>
</tr>
<tr>
<td>PFC</td>
<td>Parallel flange channel</td>
</tr>
<tr>
<td>PVB</td>
<td>Polyvinyl butyral</td>
</tr>
<tr>
<td>SGF</td>
<td>Structural glass facade</td>
</tr>
<tr>
<td>SSG</td>
<td>Structural sealant glazing</td>
</tr>
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<td>WSC</td>
<td>Wire strand core</td>
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CHAPTER 1

INTRODUCTION

1.1 Background

Cable-net systems used in structural glass facades (SGFs) have captured the interest of architects and engineers due to their simplicity, lightness and transparency. In general, glass facades are widely used in airport passenger terminals, exhibition centres, gymnasiums and hotel halls. The Beijing Poly Plaza in Beijing, China, the Kempinski Hotel, Munich, Germany, and the Sea-Tac Airport, Seattle, US; all shown in Figure 1.1 are some examples of cable-net supported glass facade systems. These support systems can be categorised as flexible structures made of pre-stressed high-strength steel wire cables. The cable structure is subjected to large deflections due to the geometric nonlinearity of the cable system. This may lead to a particular failure mechanism of a cable such as a complete loss of tension (Shi et al., 2010), or an anchorage end failure (Jo et al., 2002; Shi et al., 2010). These failures can affect the stability of the whole structure. Moreover, the individual pre-stressed cables are not the only factor that influences the stiffness of the cable structure as the glass cladding panes also have an important influence. Many studies have shown that have a significant contribution to the stiffness of the whole structural system (Feng et al., 2007, 2009; Shi et al., 2010; Wang et al., 2007). Although the glass panes contribution to glass stiffness is small compared to that of the pre-stressed cable, glass excels in damping which reduces vibration induced by wind loading. Thus, the behaviour of cable-net supported glass facade systems needs to be investigated and understood.
1.2 Objectives of the Study

i. To study the static and dynamic performances of flat and curved cable-net supported glass facade systems which are subjected to static and impact loads.

ii. To study the performance of flat and curved cable-nets due to instant anchorage failures.

iii. To establish and calibrate the finite element (FE) models of cable-net supported glass facade systems based on the experimental model.

iv. To produce design guidance on cable-net supported glass facades.

Figure 1.1. Examples of cable-net supported glass facade systems: The Beijing New Poly Plaza, Beijing (left), The Kempinski Hotel, Munich (top right), and The Sea-Tac International Airport, Seattle (bottom right)
1.3 Layout of the Thesis

This thesis comprises of seven chapters. Chapter 1 briefly describes the background of glass facades and the objectives of the study. Chapter 2 reviews each component of the structural glass facade systems particularly cable-net structures. Furthermore, some of the previous studies related to this research work are also reviewed. The experimental procedures for a series of static and dynamic tests are explained in Chapter 3. The experimental result of the static and dynamic tests are given and discussed in Chapters 4 and 5, respectively. Chapter 6 discusses the nonlinear finite element analysis. The finite element (FE) model of the cable-net glass facade systems is developed using the ABAQUS software. In addition, the validation of the FE model is also shown in this chapter. The last chapter, which is Chapter 7, contains the conclusions and recommendations for future work.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Facades are synonymous with the building skin which provides the interface between the environment outside and the user inside. Facades are usually designed in such a way as to reflect the usage and identity of the buildings. There are four types of facade, namely, exposed structure, masonry cladding, curtain wall and structural facades as shown in Figure 2.1.

*Figure 2.1*. Various types of building facade from ancient to modern facades: St. JohnLateran (1735), Rome (top left), Connaught building (1916), Ottawa (top right); Gherkin building (2003), London (bottom left); and Entrance Pavilion for GM Global Headquarters, Detroit (bottom right)
The framework of the exposed structural facade is usually uncovered and exposed to the outdoor environment. An applied masonry facade is assembled from numerous small elements such as bricks and blocks concealing the structural frame of the building. Curtain wall systems are integrated glass systems with a high level of prefabrication. Glass, metal and pre-cast panels are usually used as infill panels for the walls, and these are hung between floor slabs, like a curtain, on a multi-storey building. The original formulation of the modern metal and glass structures was the metal-glass domes of the Bourse du Commerce, Paris, which was built in 1811. The building was built during the European metal-iron revolution. The Hothouse, Paris (1836) and the Crystal Palace, London (1851) were amongst the earliest glass facade buildings built during the evolution of both the metal and glass making industries. The innovation of glass facade systems was improved by increasing the transparency level of the facades. The introduction of structural glass facades (SGFs) in 1975 that combines structural and glass systems, has driven the development of glass facade technology to the next level.

2.2 Cable-net Glass Facade Systems

Generally, structural glass facades (SGFs) comprise of three main components namely glass, glazing systems and structural support systems. The load acting on the glass is transmitted to the structural support system which is the cable-net structure via the glazing system and eventually to the boundary or building structures such as columns and beams. This concept allows large open spaces up to the full height of the facade in the building where the glass cladding is the interface between the exterior and interior of the building.
2.2.1 Glass

The first glass was made around 5000 B.C. in the Middle East, specifically in Syria. The Romans started the casting of flat sheets of glass but with poor optical properties, and it was found used as a building component, particularly as glass windows in Pompeii, Italy around 100 A.D. (Bernard, 2012). The development of glass and its use as a building material are very dependent on the technology of glass making.

As the science and engineering of glass materials were much better understood, a new revolutionary production method for glass emerged, known as float or distortion-free glass, which was successfully introduced by Sir Alastair Pilkington in 1959. Through this process, glass was produced with excellent surface quality and transparency, and consequently the process of polishing glass plates was no longer needed. Flat glass is still produced in this way to date with some minor modifications to meet a specific purpose (Le Bourhis, 2008). The development of glass was basically based on the desired application of the glass. The growing ability of glass manufactures has changed the application of glass in building construction from its use as a small part of the building to the most sophisticated application such as load bearing elements. Architects have always attempted to produce attractive designs for a glass facade by maximising the transparency of the envelope.

2.2.1.1 Annealed Glass

The most recent techniques used in the production of glass panes for facades are the float process. There are four primary operations in glass manufacturing namely batching, melting, fining and forming as shown in Figure 2.2. These operations are common to the glass manufacturing process
with some variations considered depending on the end product. The proportions by mass of the annealed glass according to the British standard BS EN 572-1:2012 (2012) are given in Table 2.1.

![Typical manufacturing process for float glass](image)

**Figure 2.2.** Typical manufacturing process for float glass (Adapted from Pilkington, 1959)

<table>
<thead>
<tr>
<th>Chemical compound</th>
<th>Chemical formula</th>
<th>Percentage of mass (%)</th>
</tr>
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<tbody>
<tr>
<td>Silicon dioxide</td>
<td>SiO₂</td>
<td>69 to 74</td>
</tr>
<tr>
<td>Calcium oxide</td>
<td>CaO</td>
<td>5 to 12</td>
</tr>
<tr>
<td>Sodium oxide</td>
<td>Na₂O</td>
<td>12 to 16</td>
</tr>
<tr>
<td>Magnesium oxide</td>
<td>MgO</td>
<td>0 to 6</td>
</tr>
<tr>
<td>Aluminium oxide</td>
<td>Al₂O₃</td>
<td>0 to 3</td>
</tr>
<tr>
<td>Others</td>
<td>-</td>
<td>0 to 5</td>
</tr>
</tbody>
</table>

(Source: BS EN 572-1:2012, 2012)

Silicon dioxide is also known as silica and is found in sand. Calcium oxide is produced from limestone, and Sodium Oxide is from sodium carbonate. In general, the raw materials required for float glass according to the UK Glass Manufactures (2008) are sand (60%), sodium carbonate (21%) and limestone (19%). All of these materials are mixed in precise proportions and fed into the furnace and left to melt at temperatures of up to 1600°C. The mixture then forms a single ribbon of molten glass, which is floated on a stream of moving molten metal, usually Tin, under a nitrogen atmosphere.
that prevents oxidation of the metal. During this process, the glass constituents are mixed thoroughly, and bubbles eliminated from the molten glass. As the molten glass approaches the end of the molten metal chamber, the temperature is gradually reduced to approximately 600°C before the glass ribbon can be lifted from the molten metal onto rollers in a glass-making kiln. The variations in the flow and roller speed are the parameters that can be used to control the thickness of the glass. The temperature in the kiln is further reduced gradually to minimise the residual stresses in the annealed glass sheet and to prevent cracks due to changes in temperature. The glass is then cut into pieces by machines, and at this stage, it is usually known as annealed glass or sometimes called float glass.

The properties of float glass can be changed significantly through chosen cooling process, which eventually produces several different types of glass such as fully tempered (toughened), and heat strengthened (partly toughened) glass. The process of producing these glasses involves some modifications to the original float glass process, and the glass can be further strengthened and used to produce other types of glass products, such as laminated glass and insulating glass units (IGUs).

2.2.1.2 Tempered Glass

In 1930, Saint Gobin invented toughened glass or fully tempered glass which is produced in a similar process to the float glass process but with some modifications at the end of the process as outlined in BS EN 12150-1:2000 (2000). Toughened glass is produced by heating the float glass pane which has been cut into the required size or shape at a temperature of around 650 to 700°C. Following this heating, the glass surface is then cooled down rapidly usually using air jets. This process causes the surface of the pane to cool down first leaving the core remaining at a high temperature. When the core has subsequently cooled down, it develops tensile stresses, and this will induce compressive stresses into the surface of the pane as shown in Figure 2.3. Both the tensile and compressive stresses
produced during the process are termed as locked-in stresses. The thickness and size of panes of toughened glass are usually between 3 mm and 25 mm, and 2.0 m x 4.2 m maximum, respectively. On the other hand, the float glass that goes through the same process as toughened glass but cooled at a different rate is known as heat strengthened glass and the process must comply with BS EN 1863-1:2011 (2012). The selected cooling process makes the locked-in stresses of heat strengthened glass lower than those of toughened glass.

Figure 2.3. Stress profile of the toughened glass (Nielson, 2009)

2.2.1.3 Laminated Glass

In 1903, the French chemist Edouard Benedictus invented laminated glass which is produced by bonding two or more glass panes to the protective interlayer as shown in Figure 2.4. The interlayer is usually made of thin plastic sheets of polyvinyl butyral (PVB) which is available in a single foil of 0.38 mm thickness and may be in a form of two-ply (0.76 mm) or four-ply (1.52 mm) PVB foil as an interlayer. PVB is good in transferring a full-shear from one pane to another and some of the typical material properties of PVB are shown in Table 2.2 (IABSE, 2008). The bonding process takes place under heat and pressure. The laminated glass is manufactured according to BS EN ISO 12543-1 to
It works as a single unit of glass and visually no different with any other types of manufactured glass. Annealed, toughened and tempered glass panes can be used in laminated glass.

Figure 2.4. A sheet of polyvinyl butyral (PVB) sandwiched between two glass panes produces laminated glass

Table 2.2.

<table>
<thead>
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<th>Material Property</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
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<tr>
<td>Density</td>
<td>$\rho$</td>
<td>kg/m$^3$</td>
<td>1070</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>$G$</td>
<td>kN/mm$^2$</td>
<td>0-4</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$\nu$</td>
<td>-</td>
<td>$\approx$0.50</td>
</tr>
<tr>
<td>Thermal coefficient of expansion</td>
<td>$\alpha_T$</td>
<td>K$^{-1}$</td>
<td>80 x 10$^{-6}$</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>$f_t$</td>
<td>N/mm$^2$</td>
<td>$\geq$20</td>
</tr>
<tr>
<td>Elongation at failure</td>
<td>$\varepsilon_t$</td>
<td>%</td>
<td>$\geq$300</td>
</tr>
</tbody>
</table>

(Source: IABSE, 2008)
2.2.1.4 Insulating Glass Units (IGU)

The Insulated Glass Unit (IGU) which is usually used for windows in four-season countries is another type of glass product. It was invented in the 1930s and is produced by combining two or more panes of glass in a hermetically sealed unit. Unlike laminated glass, the glass is separated around the perimeter, generally between 6 mm and 20 mm, by using aluminium, steel or even wooden spacers and the bonding between the individual panes is made by adhesive sealants as shown in Figure 2.5. The manufacturing of IGU should be made according to BS EN 1279-1:2004 (2004). The space between the individual panes is usually filled with air, and any humidity in the air space will be removed by a desiccant, which is contained within the spacer. Insulating units can be fabricated from all types of processed glass, including laminated glass.

![Figure 2.5. A cross section of a unit of insulated glass](image)

2.2.2 Glazing Systems

There are two main functions of the glazing system; the first is to hold and fix the glass to the structural support system and the second, to provide a weather sealant for the facade. There are two types of glazing systems, namely, frame and frameless glass systems. The frameless glass system has optimised the transparency level of the facade. Both systems consist of four basic components as
shown in Figure 2.6 (Aggarwal et al., 2008; Kallioniemi, 1999) and Figure 2.7 (Ryan et al., 1997), respectively. The application of a curtain wall is dominated by the former systems while the latter is frequently used in structural glass facades (SGFs). Glass in the curtain wall system is integrated with other cladding systems, and they are all secured to the building structure. However, the glass that is used in SGFs is held by the glazing support attachment, particularly point fittings, which are frequently used to secure glass to the structural support systems.

Figure 2.6. Framed glass systems: (1) Load bearing structure, (2) Profile system, (3) Glass cladding, and (4) Fastening system (Kallioniemi, 1999)

Figure 2.7. Frameless glass facade system: (1) Glass cladding, (2) Glass fixings, (3) Glazing support attachment, and (4) Support structure (Ryan et al., 1997)
2.2.2.1 Point-fixed Systems

Mechanical glass fixing such as the point-fixed system has a great impact on the development of SGFs. There are two basic forms of point-fixed glazing used in SGFs: point-fixed bolted and point-fixed clamped fitting as shown in Figure 2.8. Both fittings are used to hold the glass and transfer the glass self-weight as well as lateral loads to the structural support system.

![Figure 2.8. Point-Fixed Bolted comprises of glazing bolt and spider fittings (left), Point-Fixed Clamped are connected to cable structures (right) (Compagno, 1999)](image)

Clamped fittings, which are also known as a pinch-plate system is used to hold a glass pane by its edges using patch plates. The clamped fitting holds the glass panes by friction and results in no membrane actions, which usually exists when bolted fixings are used. The plates are placed on both the interior and exterior faces of the glass and pressed or tighten together by using bolts or screws. They can be in various forms as shown in Figure 2.9 and the glass needs no drilling or perforation at its edges. A suitable interface material is inserted between the patch plate and glass. Usually, pure aluminium or fibre-reinforced plastics are used to provide the required coefficient of friction and accommodate any lack of flatness between the two interfaces. The construction of the Will Faber and Dumas Buildings in Ipswich which were completed in 1975 are early examples of a modern building
facade. The glass is supported by glass fins, which are set perpendicular to the cladding plane. In this case patch plates were used to accommodate fixing of the glass.

Figure 2.9. Several types of point-fixed clamped fitting manufactured by Faraone (Faraone, Suspended curtain-walls product catalogue, 2013)

In 1980s, a point-fixed bolted system was introduced, and it was used for the first time for a Farnborough office building by Arup Associates and also by Sir Norman Foster for the Swindon Renault factory. Generally, point-fixed bolted glass integrates the bolted fixings and the glazing support attachment which are used to hold and join the glass panes at its edges via glass fixings, to the structural support system. The attachment must be able to resist any moment and internal forces that are developed due to thermal expansion or other effects acting on the glass. Furthermore, it provides the structural interconnection, and allows relative adjustment in position. Basically, there are many types of glazing support attachments, which may suit bolted fixings such as angle brackets, spider fittings and bracket spiders as shown in Figure 2.10. Toughened glass that is used together with point-fixed bolted systems requires a set of holes which are used to accommodate bolted fixing. The holes need to be drilled before the glass is toughened. In order to accommodate the insulated
glass with point-fixed bolted fixings, internal spacers for bolt holes are fitted around the edge of the unit (Figure 2.11).

![Figure 2.10. Angle brackets (left), spider fittings (centre) and paired bracket spiders (right) (Kallioniemi, 1999)](image)

![Figure 2.11. Special details for insulated glass (Greenlite Glass Systems, Glass System LITEWALL brochure, 2014)](image)

2.2.2.2 Glazing Methods

A weather seal such as silicone sealant is used to fill in the gap between the glass panes and the glazing system as shown in Figure 2.12. The glass is glazed by one or a combination of the following glazing methods; wet glazing, dry glazing, pressure-glazed system, structural sealant glazing (SSG) or butt-joint sealant. All glazing methods (excluding SSG) mentioned above are non-
structural methods, which means they only provide sealant against air and water infiltration. The quality of the glazing, especially wet glazing, SSG and butt-joint sealant should be made by a qualified craftsman to avoid any air and water leakage. Nevertheless, any leaks due to installation error of the sealant could be easily detected and repaired.

Figure 2.12. Wet glazing (top left), dry glazing (top right), pressure glazing (bottom left), and structural sealant glazing (SSG) (bottom right) (Dow Corning Manual, 2011)

Butt-joint sealant is usually applied in frameless systems and structural sealant glazing (SSG) systems (Figure 2.13) to close the gap between the adjacent glass edges for weather seal sealant. It provides sealant against air and water infiltration for the frameless system eliminating the need for a conventional aluminium frame or mullions. The size of the sealant that covers the gap should be significant to the glass thickness. Usually, the width to depth ratio of silicone sealant is 2:1. Thus, for a thicker glass pane, the sealant might not cover throughout the depth of glass thickness. In a framed
system, the gap is usually sealed by an outer mullion and transom glazing cap. However, the gap between the glass surface and the outer glazing cap edges can be glazed by wet glazing or dry glazing.

Figure 2.13. Butt-joint sealant applied into the frameless glazing system (Patterson, 2011)

2.2.3. Cable Structures

The word structure in structural glass facades (SGFs) term refers to the structural support system that works together with the glass cladding and the glazing systems. The structural support systems that are used in SGFs are well-known after the emergence of point-fixed systems along with the improvement in quality of glass at the same time. Commonly, glass facades are categorised by the integral structural systems which can be grouped as linear, reticulated spatial and cable systems (Patterson, 2008, 2011). There are various types of structural support system used in SGFs such as conventional compression structures, steel trusses, and cable trusses as shown in Figure 2.14, and the latest tension structures. Their development can be seen through the dematerialisation and simplification of structural members. Initially, the glass support structure was solely in compression structures, and this has developed over time to a combination of compression-tension systems and eventually to tension only structures.
The tension only element that is used in SGFs can be represented by pre-stressed cable structures. The concept of cable structures supporting glass facades originated from large span roof structures. Cable suspended and cable supported roofs which are typical roof structures achieve their stiffness by pre-loading the roof with cladding and pre-stressed cables, respectively (Krishna, 1978). The system with pre-stressed cables allows the structure to have an enhanced load-displacement response when compared to a non-stressed cable system. In the 1990s, the pre-stressed monolayer cable-net systems appeared to be one of the popular support structures used in structural glass facades (SGFs). The greenhouses at Parc La Vilette in Paris and the Kempinski Hotel in Munich, which were built in 1986 and 1988, respectively, are examples of the earliest glass facades supported by cable-
net systems (Patterson, 2011). In addition, the transparency of a glass facade supported by a cable structure is at the highest possible level as compared to the transparency obtained from other types of structural support systems used in SGFs. The cables are spanned and pre-stressed between two boundary structures. The cable structures for SGFs are commonly configured in a flat vertical plane and are very light and flexible, which results in having large deflections under wind loading. The cables are arranged in such a way that they are aligned with the glass cladding grids. The configuration of cable structures can be in a single (mullion) or cable-net systems.

2.2.3.1 Cable Mullion Systems

The cable mullion is the simplest system amongst the cable structures used in SGFs. The system consists of a single pre-stressed cable per mullion that spans vertically between two floor slabs or boundary structures. The cables are spaced at approximately the width of the glass pane. The cable requires pre-stressing to gain initial stiffness and carry all loads that are transmitted from the glass cladding via the glass system. The cable mullion system could support a tall glass facade but the initial force and perhaps the size of the cables has to be significant, which creates high boundary reactions, to carry the glass cladding. Thus, the strength of the boundary support structures must be designed adequately and might end up as a massive structure. The cable mullion system used in SGFs is not only built for a flat glass facade, but the system could also accommodate a curved glass facade but is limited to a single-curve. Figure 2.15 shows three examples of cable mullion supported glass facade systems.
Figure 2.15. Examples of cable mullion supported glass facade systems: Lobby of a 53-storey tower at South Wacker, Chicago (left), One of the facades of the Lufthansa Aviation Centre (LAC) (centre), and Glass facade for Alice Tully Hall, Lincoln Centre, Manhattan (right)

2.2.3.2 Cable-net Systems

A cable-net system comprises of pre-stressed horizontal and vertical cables, which are typically configured as an orthogonal grid. The two-dimensional cable-net system has better deflection characteristic compared to that of the cable mullion system. Moreover, if the cable-net system and the mullion system are designed to have the same deflection criterion, the size of cables and the boundary structures of the cable-net system can be designed to be smaller than that of the cable mullion system. As the transparency level of the building is maximised by making use of the cable-net system, architects developed more sophisticated configurations for the glass facade. There are two main configurations of cable-net namely, flat and curved cable-nets. Figure 2.16 shows examples of flat and curved cable-net supported glass facade systems, respectively. Both configurations are geometrically complex, especially the double-curved nets, and produce a unique building facade. The pre-stressed cables of the flat cable-net system span between two supports in the same plane. The principle of the cable-net was developed for the Kempinski Hotel in Munich using
only a single-layer pre-stressed cable-net with the glass panels fastened intermittently to their nodes via clamped fittings. The Beijing New Poly Plaza in Beijing, China, which was built in 2006, is currently having the largest cable-net supported glass facade systems. The New Poly Plaza is the tallest flat cable-net structure used in SGFs and is supported by a flat pre-stressed cable-net, 90 metres tall by 60 metres wide.

*Figure 2.16. Flat and curved cable-net used in structural glass facade at Kempinski Hotel, Munich (top left), and Beijing New Poly Plaza, China (top right); Glazing at the entrance to the headquarters of Channel 4, London (bottom left), and Seattle-Tacoma International Airport, Washington, United States (bottom right) (Compagno, 1999; Patterson, 2011)*
The flexibility of the cable-net was utilised to form a curved glass facade which is more attractive, also possessing a higher lateral stiffness. The glass facade of the Channel 4 headquarters in London and SeaTac International Airport in Seattle as shown in Figure 2.16, are integrated with single and double-curved net systems that were built in 1992 and 2005, respectively. The double-curved net system may present advantages in structural performance under extreme loading conditions, although research has yet to verify this hypothesis. The curved facade can be achieved by using two approaches, either by using curved glass panes (Weber, 2009) or by curving the shape of the support structure (Mazeika & Kelly-sneed, 2007). The latter approach is more significant because of the flexibility of the cable-net structure can be fully utilised to achieve a curved facade even sometimes without using curved glass panes.

A double-curved net is usually of an anticlastic shape (Figure 2.17(i)), and it demands a good interaction between form and structure, function and economy. The anticlastic shape is formed by cables, which span in two principal directions, horizontal and vertical, curved in the opposite directions. It is essential to design the level of pre-stress in the steel cables to configure the desired shape of the facade. In comparison to the flat cable-net, curved cable-net systems require a form-finding process to determine the initial shape which is dependent on the accuracy of cable pre-stressing. Furthermore, the geometrical shape of the curved net can be accomplished by forming the appropriate geometry for the boundary condition of the net as shown in Figure 2.17(ii).
2.3 Material Properties of the Structural Glass Facade Systems

2.3.1 Properties of a Glass Pane

The thickness of the annealed glass pane available is between 2 and 25 mm according to BS EN 572-2:2012 (2012). However, thermally toughened glass (BS EN 12150-1:2000, 2000) and the heat strengthened glass (BS EN 1863-1:2011, 2012) is only available in the following thickness, between 3 and 12 mm, respectively. The thickness of the float glass is controlled during the manufacturing process by the speed of the molten glass that is withdrawn from the bath of molten tin and the associated rollers speed. The thickness of glass for glazing is determined based on the wind pressure which is calculated according to BS 6262-3:2005 (2005). It is important to select the thickness of the glass for glazing to ensure adequate strength to withstand the wind pressure. Typically, annealed glass is initially produced in a rectangular pane of maximum nominal supplied sizes of 3210 mm x 3210 mm with one of the dimensions, either the length or width of the glass pane, not less than 3150 mm. The final cut size of the glass pane can be cut out of the supplied size pane to the required size for glazing. However, the minimum surface area of the pane shall not be less than

Figure 2.17. (i) An anticlastic configuration that is taken out of a donut shape (Compagno, 1999), and (ii) A single and double-curved cable-net system
0.05 m² (BS EN 572-8: 2012, 2012). The sizes of a pane also apply to the heat strengthened and thermally toughened glass.

2.3.1.1 Mechanical Properties of Glass

Glass is a brittle material which is, in general, good in compression and weak in tension. One of the characteristics of a brittle material such as glass is that there is no plastic deformation behaviour as the glass fails while the deformation is elastic. Nevertheless, toughened glass has better strain characteristics than float glass. Figure 2.18 shows the stress-strain relationship of both annealed and toughened glass. The heating process of annealed glass strengthened and tempered glass, yet it does not affect the modulus of elasticity of the glass, which is approximately 70 kN/mm². The tensile strength of the float, heat strengthened and toughened glass panes are approximately 45, 70 and 120 N/mm², respectively. The strength of the heat strengthened and toughened glass are nominally twice and four times, that of the parent annealed glass. Although the tensile strength of these glasses varies, the compression strengths of the different types of glass are approximately the same at around 1000N/mm². Moreover, the density and Poisson’s ratio of the glass are 2500 kg/m³ and 0.2, respectively. The summary of glass properties is given in Table 2.3. The stress characteristics of glass is unchanged up to about 250° to 300° C. The modulus of rupture is another property of glass that represents the integrity of glass with regards to bending or its flexural strength.
Figure 2.18. Stress-strain relationships of annealed, and toughened glass (Overend & Parke, 2002)

Table 2.3.  
General properties of annealed glass

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value and unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, $\rho$</td>
<td>2500 kg/m$^3$</td>
</tr>
<tr>
<td>Poisson’s ratio, $\mu$</td>
<td>0.2</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>45 N/mm$^2$</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>1000 N/mm$^2$</td>
</tr>
<tr>
<td>Modulus of elasticity, E</td>
<td>70 kN/mm$^2$</td>
</tr>
<tr>
<td>Shear modulus, $G$</td>
<td>30 GN/m$^2$</td>
</tr>
</tbody>
</table>

(Source: BS EN 572-1:2012, 2012)

Based on the standards, the glass supported by any type of structural systems is designed individually according to BS 6262-3:2005. The design of glass thickness is carried out without considering the supporting structure which may possibly reduce the thickness of the glass used in the
structural glass facade. This is because the glass may behave differently depending on the glass supporting structure and support attachment. The former is described in 2.2.2.1 of Chapter 2. These two components, glass and supporting structure are analysed and designed separately. The working mechanism of glass with the supporting structure such as cable-net structure is very interesting because glass and cable-net have different mechanical behaviours. The glass is a brittle material, whereas the cable-net structure behaves geometrically nonlinear under loading. However, the glass could possibly be designed individually should the supporting structure is rigid as in systems other than cable-net structure for instance in framed glass systems. Moreover, the effect of impact force is not taken into consideration when designing the thickness of the glass pane. In addition, the glass has different characteristics when subjected to wind load and impact. The former is usually assumed as uniform whereas the latter concentrates onto specific point or area of the glass. The deflection of individual glass pane under these loadings is rather important as to fulfill the allowable deflection of the glass pane. The deflection of glass pane under loading is described in 2.3.1.3.

### 2.3.1.2 Thermal Properties of Glass

Glass has a low coefficient of thermal expansion compared to other materials which are used in structural glass facade systems such as steel and aluminium. The thermal expansion coefficient is the property of the material which expands as the temperature is raised, and it is an important factor which has to be considered when glass is bonded together with the silicone sealant as a structural or weather sealant. Table 2.4 lists the thermal expansion coefficient for most of the materials joint together with glass in glass facade systems. Glass has a linear thermal expansion within the temperature range of 20° to 300° C (BS EN 572-1:2012, 2012). Thermal shock is one of the important properties of glass and requires the material to be able to withstand a temperature difference subjected to rapid change. Heat treated glass such as heat strengthened, and toughened glass has a higher
thermal shock rating than that of annealed glass (Ryan et al., 1997). The rating of thermal shock capability is verified by heating the glass to a specific temperature and then abruptly exposing it to a cooler temperature.

Table 2.4.
Coefficient of thermal expansion values for common construction material

<table>
<thead>
<tr>
<th>Material</th>
<th>Coefficient of Thermal Expansion, ($10^{-6} /°C$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>23.6</td>
</tr>
<tr>
<td>Glass</td>
<td>9.0</td>
</tr>
<tr>
<td>Concrete</td>
<td>9.0 – 12.6</td>
</tr>
<tr>
<td>Silicone</td>
<td>2.6 – 3.0</td>
</tr>
<tr>
<td>Steel</td>
<td>13.0</td>
</tr>
</tbody>
</table>

(Source: Cobb, 2009)

2.3.1.3 Deflection of Glass Panes Subjected to Loading

Wind induced pressure is a major consideration in glass pane design as it is a parameter in deciding glass thickness and glass selection using codes such as BS 6262-3:2005 (2005). Figure 2.19 shows the deflected shapes of the glass under in-plane and lateral loads, which are perpendicular to the glass surface. In a structural glass facade, the glass that is used as a facade is usually designed to resist wind pressure and its own weight rather than an in-plane load. The mid and edge deflection limits of glass under wind load are usually taken as 1/100 and 1/175 of the glass edge length, respectively (Ryan et al., 1997). These values are typically reasonable for the glass in many applications. However, the glass supported by flexible structural system such as cable-net structure may behave in a different way. This is because the deflection of cable-net structure is large when subjected to wind loading. It also depends on the type of glass support attachment used to hold the
glass and how it connects to the cable-net structure. The deflection of glass pane as shown in Figure 2.19 only happens if the glass is used in framed glass system or supported by a rigid structure. In general, the thickness of glass is designed to accommodate the deflection limit set for the glass in resisting the wind loading. The design did not take into consideration the effect of impact load imposed on the glass pane. The deflection of glass pane due to impact may be higher compared to the pane under wind loading. This is because the impact loading is concentrated at one point rather than uniformly exerted on the whole glass pane. It is important to study the deflection of glass when subjected to impact load when it is used together with the cable-net structure.

![Glass deflection](image)

*Figure 2.19. Glass subjected to in-plane and lateral loads (IABSE, 2008) (left), and the deflected shape of glass that is secured by using point-fixed systems (Ryan et al., 1997) (right)*

### 2.3.1.4 Application of Glass in Structural Glass Facades

Generally, glass is used in the structural glass facades (SGFs) as a building enclosure as well as for thermal insulation of the structure. The cladding in a frameless glass facade system has a significant contribution to the stiffness of the whole structural glass facade systems. Feng *et al.* (2007) reported that the contribution could be in two ways, which are through the bending stiffness and membrane or in-plane action of the glass panels. In addition, the membrane force which contributes
to the stiffness of the cable-net changes a little when thicker glass cladding is used in the system. The
stiffness contribution of glass, $C_g$, is calculated based on the nodal deflections of the cable-net as
defined by Equation 2.1.

$$C_g = 1 - \left( \frac{U_g}{U} \right)$$

Equation 2.1

Where $U_g$ and $U$ are the nodal deflections of cable-net with and without the glass cladding,
respectively. Basically, the stiffness of the whole structure is mainly influenced by the support
structure. However, the contribution of the glass pane to the stiffness of the structure increases in
certain circumstances such as when failure of the structural support system occurs. The behaviour of
the glass panes should be clearly understood. It is important to ensure that the burden of pressure on
the glass does not exceed the allowable capacity of the glass pane. In addition, the deflection of glass
pane may also depends on the type of supporting structure used.

2.3.2 Properties of Silicone Sealant

A sealant can be classified according to its chemical composition, intended use and
mechanical properties. A sealant must be flexible to allow the substrates to move freely. Various
types of sealant are listed in Table 2.5. Silicone is used as a sealant in a structural glass facade because
of their outstanding performance against environment exposure for a long period of time (Oldfield &
Symes, 1996). The service life of silicone sealant can be more than 25 years, although most of the
sealant manufacturers only provide a 10 year performance warranty period. Silicone has a high
resistance to extreme temperature conditions and has the capability to serve as a sealant at
temperatures in the range of -50 to 150 °C. The flexibility of silicone sealant used in a glazing element can easily accommodate any movement such as in-plane, out-plane and rotation.

Table 2.5.
The basic properties of various types of sealant used in building industries

<table>
<thead>
<tr>
<th>Type of Sealant</th>
<th>Behaviour</th>
<th>Recovery ¹ (%)</th>
<th>MC ² (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy sealant</td>
<td>Plastic</td>
<td>0 – 5</td>
<td>2 – 5</td>
</tr>
<tr>
<td>Butyl sealant</td>
<td>Plasto-Elastic</td>
<td>5 – 40</td>
<td>5</td>
</tr>
<tr>
<td>Acrylic sealant</td>
<td>Elasto-Plastic</td>
<td>40 – 78</td>
<td>7 – 10</td>
</tr>
<tr>
<td>Polysulphide sealant</td>
<td>Elastic</td>
<td>70 – 100</td>
<td>15 – 20</td>
</tr>
<tr>
<td>Polyurethane sealant</td>
<td>Elastic</td>
<td>70 – 100</td>
<td>25</td>
</tr>
<tr>
<td>Silicone sealant – One part</td>
<td>Elastic</td>
<td>90 – 100</td>
<td>12.5 – 25</td>
</tr>
<tr>
<td>Silicone sealant – Two part</td>
<td>Elastic</td>
<td>90 – 100</td>
<td>25 – 50</td>
</tr>
</tbody>
</table>

(Source: Lee, 2003)

¹ Elastic recovery of material after 24 hours; ² Movement Capability

Silicone that is used as a weatherseal or structural glazing has excellent movement capability whereby the material remains in its elastic state. The silicone sealant has excellent elastic recovery of 90-100% compared to other structural elastomeric sealants that are used as glazing material in glass facade systems (Chew & Yi, 1997). Figure 2.20 shows an example of the stress-strain relationship for low modulus sealant (De Buyl, 2001). The material has the ability to elongate greater than 400% of its original length. Most of the silicone sealant manufacturers such as Dow Corning and Bondaflex Technologies, manufacture a silicone sealant product that has the ability to elongate between 600 to 800% for weatherseal and structural sealant glazing. Generally, silicone sealants with medium and high modulus are used in structural sealant glazing systems.
Figure 2.20. Tensile strength versus percentage strain for low modulus silicone sealant (De Buyl, 2001)

Silicone sealant is one of the small number of parts that are used in structural glass facades (SGFs) to create continuity between the glass pane for a complete facade. Glass and the structural support systems are subjected to movement due to thermal changes and wind pressure. The movement that is created between the sealant and the substrates can be in the form of in-plane, shear and rotation. Thus, the silicone sealant that is used as a jointing element must be flexible and able to accommodate any movement of the glass cladding. Furthermore, the movement of the cladding units might lead to tensile and compressive forces. Sufficient movement capability and the strength of sealant must be designed to accommodate the movement. The silicone sealant that is used in frame structural systems, must be able to create intact bonding between the structural seal support frame, such as aluminium transom and mullions, and glass at the same time. The silicone sealant that is used in the frameless glass system is only for weatherseal and not intended for structural purposes. The movement of the substrates such as the glass and the structural support frame must be accommodated by the structural glazing sealant.
Table 2.6.

The properties of Dow Corning® 121, structural glazing sealant which is manufactured by Dow Corning

<table>
<thead>
<tr>
<th>Test</th>
<th>Property(^3)</th>
<th>Unit</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Supplied – As Test at 23°C (75°F) and 50% RH</td>
<td>Color – Base</td>
<td>Black/dark gray</td>
<td></td>
</tr>
<tr>
<td></td>
<td>– Catalyst</td>
<td>White</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Physical Form</td>
<td>Paste</td>
<td></td>
</tr>
<tr>
<td>ASTM D1475</td>
<td>Specific Gravity – Base</td>
<td>1.35</td>
<td></td>
</tr>
<tr>
<td></td>
<td>– Catalyst</td>
<td>1.24</td>
<td></td>
</tr>
<tr>
<td>As Catalyzed – Mixed at 1:1 Base to Catalyst by Volume</td>
<td>Working Time</td>
<td>minutes</td>
<td>15-45</td>
</tr>
<tr>
<td></td>
<td>Unit Handling Time at 23°C</td>
<td>hours(^3)</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>(75°F), minimum(^4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>VOC Content, mixed</td>
<td>g/L</td>
<td>&lt;25</td>
</tr>
<tr>
<td>ASTM D2202</td>
<td>Flow/Sag (slump)</td>
<td>inches (mm)</td>
<td>&lt;0.2 (&lt;5)</td>
</tr>
<tr>
<td>Cured – After 1 day at 75°F (23°C) and 50% RH</td>
<td>ASTM C661</td>
<td>Durometer, Type A</td>
<td>points</td>
</tr>
<tr>
<td></td>
<td>ASTM D412</td>
<td>Tensile Strength</td>
<td>psi (MPa)</td>
</tr>
<tr>
<td></td>
<td>ASTM C1135</td>
<td>Tensile Strength at 25%</td>
<td>psi (MPa)</td>
</tr>
<tr>
<td></td>
<td>ASTM C1135</td>
<td>Tensile Strength, Ultimate</td>
<td>psi (MPa)</td>
</tr>
<tr>
<td></td>
<td>ASTM C1135</td>
<td>Elongation, Ultimate</td>
<td>%</td>
</tr>
<tr>
<td>Cured – After 7 days at 75°F (23°C) and 50% RH</td>
<td>ASTM C661</td>
<td>Durometer, Type A</td>
<td>points</td>
</tr>
<tr>
<td></td>
<td>ASTM D412</td>
<td>Tensile Strength</td>
<td>psi (MPa)</td>
</tr>
<tr>
<td></td>
<td>ASTM C1135</td>
<td>Tensile Strength at 25%</td>
<td>psi (MPa)</td>
</tr>
<tr>
<td></td>
<td>ASTM C1135</td>
<td>Tensile Strength, Ultimate</td>
<td>psi (MPa)</td>
</tr>
<tr>
<td></td>
<td>ASTM C1135</td>
<td>Elongation, Ultimate</td>
<td>%</td>
</tr>
<tr>
<td></td>
<td>ASTM D 719</td>
<td>Movement Capability</td>
<td>%</td>
</tr>
</tbody>
</table>

(Source: Dow Corning® 121 Structural Glazing Sealant, Dow Corning Manual, 2013)
Table 2.7.

*The requirement for physical, mechanical and performance qualities of silicone sealant*

<table>
<thead>
<tr>
<th>Property</th>
<th>Requirement</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rheologic, max</td>
<td>4.8 mm (5/32 in.)</td>
<td>C639</td>
</tr>
<tr>
<td>Vertical</td>
<td>no deformation</td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>10 s</td>
<td>C603</td>
</tr>
<tr>
<td>Extrudability, max</td>
<td>20-60</td>
<td>C661</td>
</tr>
<tr>
<td>Hardness, Shore A</td>
<td>10 %</td>
<td></td>
</tr>
<tr>
<td>Heat aging</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Weight loss, max</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>Cracking</td>
<td>no transfer in 3 h</td>
<td>C679</td>
</tr>
<tr>
<td>Chalking</td>
<td>no transfer in 3 h</td>
<td>C1135</td>
</tr>
<tr>
<td>Standard conditions:</td>
<td>345 kPa (50 psi)</td>
<td></td>
</tr>
<tr>
<td>88°C (190°F)</td>
<td>345 kPa (50 psi)</td>
<td></td>
</tr>
<tr>
<td>–25°C (–20°F)</td>
<td>345 kPa (50 psi)</td>
<td></td>
</tr>
<tr>
<td>Water immersion</td>
<td>345 kPa (50 psi)</td>
<td></td>
</tr>
<tr>
<td>A minimum of 5000 h weathering</td>
<td>345 kPa (50 psi)</td>
<td></td>
</tr>
<tr>
<td>Shelf life, min</td>
<td>6 months</td>
<td></td>
</tr>
</tbody>
</table>

(Source: ASTM C1184-14, 2005)

The value of the mechanical properties of the silicone sealant may vary and depends on the intended use of the material. However, the mechanical properties that are listed in Table 2.6 are common for weatherseal and structural sealant glazing. Some of these properties must fulfill the requirements that are listed in Table 2.7. All the advantages that are mentioned above have made silicone the most practical and suitable elastomer for many applications, particularly as structural glazing sealant.

2.3.3 Steel Wire Cable Constructions

Steel wire cables are commonly used as a tension element, and are one of the most efficient structural components due to their high strength to weight ratio and flexibility. Steel wire cables are widely used as the main structural components for cable roof structures, cable-stayed bridges, pre- and post-tensioned elements and cable structures, which are used in structural glass facades. A wire
cable consists of wires, strands and a core. The cable, herein, is referred to wire rope and wire strand.

Wire rope consists of multiple strands laid or twisted into a helix. The strand is constructed using steel wires that are twisted helically about a central wire. The basic construction of wire rope is illustrated in Figure 2.21. In addition, there are various types of wire rope (Figure 2.22) that can be categorised by their construction, grade, and the way in which the wires and strands are wound or laid about each other, and the type of core.

![Figure 2.21. Construction of wire rope or cable: (i) wire, (ii) strand, (iii) fibre core (FC), (iv) 6x7 FC, and (v) 7x7 wire strand core (WSC)](image)

![Figure 2.22. Various types of wire rope construction of independent wire rope core (IWRC) and fibre core (FC) (Bridon International Ltd, 2014)](image)
2.3.3.1 Wires

Steel wires are made from alloy carbon steel with a carbon content of 0.4 to 0.95%. The steel used in wire ropes is made using a heat process where the wire cross-section is reduced in stages. The most common wire grades that also represent the strength of the wires are usually categorised by their material such as plow steel, galvanised and stainless steel. There are various types of Plow Steel such as Improved Plow Steel (IPS) and Extra Improved Plow Steel (EIPS), and Extra Improved Plow Steel (EEIPS) (Glerum, 2007). The approximate strengths of each type of materials are given in Table 2.8. Typically, a high-strength wire has a high breaking load capacity. However, the higher the strength of wire rope, the lower is its ductility.

Table 2.8.  
*Approximate strength for various wire grades*

<table>
<thead>
<tr>
<th>Wire grade</th>
<th>Approximate strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>1570</td>
</tr>
<tr>
<td>Improved plow steel (IPS)</td>
<td>1770</td>
</tr>
<tr>
<td>Extra improved plow steel (EIPS)</td>
<td>1960</td>
</tr>
<tr>
<td>Extra improved plow steel (EEIPS)</td>
<td>2160</td>
</tr>
</tbody>
</table>

2.3.3.2 Strands

A strand is made by multiple wires that are twisted helically. Basically, there are two categories of strands, which are used to form wire cable and wire strand alone such as spiral and locked coil strands. All types of strand constructions are given in Figure 2.23. Spiral strand can be modified by adding one or more outer layers, which are formed by specially shaped interlocking wires. The modified strand is known as a locked coil strand which is also a form of spiral strand. Wire
ropes that are formed by standard strand construction, such as Filler wire, Seale and Warrington, have to be pre-stretched in order to remove the constructional stretch. However, spiral, compacted and locked coil strands do not require any pre-stressing as the constructional stretch has been reduced or removed during the manufacturing process of the wire strand (Bridon International Ltd, 2014).

Constructional stretch is a condition where the wires and strands of wire cables interact with each other when subjected to loads. This condition brings the elements of the ropes into closer contact and eventually compresses the core of the rope. Usually, the constructional stretch is reduced or removed when the wire cable is cyclically loaded. The wire cables that are formed by multiple strands are much more flexible, axially and in bending, compared to that of spiral strands. Due to this characteristic, wire rope is widely used in cranes, cable cars, and mining industries. While spiral strand and locked coil strands, which have better axial and bending stiffness are commonly used in cable structures such as cable roof structures, suspension and cable stayed bridges, and guys to various mast and towers. These structures do not require a cable that has low bending stiffness. In addition, compacted strand is commonly used in cable-nets to support glass facade systems (Bridon International Ltd, 2014).

2.3.3.3 Cores

Prior to 1830, wire ropes are assembled without a core. However, Wilhem Albert introduced a core made of hemp, which was surrounded by wrought-iron strand (Sayenga, 2008). Later, John A. Roebling used a more flexible core rather than hemp rope for a wire rope. The introduction of a core ensured the strands around the core are equidistant, and maintaining the position of the outer strands to provide extra stability. In addition, wire cores offer less stretch, have better load carrying capacity and are not affected by heat. There are three types of core for the wire rope: fibre core (FC), wire strand core (WSC) and independent wire rope core (IWRC) as described in Table 2.9.

Table 2.9.
Three types of cores that are usually used for wire rope

<table>
<thead>
<tr>
<th>Type of Core</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre core (FC)</td>
<td>• The core provides excellent flexibility.</td>
</tr>
<tr>
<td></td>
<td>• Additionally, the fibre core is impregnated with lubricant during manufacture thus providing internal lubrication to reduce internal corrosion and wear between wires.</td>
</tr>
<tr>
<td></td>
<td>• Inadequate when wire rope is subjected to prolonged outdoor exposure.</td>
</tr>
<tr>
<td>Wire strand core (WSC)</td>
<td>• Offers significant high tensile strength.</td>
</tr>
<tr>
<td></td>
<td>• The core is usually used for standing ropes such as ringing.</td>
</tr>
<tr>
<td></td>
<td>• Good resistance against abrasion.</td>
</tr>
</tbody>
</table>
Independent Wire Rope Core (IWRC)

- The strength of wire rope with IWRC is better than that of WSC and FC.
- The flexibility of IWRC wire rope and FC wire rope are about the same.
- The core is usually used in applications demanding high tensile stress and high temperature capability.

2.3.4 Mechanical Properties of Steel Wire Cables

Steel wire rope is manufactured in various strengths, sizes and types. The varieties in wire cables produced by manufacturers are to cater for various requirements in many diverse applications. Wire rope is usually manufactured in the following grades; 1570, 1770, 1960, and 2160 N/mm². The strength of wire cable is usually published by the wire cable manufacturers in terms of minimum breaking load and safe working load. At the minimum breaking load, also known as ultimate load (BS EN 12385-2:2002+A1:2008, 2003), the wire cable is likely to show signs of failure. The wire cable may rupture and break. In order to avoid any damage or failure to the wire rope, a safe working load, which is less than the breaking strength is introduced. The safe working load is usually taken as 15 to 25% of the tensile strength of the wire cable. Figure 2.24 shows an example of the minimum breaking load for various diameters of wire cable that are provided by the manufacturers (Bridon, 2012) and recommended by BS EN 12385-10:2003+A1:2008 (2004). The figure shows that the strength of the wire cable increases as a larger cable diameter is used. The minimum breaking load is associated with the size and tensile strength of the individual wires.
Figure 2.24. The relationships between wire rope and strand size, and their minimum breaking load for locked coil strand, spiral strand, compacted strand, and 6x19 IWRC of various steel grades (Bridon International Ltd, 2012; BS EN 12385-10:2003+A1:2008, 2004)

2.3.5 Cable End Fittings

They are many types of wire cable end fittings. Most of them are explained in BS EN 1993-1-11:2006 (2008). Some of the wire rope end connectors are shown in Figure 2.25.
Cylindrical socket with external thread and nut

Swaged fitting with thread

Open swaged socket

Open spelter socket

Closed swaged socket

Open swaged socket

U-bolt grip according to EN 13411-5

Figure 2.25. Typical end fittings used for steel wire cable (BS EN 1993-1-11:2006, 2008)

2.3.6 Geometric Nonlinearity of Wire Cables

A wire cable hanging under its own self-weight plus the weight of the cladding forms a curve called a catenary. The equation of the catenary is given in Equation 2.2, and the derivation of the equation is presented in Appendix A.

\[ y = a \cosh \frac{x}{a} \]  

Equation 2.2

Where \( a \) is the ratio of force in the cable to the cable mass and gravitational force. These parameters are stated in the derivation of Equation 2.2 in Appendix A. A static analysis of cable structures can be undertaken by using a method that is based on the catenary equation (Miguel et al.,
However, in most practical cases, where the sag to span ratio is low, the deflected shape of the wire cable is assumed to be in a parabolic arc (Bridon International Ltd, 2014). The vertical deflection at any point in the span and the length of the wire cable are calculated based on this assumption. All formulae are given in Appendix B. The deflection of a wire cable that is subjected to load can be very large even when the system is working within the elastic limit. This behaviour is a form of geometric non-linearity. The stiffness of the wire cable changes as the cable is deformed. The fundamentals of geometric non-linearity of a cable can be shown by the load-displacement relationship of the two element structural system (Figure 2.26) as shown in Equation 2.3.

\[ \sum V = 0 \]

\[ P = 2K(\Delta L)\sin \theta_1 \]
\[ = 2K \frac{\sqrt{(L_0 + \Delta L)^2 - b^2}}{L_0 + \Delta L} \]
\[ = 2K \frac{\Delta L}{L_0 + \Delta L}(\delta_2 + \delta_1) \]
\[ = 2K \left( 1 - \frac{L_0}{L_0 + \Delta L} \right)(\delta_2 + \delta_1) \]
\[ = 2K \left( \delta_1 + \delta_2 - \frac{\Delta L(\delta_1 + \delta_2)}{\sqrt{b^2 + (\delta_1 + \delta_2)^2}} \right) \]

Equation 2.3

*Figure 2.26. Two element structural system (Lewis, 2003)*
Equation 2.3 shows that the load-displacement relationship is non-linear. $L_0$ is the original length of $AB$ before the element is loaded by load $P$. $\delta_1$ and $\delta_2$ are the vertical displacements at $B$ before and after point $B$ is loaded by $P$, respectively. $K$ is the elastic stiffness of the cable, $EA/L_0$. $E$ and $A$ are Young’s modulus and cross-sectional area of the cable, respectively. In addition, the force in the cable increases non-linearly as the cable is deflected under the action of lateral loads (Pintea, 2012). The geometric non-linearity of structures can be solved by a variety of numerical methods and techniques such as the transient stiffness method, force density method, and dynamic relaxation method (Lewis, 2003). The most common computational approaches are discussed in the next section.

2.3.7 Structural Performance of Cable Structures

The sources of structural non-linearity can be in the form of geometry, materials, friction, inertia or body forces. Wire cable is geometrically non-linear as it is subjected to large deflections when loaded perpendicularly to its neutral axis. The cable will experience relatively large deflections when it is loaded. As the cables deflect under loads particularly wind loading, the tension force as well as the stiffness of the cables are increased significantly. The stiffness of a cable-net system is not only dependent on the pre-stress force in the cable but also the configuration of the net itself (Talvik, 2001). The load-deflection response of a curved net under wind and seismic loads may be lower than that obtained for the flat nets because the former has been built with a partially deflected configuration. The geometry of the cable-net also contributes to the whole structural stiffness. The initial pre-stressing of the curved cable-net which has the same deflection criteria as the flat cable-net can be lower than that of the flat cable-net. Moreover, the curved cable-net can accommodate the criteria with lower cable initial pre-stress and boundary reactions. Thus, the size of the boundary structure for the curved cable-net could possibly be smaller than that is required for a flat cable-net.
Common deflection criteria set for cable structures are between L/35 to L/50 (Mazeika & Kelly-Sneed, 2007; Patterson, 2011) where L is the shortest length of cable measured between both ends. It is important to note that these deflection limits are imposed to accommodate the strength capacities of the structural support system and movement of the glass facade. The glass might break under excessive deflection. Furthermore, if the deflection of a facade is quite noticeable, the public perception may cause undue concerns that the wall is not sufficiently strong. A configuration consisting of flat cable mullions and cable-net systems is rather simple compared to a curved cable-net, particularly during pre-stressing of the cables. The pre-stressing of cables in the curved cable-net system must be in the correct sequence to obtain the exact configuration of the double curvature cable-net, as designed.

Additional parts such as dissipative device at the end of the cable structures can improve the dynamic performance of the structural glass facade (Amadio & Bedon, 2012b). The device assists in reducing the axial force in the cable without increasing the deflection of cable structures under excessive pressure, such as extreme wind and blast wave loading due to an explosion. However, there is no dissipative device for improving the dynamic performance of the structure considered or installed in this research. The influence of glazing system on the global behaviour particularly dynamic performance of the structural glass facade is one of the interesting subjects in this study.

The hogging cables as illustrated in Figure 2.27 might lose some stiffness as the force in the cable is reduced. The cable might reach zero stress if the initial stress in the cable is not adequate. The performance of a curved cable-net might be better than a flat cable-net, but it is yet to be proven by research. However, some cables in the curved configuration might lose stress in tension due to the direction of wind pressure. The direction of wind acting on the glass cladding might be crucial for the curved cable-net. The losses might affect the stiffness and the performance of the cable-net system.
2.4 Failures of Glass and Wire Cables

2.4.1 Glass Failure

Failure of glass may be due to many factors such as the actual material forming the glass, the processing of glass and physical contact which may be subjected to wind and impact loadings. The most common and well known failures of glass are caused by Nickel Sulphide (NiS) inclusions, surface flaws, thermal breakage, impact pressure, and movement of the structural support systems. The glass has significant influence on the dynamic performance of structural glass facades. However, the breakage of glass may reduce the structural dynamic performance (Amadio & Bedon, 2012a).

2.4.1.1 Imperfections in Glass - Nickel Sulphide Inclusion

The Nickel Sulphide (NiS) inclusion problem was first acknowledged in the 1940s (Jacob, 1997). The imperfections in the glass occur during the glass production process, especially in the heat-treated glass. The glass may be subjected to spontaneous breakage due to NiS inclusion that is NiS presence within a tension zone of the heat-treated glass may induce a fracture (Jacob, 1997). NiS is formed by the reaction between metal and alloy particles with the Nickel components and molten glass reacting together during the annealing process in the manufacture of annealed glass. NiS which is usually spherical in shape cannot be traced or seen by the naked eye as the size of the NiS inclusion is very small, typically from 0.1 to 0.5 mm (Pilkington, 2011). Many researchers have explained that

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*Figure 2.27. The direction of loads against the hogging (left), and sagging (right) cables*
the spontaneous breakage of toughened glass is due to the volumetric changes of NiS stone (Barry & Ford, 2001; Ford, 1997; Jacob, 1997; Sakai & Kikuta, 1999). The expansion of NiS stone initiates cracks (Figure 2.28) which subsequently, creates additional compressive stress adjacent to the stone in the body of the glass. However, Solinov (2007) disagreed with the explanation given by the previous researchers on the leading cause of spontaneous glass breakage caused by NiS inclusion. Solinov stated that the problem is initiated by a high level of stresses at the location of the NiS stone and a sharp decrease of the life time of the glass under the action of NiS. Nevertheless, both explanations are fundamentally almost the same. The appearance of NiS stone in the compressive zone of the toughened glass is not critical. The stresses that are initiated by the expansion of the NiS stone are compensated by the compression stresses.

![Image](image.png)

*Figure 2.28. Cracks adjacent to a Nickel Sulphide inclusion in the body of intact glass (Barry, 2006)*

In order to reduce the risk of spontaneous breakage of tempered glass, a method known as Heat Soaking was introduced. This process was developed by Pilkington, a major glass company, to reduce the incident associated with NiS inclusions by up to 95%. The process is undertaken by heating tempered glass in a furnace to a temperature up to 280°C for several hours in order to induce fracture. The infected glass will be destroyed in a heat soaking chamber at the factory. The glass exposed to this process is known as heat soaked thermally toughened glass and must be produced according to
BS EN 14179-2:2005 (2005). The problem of NiS inclusion was reported to be approximately less than 2% of the total production of tempered glass (Jacob, 2001).

2.4.1.2 Surface Flaws in Glass

Surface flaws in glass are subjected to ion-exchange which delayed the breakage of glass. The flaws are mostly resulting from the cutting and finishing process of annealed glass (Gulati et al., 2012). Consequently, microcracks might be formed and in certain circumstances, they can be deep enough to experience tensile stress from ion-exchange. The stress in glass that is used as cladding in a structural glass facade is usually subjected to wind pressure. The resulting stress might propagate these cracks and lead to glass breakage.

2.4.1.3 Thermal Breakage

Thermal stress which may act on the glass edge due to non-uniform temperature within the glass pane may lead to thermal breakage. The event usually occurs in framed glazing systems. When direct sunlight falls on a pane of glass, the glass surface tends to heat up. This heating is not uniform in nature. The central part that is exposed gets more sunlight and heats up faster while the edges (glass surfaces that are covered by the frame) are relatively cooler. The temperature difference causes the centre and edges of the glass to expand unevenly, which induces stress within the glass pane. There is a chance of thermal breakage if the stress developed in the glass exceeds a certain limit, particularly at the weakest point in the glass which is usually at the edges of the glass. The weakest point of the glass might be related to the surface flaws resulting from the cutting and finishing process of float glass, particularly at the edges of the glass. Nevertheless, thermally toughened glass has significantly higher edge strength to withstand the thermal breakage. The edge strength of the glass is one of the
crucial criteria used to resist thermal breakage, which is also important for point fixed glazing. Although the edges of heat-treated glass are the weakest part, the resistance of the glass against thermal breakage is much better than annealed glass.

2.4.1.4 Impact Pressure

The other common causes of glass failure are due to impact loading and thermal stress loading (Gunasekaran et al., 2010). The failure of glass caused by impact may subject the glass to a sudden localised contact. In the event of extreme wind pressure such as a typhoon, the wind might carry together a hard body object and accidentally smash the glass facade. The impact of the object might result in glass fracture if the force is sufficient to overcome the strength of the glass. Such pressure may also be caused by an explosion near to the building facade. The explosion creates a pressure wave travelling at a very high velocity and, at the same time, increasing the surrounding temperature at the centre of the blast to around 3000 to 4000°C. Although the pressure wave of the blast happened in a short period of time, the impact to any nearby surface is very severe. In the event of an explosion, the impact may break the glass facade and leave the support structure to absorb the impact. The glass that is supported by a rigid structure may not have much room for movement under impact. This is because, the support structure may experience small deformation and leave the glass to initially absorb the impact force. The deflection of glass under loading is also limited. The individual glass may deform significantly before breaking under the impact. This is because the glass is brittle where the failure such as glass breakage happens within the elastic zone and without plastic deformations. As for glass supported by cable-net structure which is flexible with large deformation under loading, the cable-net structure will initially respond to the imposed load. This allows the glass to remain intact before the cable-net stiffened with small deformation under loading. The impact force exerted on the glass pane can be determined based on Equation 2.4.
\[ F = 0.5mv^2/d \] \hspace{1cm} \text{Equation 2.4}

Equation 2.4 calculates the impact force exerted on the glass pane, where \( m \) and \( v \) are the mass and impact velocity of the object that hit the glass pane, respectively. While \( d \) is the distance travelled by the object during the impact before it bounced back or stopped. The glass may break should the impact force is greater than the surface compressive strength of the glass. In addition, the impact force exerted on the glass pane may deflect the glass significantly. The deflection limit of the glass pane in the structural glass facade shall not be exceeded.

2.4.1.5 Movement of the Structural Support System

Glass breakage may also occur resulting from the movement of the structural support due to wind loading, particularly in high-rise buildings. Excessive movement of the structural support system or building structure may initially create a fracture and eventually lead to glass breakage. It is important to control the deflection of the support structure and check the maximum allowable deflection or movement of the glass. The synchronisation of movement between the glass facade and the structural support system is essential to control the deflection and must be checked during design. The deflection characteristics of glass were discussed in 2.3.1.3.

2.4.2 Glass Breakage Characteristics

In the event of breakage, glass fractures have specific characteristics depending on the type of glass. Figure 2.29 shows the breakage characteristics for float, toughened and laminated glass as described in BS 6262-4:2005 (2005). Float glass is not included in the safety glass category as it tends
to break by shattering into sharp and large pieces. Unlike float glass, toughened glass is categorised as a safety glass which tends to break into small fragments. Thus, toughened glass is used extensively in areas where glass strength is required and the risk of thermal or impact breakage is high such as in car windshields and cladding in facades. Another processed glass is heat strengthened glass, which is processed in a similar fashion with the toughened glass, but it has similar breakage characteristics as the float glass. Laminated glass has the safest breakage behaviour amongst all the processed and heat treated glass. The fractures of either sharp shards or small fragments are not freely scattered because they are bonded by the PVB interlayer. Figure 2.29 (right) shows the broken pieces of glass are still intact without being scattered or falling off. Laminated glass which is produced according to BS EN ISO 12543-1:2011 (2011) is considered to be a safety glass.

![Figure 2.29. Breakage characteristics of float glass (left), toughened glass (centre) and laminated glass (right)](image)

### 2.4.3 Causes and Effect of Wire Cable Failure

The failure of wire cable can possibly cause disastrous consequences and can occur without warning, causing damages and endangering lives. The condition of wire ropes has to be frequently checked in order to avoid any damage (Chaplin, 1995). Sometimes, the cable fails prior to its normal life expectancy. Torkar and Arzensek (2002) investigated the failures of wire rope from a crane and
found that the wire rope failed after 12 months of services. They reported that the fatigue crack growth was initiated by the broken wires and the lack of maintenance, and were the reasons for the wire rope failures. The increasing number of broken wires decreases the load-bearing capacity of the wire rope and eventually breaks the wire rope. Judging from this situation, the failure of the cable does not necessarily occur near the end of its normal lifespan. The potentially catastrophic failures may happen at any moment within the cable life (Verreet, 2011). Although sophisticated discard criteria are used to monitor and evaluate the conditions of the wire cable, accidents may still occur. Corrosion, excessive heat, fatigue, and abrasion wear are some of the causes that may lead to wire rope failure (Silva & Long, 2002; Verreet & Ridge, 2005).

2.4.3.1 Corrosion and Fatigue of Wire Cable

Wire cables which are used in the structural support system are usually exposed to the environment. Thus, the wire cables may be at risk of corrosion. Although some of the cable structures such as cable-nets which are built in building enclosures, humidity can also cause corrosion. The deterioration of wire cable that is subjected to corrosion can happen internally without visible signs on the outer surface. However, the expansion in diameter of the wire rope is an indication that the rope is corroding internally. Wire cable can be protected against corrosion by galvanising the wire and making all necessary surface protection such as protecting the wire core with plastic coatings. The interest of some researchers into cable failures caused by fatigue and corrosion has shown that the effects of these causes are crucial (Chaplin, 1995; Mapelli & Barella, 2009; Nakamura et al., 2009; Paton et al., 2001; Verreet, 2011). Sometimes, fatigue may be initiated from the effects of abrasive wear and corrosion or perhaps by mixed effects.
2.4.3.2 Excessive Stress in Wire Cable

Stress in the cable structures vary with the fluctuation of forces. These events create cyclic stresses in the cable which may lead to wire fracture (Nakamura et al., 2009). In addition, the variation of force in the cable structures over the years has a significant effect on the behaviour of fatigue crack growth (Sih et al., 2008). However, the failure of wire cable under extreme load is not a common cause of cable failure. This is because the force in the cable is designed not to exceed the safe working load which is usually 20% of the minimum breaking load (MBL) of the cable.

2.4.3.3 Failure of Wire Cable Due to Excessive Heat

Another cause of wire cable failure is excessive heat, even though the steel wire cable is a very good heat conductor, and has a melting point of approximately 1500°C. The recrystallisation of steel will decrease its tensile strength and increase its ductility (Kang et al., 2010). Wire cable recrystallises under heat, at approximately 300°C, and the tensile strength of the wire cable is decreased by about two-thirds during this process (Verreet, 2005). BS EN 12385-3:2004+A1:2008 (2004) has recommended that wire rope with both a fibre core and a steel core can be used up to a temperature of between 100°C and 200°C, respectively. In addition, special attention needs to be given to the limitation of temperature on the wire cable terminations as recommended by BS EN 12385-3:2004+A1:2008 (2004) or otherwise stated by the manufacturer. Atienza and Elices (2009) reported that the performance of pre-stressed cable which has been subjected to fire need to be reassessed after the event of the fire or after cooling even if the cable is not damaged.
2.4.3.4 Failure of Wire Cable’s Fittings and Anchorage

Other sources of wire cable failures include broken cable terminations and boundary structures, which support the cable systems. There is not much being reported on the failure of wire cables that are used as cable structures for glass facades. However, for any cable structure that has end fittings which are connected to an anchorage, the failure may be similar to the case of a cable failure in a cable stayed bridge.

2.4.3.5 Wire Cable Loss in Tension

The stress in pre-stressed wire cables decreases with time and also varies along its length. One of the factors that affect the losses in pre-stressed wire cable is due to the phenomenon known as the relaxation of steel (Bijan & Aalami, 2004; Zeren & Zeren, 2003). The losses happened when the cable is stretched and held between two supports at a constant length for a period of time. The stress in the cable is reduced due to this event which also reduces the load bearing capacity and consequently increases the deflection of the cable structure under loading. In pre-stressed concrete, the losses in tension due to steel relaxation is estimated at around 10% of the initial stress induced in the cable. The phenomenon reduces the design stress in the cable and may result in the cable structure having excessive deflection under wind loading (Sasaki & Nishizaki, 2012).

2.5 Previous Studies

Finite element analysis is widely used in the analysis of complex structures with geometric nonlinear behaviour. The analysis can be used to predict the performance and the behaviour of structures under various conditions. Nevertheless, the experimental investigation of specific types of
structures is still the most reliable technique producing realistic results. There are several standards that are usually used for the design of building facades such as BS 6262-1 to 7:2005 (published between 2005 to 2006), BS EN 13022-1 and 2:2014 (2014), and BS EN 15434:2006+A1:2010 (2006). The glass facade system might comprise of the latest structural steel-glass components and the working mechanism between the components, perhaps may not even been tested. For that purpose, a portion of a full-scale mock-up glass facade is usually constructed and then tested. The objectives of the mock-up tests are basically to find any potential problems that might arise during construction and to ensure the constructability of the building facade. Unfortunately, the details or outcomes of the testing are usually kept confidential by the building facade consultant. This results in a lack of experimental test data.

In terms of academic investigations, Feng et al. (2007) have concluded that glass cladding influences the stiffness of the structural facade which incorporate cable-nets. They carried out an experimental investigation on a flat cable-net system as well as a finite element analysis. However, the percentage values of the glass stiffness contribution at the mid span of the cable structures which used clamped fitting are reported as a maximum of 2%. The larger stiffness contribution, as much as 4% is reported at nodes near the boundary of the structure. Nevertheless, the contribution is still considered small because the glass is expected to be more significant in stiffening the structural facade systems. In addition, they also studied the effects of cable pre-stress, severity of loading, cable diameter, glass thickness and glass mesh size on the performance of cable-net systems.

Consequently, Wang et al. (2007) carried out an experimental and finite-element study on the performance of flat cable-nets. The structural displacement of a cable-net with glass panes was reported to be smaller than that obtained without glass panes. The pre-stressed cable having tension can result in higher deflections in cable structures. The percentage of glass stiffness contribution to
the flat cable-net structure with one third of pre-stressing force was reported at approximately 46%. It shows the importance of glass to the structural glass facade systems. However, the contribution of glass is reduced as the stiffness of the cable structure is increased.

Based on the recent experimental data (Feng et al., 2007; Shi et al., 2007), the contribution of the glass panels to the stiffness of the structural systems is only apparent when the stiffness contribution of the cable-net is at a relatively low level. This increased the distribution of load on glass panes which is a disadvantage to the safety of glass. The glass may undergo local failure such as glass breakage. All of the researches mentioned above were only concerned with flat cable-net systems.

Shi et al. (2007) studied the influence of the initial pre-stress intensity and the geometric nonlinearity of the flat cable systems on the dynamic properties of a flat cable-net facade. They concluded that the pre-stressing force and geometric shape of the cable structure are two important parameters that influence the dynamic properties of cable structures. The stiffness of the cable structures can be measured based on its modal frequency. The influence of the geometric shape of the cable structure is far greater than that of the pre-stressing force as a cable structure generally has large deformations. The force in the cable increases as the cable deforms and this stiffens the structure (Feng et al., 2007). From the results reported by Shi et al. (2007), the stiffness of curved cable structures is thought to be better than that of the flat configuration of a cable-net.

Shi et al. (2010) also investigated the effects of cable failures on the performance of flat cable-net systems. They considered two types of cable damage in their experimental investigation namely, cable pre-stress loss and cable anchorage failure. The contribution of the glass cladding to the overall stiffness of the damaged cable system was reported to be greater than that of the undamaged system.
In this experiment, the anchorage failure was simulated by loosening a nut at one of the cable end fittings (Shi et al., 2010). This reduced the force in the cable to zero. The glass stiffness contribution of the damaged cable-net increases as the load is increased. The glass support attachment (GSA) remains steady after the load reached 50% of the maximum applied load. This showed that the glass contributed to the stiffness of the structure when the cable-net lost its stiffness because of the damage. The cable-net gained the stiffness as the force in the cable increased and stiffened the cable-net structure as the load is increased. However, the deflection of damaged cable-net is larger than the intact structure. The effects of anchorage failure on the dynamic properties of the cable structure can be crucial. Furthermore, the failure could be best simulated by breaking the anchorage or sudden loosening the cable while in operation. Such failure may release significant energy not only to the cable structures but also to the whole structural glass facade system.

Vassilopoulou and Gantes (2010) posited that, under high loading conditions, the cable-net may experience large amplitude oscillations, overstressing the cables and causing fatigue problems at the anchorages. Cable structures, which are flexible, may perform better under extreme loading conditions such as blast loading, although the cable system may undergo large deformations. Many researches studied the performance of glass under blast loading without considering the supporting structure such as cable-net structure (Larcher et al., 2012; Zhang et al., 2014, 2015a, 2015b). A single glass pane which is supported by a rigid steel frame was exposed to blast loading in the test.

A series of experimental studies on laminated glass subjected to uniform impact pressure were carried out by Zhang et al. (2015b). The glass was held by rigid steel frame which represents the framed glass system. The glass pane was stroke by the pendulum impact and all the glass tested broke into small fragments under the impact. The maximum central deflection was recorded to be between 1% and 5% of the shortest edge length of the glass. In design, the glass is allowed to deflect at a
maximum of 1% of the shortest edge length of the glass. Zhang et al. (2015b) stated that the deflection of glass pane is influenced by the glass thickness. This is because thicker glass pane has a greater flexural stiffness which reduces the deflection of glass pane. Moreover, Zhang et al. (2015b) also stated that the ASTM F2248 overestimated the stiffness of glass used to calculate the deflection of glass under impact pressure. The deflection of glass calculated based on ASTM F2248 was lower than the deflection of glass under impact pressure reported by Zhang et al. (2015b). From this study, the maximum deflection of glass pane calculated by ASTM standard is rather conservative. Thus, it is important to carry out an experimental investigation rather than rely on the established standards. The standards may be useful for general use which may be possible to represent all circumstances.

The maximum deflection of glass pane is rather important as to fulfill the minimum requirement set by the standards. Most of the studies considered only a single glass pane supported by a rigid structure in order to determine the maximum deflection of glass under loading.

2.6 Summary

The design complexity and the shapes of the structural glass facade systems that are available today are nearly limitless. The popularity of glass facade systems is increasing due to a number of reasons, including enhanced aesthetics, increase in natural light and sustainability considerations. In addition, sealing methods have evolved over the years, and as a result, today’s glass facades are regarded as high-performance systems, which require little maintenance. The invention of the point-fixed system has opened a new chapter in the history of building facade particularly structural glass facades (SGFs). This system consists of three main components namely glass, glazing system and structural support system. Each of these components has an important contribution to the stability of the structural system. The interaction between flexible and brittle materials such as pre-stressed wire
cable and glass, respectively is crucial as both materials have opposite characteristics. The deflection of transversely loaded cable structures is very large due to the geometric nonlinearity of the wire cable and needs to be designed to accommodate the limits of glass. From the literature review presented in this Chapter, it is found that the stiffness of cable structures particularly cable-net system used in building facades depends mainly on the geometry, cross sectional area and level of pretension of the cables and the stiffness of the supporting structure (Talvik, 2001). In addition, the glass also has a significant contribution to the stiffness of the whole structural system. Failure of one or a part of those components may lead to the instability of the structural system. Glass may break not only due to external causes such as impact pressure but also due to imperfection in the glass such as nickel sulphide inclusions. This shows that there is a possibility that the glass may experience sudden failure which eventually leads to glass breakage. In the event of glass breakage, the glass may fall from the building facade and may endanger people who are standing near the building. Although, the glass stiffness contribution is smaller compared to that of the pre-stressed cables, it is expected to be significant when the stiffness of the cable structure is reduced due to a cable failure. Furthermore, the glass was also shown to have a significant influence on the dynamic behaviour of cable-net structures. In certain circumstances, the failure might change the performance of the SGFs. Most of the researchers reported on the performance of flat cable-nets but less on curved cable-nets. The geometrical shapes of the cable-net, particularly a curved net, may also influence the structural stiffness and the performance of these structures. The performance of the curved cable-nets which may be better than the flat cable-net needs to be further investigated. However, this has yet to be proven and needs further investigation. The configuration of a curved cable-net is not determined by using any form finding technique but by using the position of the end cable at the anchorages and the level of pre-stress for all tests considered. Furthermore, the cable-net is uniformly pre-stressed. Basically, the investigation presented in this thesis involves two methods of analysis, namely experimental and nonlinear finite-element analysis (FEA). The latter is much easier and more cost
effective. However, this method alone may not produce satisfactory results even though the theory of the nonlinear analysis has grown steadily. Experimental analysis is important to determine the behaviour of flexible cable structures, however it still seems to lag behind the engineering practice as the process involves high costs. Nonetheless, some of the important observations may only be possible through experimental investigation instead of FEA. In this research, the ABAQUS software is used for the finite element modelling where it is used to undertake the nonlinear finite element analysis.

There are still lack of studies reported on the cable-net analysed together with glass pane. Most of the studies reported in the literature are only concerned with the flat cable-net system and there is a lack of reports on the curved cable-net with glass pane. The performance of glass on curved cable-net may differ from that of the flat cable-net. Moreover, the researchers only studied the performance of a glass pane held by rigid framed structure. The design of glass pane under wind loading without considering the supporting structure is rather conservative, especially when the cable-net structure is used to support the glass pane. This is because, the actual characteristics of glass working together in the structural glass system could not be well understood. The glass used in structural glass facade is usually designed individually without considering the supporting structure. The thickness of glass is determined based on wind loading according to established standards. However, the results may not represent the actual required glass thickness. The cable-net structure may reduce the thickness as the deflection of the cable-net is reduced when the load is increased. Moreover, the glass pane may assist in reducing the force in cable-net structure to accommodate the deflection criterion of the cable-net. The working mechanism between the glass and all other components of a structural glass facade is rather important to avoid conservative or overestimate design.
CHAPTER 3

THE EXPERIMENTAL INVESTIGATION OF STATIC AND DYNAMIC BEHAVIOUR

3.1 Introduction

The experimental model of cable-net systems was built in the Structural and Material Laboratory of the University of Surrey. Three cable-net configurations were considered, these were flat, curved-1 and curved-2 cable-nets. Both curved cable-nets were doubly-curved with different levels of curvature. Curved-2 has greater curvature than the curved-1 net. The cable-net was configured both with and without glass panes. In this study, static and dynamic tests were carried out. The stiffness contribution of the glass on the structure and the performance of cable-net systems under various failure conditions were investigated.

3.2 Specifications of the Experimental Models

Figure 3.1 shows the layout of the experimental model of the cable-net without glass panes that consists of four major components namely the supporting frame, pre-stressed cables, glass panes and the glass support attachments. The gap between the glass panes which is usually filled in with silicone sealant is approximately 5 mm. However, the sealant is not considered for the experimental model as the modulus of elasticity of the silicone is substantially lower than that of the glass (Feng et al., 2007; Wang et al., 2007).
3.2.1 Supporting Frame

The cable-net systems were supported by a supporting frame that comprises of four pairs of girders and four legs as shown in Figure 3.2. The outer dimension of the steel frame is approximately 3000 mm x 3000 mm x 1200 mm (length, width, height). The frame was designed to be a self-reacting frame that has a total weight of approximately one tonne. Each girder and leg of the structural frames consist of a pair of parallel flange channels (PFC) section of 180 mm x 90 mm of 2438 mm and 1219 mm length, respectively. Both ends of each girder were welded to a 200 mm by 150 mm of 12 mm thickness of steel plate as shown in Figure 3.3. The plate has four holes that used 12 mm bolt to connect the girders to the leg of the supporting frame.
Figure 3.2. The self-reacting supporting structure used to hold the cable structures.

Figure 3.3. An end plate is welded on to each end of the steel channel sections.

The gap between the top and the bottom steel channel sections is fitted with a total of 28 cable anchorages as shown in Figure 3.4 used to configure a the 7 by 7 cable-net systems. In addition, the number of anchorages can be changed for any configuration of cable-net system. The anchorage consists of two main parts, namely a pair of 125mm by 250mm 6mm thick steel plates and four 25 mm by 25 mm of 180 mm length square steel spacers bars. The spacers were held together to the steel
plates by 10 mm bolts. The steel plates are clamped to the channel sections of the supporting frame by using eight units of 10mm bolt. The anchorage can be adjusted horizontally and is designed to allow both cable ends to be moved vertically via elongated slots as shown in Figure 3.5 (i) and (ii). One of the anchorages is fitted with a 16 mm diameter bolt that is connected to one of the cable end fitting and the anchorage at the other ends are used to accommodate a compression load cell.

Figure 3.4. Cable anchorages are placed in between a pair of steel channel section of the supporting frame

(i)  
(ii)

Figure 3.5. Shows the elongated slots on an outer steel plate of the anchorage for (i) 16 mm bolt, and (ii) left hand threaded stud with a compression load cell
The four girders which are used to accommodate the anchorages are not perfectly level as the supporting frame was setup on an uneven floor. Thus, a reference or datum line has been marked along the perimeter of the steel girders as illustrated in Figure 3.6. The datum was set up using a total station and appropriate surveying technique as explained in 3.3.5. The position of the cable ends for any configuration of cable-nets such as both flat and curved nets were offset from the datum line. The cable-net glass facade systems are configured within the perimeter of the supporting frame.

*Figure 3.6. A datum line marked on the top channel sections of the supporting structure*

### 3.2.2 Pre-stressed Cable-net

The cable-net was configured about the horizontal plane using 7 by 7 cables, which span in two major directions as shown in Figure 3.7. The anchorages were spaced at approximately 305 mm centre to centre which forms a 305mm by 305mm cable-net to accommodate 300 mm by 300 mm glass panes. However, the length of the outer mesh of the cable-net is longer than the aforementioned as the lengths of cables that span in two major directions are not the same. The cables that span along the y-axis as shown in Figure 3.7 are approximately 40 mm longer than the cables that span along the
x-axis. This is due to the arrangement of a pair of PFC sections that forms the columns of the supporting frame. In general, the length of each cable is measured from the inner plate of the anchorage with a 16 mm bolt to the end of the cable end fitting that is fitted to another anchorage as illustrated in Figure 3.8. The properties of the cables used in this experiment are described in the following sub-section.

**Figure 3.7.** The cable-net is configured using 14 pre-stressed cables that span in two major directions

**Figure 3.8.** The length of a pre-stressed cable measured between the two boundaries
3.2.2.1 Steel Wire Rope

The wire rope used in this experiment is 4 mm diameter of 7 by 7 wire strand core (WSC), which consists of seven (7) strands with each of those having seven (7) galvanised steel wires, grade 1770 N/mm\(^2\). The minimum breaking load (MBL) of the cable, that was provided by the cable’s manufacturer, Tecni-Cable Ltd, is 10200 N. The wire cable was manufactured according to EN 12385-4. Both cable ends were fitted with 8 mm left hand threaded swage studs and the swaging procedure of the wire rope is described in 3.2.2.2.

The properties of the cable-net such as the Young’s modulus of the cable was determined by a simple tensile test on three (3) samples. The cables were not tested to failure as the test was also carried out intentionally to determine the grip strength of the swage stud. Figure 3.9 shows the setup for the tensile test accordance to BS EN ISO 6892-1:2009 (2009). An extensometer with a gauge length of 50 mm was attached to the specimen to measure the axial strain of the wire cable. Each specimen was pre-stretched for several cycles to reduce or eliminate its constructional stretch. Furthermore, the wire rope was loaded, within 1000 N, to the maximum of 3000 N for a couple of cycles in order to determine the stress and strain relationship of the material as plotted in Figure 3.10. The Young’s modulus for each sample and the stress-strain cycles are shown in Figure 3.10 and tabulated in Table 3.1. The first line of the stress-strain curve when the load was increased as shown in the figure does not representing the nonlinearity of the cable. It was because the cable initial setup of the tensile test when positioning the cable on the testing machine. As the tensile test was running, the nonlinear curve of the stress-strain response has been eliminated. The average Young’s modulus is taken as 82.85 kN/mm\(^2\). This value is used to define the material properties of the cable in the finite element modelling of the cable-net supported glass facade as reported in Chapter 6.
Figure 3.9. (i) Tensile test setup for a 4mm diameter wire rope fitted with 8mm left hand threaded swage stud, and (ii) An extensometer with gauge length of 50 mm

Figure 3.10. Stress-strain relationships of three specimens that have gone through at least two pre-stretching cycles
Table 3.1.

*Young’s modulus for the three specimens tested*

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Young’s modulus for each loading cycle (kN/mm²)</th>
<th>Mean Young’s modulus (kN/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>80.26</td>
<td>81.28</td>
</tr>
<tr>
<td>2</td>
<td>82.85</td>
<td>83.25</td>
</tr>
<tr>
<td>3</td>
<td>85.49</td>
<td>85.72</td>
</tr>
</tbody>
</table>

3.2.2.2 Wire Cable End Fitting

The wire cables are terminated at both ends with an 8mm left hand threaded swage stud. Figure 3.11 shows the threaded stud that was supplied by Tecni-Cable Ltd. The wire rope used in this experiment was cut to the required length with an extra extension of 90mm. A 45mm length of wire rope was inserted onto the swage stud and that part was put in between a pair of steel block that were used as a die as shown in Figure 3.12(i). The wooden formwork is used to hold and align the two steel blocks together. All of the parts were placed on the bottom flat circular platform of the compression machine. The end fitting was squashed at approximately 180 kN of compression force using 1000 kN capacity of compression machine. The wire rope end with the left hand threaded swage stud is shown in Figure 3.12(ii). The strength of the grip between the wire rope and the stud was determined by a simple tensile test as described in paragraph 3.2.2.1.

*Figure 3.11. An 8 mm left hand threaded swage stud for 4mm diameter wire rope*
Figure 3.12. (i) The wire rope and the left hand threaded swage stud are placed in between two blocks of steel before compress using a compression machine of 1000kN at approximately 180 kN, and (ii) The wire rope end has been terminated and fitted with a left hand threaded swage stud.

The constructional stretch of the wire rope which is influenced by many factors such as the type of core, the steel grade, construction of the rope etc can be minimised or eliminated by pre-stretching the cable before the rope was used in the experimental investigation. ASCE/CEI 19-10 (2010) has recommended that the pre-stretching force should not exceed 55% of the MBL. In this research, the wire rope was pre-stretched to approximately 5000 N and was left in a state of tension for about an hour. The force in the cable was then released to zero. The process has been repeated for a number of cycles. In addition, this exercise was also carried out to ensure there was no slip between the wire rope and the swage stud. The wire rope that was fitted with a swage stud was pre stretched by attaching it to an overhead crane via its hook. On the other end of the cable a 500kg steel beam was then supported. This process is shown in Figure 3.13.
3.2.3 Glass Support Attachments (GSA)

There are two types of glass support attachment that are usually used in structural glass facades, namely point fixed bolted and point-fixed clamped. The latter was used in this research for the experimental model of cable-net glass facade systems. Each node of the cable-net was installed with a glass support attachment which was used to hold the cable-net at their intersection and to hold the glass pane for the experimental model with glass panes. The glass support attachment consists of two parts, namely, a pair of 75mm by 75mm of 3mm thickness steel plates and a set of three 25mm by 25mm square steel blocks as shown in Figure 3.14. Both parts were connected together by a 6 mm screw. Each unit of GSA was made from steel and has been fabricated in the Engineering Workshop of the Faculty of Engineering and Sciences of the University of Surrey.

In general, the bottom part of the glass support attachment was formed by a set of three units of blocks of various depths. All of the parts were secured by at least two 6 mm screws to form a 25 mm by 25 mm by 24 mm thick assembly. Semi-circular or radius groove was engraved on one or
both sides of the block and was used to accommodate 4 mm diameter steel wire cable which spans in two main directions.

![Image](image.jpg)

*Figure 3.14.* Glass support attachment comprises of three 25mm by 25mm of square blocks and a pair of 75mm by 75mm by3mm thickness steel plate

A pair of 75 mm square plates was used to hold the glass at its corners. Both square plates were fitted with 1 mm thick rubber pad which provided a layer that prevents any rough contact occurring between the glass panes and the steel square plate. The bottom square plate that was closer to the square block was stuck with four strips of approximately 4mm x 4mm x 50mm (depth x width x length) rubber spacer as shown in Figures 3.15(i) and (ii). The strips created four quadrants to accommodate the glass panes and were used to create a gap between the adjacent glass pane of approximately 5 mm.
Figure 3.15. A pair of 75mm by 75mm by 3mm thick steel plates fitted with a 1mm thick neoprene rubber pad (left) and one of those plates with four rubber strips which created an approximate 5 mm gap between the glass panes (right)

3.2.4 Glass Panes

A glass pane 300 by 300 mm by 4 mm thickness as shown Figure 3.16 was only used for the experimental model of the cable-net with glass. The glass was toughened and was purchased from the Addison Glass, Guildford. The value of Young’s Modulus of the glass was 72 kN/mm² as provided by the supplier. The weight of each glass pane is approximately 800g.

Figure 3.16. A typical pane of toughened glass as used in the experiments
3.3 Equipments

3.3.1 Linear Variable Differential Transformer (LVDT)

In this experiment, LVDT transducers as shown in Figure 3.17 were used to measure specified nodal vertical displacements of the cable-net and also some points on a glass pane. Figure 3.18 illustrates the basic layout of an LVDT which consists of a primary coil, two secondary coils and a core that is moveable in between the two secondary coils. The operational principle of LVDT transducer is based on the change in voltage between primary and secondary coil as the internal core is moved towards the latter. The LVDTs were initially calibrated using a matrix gauge block made by Coventry Gauge Limited (Figure 3.19) using the same data logger that was used in the experiment. The calibration was carried out to obtain the relationships between the core displacement and voltage output as shown in Figure 3.20. The voltage changes linearly as the core is moved away from the primary towards the secondary coils. The core that moves towards any particular secondary coil increases the voltage output in that coil due to the greater flux linkage while decreases the voltage in the other secondary coil.

Figure 3.17. Linear variable differential transformers (LVDTs) transducers
Figure 3.18. Basic layout of an LVDT

Figure 3.19. One of the LVDT transducers used in the experiment which was calibrated using a matrix gauge block made by Coventry Gauge Limited, UK

Figure 3.20. Relationships between the core position of a LVDT and the voltage output where (i) core at -100%, (ii) core at the centre of the primary coil (null position), and (iii) core at +100%
The LVDTs that are available in the laboratory and were used in the experiment had various stroke lengths. Figure 3.21 (i) and (ii) show the cantilever arm steel rod with a magnetic base which was placed at the required position on an independent steel frame. The frame was made of equal angle section. The LVDT transducers which were used in this experiment were the unsprung loaded type rather than the sprung-loaded type as the probe must be able to freely move to avoid any additional loading and damping due to the spring force acting on the model of the cable-net structure. In addition, the spring force from the sprung-loaded LVDT transducers has led to deformation of the cable-net with of less than 1 mm. Although the initial deformation is small, it has changed the stiffness of the pre-stressed cable-net by approximately 3%. This factor needs to be considered as the pre-stressed cable-net behaves in a geometrically nonlinear manor.

Figure 3.21. (i) An LVDT that is held by a cantilever steel rod with a magnetic base, and (ii) An independent frame structure used as a platform to hold the LVDTs in position via the magnetic bases
3.3.2 Loading System

The loading system was setup underneath the cable-net system as shown in Figure 3.22 and was only used for a series of static tests on the experimental model of a cable-net both with and without glass panes. The loading system comprised of two main parts namely, the loading frame and a scissor jack that was clamped onto a 500kg steel beam.

![Figure 3.22. The loading setup used to impose a concentrated load at specific nodes](image)

The loading frame comprised of two parts which are a set of three aluminum sections and four 6 mm steel rods. The aluminum frame was hung from the cable-net system via four 200 mm long 6 mm diameter of steel rods. Each of the rods was connected to a set of four steel blocks of the glass support attachment as shown in Figure 3.23. The positions of the loading points are marked by the red circles as shown in Figure 3.24. Each of the four loading points was loaded with approximately 200N giving a total of 800 N, which was measured using a tension load cell. The weight of the loading frame was about 3 kg and was considered as an initial loading on top of the cable-net systems. Prior
to loading, the loading frame which was configured to be a simply supported system, was connected to a tension load cell of approximately 2224 N capacity via an eyebolt and threaded jaw as shown in Figure 3.25. In addition, a 25mm diameter 50mm long connector was used to connect the threaded jaw and the load cell together.

*Figure 3.23.* A set of four steel block of GSA that was used only at the loading points

*Figure 3.24.* Layout of the loading position on the cable-net systems
Figure 3.25. The loading frame and the scissor jack were connected together by an eyebolt, a threaded jaw and a connector

### 3.3.3 Compression Load Cells

The forces in the wire cables were measured by two means, namely by the use of compression load cells of the diaphragm type with a 500kg maximum capacity and by fabricated load cells, as shown in Figure 3.26 (i) and (ii), respectively. The pre-stressing force in six (6) out of fourteen (14) wire cables was measured using diaphragm load cells and eight (8) by fabricated load cells. The position of each load cell was offset from a datum line as illustrated in Figure 3.27.
Figure 3.26. The force in the cable is measured by two types of load cells; (i) A diaphragm compression load cell of 500kg capacity manufactured by PCM Ltd and (ii) A fabricated load cell made of aluminium tube and a steel plate 2mm thick and a 50mm by 75mm steel plate.

Figure 3.27. The position of load cell that is measured from the datum.

The fabricated load cell was calibrated using a 100 kN capacity universal testing machine based in the University of Surrey as shown in Figure 3.28. The load cell was configured using four
linear strain gauges (Figure 3.29) with full bridge wiring. The full bridge configuration used for the strains gauges is illustrated in Figure 3.30. The room temperature in the laboratory where the experiment was carried out was monitored and no significant drift in temperature was measured. Therefore, additional temperature compensation for the strain gauges was not necessary. A total of six compression load cells of the diaphragm type were fabricated and calibrated by PCM Ltd. However, all the load cells were re-calibrated using a universal testing machine, although the diaphragm load cell was been calibrated by the manufacturer. The load cell has a maximum capacity of 500 kg (4905 N). The accuracy of both the diaphragm load cells and the fabricated load cells are within 1% and 5%, respectively.

*Figure 3.28. Calibration of the fabricated compression load cell to determine its load-voltage response*

*Figure 3.29. Linear pattern strain gauge*
3.3.4 Data Logger

StrainSmart is a ready-to-use Windows® based software system for acquiring, reducing, presenting, and storing measurement data from strain gages, strain-gage-based transducers, thermocouples, temperature sensors, LVDTs, potentiometers, piezoelectric sensors, and other commonly used transducers. In this research the data logger was used to capture and store data from home-made load cells, compression diaphragm load cells and LVDT transducers. The data logger as shown in Figure 3.31 has 24 channels where 8 of those was used for the LVDT transducers and 14 channels for the compression load cell and one channel for a tension load cell. Furthermore, the data logger is capable of capturing data within 10 to 10000 readings per second. All data is formatted into Microsoft Excel. The control station for the experiment is placed near to the experimental models for easy access.
3.3.5 Surveying Equipment: Total Station

A total station was used with a mini prism as shown in Figure 3.32 to mark a datum line on the steel girder of the supporting structure and determine the position of each node for the flat and curved nets. The datum was used as a reference line when positioning the cable end fittings as mentioned in 3.3.3. Furthermore, the position of each node of the cable-net systems was determined by using the same surveying equipment as mentioned above. The radial survey was performed by setting the first point as a reference point (RP) followed by observing each node of the cable-net structure. The positive and negative differences of height between the observed point and the reference points indicate that the node is higher or lower than the reference point, respectively. Figure 3.33 illustrates the technique that was used to measure the height of each point from underneath the cable-net structures using a total station and mini prism. The measurements were easily accessible from underneath of the cable-net structures as shown in Figure 3.34.
3.3.6 High-Speed Camera

A Nikon Hot Shot, CC series, high-speed camera as shown in Figure 3.34 was used in this research to observe the deformation of the glass and the breakage characteristics when subjected to an impact point load. HotShot Link software was used to control and configure the camera that was fitted with suitable camera lens. The camera and the software were supplied by NAC Image Technology Inc. The speed of impact that was determined at the time when the ball bearing touched the glass pane is calculated using Equation 3.1.
The object was released from various heights, \( h \), resulting in impacts at different speeds and energy prior to hitting the glass. The lighting system that was used with the high-speed camera when recording the slow motion movement of the object was crucial. A sport light with a stand was used to supply adequate light for clear photos. In addition, the lighting system was also controlled by the shutter speed of the camera.

![Figure 3.34. A NAC Hot shot, CC series, high-speed camera with a lighting system that was used in the series of dynamic tests](image)

**3.3.7 Anchorage Failure Test Rig**

The failure of the wire rope anchorage was simulated by releasing one of the cable ends that was clamped to the steel L-shaped block as shown in Figure 3.35. The rig comprises of two parts which are made of steel and formed from a single unit of L-shape whereby the part with a cantilever portion was positioned at the bottom. Both parts of the L-shape unit were held together at an angle of approximately 30° and stayed in positioned as the cable is pre-stressed to the desired pre-stress force.
A 17mm wide groove that created at the intersection between the two parts was designed to provide adequate passage for the 16 mm bolt. The test rig that was used to release the pre-stressed cable and simulate the failure of the anchorage was designed to be non-destructive. The cable anchorage as explained in 3.2.1 remained intact on the girders of the supporting frame.

Figure 3.35. Test rig for the anchorage failure

Prior to this particular test, a couple of destructive test had been proposed to simulate the failure of a cable anchorage. One of the pre-stressed cables was cut at a point near to the anchorage. However, the pre-stressed wire rope was not easy to cut using wire cutter as there was a constraint with the space to slot in the wire cutter in between the anchorages. Another idea was to use an explosive bolt but there was difficulty in accommodating the bolt within the pre-stressed cable anchorage. In addition, there was an issue of health and safety. The proposed non-destructive test was chosen as it was more reliable and sensible to maintain the specimen in good condition and allowed the simulation of a sudden anchorage failure as the pre-stressed cable was released immediately after the anchorage failed. Furthermore, the proposed rig was still reusable for a number of repetitive tests. Figure 3.36 shows the image of the cable end released from the cable anchorage as soon as the L-shape was hit by a hammer.
Figure 3.36. The L-shaped rig was split into two parts to release the pre-stressed cable by hitting the cantilever part of the rig via a steel bar by a hammer

3.4 Setting up the Experimental Model Procedure

The setup procedures written below were applied to most of the tests that were considered in this research. However, some modifications did apply depending on each particular case study.

3.4.1 Configuration of the Cable-net Structures

In general, there are two types of cable-net configuration considered in this research, namely flat and curved cable-nets. Two experimental models of curved cable-nets of different curvature were formed to study its characteristics on the performance of the cable-net systems. For all the models, the anchorages are spaced at approximately 305mm centre to centre. The cable end fittings were fixed by bolts at a particular point in the slots of the steel plate of the anchorage. One of the cable end fittings was secured to a 16 mm bolt which was used to pre-stress the cable as shown in Figure 3.37. The position of the end fitting was an important key in configuring the shape of the cable-net and was...
projected from the datum that was set and marked using surveying technique as explained in 3.3.5. Each position of the respective cable end fittings is tabulated in Table 3.2 and is illustrated in Figure 3.38. The pre-stressed cables spanned in two main directions on the horizontal plan and those cables are known as load bearing and supporting cables which were labeled as S1 to S7 and H1 to H7, respectively, as illustrated in Figure 3.39. The load bearing cables were positioned 7 mm lower than the supporting cables so that there was a gap between the two cables that created space for a steel block use as the glass support attachment as shown in Figure 3.40.

*Figure 3.37.* The end fittings of the wire rope are bolted directly to the steel plate and at the other end via a M16 bolt
Table 3.2.

Position of cable end fitting on the anchorage through the elongated slots

<table>
<thead>
<tr>
<th>Net Shape</th>
<th>Code</th>
<th>Supporting cables</th>
<th>Load bearing cables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>x</td>
<td>y</td>
</tr>
<tr>
<td>Flat</td>
<td>FN</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Curved</td>
<td>CN30</td>
<td>0</td>
<td>-30</td>
</tr>
<tr>
<td></td>
<td>CN45</td>
<td>0</td>
<td>-45</td>
</tr>
</tbody>
</table>

Note: Owing to symmetry, only half of the cable end positions are given in the above table.

\[ \text{Figure 3.38.} \text{ The position of the cable end fittings for (i) the flat cable-net and (ii) the curved cable-net} \]
Two units of 38 mm by 38 mm by 3 mm thick steel were secured on the inner steel plate of the anchorage. The units were placed one at top and one below the pre-stressed cable as shown in Figure 3.41. The plates were secured to the 200mm by 125mm by 6mm thick steel plate of the anchorage by a 6mm diameter bolt. The plate was placed in that position as a boundary which restrains the vertical displacement of one of the cable ends. The friction force created by the bolt was adequate to prevent any vertical movement at the support when the wire cable was being loaded.
3.4.2 Pre-stressing the Wire Cables

Figure 3.42 shows one of the cable ends that was connected to the M16 bolt which was secured initially to the steel plate of the anchorage using two nuts. The wire rope was pre-stressed by twisting the outer nut in a clockwise direction using a spanner while the head of the M16 bolt was held in position by another spanner. This technique was used to pull the bolt out of the anchorage and consequently pre-stressed the wire rope. This technique was simulating the same way in pre-stressing the cable using hydraulic jack in the actual practices. Any cable twisting has to be minimised or avoided as the compression load cell may not give the actual pre-stressing force in cable. All cables were initially pre-stressed to a sensible level prior to setting the load cell to zero. The cable that was being calibrated was slackened until the respective cable end fittings became loose from the load cell. The cable was slackened using the same technique to pre-stress the cable but turning the bolt in the opposite direction. The force in the cable that was measured using either the diaphragm or fabricated load cells, was set to zero. The cable that was initially set to a zero force was pre-stressed again to at
least 30% of the final pre-stress force before moving to another cable for force adjustment. The adjustment of the force in the cable was made individually. The interaction between different cables in the cable-net systems during the adjustment was monitored. The force in the cable was gradually increased until all cables have reached the intended pre-stress force. Some cables were required small adjustment of force at the end. The test was carried out soon after all cables have been adjusted to the intended pre-stress force. Three pre-stress force considered in this study were 1000N, 1500N and 2000N. The calibration of the load cells for the measurement of force in the cables were commenced individually.

The cable that was being pre-stressed had a significant effect on the boundary structure and the steel plate of the particular anchorage. The respective parts were deformed and resulted in the reduction of the force in the other cables, particularly the adjacent ones during the pre-stressing process. Thus, the wire ropes were not initially pre-stressed to the required level of the final pre-stress force as each pre-stressing stage of the wire rope affected the other pre-stressed wire ropes. Consequently, the wire rope was pre-stressed in stages at approximately 30%, 60% and 100% of the

Figure 3.42. The wire rope was pre-stressed by extending the M16 bolt using two spanners

The cable that was being pre-stressed had a significant effect on the boundary structure and the steel plate of the particular anchorage. The respective parts were deformed and resulted in the reduction of the force in the other cables, particularly the adjacent ones during the pre-stressing process. Thus, the wire ropes were not initially pre-stressed to the required level of the final pre-stress force as each pre-stressing stage of the wire rope affected the other pre-stressed wire ropes. Consequently, the wire rope was pre-stressed in stages at approximately 30%, 60% and 100% of the
required pre-stress level. Nevertheless, the actual designed pre-stress level for each cable was unachievable owing to the sensitivity of the compression load cell and stress relaxation of the wire rope. Thus, the final pre-stress level of each wire rope was acceptable within approximately 95% to 105% of the required level. The final pre-stress force was monitored continuously prior to any test using the data logger. The inner bolt was secured to the steel plate of the anchorage after the cables had been pre-stressed accordingly. The inner bolt was used to lock the bolt off for the safety precautions. Figure 3.43 illustrates the recommended sequence for pre-stressing the cable-net systems.

![Diagram](attachment:image.png)

*Figure 3.43. The pre-stressing sequence of the load bearing and supporting cables used in the cable-net structure*

Pre-stressing a flat cable-net is easier compared to that of a curved cable-net. There is a specific procedure when pre-stressing the cable for the curved net. The curved cable-nets considered in this research are divided into two types, namely, single and double-curved nets. Irrespective of the type of curved cable-net, the end fittings of the wire rope are positioned at the right position to achieve the correct curved configuration as shown in Figure 3.44.
Before the curved net structure is configured, the force in each cable is first set to zero according to the procedure explained in 3.5. For a double curved cable structure, the load bearing cables (sagging shape) are initially pre-stressed at approximately 30% of the final pre-stressed level. The supporting cable (hogging shape), which are laid over the sagging cables are then pre-stressed individually to approximately 30% of the final pre-stressing level. During this process, the sagging cables which had been pre-stressed and initially straight, are contorted to sag. Furthermore, the force in the sagging cable is increased significantly. The pre-stressing process of the sagging and hogging cables was done in three stages. At each pre-stressing stage, the cables are pre-stressed in sequence as illustrated in Figure 3.43. The final pre-stress value cannot be set at the exact desired value as changing the pre-stress changes the pre-stress in all the other cables. The cables in all three models were adjusted to have the same three levels of pre-stress namely 1000 N, 1500 N and 2000 N with ±5% tolerance. The performance of the three models can be easily compared as all cables in each particular model had the same pre-stress level.

3.4.3 Clamping the Cable-net Structure

Each node of the cable-net was fitted with a set of three blocks forming the glass support attachment which is described in 3.2.3. The steel block was accommodated with four M3 screws, and it was left unsecured for the pre-stressing process. This was to avoid any restraint between the cable
and the steel blocks while the wire rope is being pre-stressed. The glass support attachment was completely secured by the four screws when the cables had been pre-stress to the required pre-stress level. However, the blocks that connected with the loading frame via a 200 mm long 6mm in diameter mild steel bar remained unsecured as another block of 25mm by 25mm by 12 mm of depth as shown in Figure 3.45 was added at the bottom of the existing steel block of glass support attachment. The additional block has four holes for M3 screws and a threaded hole at the centre of the block which was used to accommodate a 6mm diameter mild steel bar. The steel bar was threaded at its end to fit the fourth steel block of the GSA.

Figure 3.45. A set of four blocks used for the glass support attachment was only used at the loading points to accommodate a loading system.

3.4.4 Placing Glass Panes onto the Cable-net Structures

The glass panes are only considered for a series of static and dynamic tests that are carried out on the experimental model of a cable-net with glass panes. Thirty six units of toughened glass panes were installed on the pre-stressed cable-net via the glass support attachments as shown in Figure 3.46. The glass is clamped by a pair of 75mm by 75mm of 3mm thickness of steel plate. The plate is first
secured to a set of three or four steel blocks of the glass support attachment by an M3 screw. The installation of the glass pane on top of the cable-net structure was begun from the middle and was arranged in clockwise direction until the last piece of the glass was fitted as illustrated in Figure 3.47. This sequence was adopted by considering the difficulties in positioning the LVDT on the plate of the glass supported attachment once all glass panes have been installed on the cable-net structure. It was found very difficult to reach or adjust the LVDT at the middle of glass panes (LVDT 1, 3 and 4) from the boundary structure. Thus, the respective LVDT was positioned on the plate as soon as it already clamped four glass panes.

*Figure 3.46. Toughened glass panes held by a pair of steel plates in the glass support attachment that is clamped to each node of the cable-net structure*
3.4.5 Positioning the LVDTs at Specified Points

The vertical displacement at a specified node of the cable-net was measured by using a LVDT transducer as explained in 3.3.1. The position of LVDT transducers for various configuration of the cable-net system is shown in Figure 3.48. Figure 3.49 shows the position of the transducers on top of the selected nodes and at the centre of the GSA cable-net both with and without glass panes, respectively. The middle node of the cable was difficult to reach when all the glass panes had been installed onto the pre-stressed cable-net structure. Thus, the installation of the LVDT transducers was easier made in conjunction with the installation of glass panes especially those at the middle of the cable-net.

Figure 3.47. The installation sequence of the glass panes on the pre-stressed cable-net structure
Figure 3.48. The position of LVDT transducers on the cable-net systems

Figure 3.49. Setup of the LVDT transducers on the experimental model of the cable-net with and without glass panes (i) The transducer is set on the selected nodes of cable-net without glass panes (ii) The transducer is positioned on top of a pair of steel plate forming the glass support attachments

3.5 Experimental Studies

A series of static and dynamic tests were considered in this research primarily to study the performance of cable-net glass facade systems. The scan rate of the data logger for the static and dynamic tests was set to 10 and 100 readings per second, respectively. The procedures for the experiments are explained in the following paragraphs.
3.5.1 Static Performance of Cable-net Systems subjected to Four Point Loads.

The objective of this study was to determine the performance of flat and curved cable-net systems and to determine the contribution of the glass pane to the stiffness of the cable-net systems. The experimental models of the flat and curved cable-net systems were set up in the horizontal plane. The performance of the cable-net systems was determined based on the deflection characteristics of the cable-net and the changes of forces in the cables. Various initial pre-stress forces were considered for each configuration such as 1000N, 1500N, and 2000N. The final pre-stress value in each cable is difficult to achieve at the desired force. However, the force for all cables in any cases is approximately the same. Furthermore, the final pre-stressed value in each cable was monitored before the structure was loaded. The pre-stress force in each cable was within 95% to 105% of the required pre-stress force.

The cable-net structure was loaded at four points as described in 3.3.2 and the loading system is shown in Figure 3.50. The loading frame was hung to the threaded bar that was fitted to the four loading points and was initially unconnected from the scissor jack. In addition, the loading frame was supported by a pair of cardboard tube which left the cable structures temporarily unloaded as shown in Figure 3.51.
The force in the cable was monitored before the load was applied to the four-points of the cable-net structure and the tolerance of the force should be within ±5% of the initial design pre-stress force. The data was recorded and followed by removing the temporary support that was used to hold the loading frame. The weight of the loading frame acted as an initial load on the cable structure.

The scissor jack via a threaded jaw was then connected to the eye bolt of the loading frame by a pin as shown in Figure 3.51(ii). The load was applied to the cable structure at four nodes by lower down the scissor jack that was fixed to a 500 kg steel beam acting as a holding down reaction. The weight of the steel beam is much greater than the total load applied to the cable-net structure in order to prevent uplift. A 4mm steel bar as shown in Figure 3.52 was used as a hand-held driver to turn down the scissor jack. The driver is bent at one end for easy handling and hooked at the other end to fit turning mechanism. The total load applied was approximately 800N and was measured using a tension load cell that was placed between the scissor jack and the loading frame. Each loading point was loaded with approximately 200N. All measurements such as the force in the wire ropes and
the vertical displacements at specified nodes were recorded using a high speed data logger. The cable-net was left unloaded by supporting the loading frame using a pair of cardboard tube prior to any static testing. This was to eliminate an initial loading that contributes from the self-weight of the loading frame onto the cable-net systems.

Figure 3.51. The loading frame was supported by a pair of cardboard tubes (left), and the loading frame was attached to the scissor jack via an eye bolt and threaded jaw, using a pin (right)

Figure 3.52. Loading the cable-net structures at four-points was achieved by lower down the scissor jack using a 4mm diameter steel rod. The rod was bent at both ends for easy handling and hooking into the scissor jack
3.5.2 Glass Impact Tests

The impact tests can be divided into two studies. First, the performance of three types of cable-net configurations with glass panes were subjected to an impact load which was a ball bearing released from three different heights. Second, the performance of the glass pane on different types of support structure namely intact and flexible structures that were also subjected to an impact load was studied. An impact test was performed on the experimental model of the cable-net with glass panes. The impact load was created by releasing a ball bearing from various heights on to the selected glass panes, as illustrated in Figure 3.53.

![Figure 3.53](image)

*Figure 3.53.* The ball bearing was dropped on to the centre of the selected glass panes namely X, Y and Z

The ball bearing was initially held by an electromagnetic holder which was fitted to an independent frame as shown in Figure 3.54. The independent frame consisted of a pair of vertical members and a cross beam of equal angles section. The vertical members of the independent frame were clamped to a pair of girder of the supporting frame by a couple of G-clamped as shown in Figure 3.55. The horizontal member of the independent frame was also clamped to the vertical member of the frame. The height of the horizontal member was set at various values which were based on the drop height of the ball bearing considered in a series of respective impact test as illustrated in Figure
3.56. The drop height was measured from the lowest point of the ball bearing to the top surface of the selected glass pane. According to BS EN 12600:2002 (2003), the impact should achieve a maximum force of 25N without penetration however this applies to a horizontal impact force. The steel ball bearing is approximately 60mm diameter and has a weight of 760g.

Figure 3.54. An independent frame was used as a platform for a magnetic base with a cantilever lever arm which held the ball bearing via a magnetic holder

Figure 3.55. A couple of G-clamped were used to fix the independent frame to the supporting frame (left), and to clamp together the vertical and horizontal members of the independent frame (right)
Figure 3.56. (i) A steel ball bearing held by an electromagnetic holder that was attached to the magnetic base via a steel lever arm, and (ii) The drop height was measured between the lowest point of the ball bearing and the top surface of glass pane.

The glass was held by a glass support attachment at its four edges as shown in Figure 3.57. The support condition was made similar to that of a glass pane on the cable structure. A steel ball bearing was dropped on the chosen glass from various heights such as 1.0m, 1.5m and 2.0m. The glass that was hit by the ball bearing did not break but oscillated due to the flexibility of the cable-net structure. A trigger button was used to release the ball bearing from the electromagnetic holder. The ball bearing was released from the electromagnetic holder immediately after pressing the trigger button which cut off the electric supply for a brief moment which cancels the magnetic capabilities of the electromagnetic holder. The ball bearing then hit the respected glass pane and the post-glass-behaviour after the impact was studied.
Figure 3.57. An experimental setup for a single glass pane that was impacted by a steel ball bearing dropped from various heights

Figure 3.58 shows the technique used to place a ball bearing onto the electromagnetic holder which was at a certain height from the targeted glass. The drop target of the ball bearing onto the glass at the specific position was determined using a rope with a weigh (bolt) at its end as shown in Figure 3.59. This technique was used to ensure the ball bearing was dropped onto the particular target pane of glass.
Figure 3.58. The ball bearing was placed on the electromagnetic holder

Figure 3.59. A rope with a weight was used as a plumb bob to ensure that the ball bearing hit the correct glass pane

3.5.3 Cable Anchorage Failure

Wire cables in the cable-net system are the structural support system that was used to support the glass facade structure. The failure of a wire cable might happen without any warning and may be catastrophic. Cable breakage is usually initiated by one or a combination of the following causes;
corrosion, fatigue, or overloading etc. These events may initially break the wires and consequently, decrease the load-bearing capacity of the wire cable which may eventually fail and break. In this study, the selected cable which was fitted to the anchorage via the L-shaped rig (Figure 3.60) as describes in 3.3.7 was instantaneously released from the anchorage by breaking up the L-shape rig into two parts. The rig was split by hitting the bottom cantilever part via a steel bar by using a wooden hammer as shown in Figure 3.62. The cable end was released from the cable anchorage as soon as the rig was hit. Initially, the rig was hit directly using a wooden hammer as shown in Figure 3.62. However, the hammer tended to hit the 16mm bolt as it was moving prior to hitting the rig.

Figure 3.60. L-shape rig used to hold a 16mm bolt at one of the cable anchorages
Figure 3.61. The steel L-shape rig was knocked by a wooden hammer via a steel rod

Figure 3.62. The steel L-shape section was knocked out by using a wooden hammer
3.6 Summary

The cable-net both with and without glass panes were established for a series of static and dynamic tests. Three configurations of cable-net were considered namely, flat, curved-1 and curved-2 nets. The different between curved-1 and curved-2 configurations was its level of curvature. Both curved nets were doubly curved and obtained their shape by configuring the position of the cable ends of the cable anchorages attached onto the steel girders of the supporting structure. Furthermore, the cables were pre-stressed at the same pre-stress level for comparison purposes. The static test comprised of a total of 18 sets of tests while the dynamic tests included impact tests and the simulation of cable anchorage failure. The load was applied incrementally at four nodes of the cable-net structure for a series of static tests. The impact test was carried out by drop a ball bearing from various heights onto selected glass panes. The failure of a cable anchorage was also simulated by releasing the cable end that was held by an L-shape steel rig from the cable anchorage. The performance of both the flat and curved cable-nets with and without glass panes was studied. Furthermore, the contribution and the importance of glass adding towards the stiffness of the whole cable-net structure were also studied.
CHAPTER 4

EXPERIMENTAL RESULTS: STATIC TESTS

4.1 Introduction

A series of static tests as tabulated in Table 4.1 were carried out on the experimental model of the cable-net both with and without glass panes. Three types of cable-net shapes were considered; these were flat (FCN), curved-1 (CCN-1) and curved-2 (CCN-2) cable-nets. Both of the curved nets are doubly-curved and the details of those configurations are explained in Chapter 3. The cable-nets were formed by 7 by 7 cables in two major perpendicular directions on the horizontal plane. Cable S1 to S7 and H1 to H7 of the curved cable-nets were in sagging and hogging modes respectively. The experimental model was loaded at four points (Figure 4.1) via the loading system that was explained in Chapter 3. Figure 4.1 also shows the position of eight LVDTs that are used to measure the vertical displacement of the selected nodes on the cable-net systems.
Table 4.1.

A series of static test of flat and curved cable-nets both with and without glass panes at various pre-stress levels.

<table>
<thead>
<tr>
<th>Test</th>
<th>FCN</th>
<th>CCN-1</th>
<th>CCN-2</th>
<th>Glass panes</th>
<th>Pre-stress levels (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>S1</td>
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<td>S2</td>
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<td>S3</td>
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<td>S18</td>
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</table>

Note: FCN is flat cable-net; CCN-1 is curved-1 cable-net; CCN-2 is curved-2 cable-net

Figure 4.1. The cable-net was loaded at four points for a total of 830N. Each node of the loading point was applied with a maximum of 207.5N. Eight LVDTs available on the cable-net systems
4.2 Deflection of Flat and Curved Cable-net Glass Facade Systems

Each set of test listed in Table 4.1 was repeated at least three times. The tests have been carried out with care by following the procedure mentioned in Chapter 3. Figure 4.2 to 4.4 show the mean vertical displacement of cable-net without glass panes for all nodes. These figures show that the experimental setup was conducted with acceptable consistency and that all measurement were taken with sensible accuracy with a standard deviation of less than 0.4. In addition, the consistency of the results can be seen from the results given by all nodes which have identical load-displacement responses. The load-displacement response for all nodes of tests S1, S8 and S15 that were used to plot Figure 4.2 to 4.4, respectively, are shown in Appendix C. The vertical displacement of node 7 of the flat cable-net without glass panes is not presented as the data was corrupted. Furthermore, node 2 is not identical to nodes 5 and 7 because the length of sagging ($S$) and hogging ($H$) cables are not the same. Cable $S$ was approximately 40mm longer than cable $H$ and this makes the cable-net symmetrical about cable $S_4$. 
Figure 4.2. Mean vertical displacement at the selected nodes of the flat cable-net systems without glass panes that is pre-stressed to approximately 1000N per cable.

Figure 4.3. Mean vertical displacement at the selected nodes of the curved-1 cable-net systems without glass panes that is pre-stressed to approximately 1500N per cable.
As explained in Chapter 3, cables behave geometrically nonlinearly when subjected to loads that are perpendicular to their neutral axis. However, Figure 4.4 shows that the cables in the curved cable-net have linear load-displacement responses. The curved cable-net that is subjected to four point loads deflects less than the one that is initially flat. In addition, the vertical displacement of the curved cable-net increased in a linear manner when the load was increased. This was due to the fact that the cables in the curved cable-net were initially in a deformed shape which created a stiff grid of intersection nodes. Unlike the flat cable-net, where the cables were initially straight in the horizontal plane and initially have little interaction at their intersections.

The maximum nodal deflection of the curved cable-net can be predicted using a load-displacement linear relationship. However, there is the possibility where the load-displacement response turns into a non-linear relationship. This effect can be seen in Test S7 where the results are shown in Figure C4 of Appendix C. The hogging cables in the curved-1 cable-net were nearly in the
horizontal position when the nodal displacement at node 4 was at 31.2mm (Table 4.2) at the maximum applied load. Based on the surveying data as explained in Chapter 3, the positions of the central nodes of the curved cable-net such as nodes 1, 3 and 4 were at midway between the level of both cable ends. This means that node 1 was located 30mm lower and 30mm higher than the ends of cables S4 and H4 in the curved-1 cable-net, respectively. For the curved-2 cable-net, node 1 was at 45mm midway between the two cable ends. This is due to the level difference between the end of cables S4 (the highest cable end) and H4 (the lowest cable end) of the curved-1 cable-net which are approximately 60mm apart. While for the curved-2 cable-net, the difference in the levels at the end of cables S4 and H4 is approximately 90mm. As the hogging cables (cable H3) in the curved cable-nets were nearly becoming horizontal, they started to exhibit a nonlinear load-nodal displacement response. The level of node 4 of the curved cable-net was near or lower than the level of the lowest cable end for the hogging cables (Cable H4). The hogging cable in the curved cable-net may then sag if the structure is continuously loaded and then a nonlinear load-displacement response can be seen. The deflected shape of the curved-1 cable-net was then similar to that of flat cable-net under loading where the load-displacement response was non-linear.

Although the curved-2 cable-net has shown a linear load-displacement response, there was the possibility, when the hogging cables in the curved-2 cable-net system became straight, and the sagging cables continued to sag that the system exhibited a non-linear response under full load. The maximum nodal deflection (node 4) of the curved-2 cable-net was low compared to its deflection criterion when the structure was subjected to four small point loads. A cable-net is usually designed to have a deflection criterion of 1/40 or 1/50 of the shortest length of cable in cable-net system. Based on this criterion, the curved-2 cable-net may be allowed to deflect to approximately a maximum of 60mm. This magnitude is beyond the depth (node 1) of the curved-2 cable-net that was 45mm lower and higher than the end of cables S4 and H4, respectively. The hogging cables may deflect to become horizontal as the curved-2 cable-net deflected to 45mm and then sagged should the loading on the
The stiffness of the curved net was influenced by the pre-deformed shape and the initial force distribution in the cables. The changes in the hogging cable geometry in the curved cable-net, becoming horizontal as the loading increased, simultaneously reduced and increased the force in hogging and sagging cables, respectively. The changes of force and stiffness occurring in cable-net systems as the load was increased are explained in paragraph 4.4 of this chapter.

### Table 4.2

**Maximum nodal displacements of both flat and curved cable-nets with and without glass panes attached at nodes 3 and 4 for tests S1 to S18.**

<table>
<thead>
<tr>
<th>Test</th>
<th>FCN</th>
<th>CCN-1</th>
<th>CCN-2</th>
<th>Glass panes</th>
<th>Pre-stress levels (N)</th>
<th>Maximum deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1000 1500 2000</td>
<td>Node 3  Node 4</td>
</tr>
<tr>
<td>S1</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>/          /</td>
<td>36.07  35.44</td>
</tr>
<tr>
<td>S2</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>29.53      /</td>
<td>29.24</td>
</tr>
<tr>
<td>S3</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>24.28      /</td>
<td>23.88</td>
</tr>
<tr>
<td>S4</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>25.57      /</td>
<td>25.51</td>
</tr>
<tr>
<td>S5</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>23.09      /</td>
<td>22.81</td>
</tr>
<tr>
<td>S6</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>20.05      /</td>
<td>19.95</td>
</tr>
<tr>
<td>S7</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>31.98      /</td>
<td>31.20</td>
</tr>
<tr>
<td>S8</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>25.46      /</td>
<td>25.55</td>
</tr>
<tr>
<td>S9</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>21.51      /</td>
<td>21.11</td>
</tr>
<tr>
<td>S10</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
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<td>22.66</td>
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<tr>
<td>S11</td>
<td>/</td>
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<td></td>
<td>No/Yes</td>
<td>20.88      /</td>
<td>20.56</td>
</tr>
<tr>
<td>S12</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>17.61      /</td>
<td>17.72</td>
</tr>
<tr>
<td>S13</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>29.39      /</td>
<td>28.67</td>
</tr>
<tr>
<td>S14</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>22.99      /</td>
<td>22.66</td>
</tr>
<tr>
<td>S15</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>19.41      /</td>
<td>18.89</td>
</tr>
<tr>
<td>S16</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>20.49      /</td>
<td>20.36</td>
</tr>
<tr>
<td>S17</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>18.26      /</td>
<td>18.24</td>
</tr>
<tr>
<td>S18</td>
<td>/</td>
<td></td>
<td></td>
<td>No/Yes</td>
<td>16.01      /</td>
<td>15.70</td>
</tr>
</tbody>
</table>

Note: FCN is flat cable-net; CCN-1 is curved-1 cable-net; CCN-2 is curved-2 cable-net

Table 4.2 summarises the maximum deflection at node 4 of the cable-nets both with and without glass panes at the maximum total applied load of approximately 830N. The deflection criterion of the cable-net is determined based on the stiffness of the cable-net without considering the influence of the glass panes. In addition, the glass panes are usually ignored in the analysis and the glass thickness is determined in a separate analysis according to BS 6262-3 and the calculation of
design wind loading is based on BS 6399-2. The design wind loading is then transmitted onto the connection nodes of the cable-net instead of by the wind pressure acting directly on the glass panes. The concentrated load on each node is calculated based on the principle that is usually used to transfer wind load pressure to the frame structure. The pressure is replaced by a concentrated load acting at the connection of beam-column elements. In this research, the maximum deflection of the cable-net was given at nodes 3 and 4 which are expected to be the same owing to the symmetrical geometry of the cable-net systems.

In this research, the experimental results of vertical displacement of all of the flat and curved cable-nets were lower than the deflection limit used for cable-net structure. This is a direct result of the applied load at each loading point being limited to a maximum of 207.5N. The highest displacement of the cable-nets as tabulated in Table 4.2 was experienced by the flat cable-net while the curved-2 net was the lowest. The deflection characteristic of the curved-1 net is always in between the flat and the curved-2 cable-nets. Figure 4.5 shows the maximum vertical displacement at node 4 of the flat and curved cable-nets both with and without glass panes. The deflection of the cable-net with glass panes was lower than the cable-net without glass panes. This is due to the addition of glass panes on the cable-net systems that has increased the stiffness of the cable-net structures. In general, the reduction of the vertical displacement of the cable-net has shown that the glass made a significant contribution towards the stiffness of the overall structural systems. In design, the force in a cable-net is chosen based on the deflection criterion of the cable-net structure only, regardless of the geometrical shape of the cable-net.
Figure 4.5. Maximum nodal displacement (node 4) of flat (FCN) and curved cable-nets (CCN-1 and CCN-2) with and without glass panes (Pre-stress at 1500N)

Figure 4.5 shows that the geometrical shape of the cable-net is one of the important factors that influence the characteristics of cable-net deflection. Cables in curved cable-nets have a greater stiffness than that of a flat cable-net although cables in both systems were pre-stressed at the same level of pre-stress force. The curved cable-net can be designed to have the same deflection limit as the flat cable-net but with a lower design pre-stress force. Based on the experimental result, the cables in the curved cable-net can be designed to have lower pre-stress force to meet the deflection criterion of the cable-net. With a lower pre-stress force in the cables, in the curved cable-net and a low structural deflection, lower reaction forces developed and transferred via the cable anchorage onto the boundary structure resulting in the possibility of a smaller boundary supporting structure. A cable-net with a high level of curvature can reduce the deflection criterion although the cable-net is pre-stressed at the same pre-stress level. In addition, the pre-stressed cables behave geometrically nonlinearly. In Figure 4.5, the nonlinearity of the cables can be clearly seen in the load-displacement response. However, the cable-net with a certain level of curvature seems to eliminate the
characteristics of geometrical nonlinearity of the cables. The curved cable-nets not only gained the initial stiffness from the pre-stress force in the cables but from its shape as well. The deflection of the cable-net did not reach to the actual deflection criterion for design as the applied load was limited. The graphs show that the cable-net behave geometrically non-linearly and this is because the cables in the cable-net stiffened when the load was increased. The stiffness of a cable-net is mainly derived from the pre-stress force in the cables. The load-displacement response is discussed in the next sub-topic. Although the thickness of glass can be determined using BS 6262-3 based on design wind loading which can be calculated based on BS 6399-2. In the current practice, the design analysis of the cable-net system ignores the impact of glass in the systems. In addition, the deflection criterion of the cable-net is not only determined by the stiffness of the cables but also by the glass panes attached to the configuration of cable-net. The working mechanism of glass in the cable-net system and its contribution to stiffness on the whole structural system is discussed in the following sequel.

4.3 The Performance of Cable-net Glass Facade subjected to Various Pre-stress Levels.

In this research, three levels of pre-stress were considered for each configuration of cable-net both with and without glass panes. The cables were pre-stressed at 1000N, 1500N and 2000N. Figure 4.6 to 4.8 show the load-vertical displacement relationships of the cable-net both with and without glass panes at node 4. The deflection of the cable-net that was pre-stressed to 2000N was lower than the ones that were pre-stressed to approximately 1000N and 1500N. It is known that the stiffness of cable-net is influenced by the level of pre-stress force in the cables. In addition, cable-net systems are stiffer with glass panes compared to those without glass panes. The addition of glass panes are known to influence the stiffness of the whole structural systems. Thus, the motivation behind this study is to look at the contribution of glass panes as the load was increased. The deflection of the cable-net reduced with the glass included in the structural systems. Based on Figures 4.6 to 4.8,
the deflection pattern of cable-net pre-stressed at 2000N without glass panes is similar to that of cable-net pre-stressed at 1000N with glass panes. The later has almost the same maximum deflection to the former at the maximum load applied load. This shows that by including glass panes in the analysis of the cable-net structure, the pre-stress force in the cable can be reduced by nearly 50% compared to the pre-stress of the cables in the cable-net without glass panes. The reduction of force in the cables may result in a reduction in the cost in construction of the boundary structure which can be designed with a lower stiffness according to the optimum pre-stress force. The contribution of glass to the stiffness of the cable-net structure is further discussed in paragraph 4.5 of this chapter. The stiffness of the cable-net was determined based on the deflection at a specified node. In general, the load-maximum deflection of the cable-net is used to indicate the stiffness of the structure and shows how the stiffness of the cable-nets differs from each other.

Figure 4.6. Maximum displacement of the flat cable-net both with and without glass panes subjected to various pre-stress levels
Figure 4.7. Maximum displacement of the curved-1 cable-net both with and without glass panes subjected to various pre-stress levels

Figure 4.8. Maximum displacement of the curved-2 cable-net both with and without glass panes subjected to various pre-stress levels
Table 4.3.

The increment of force in cables H3, H4, S4 and S5 in the flat and curved cable-nets without glass panes subjected to four point loads of 207.5N each.

<table>
<thead>
<tr>
<th>Type</th>
<th>Cable</th>
<th>Pre-stress level (N)</th>
<th>Percentage difference between F₀ &amp; Fᵢ (%)</th>
<th>Percentage difference between F₀ &amp; Fᵢ (%)</th>
<th>Percentage difference between F₀ &amp; Fᵢ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1000N</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FCN</td>
<td>H3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>F₀</td>
<td>1001</td>
<td>1497</td>
<td>1999</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fᵢ</td>
<td>1532</td>
<td>1836</td>
<td>2245</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>F₀</td>
<td>1000</td>
<td>1497</td>
<td>1999</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fᵢ</td>
<td>1532</td>
<td>1836</td>
<td>2245</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>F₀</td>
<td>1000</td>
<td>1497</td>
<td>1999</td>
</tr>
<tr>
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<td>Fᵢ</td>
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<td>1836</td>
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<td>S5</td>
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<td>H3</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>F₀</td>
<td>999</td>
<td>1499</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Fᵢ</td>
<td>1418</td>
<td>1764</td>
<td>2191</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>F₀</td>
<td>997</td>
<td>1499</td>
<td>2003</td>
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<tr>
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<td>1418</td>
<td>1764</td>
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<td></td>
<td></td>
<td>S4</td>
<td></td>
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</tr>
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<td></td>
<td></td>
<td>F₀</td>
<td>1003</td>
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<td>S5</td>
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<td></td>
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<td>F₀</td>
<td>1003</td>
<td>1499</td>
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<td>1764</td>
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<td>999</td>
<td>1499</td>
<td>2003</td>
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<td>Fᵢ</td>
<td>1418</td>
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<tr>
<td></td>
<td></td>
<td>H4</td>
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<td>1004</td>
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<td></td>
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<td>2069</td>
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<td>S5</td>
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<td></td>
<td>F₀</td>
<td>1004</td>
<td>1503</td>
<td>2003</td>
</tr>
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<td></td>
<td>Fᵢ</td>
<td>1674</td>
<td>2069</td>
<td>2482</td>
</tr>
</tbody>
</table>

Note: FCN is flat cable-net; CCN-1 is curved-1 cable-net; CCN-2 is curved-2 cable-net; F₀ is an initial pre-stress force of the cable; Fᵢ is force in the cable at the maximum applied load.

Table 4.3 summarises the maximum force in the cables of the flat and curved cable-nets without glass panes at the maximum applied vertical load. The cable-net was pre-stressed at three different pre-stress levels. The increment of force in the cable is presented as a percentage increase. The force in the cables increased significantly as the load was increased. However, the increment of the force in the cables decreased for the cable-net with a high pre-stress level. The increment of force...
is significant in the case of the loss in tension due to the steel relaxation phenomenon and other factors that may reduce the force in the cables in cable-net systems. However, this phenomenon has not been specifically replicated in the experiments.

4.4 The Force in the Cables of the Flat and Curved Cable-net Structures

The force in the cables in the cable-net structure can be used to control the deflection of the cable-net. Excessive deflection has led to the perception that the structure is not safe and that the glass may break. Moreover, a cable-net that is subjected to large deflection under loading has to work with the deflection limit imposed by the glass panes. The pre-stressing force in the cable is designed to fulfil the deflection criterion of the cable-net structure which is usually overly conservative. This is because the criterion is determined based on the stiffness of the cable-net structure only without considering the cladding elements such as glass panes. In the long term, the force in the cables in the cable-net system may reduce due to steel relaxation and as a consequence result in greater deflections.

In this research, the effect of steel relaxation was not considered. As mentioned previously, the cables were pre-stressed to approximately 1000N, 1500N and 2000N. The minimum breaking load (MBL) of the cables used in this experiment was approximately 10000 N. In practice, the cable used in a cable structure are usually pre-stressed to 20% of the MBL of the cable. Hence, the highest pre-stress force in a cable considered for this experiment was 2000 N. However, the limitation of the design pre-stress to 20% is overly conservative when considering the nonlinearity of force in a cable forming part of the cable-net systems. The results shown in this section are based on the static tests listed in Table 4.1. The increment of force in the sagging cables has stiffened the cable-net in spite of the reduction of the force in the cables. The force in cables is one of the important parameters that influenced the stiffness of the cable-net structure. The increment of force in the sagging cables in the
curved cable-net is 25% with a reduction of 12% occurring in the hogging cables in the same curved cable-net system as the applied vertical load was slowly increased.

Figure 4.9. Force in cables S1 to S7 in the flat cable-net without glass panes
Figure 4.10. Force in cables H1 to H7 in the flat cable-net without glass panes

Figure 4.9 to 4.14 show the forces in the cables in both the flat and curved cable-nets with and without the glass panes. Based on these figures, the measurement of the force in the cables to the applied load response acting on the cable-net systems were obtained with acceptable accuracy. Owing to symmetry, the force in cables S1 and S7, S2 and S6, S3 and S5, H1 and H7, H2 and H6, and H3 and H5 were identical. In addition, only the forces in cables H3, H4, S4 and S5 are presented for discussion due to the changes of the forces in these cables either increasing or decreasing which were greater than the changes in force occurring in the other cables when the applied load was increased. The consequences of this is that the vertical displacement of the cable-net is maximum at nodes 1, 3 and 4. These deformations have resulted in high increments or decrements of the force in these cables. The central cables such as S4 and H4 of the flat cable-net without glass panes have almost the same changes of force in the cables as the load was increased. The relationship between the force in the cable and the applied vertical load is nonlinear. The force in cables S3, S5, H3 and H5 increased at a
higher rate than the forces in cables S4 and H4. In addition, the forces in cables S3, S5, H3 and H5 increased at approximately the same rate, owing to the symmetry of the flat cable-net. Thus, the relationship of cable force versus the vertical applied load in these four cables namely H3, H4, S4 and S5 are presented.

Figure 4.11. Force in all the sagging cables in the curved-1 cable-net without glass panes
Figure 4.12. Force in all the hogging cables in the curved-1 cable-net without glass panes

Figure 4.13. Force in all the sagging cables in the curved-2 cable-net without glass panes
Figure 4.14. Force in hogging cables in curved-2 cable-net without glass panes

Figure 4.15 shows the relationship of the maximum force in the cables in the flat cable-net both with and without glass panes. The glass has no significant effect on the changes of force in the cable in the flat cable-net as the force increased at almost the same rate when the load was increased. However, the force in cables S4 and H4 in the flat cable-net without glass panes are lower than that with glass panes.
Figure 4.15. The force in cables H3, H4, S4 and S5 in the flat cable-net both with and without glass panes (Pre-stress at 1500N)

The force-displacement relationship for selected cables for the curved-1 and curved-2 cable-nets both with and without glass panes are shown in Figure 4.16 and 4.17. All cables presented in the figures were pre-stressed at approximately to 1500N. The increment of force in the sagging cables in the curved cable-net without glass panes is higher than that obtained with glass panes attached. In general, the force in the sagging cables increased when the applied load was increased. Furthermore, the difference in the force in the cables for both conditions, with and without glass cladding, were insignificant and this true for the force in the cables in flat cable-net. However, the percentage of changes of the force in the sagging cables in the curved cable-nets with and without glass are 12% and 20% higher, respectively, than that of the cables in the flat cable-net although the deflection of the curved cable-net was lower than the flat net. This is because the force in the hogging cables reduced when the load was increased. The hogging cables lost their stiffness because the hogging cable sagged when the geometry changed from curved to straight. The increment of force in the sagging cables in the curved cable-nets did not approach the minimum breaking load (MBL) of the cable. However, this increment also resulted in an increment in the reaction force at the end of cable.
on the boundary structure. The boundary structure that supported the curved cable-nets has to be designed taking this increment in force into consideration. The boundary structure that supported the hogging cables also needs to be designed by considering the excessive force increments although, in this research, the force in the hogging cables decreased when the applied load was increased. However the force in hogging cables may increase should the direction of the applied lateral load reverse, possibly due to changes in the wind loading resulting in an applied suction force.

![Figure 4.16. The maximum force in the sagging cables of the curved-1 (CCN-1) and curved-2 (CCN-2) cable-nets both with and without glass panes (Pre-stress at 1500N)](image-url)
Figure 4.17. The force in the hogging cables in the curved-1 and curved-2 cable-nets both with and without glass panes (Pre-stress at 1500N)

The forces in cables S4 and S5 and H3 and H4 in the flat cable-net both with and without glass panes increased significantly as the applied load was increased. However, the hogging cables (H3 and H4) in the curved cable-net both with and without glass panes behaved in the opposite way. The force in cable S4 and S5 in the sagging cables in the curved cable-net has increased greater than that of S3 to S5 of the flat cable-net. This is because the hogging cables of the curved cables net did not contribute in resisting the applied load up to a certain level. The force in the hogging cables of the curved cable-net decreased as the load was increased. The sagging cables in the curved cable-net seemed to resist the applied load without any contribution from the hogging cables towards the stiffness of the structural systems. The changes of force in the sagging cable of the curved cable-net was higher than cables S4 and S5 in flat cable-net. The force in the hogging cables of the curved net both with and without glass panes reduced as the applied load was increased. The trend of the force in the hogging cables had changed significantly. The cable force-applied load curve of the hogging
cable in the curved-1 both with and without glass panes changed after which the applied load at each loading point reached approximately 100N and 200N. The force in cables H3 and H5 in the curved-1 cable-net both with and without glass panes had increased as the applied load reached approximately 100N. However, the force in cable H4 in the curved-1 cable-net increased when the load reached approximately 200N. The cable force-applied load behaviour of hogging cables H3 and H4 in the curved-2 cable-net with glass panes changed compared to that without glass panes as shown in Figure 4.17. In addition, the hogging cables in the curved-2 cable-net with and without glass panes started to contribute to the stiffness as the applied load reached a maximum. Please note that the level of the curvature for the curved-2 cable-net was higher than that of the curved-1 net.

4.5 Contribution of Glass on the Overall Structural Stiffness

There are two ways in which the glass can contribute to the structural stiffness such as by introducing bending stiffness and also by membrane actions which are dependent on the type of point-fixed system or glass support attachment (Feng et al., 2007). Point-fixed bolted attachment for the glass influences the stiffness of cable-net via both ways. However, if point-fixed clamped attachment is used for the glass this only contributes to the structural stiffness via the bending stiffness of glass since there is no membrane stress developed between the fittings and the glass surface. Unlike point-fixed bolted, tension forces have developed between the bolted fixing and the glass pane. In this research, point-fixed clamped was used in setting up the cable-net supported glass facade systems. Although glass panes were assembled to form a unit of facade, the glass stiffness contribution (GSC) differs from one node to another. The contribution of glass on the vertical stiffness of the cable-net systems is presented in percentages and is calculated based on the deflection of cable-net with and without glass panes. Equation 4.1 as reported by Feng et al. (2007) is used to calculate the percentage of the glass vertical stiffness contribution.
Glass stiffness contribution = \( (1 - (U_g/U)) \times 100 \)  

\( U_g \) and \( U \) are the deflections at the specified node of the cable-net with and without glass panes, respectively. The percentage of glass stiffness was calculated based on the maximum deflection of the cable-net at the specified node both with and without glass panes that is subjected to the maximum total load of approximately 830N. The load was applied at four nodes whereby each node was loaded at 207.5N. Figure 4.18 to 4.20 show the percentage of glass stiffness contribution of the specified nodes on the flat and the two curved cable-net systems that are pre-stressed at three pre-stressed levels; 1000N, 1500N and 2000N. Furthermore, the GSC shown in those figures are at the maximum applied load. In general, the contribution of glass on the vertical stiffness of the cable-net systems reduced when the pre-stress level of cable-net was higher. The GSC at all nodes shown in the figure varies. Albeit the same glass pane was considered. The results for node 2 indicate that the glass has less contribution on the stiffness while node 4, where the load was applied, has the highest percentage of glass vertical stiffness contribution. The GSC at node 6 has an interesting feature where the percentage different in stiffness is between GSC at node 4 and 8. Node 6 was a connecting node between glass panes H2-H3/S5-S6 and H1-H2/S6-S7. Furthermore, the contribution of the glass on vertical stiffness is reduced significantly as the load was increased.

\[ \text{Figure 4.18. The percentage of glass stiffness contribution on the flat cable-net supported glass facade systems at various levels of cable pre-stress} \]
The configuration of the cable-net has a significant influence on the stiffness of the cable-net glass facade systems. Figure 4.21 to 4.23 shows the percentage of glass vertical stiffness contribution for all three types of cable-nets at nodes 1, 4 and 6. The curved-1 net has an approximately consistent percentage of glass stiffness contribution as the load is increased. However, the flat and the curved-2 cable-nets are exhibiting interesting characteristics. The glass vertical stiffness contribution for the flat cable-net is higher at the initial loading stage and decreases as the load increases. This was a direct result of an increase in the stiffness of the cables as the applied load was increased and the cable-net deflected correspondingly. Although the force in the cable is the main factor influencing the stiffness of a cable-net, the glass stiffness contribution is then steady when the vertical load
reached approximately 75N (Figure 4.21). This has shown that the glass panes still contributed to the stiffness of the whole structure. However, the curved-2 net behaves in the opposite way in that the glass contributed to the vertical stiffness of the structural system as the load was increased. The percentage of the glass vertical stiffness for the curved-2 cable-net at node 1 and 4 shows the same glass stiffness contribution pattern. However, the glass stiffness contribution is higher at node 4, compare to node 1, as one of the loading points was applied at node 4. The curved cable-net is stiffer than the flat cable-net based on the maximum deflection of the cable-net at the maximum applied load. However, the glass stiffness contribution on the curved-2 cable-net increased when the load was increased. This is due to the force in the hogging cable of the cable-net reducing as the applied load was increased.

Figure 4.21. Contribution of the glass on the vertical stiffness of the cable-net glass facade systems at node 1
Figure 4.22. Contribution of the glass on the vertical stiffness of cable-net glass facade systems at node 4

The deflection criterion of a cable-net is based on the maximum deflection of the net. In this research, the maximum deflection was found to be at nodes 3 and 4. Thus, the glass stiffness contribution for the whole system can be based on the node where the maximum deflection occurred. Figure 4.22 shows that the glass contributed approximately 20% of the stiffness of the whole structural system at the maximum applied load. In previous research reported by Feng et al. (2007), the glass stiffness contribution was much lower than 20% at 4%. Feng et al. stated that the glass panes have less contribution to the structural stiffness of flat cable-nets with clamped fittings. This was due to the type of glass support attachment used. However, the results reported contradict with the findings in this research. The glass stiffness contribution measured in this experimental investigation is still high although clamped fittings were used. The glass stiffness contribution was maximum at the beginning of the loading stage in the flat cable-net system and reduced when the applied load was increased. In the curved cable-net system, the glass stiffness contribution increased when the applied load increased. It can be seen that the glass stiffness contributions were approximately the same at
the maximum load applied for both the flat and curved cable-nets. Although the percentage of glass stiffness contribution for the flat and curved cable-net system were the same at the maximum applied load, the deflection of the curved cable-net was lower than that of the flat cable-net. The value of GSC is an indication that the glass has a significant impact on the stiffness of the whole structural system. A value of the stiffness contribution of 15 to 20% may be use to calculate the deflection of the cable-net with glass panes should the analysis be carried out without the effect of glass panes taken into consideration. However, it is strongly recommended that the analysis of a cable-net system should be carried out by including the glass panes for optimum structural design.

The glass stiffness contribution is always highest at the node that is nearest to the edge of the cable-net glass facade systems. Figure 4.23 shows the glass vertical stiffness contribution of the cable-nets glass facade at node 6. All types of cable-net show a high glass vertical stiffness contribution as the cable-net is initially loaded with the aluminium loading frame which has total weight of 30N. The glass vertical stiffness contribution decreased as the load was increased and remained constant as the load reached approximately 50N. The glass vertical stiffness contribution of the flat cable-net was consistent at 10% as the maximum load was applied onto the structure. Node 6 of the curved-1 and curved-2 cable-nets showed nearly zero and -10% of the glass vertical stiffness contribution, respectively. The negative percentage value indicates that the glass has no contribution on the vertical stiffness of the cable-net glass facade system.
Figure 4.23. Contribution of the glass on the vertical stiffness of the cable-net glass facade systems at node 6

4.6 Summary

A series of 18 sets of static tests have been carried out on flat, curved-1 and curved-2 cable-nets both with and without glass panes. The cables for any particular cable-net configuration were pre-stressed to approximately the same level. Three levels of pre-stress were considered in this study, namely, 1000N, 1500N and 2000N. The findings from a series of static test are summarized as follows.

(i) Glass Stiffness Contribution

The deflection criterion of a cable-net has to be determined based on the overall contribution of each element forming the structural glass facade. The deflection of tension only cable structures is usually large under wind loading conditions. In the current practice, the design of cable-net supported glass facade systems is made by analysing the elements separately. The deflection limit of a cable-
net shall be determined by considering the stiffness of the cable-net structure which is gained from the pre-stress force in cable, the glass thickness, and the configuration of the cable-net. It is known that with the addition of glass panes in the cable-net system the stiffness of the whole structure has increased. However, the contribution of glass panes to the stiffness of the whole structure depends on the stiffness of the cable-net systems. The cables in the cable-net system that was pre-stressed to approximately 2000N has reduced the effective glass stiffness contribution in the structural system compared to the one where the cables were pre-stressed to 1000N. The glass stiffness contribution reduced as the cables were pre-stressed to the higher levels of pre-stress force. The contribution of glass to the structural stiffness was high when the cable in cable-net were at a low pre-stress force. Thus, the glass has made a high contribution to the structural stiffness at the beginning of the loading stage but this reduced when the load was increased. This is because the force in the cables in the cable-net system increased as the applied load was increased and subsequently this has stiffened the cable-net system. The contribution of glass is calculated based on nodal deflections of the cable-net both with and without glass panes.

By comparison, the deflection of the flat cable-net with glass that was pre-stressed to 1000N has a nearly similar deflection pattern to the cable-net without glass that was pre-stressed to 2000N. The former which has 20% and 30% of glass stiffness contributions at nodes 4 and 1 can reduce the pre-stress force to match with the cable-net that has a higher pre-stress force and analysed without the glass panes. This proves that by including the glass panes in the analysis, the pre-stress force in the cables in the cable-net system can possibly be reduced by 50% to accommodate the same deflection criterion of the cable-net systems. Based on the results of the static tests, the analysis of the cable-nets without glass panes to be within typical deflection criterion of a cable-net structure is too conservative and may resulted in overestimated design. In addition, the analysis of the curved cable-net with glass panes also agrees with the above statement even with a lower percentage of glass
stiffness contribution. Although the contribution of the glass is different from one node to another, the deflection criterion of the cable-net is always determined based on the maximum deflection of the cable-net. Furthermore, the deflection limit of the cable-net should be determined by considering all of the factors mentioned above.

(ii) Force in the Cables

It is known that the pre-stress force in the cables in cable-net systems is the main contribution to the stiffness of the structure. The deflection of the cable-net both with and without glass was influenced by the pre-stress force in the cables. The force in the cables in the flat cable-nets without glass panes was lower than that with the glass panes attached. The force in all the cables in the flat cable-net system increased when the applied load was increased. However, the force in the sagging and hogging cables in the curved cable-nets increased and decreased respectively as the applied load was increased. The sagging cables in the curved cable-nets have to carry most of the applied load and resulted in a higher increment of force in these cables as the applied load was incremented compared to those in the flat cable-net. The force in the sagging cables in the curved cable-net increased by approximately 15% higher than the cables in flat cable-net when the load was increased. Moreover, the force in the sagging cables in the curved cable-net at the maximum applied load was approximately twice that of the same cables in the flat cable-net.

However, the additional of glass panes has no significant impact on the force in the sagging cables in the curved cable-net systems but this is not true for the hogging cables. This is because the increment of force in the sagging cables has stiffened the cable-net structure which dominates the effect of attaching the glass panes. The losses of force in the hogging cables in the curved cable-net without glass panes is greater than the loss of force in these cables with the glass panes. Furthermore, the loss of force in the hogging cables in the curved-2 cable-net is slightly greater than in the curved-
l cable-net. This is because the level of curvature of the curved-2 net is higher than that of the curved-1 net. The hogging cables in the curved-1 cable-net tend to gain stiffness earlier than the hogging cables in the curved-2 cable-net as the applied load was increased. This is due to the curvature of the hogging cable in the curved-1 cable-net is shallower than the hogging cables in the curved-2 cable-net.

(iii) Implication for Cable-net Design.

The force in the cables in a curved cable-net system was not heavily influenced by the attachment of the glass pane cladding. Although the force in the cables in a cable-net with glass panes is slightly lower than the cable forces in the net with glass panes, the difference in the forces in cables between both models ranged from zero to 2%. However, the force in the cables in the flat cable-net system was strongly influenced by the glass panes. The force in the cables in the flat cable-net with glass panes is higher than that of the flat cable-net without glass panes. The force in the cables to applied load response between both cable-net configurations are not the same. This characteristic indicated that the analysis of cable-net supported glass facade system for any configuration of cable-net cannot be treated as the same. It is strongly suggested that the analysis of a cable-net is carried out by including glass and all the other components of a cable-net glass facades for optimum structural design.

The actual deflection of a cable-net under the maximum applied load is useful in designing the optimum pre-stress force in the cable to fulfil the deflection criterion of the cable-net. The deflected shape of the cable-net obtained from the analysis that does not consider the glass panes may not represent the actual deflection of the cable-net. Moreover, the force in the cable controls the deflection of the cable-net. Without considering the glass cladding in the cable-net system, the pre-stress force in the cables to accommodate the cable-net criterion could not be optimised. This leads
to a conservative or over estimate of the design of force in the cables. Although the glass stiffness contribution is only high at the initial loading stage and differs at all nodes of cable-net, the percentage of glass stiffness contribution is still significant at the maximum applied load. The glass contributed about 20% to the structural stiffness at the maximum applied load. By considering the glass in the analysis of cable-net glass facade systems, the design pre-stress force in the cable can be reduced by up to 50%. This leads to the possibility of using a lower pre-stress force in the cables to achieve the deflection criterion of cable-net structure. Lower initial pre-stress forces in the cables leads to a smaller boundary structure used to support the cable-net systems.
CHAPTER 5

EXPERIMENTAL RESULTS: DYNAMIC TESTS

5.1 Introduction

This chapter discusses the dynamic test performed on the cable-net systems. There were two dynamic tests considered in this study namely the glass impact test and the simulation of a cable anchorage failure. Each set of tests took into consideration the shape of the cable-net, which was either flat or curved net, the pre-stress levels, the impact test where the impactor was dropped on the glass panes from three different heights, cable anchorage failure, and the influence of rigid and flexible structural systems on the glass pane network.

5.2 Impact Tests

A series of impact tests were carried out to study the effect of impact loads on the glass panes supported by a rigid and flexible structure via clamped fittings. For all tests that corresponding to the glass supported by cable-net structures, the cables were pre-stressed to approximately 1500N and the impactor was released from the magnetic steel holder at three different heights, these being 1.0m, 1.5m and 2.0m. The impactor was a steel ball bearing that had a diameter and weight of 60mm and approximately 760g, respectively. Furthermore, the ball bearing was dropped on three different glass panes as discussed in 5.2.2.
5.2.1 The Effect of the Impact Load on a Single Glass Pane Supported by a Rigid Structure.

This test was carried out to provide preliminary data such as the deflections of an individual glass pane subjected to impact load prior to the facade system tests. A single glass pane was held by a set of clamped fitting at its corners and supported by a rigid structure. This type of arrangement is usually used in framed glass facade systems. In this system, the glass pane acts individually under the applied loading. The data obtained from this test was used to evaluate the deflection characteristics of the glass that was supported by the cable-net structure. Three sets of tests as listed in Table 5.1 were undertaken. A single glass pane was held by point-fixed clamps at its four corners which in turn were supported by a rigid frame structure. The setup for the tests is shown in Figure 5.1(a). A ball bearing was dropped from various heights onto a single glass pane that was supported at its four corners by a rigid support structure. The clamped fitting remain rigid when subjected to loading. The position of the LVDTs for the test is shown in Figure 5.1(b). Furthermore, Figure 5.2 shows the deflected glass pane during the impact event and the photo was taken using a Hot Shot high-speed camera.

Table 5.1.
The series of impact tests. The ball bearing was dropped from various heights onto a glass pane supported by a rigid support structure.

<table>
<thead>
<tr>
<th>Test</th>
<th>Drop height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td>DA1</td>
<td>/</td>
</tr>
<tr>
<td>DA2</td>
<td>/</td>
</tr>
<tr>
<td>DA3</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5.1. (i) The experimental setup for tests DA1-DA3, and (ii) The position of the LVDTs (red dots) located on a single glass pane supported by a 4-point support rigid structure. The ball bearing was dropped at the centre (green dot) of the glass.

Figure 5.2. The glass deflected as soon as the ball bearing hit the centre of the target glass pane.

Figure 5.3 shows the deflection of node 1 of a single glass pane which was subjected to an impact load dropped from 1.0m, 1.5m and 2.0m heights. The oscillation pattern of the glass at the specified node is the same for all cases. However, the oscillation amplitude varies for each respective drop height. The amplitude of oscillation was larger as the ball fell from a higher point. The ball bearing bounced a total of four times with an interval of less than 1.5s. The oscillation of the glass that was supported by a rigid 4-point support structure happened in just a very short time period which
was approximately 0.15s. Figure 5.4 shows the first oscillation of the glass as the ball bearing was dropped on to the glass surface. The following impacts can be seen in the figure as the ball bearing bounced a few times within a period of less than 1.5s. This study only focused on the oscillation of glass due to the first impact as the ball bearing was dropped on the glass pane.

Figure 5.3. Nodal oscillation of the glass pane supported by a rigid 4-point support structure
Figure 5.4. The first cycle of nodal oscillation of the glass pane held by glass support attachments at 4 corners which was supported by a rigid support structure.

In the static tests, as explained in the previous chapter, the deflection of the glass is not crucial. This is because the load was applied at the nodes and not on the glass pane itself. Thus, the deformation of the glass pane was small as the cable-net deflected under the applied loading. Besides wind loading, another source of loading that induces the glass to deflect is impact loading. The deflection of the glass is nonlinear, because the deflection is not doubled as the applied load is doubled. This effect can be seen in Figure 5.4 where the maximum amplitude corresponding to a ball bearing that was dropped on the glass pane at 3 different heights are nonlinear. Table 5.2 represents the maximum vertical displacement amplitude that was measured from the impact. The impact force exerted on the glass panes for tests DA1, DA2 and DA3 were 2814N, 3264N and 3798N, respectively and were calculated using Equation 5.1. The maximum amplitude is related to the distance travelled by the ball bearing during the impact. The calculation of impact force exerted on the glass pane is presented in Appendix D and given in Equation 5.1.
Where $m$ and $v$ are the mass of the ball bearing which was 0.76kg and velocity of the ball bearing at impact, respectively. While $d$ is the distance travelled by the ball bearing during the impact before it bounced back. The deflection limits of glass under wind load are usually taken as $1/100$ (mid-span) and $1/175$ (edge) at the glass edge as described in 2.3.1.3 of this thesis. Based on this guideline, the deflection of glass due to the impact of a ball bearing that was released from 1.5m and 2.0m was higher than the suggested deflection limit. However, the glass remained intact which may be due to the impact force exerted on the glass pane being lower than the compressive surface strength or the tensile strength of the underside of the glass pane. In general, the glass may break should the force exerted on the glass surface due to the external loading exceeding than the tensile strength of the glass surface. The deflection of glass panes used in a building facade is induced by the wind loading which is assumed to be acting as a uniform pressure on the glass surface. However, even with a small impact force, which may create a stress lower than the tensile strength of the glass surface, the deflection of the glass panes due to impact is greater than the deflection limit of glass used in buildings. The results reported in this section are used as a reference to study the performance of glass panes supported by a cable-net structure.

Table 5.2.

*Maximum amplitude of vertical displacement corresponding to respective impact forces.*

<table>
<thead>
<tr>
<th>Test</th>
<th>Drop height (mm)</th>
<th>Maximum vertical deflection (mm)</th>
<th>Impact Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DA1</td>
<td>1000</td>
<td>2.65</td>
<td>2814</td>
</tr>
<tr>
<td>DA2</td>
<td>1500</td>
<td>3.42</td>
<td>3264</td>
</tr>
<tr>
<td>DA3</td>
<td>2000</td>
<td>3.92</td>
<td>3798</td>
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</table>
5.2.2 The Effect of Impact Loads on Glass Panes Supported by Cable-net Structures

Table 5.3 lists the series of impact tests performed on the experimental model of the cable-net with glass panes. The impact tests comprised of a total of 18 individual tests for the flat and the curved-2 cable-nets with glass panes. Initially, the test was designed to drop a ball bearing on a glass pane that was held by the clamped fitting of the cable-net structure. However, the results obtained from Test D1, D2 and D3 were unexpected although each set of the tests was repeated 3 times. This was because the oscillation of node 8 was almost the same as node 1 although the former was the farthest node in the glass facade system. Moreover, according to the result from the static test, the deflection of node 8 of the cable-net with glass panes was the smallest. Thus, in this investigation, the ball bearing was dropped on glass panes X, Y and Z as these three panes were interconnected via glass support attachments towards the corner of glass facade systems as illustrated in Figure 5.5.

![Figure 5.5](image)

*Figure 5.5. The ball bearing was dropped on the selected glass panes X, Y and Z.*
Table 5.3.

The series of impact tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Flat</th>
<th>Curved-2</th>
<th>Drop height (m)</th>
<th>Target</th>
</tr>
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<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>1.5</td>
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<td>D1</td>
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<td>D18</td>
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5.2.2.1 Impact Load on the Glass Pane Near to the Centre Node of the Glass Facade System

Figure 5.6 shows the deflection of the flat cable-net subjected to an impact load released from a height of 1.0m (Test D1). The graph of time versus vertical deflection oscillation history for Tests D2 and D3 are attached in Appendix E for reference. The oscillation frequency of each node were almost the same. It showed that the cable-net supported glass panes were acting as a single large unit despite each node of the cable-nets oscillated at different amplitudes. The deflection amplitude of nodes 1 and 4 are the highest as the ball hit the central glass pane X. While other nodes have lower deflection amplitudes than the two nodes mentioned except node 8 which had almost the same deflection amplitude as nodes 1 and 4. Based on the static test, the deflection of node 8 of the cable-net with glass panes was very small. This has resulted in an additional test that is discussed in 5.2.2.2.
Figure 5.6. Deflection oscillation of the flat cable-net subjected to the impact load. The ball bearing was dropped on the glass pane X from a 1.0m height.

The oscillation pattern of node 1 and the rest of the recorded nodes are not really smooth as the cable-net oscillated in a distressed way due to the impact. Figure 5.7 and 5.8 show the oscillation period of node 1 of the flat and curved-2 cable-nets when glass pane X was subjected to the impact of ball bearing that was dropped from 1.0m, 1.5m and 2.0m heights. The vertical displacement oscillation of node 1 was the oscillation of the cable-net and not the glass pane. The oscillation shows the same pattern as the series of test described in 5.2.1. The maximum vertical displacement of the first cycle of the oscillation reduced as the drop height was increased. The impact force to vertical displacement response was nonlinear where the maximum amplitude of vertical displacements were 6.05mm, 8.42mm and 10.25mm for drop heights of impact from 1.0m, 1.5m and 2.0m, respectively. Although these displacement values were larger compared to that of Test DA1, DA2 and DA3 as presented in Table 4.1, these were not the actual deformation of the glass pane that can be used to compare with the deflection limit of glass panes stated in the standards. The actual deflection of glass panes supported by a cable-net structure is discussed in 5.2.3.
Figure 5.7. Oscillation of node 1 of the flat cable-net that was subjected to the impact load. The ball bearing was dropped onto glass pane X, from various heights.

Figure 5.8. Oscillation of node 1 of the curved-2 cable-net that was subjected to the impact load. The ball bearing was dropped onto glass pane X, from various heights.

Figure 5.9 shows the comparison between the oscillation of the flat and curved-2 cable-nets subjected to an impact load that was dropped from 1.5m height onto glass pane X. The oscillation
amplitude for the curved-2 net is always lower than the flat cable-net except for the first cycle of the oscillation period. The amplitude of the vertical displacement of the first oscillation of the curved-2 net is higher than that of flat net. This is due to only the sagging cable in the curved-2 cable-net resisting the impact as compared to that of flat cable-net where all of the cables deformed in the same directions. In the static test, the force in sagging cables increased twice as much as the force in the hogging cable reduced when the applied load was increased. This effect is also discussed in 5.2.4. In the second oscillation and onwards, the amplitude of the vertical displacement of the curved-2 cable-net is lower than the flat cable-net. This is because the curved cable-net was a stiffer structural system based on the static test results reported in Chapter 4. The deflection of the flat cable-net was higher than that of the curved-2 cable-net when the applied load was increased.

![Figure 5.9](image.png)

*Figure 5.9.* Time vs vertical displacement oscillation history at node 1 for both the flat and curved-2 cable-nets subjected to an impact load. A ball bearing was dropped onto glass pane X from a 1.5m height

Based on Figure 5.6, node 8 has oscillated differently from the others. Figure 5.10 and 5.11 highlight the oscillation of nodes 1 and 8 of the flat and curved-2 cable-nets when the ball bearing
was dropped onto glass pane X from a 1.0m height. Only the oscillation magnitude within a second period of time for nodes 1 and 8 of the cable-nets are highlighted in the graph. The oscillation for both case are almost the same. The oscillation of node 8 is maximum only in the first cycle of the oscillation and was damped afterwards. The oscillation of node 8 was very small after the first cycle and shows that the node at the edge is very stiff but still able to accommodate the impact force. The amplitude of the first cycle is high when the ball bearing was dropped on the surface of glass pane X. Based on a series of static tests, node 8 was not expected to deflect as high as node 1 in the same cable-net systems. Node 8 was predicted to be semi-rigid as it was closer to the edge of cable-net systems. The large deformation of node 8 of the cable-net may affect the glass pane clamped to it and at the far corner of the glass facade. This is because two edges of the glass pane at the corner are practically fixed to the intact boundary structure. If node 8 deflected by about the same as node 1 of the cable-net under impact, the glass pane at the corner may become twisted and experience a large distortion. The flexibility of node 8 that was predicted to be very stiff is discussed further in the following sub-topic 5.2.2.2.
Figure 5.10. Oscillation of nodes 1 and 8 of the flat cable-net that was subjected to the impact load. The ball bearing was dropped onto glass pane X, from a 1.0m height.

Figure 5.11. Oscillations of nodes 1 and 8 of the curved-2 cable-net that was subjected to the impact load. The ball bearing was dropped onto glass pane X, from a 1.0m height.
There are various factors that may affect the deformation of glass under impact, such as thickness of the glass, the pre-stressing force in the supporting cables, the impact velocity of an object that hits the glass pane etc. The level of deformation of the glass is rather important as it should not exceed the allowable deformation. This value is stated in a few standards such as the Australian Standards where it is restricted to span/60. Furthermore, Figure 5.7 and 5.8 do not show the actual deformation of glass. The actual deformation of the glass attached onto the cable-net system was determined based on a series of impact test DA4 to DA6 described previously.

5.2.2.2 Impact Load on the Glass Pane Near to the Corner of the Glass Facade Systems

A series of tests has been carried out to investigate the oscillation of the vertical displacement of nodes 1, 4, 6 and 8 which were diagonal from the central node to the corner node of glass pane Z. These tests were carried out to compare with the results obtained in Tests D1 to D3 and D10 to D12. Node 8 deflected by almost the same amount as nodes 1 and 4 of the cable-net when the ball bearing was dropped onto glass pane X. Please note that LVDT 8 was the farthest node from glass pane X and positioned at the corner of the glass facade systems. In addition, based on a series of static tests reported in Chapter 4, the same node of the cable-net had a large glass stiffness contribution and very small deflection.
Figure 5.12. Oscillation of nodes 1, 4, 6 and 8 of the flat cable-net that was subjected to the impact load. The ball bearing was dropped onto glass pane Y, from a 2.0m height.

Figure 5.13. Oscillation of nodes 1, 4, 6 and 8 of the flat cable-net that was subjected to the impact load. The ball bearing was dropped onto the glass pane Z, from a 2.0m height.
The ball bearing was dropped onto glass panes Y and Z that were closer to the corner nodes of the glass facade systems. Figure 5.12 and 5.13 show the time versus vertical displacement oscillation history of nodes 1 and 8 when the ball bearing was dropped onto glass panes Y and Z, respectively. It was found that node 8 oscillated at the same amplitude as node 1. But the oscillation amplitude of node 8 was higher as the impact was acting on the glass pane that was closer to the node in the far corner of glass facade system. Based on observation of a slow motion video taken using high speed camera, node 8 had the highest amplitude of oscillation because the node was only used to clamp a single glass pane. A screen shot of the oscillation of node 8 when the ball bearing landed on glass pane Z is shown Figure 5.14.

Figure 5.14. Node 8 deflected as the impact acting on glass pane Z (i) at impact, and (ii) as the ball bearing bounced back.

Compared to node 1 that was used to hold 4 glass panes, the glass pane at the corner of a glass facade should be restraint adequately. The clamped fittings at node 8 was used to hold one corner of glass pane Z. In the static test, the deflection of node 8 of any flat and curved-2 cable-net pre-stressed at 1500N, with glass panes, were 1.92mm and 1.15mm, respectively, at the maximum applied load. The deflection was considered very small at the maximum applied load. There was no other glass
panes held by the clamped fitting at node 8 such as on grid S7/H2-H3, H1/S6-S7 which was the farthest grid at the corner of the systems which has resulted in higher deformation at the edges when subjected to impact loading. In addition, node 8 may represents the farthest corner of the glass pane that is not perfectly clamped or supported. If there was a glass pane at a grid location mentioned above, the edge far corner of the glass should be held by a clamped fitting which is fixed onto a rigid structure. The results obtained from the impact test showed that even the farthest corner of the glass facade deflected significantly. The oscillation magnitude was approximately the same as the maximum amplitude of the vertical displacement when subjected to the impact. In considering this effect, it is important to restrain the corners of a glass facade and the edges of glass panes to the boundary structure however still maintaining a certain amount of allowable movement. Based on the results of a series static tests, the nodes at the corner of glass facade systems was the lowest deflection region under the applied loading. However, the corner node of the glass facade behaved differently when subjected to impact loading.

5.2.3 The Oscillation Characteristics of the Glass Pane Located at the Far Corner of Glass Facades subjected to an Impact Loading.

A series of impact tests that was focused on the impact loading on glass pane Z has been carried out to observe closely the deflection characteristic of the glass pane located at the far corner of the glass facade. The deflection of node 8 under static load, as reported in Chapter 4, was the lowest of all of the nodes as the node was at the far corner of the glass facade systems. However, the amplitude of vertical displacement of node 8 was similar with that of node 1 when glass pane X was subjected to the impact load. Three sets of tests as listed in Table 5.2 were undertaken where tests DA1 to DA3 have been carried out earlier and reported in 5.2.1. The setup for tests DA4 to DA6 is shown in 5.15. A ball bearing was dropped from various heights onto the glass pane Z that was
supported by the flat cable-net. The cables were pre-stressed at approximately 1500N. The position of the LVDTs for tests DA4 to DA6 is shown in Figure 5.16. Eight LVDTs have been setup close to the corners and on glass pane Z. Furthermore, Figure 5.17 shows the deflected glass pane during the impact event and the photo was taken using a Hot Shot high-speed camera.

Table 5.4.

The series of impact tests. The ball bearing was dropped from various heights onto a glass pane supported by rigid supports and flat cable-net structures.

<table>
<thead>
<tr>
<th>Test</th>
<th>Support structure</th>
<th>Drop height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rigid</td>
<td>Flat cable-net</td>
</tr>
<tr>
<td>DA1</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>DA2</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>DA3</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>DA4</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>DA5</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>DA6</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

Note: The results for tests DA1 to D3 were reported in 5.2.1.

Figure 5.15. The experimental setup for tests DA4-DA6.
Figure 5.16. The position of the LVDTs (red dots) located on glass pane Z supported by the flat cable-net systems. The ball bearing was dropped at the centre (green dot) of the target glass X, Y and Z respectively.

Figure 5.17. The glass deflected as soon as the ball bearing hit the centre of the target glass pane for both support cases.

Figure 5.18 shows the oscillation of glass pane Z and also the four corners of the glass pane Z when incorporated into the cable-net systems. All nodes have the same oscillation pattern except for a pair of nodes, which are nodes L3 and L8. These two nodes have different oscillation amplitudes which are lower than the other nodes. The results shows that the vertical displacement of glass pane Z at node L2, L4 and L6 are approximately the same while node L3 is far less. This shows that the glass pane warped extensively at locations L3 and L8. Figure 5.19 illustrates the warping mechanism of glass pane Z under impact. The glass can be seen twisting about its horizontal plane after the
impact, however, the glass deflected at the same level as the cable-net. The glass may break should the impact force acting on the glass pane exceeding the surface compressive strength or the tensile strength of the underside of the glass surface.

![Image of oscillation and displacement response](image)

*Figure 5.18. Oscillation of the glass pane Z and the corners of the flat cable-net, subjected to an impact load dropped from a 1.0m height*

Only node L1, L2, L3 and L8 are presented in the time – displacement response as the other nodes oscillated approximately in a symmetrical manner as shown in Figure 5.20. Nodes L2 and L3 are the nodes on the clamped fittings, while nodes L1 and L8 are the ones on the glass pane Z. Nodes L1 and L2 are the adjacent node at the edges of the cable-net systems. Nodes L3 and L8 are a pair of nodes that are close to the centre of the cable-net system. Note that node L2 and L3 were known as node 8 and 6, respectively in Tests D1 to D18. As the ball bearing was released from a height of 1.5m and hit the centre of the glass pane, the nodes on the glass deformed similarly to that of the clamped fittings. Although the vertical displacement of nodes L1 and L2 are more than 12mm, both nodes
deflected about the same level. The flexibility of the cable-net makes the glass follow the shape of the deformed cable-net.

*Figure 5.19. Warping of glass pane Z at the far corner (L2) when subjected to impact. Before the impact (top), and after the impact (bottom)*
Figure 5.20. Oscillation of the selected nodes of the glass pane Z and the glass support attachments in the flat cable-net. The ball bearing was dropped on glass pane Z from a 1.0m height.

Figure 5.21 shows the deflection of node 1 on the flat cable-net subjected to impacts from three different heights. The oscillation amplitude is the highest as the ball was dropped on the glass pane Z and node 1 oscillated with the largest displacement for the highest drop height. The oscillation pattern of node 1 for all cases are approximately the same except the first oscillation amplitude occurring as soon as the ball bearing hit the centre of the target glass pane Z. Figure 5.22 highlights closely the oscillation of glass pane Z within the first 0.5s. It can be seen that the amplitude of the vertical displacement of node 1 on glass pane Z increased when the ball bearing was dropped from a higher position. In general, the impact force increased when the object fell from a higher position. However, in this experiment, the impact force which is calculated based on Equation 5.1 and presented in Table 5.5 is less than the values reported in 5.2.1. The travelling distance of the ball bearing which is equivalent to the deflection of glass pane during the impact has reduced the impact force. This is because of the smaller change in momentum.
Figure 5.21. Oscillation of node 1 on glass pane Z supported by the flat cable-net. The ball bearing was dropped on glass pane Z from various heights.

Table 5.5.

<table>
<thead>
<tr>
<th>Test</th>
<th>Drop height (mm)</th>
<th>Maximum vertical deflection (mm)</th>
<th>Impact Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DA1</td>
<td>1000</td>
<td>2.65</td>
<td>2814</td>
</tr>
<tr>
<td>DA2</td>
<td>1500</td>
<td>3.42</td>
<td>3264</td>
</tr>
<tr>
<td>DA3</td>
<td>2000</td>
<td>3.92</td>
<td>3798</td>
</tr>
<tr>
<td>DA4</td>
<td>1000</td>
<td>8.27</td>
<td>902</td>
</tr>
<tr>
<td>DA5</td>
<td>1500</td>
<td>12.29</td>
<td>908</td>
</tr>
<tr>
<td>DA6</td>
<td>2000</td>
<td>14.14</td>
<td>1053</td>
</tr>
</tbody>
</table>

Note: The results for Tests DA1 to DA3 were reported in 5.2.1.
Figure 5.22. Oscillation of node 1 on glass pane Z, supported by the flat cable-net, for a period of 0.5s. The ball bearing was dropped onto glass pane Z from various heights.

Figure 5.22 shows a comparison of the oscillation of glass pane Z between the two cases considered. The oscillation of the glass pane for Test DA1 to DA3 is smaller than that for Test DA4 to DA6. However, the level of oscillation presented in the graph does not represent the actual deflection profile. For a ball that is dropped onto a single glass pane, the clamped fittings were only rotated about the plane of the glass pane. The central clamped fittings in respected to these tests remain at zero deflection as the glass was supported by the rigid structure. The oscillation period between the two cases also differ with each other. The glass pane in Test DA1 to DA3 oscillated with a period of about 0.15s which is a short period of time compared to that obtained from Tests DA4 to DA6 that oscillated with a period of about a second. This shows the flexibility of cable-net systems had a great influence on the oscillation period of the glass subjected to an impact loading. The cable-net structure has protected the glass panes and increased the damping. The cable-net has absorbed the impact energy while oscillating with the glass with approximately at the same frequency and time.
period. This is because the impact force reduced as the ball bearing that dropped on the glass pane has travelled significantly during the impact.

![Figure 5.23. Oscillation of node 1 on glass pane Z supported by both rigid and cable-net structures.](image)

The ball bearing was dropped on the glass pane from various heights.

The single pane impact test that was supported by a rigid structure and adopted the same glazing system to hold the glass so that one could observe the deformation of glass pane compared to the allowable value based on the standards. The deformation of glass supported by a cable-net system is greater than that supported by an intact element because of the flexibility of the cable-net system. However, the actual deformation of the glass on cable-net systems is very low as the displacement of glass pane and node that holds the glass pane are almost the same. As a comparison, the deflection of a glass pane supported by a cable-net was very small although the cable-net deflected 3 times greater than when that glass pane was supported by an intact or rigid structure. Based on the results reported here, the deflection of glass pane supported by the cable-net structure is much lower than the deflection limit of glass pane. The cable-net prevents the glass pane from deforming past the
deflection limit under impact loading. In Tests DA1 to DA3, the value of deformation of glass pane obtained from the impact event was nearly 80% of the allowable displacement. The deflection of glass may be higher if a greater impact force was exerted on the glass pane. With the glass on the cable-net structure, this greatly reduces the possibility of glass breakage where the compressive force exerted on the glass pane may be low. This is because the glass deformed approximately the same as the node that clamped to it. However, the glass warping mechanism has led to the glass deforming excessively and the glass may break under this condition. This mechanism may make the glass deflection exceed the deflection limit of glass. In practical, the glass pane at the edge of glass facade system is fixed to rigid boundary structure. In this research, the glass pane at the edges of the glass facade were not assembled because there were some difficulties in attaching the glass on to the boundary structure. However, without the glass pane at the edge, a series of test D1 to D18 were carried out and these have shown inadvertently the importance of the glass pane at the corner of glass facade. In the static tests, the nodes of the cable-net system that near to the boundary structure are very stiff with low deflections. However, in the impact test, the impact event may induce significant force at the edge and corners of the glass panes that located at the edges and corners of the glass facade systems. Although the impact was imposed at the centre of the glass facade, it still induced a significant almost equivalent deformation on the far corner node of cable-net. The important of the glass edges is discussed in 5.3.

5.2.4 The Effect of the Impact on the Force in the Cable

Figures 5.24 and 5.25 show the force in cable S3 to S5 and H3 to H5, respectively, of the flat cable-net subjected to the impact load, dropped from a 1.0m height. The oscillation of force in the cable ‘S’ and ‘H’ directions are approximately the same. The force in cables S3 to S5 and H3 to H5 in the flat cable-net increased at approximately 3% of initial pre-stress force in the cable. The changes
of force in the first oscillation frequency can be considered to be very low. The oscillation of the cable was damped out in about 2.5s for both cable directions. Cables in both directions oscillated in approximately the same pattern.

![Diagram showing forces in cables S3 to S5 in the flat cable-net subjected to the impact load. The ball bearing was dropped on glass pane X from 1.0m height]

*Figure 5.24. Forces in cables S3 to S5 in the flat cable-net subjected to the impact load. The ball bearing was dropped on glass pane X from 1.0m height*
Figure 5.25. Forces in cable H3 to H5 in the flat cable-net subjected to the impact load. The ball bearing was dropped on glass pane X from 1.0m height.

Figure 5.26 and 5.27 show the oscillation of the force in cable S4 and H4, respectively, for the flat cable-net systems subjected to an impact load that was dropped on glass pane X from three different heights. The two cables are presented in the graph as they show the maximum changes in force due to the impact. The cables in both directions were damped in a short period of time as the systems were subjected to a lower drop height of 1.0m. The oscillation amplitude was high for the cable that was subjected to an impact load dropped from a 2.0m height.
Figure 5.26. Force in cable S4 in the flat cable-net subjected to the impact. The ball bearing was dropped on glass pane X from various heights.

Figure 5.27. Force in cable H4 in the flat cable-net subjected to the impact load. The ball bearing was dropped on glass pane X from various heights.
Figures 5.28 and 5.29 show the oscillation of the force in cables S4, S5, H4 and H5 in both the flat and curved-2 cable-nets. The force in the sagging and hogging cable of curved-2 cable-net oscillated longer than that of the flat cable-net. The oscillation amplitude of the sagging cable has increased by nearly 13% of the original pre-stressing force. Unlike the force in the flat cable-net which increased by approximately 3% of the initial pre-stress force. The oscillation frequency of the force in the cable in the curved-2 cable-net is higher than that of the flat cable-net. The oscillation amplitude for the sagging cable in the curved-2 cable-net is greater than the hogging cables in the curved-2 net.

Figure 5.28. Forces in cables S4 and S5 in the flat and curved-2 cable-nets subjected to the impact load. The ball bearing was dropped on glass pane X from 1.5m height.
Figure 5.29. Forces in cable H4 and H5 in the flat and curved-2 cable-nets subjected to the impact load. The ball bearing was dropped on glass pane X from 1.5m height.

Figure 5.30. Forces in cables S4-S5 and H4-H5 in the curved-2 cable-nets subjected to the impact load. The ball bearing was dropped on glass pane X from 1.5m height.
Figure 5.30 shows a comparison of the oscillation of the force in both sagging and hogging cables in the curved-2 cable-net glass facade systems. The force in the cables in the flat cable-net subjected to an impact load dropped from certain heights oscillated in the same pattern with almost the same oscillation amplitude and frequency. However, the force in the sagging and hogging cables in the curved-2 cable-net oscillated in the opposite way. As soon as the ball bearing touched the glass pane, forces in sagging cables were increased while hogging cables were decreased. The forces in both cable directions oscillated in opposite directions but the frequency remain constant.

It was found that the force in flat cable is not affected by the impact event. This is because the changes of force in the cables in flat cable-net was only about ±3% of the initial pre-stress force. However, the force in the sagging cable in the curved-2 cable-net oscillated approximately ±13% of the initial pre-stress force. The increment of force in the sagging cables was due to the decrement of force in the hogging cables as the cable-net deformed under impact load. Based on the static test, the force in the sagging and hogging cables increased and decreased, respectively when the load was increased. While in the impact test, the force in the sagging and hogging cables increased and decreased alternately after the force was exerted on the glass pane. The changes of force in the short period of time due to the impact may affect the end fittings of the cables to the anchorages. Moreover, this event may distressed the end fittings and accelerate the stress relaxation of cables. This is because the force in the sagging and hogging cables changed soon after the oscillation event. Most importantly, the cable-net structure has reduced the effect of impact on glass pane where the glass pane and the cable-net structure deflected by the same amount. The deflection limit of individual glass supported by a cable-net is not affected although the deformation of the cable-net structure itself is large under impact.
5.3 Sensitivity Tests

In the previous tests, the cable-net structure was found to be very good in reducing the deflection of individual glass panes when subjected to impact. This is because the cable-net, which is flexible, and the glass deformed the same amount as the cable-net structure. This indirectly prevents the glass from breaking. It is known that the weakest points of a toughened glass pane are its edges. The tests carried out in this investigation was to observe the capability of the cable-net structure in preventing glass from breaking if the impact imposed is near to the edge of the toughened glass pane.

Table 5.6 lists the related tests undertaken for the sensitivity investigation. The selected glass pane was subjected to an impact load of a ball bearing which was dropped from a height of 1.5m. The cables of the flat and curved-2 cable-nets were pre-stressed at approximately 1500N. Five different targets which were near to the edge of the glass pane Y as shown in Figure 5.31 were considered. Three drop targets on glass pane Y are point C (near to the edge of glass pane Y) and points A and B (near to the glass support attachments (GSA)). One point target each on GSA (point D) and at the middle of two adjacent glass panes (point E). Figures 5.32 and 5.33 show the images of the ball bearing which were taken using a Hot Shot high speed camera as soon as the steel ball touched the respective target on the glass pane.

Figure 5.31. The ball bearing was dropped on glass pane Y from a 1.5m height
The glass pane remains intact as there were no broken shards as the ball bearing dropped on to the selected target as shown in Figure 5.31 except for the glass pane in test DS5 and DS9. The glass pane was broken in tests DS5 and DS9 where, for both cases, the ball was dropped approximately at the centre of the gap between two adjacent glass panes. The glass was broken as soon as the ball bearing touched the edge of the adjacent glass which is the weakest zone of the toughened glass as shown in Figure 5.34. All tests were carried out several times so as to confirm the results especially for tests DS5 and DS9. The broken glass panes were replaced with a new glass panes and the same test procedure was performed for both tests. The results do not show any difference between the glass panes on either the flat or curved-2 cable-net structures. The cable-net structure has no capability to prevent the glass from breaking when subjected to an impact load that hits the edge of the glass pane. The glass breaks because the impact force that hits the edge of the glass pane was greater than the compressive strength of the glass at the edge. Based on this test, the edge of the glass had a lower compressive strength compared to the surface of glass. This is because of the complex residual stress distribution existing along the edges of a toughened glass pane. The reduction in strength and stiffness along the edges is evident because the glass pane that was subjected to the same impact, load but applied at the centre of the glass, did not break. It is important to provide adequate cover to the edges of glass panes to prevent premature glass breakage. In framed glass systems the edge of the glass is usually enclosed by the aluminium frame, however in frameless glass systems, the glass edges have no cover at all except the silicone sealant that is used to fill-in the gap between the adjacent glass panes. It is recommended to protect the glass edges by any means such as a transparent thin strip which not only covers the edge but preserve the transparency of frameless glass system.
Table 5.6.

A series of impact tests to check the sensitivity of glass on the cable-net structures. The ball bearing was dropped at different positions onto the glass pane Y.

<table>
<thead>
<tr>
<th>Test</th>
<th>Flat</th>
<th>Curved-2</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>DS1</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>DS2</td>
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<tr>
<td>DS9</td>
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</tbody>
</table>

Figure 5.32. The ball bearing was dropped onto several target spots on glass pane Y that was supported by the flat cable-net.
Figure 5.33. The ball bearing that was dropped on several target spots on the glass pane supported by the curved-2 cable-net

Figure 5.34. Failure mode of a toughened glass pane under impact loading for tests DS5 (top) and DS9 (bottom)
5.4 Cable Anchorage Failure

Table 5.7 lists a series of tests that were used to simulate the failure of a cable anchorage. The test was performed by releasing one of the cable fittings from the cable anchorage. Cables S3, S4, H3 and H4 were chosen to simulate the failure. The procedure used to release the cable fittings from the anchorage was explained in chapter 3.

Table 5.7.
A series of dynamic test that were used to model cable anchorage failure.

<table>
<thead>
<tr>
<th>Test</th>
<th>Flat</th>
<th>Curved-2</th>
<th>Glass</th>
<th>Failure cable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>DF1</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>DF2</td>
<td>/</td>
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<tr>
<td>DF3</td>
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<tr>
<td>DF4</td>
<td>/</td>
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<tr>
<td>DF5</td>
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<tr>
<td>DF11</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>DF12</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

Figure 5.35 shows the force in cables S3, S4 and H4 from the flat cable-net without glass panes. The force in cables S3 and S5 increased by approximately 3%. However, the force in cable H4 decreased by less than 1%. The increment and decrement of the force in those cables is small and the oscillation of the force is almost not significant. Losing one of the cables i.e. cable S4 in the flat cable-net did not show significant changes in the forces in the other cables. This is because the force in the S and H cables of the flat cable-net are independent and the two sets of cables initially did not interact with each other. Although the two sets of cable were clamped at their intersection, the forces in all cables had little influence on each other. Thus, when cable S4 suddenly lost tension, only the force in the adjacent cables, such as cables S3 and S5 increased but not significantly. The increment of force
in the adjacent cables also resulted in a small deformation of the boundary structure at the cable anchorage S4. Unlike the curved cable-net where the force in the cables in the curve cable-net were interlocked with each other due to the curvature in the structure. The force in cables S3, S5 and H4 in the curved-2 net without glass panes as shown in Figure 5.36, the force changes and oscillated for a half of second. The force in cables S3 and S5 which were the sagging cables increased by approximately 15% for the first oscillation cycle and damped down to approximately 10% of the initial pre-stress force of 1500N. The force in cable H4 which was the hogging cable decreased by about 12% for the first oscillation cycle and then settled down at 95% of the initial pre-stress force. The oscillation of the force in the sagging and hogging cables was in the opposite sense. As the force in the sagging cable increased, that in the hogging cable decreased.

![Oscillation of the force in cables S3, S5 and H4 in the flat cable-net without glass panes subjected to the failure of cable S4 anchorage](image)

*Figure 5.35. Oscillation of the force in cables S3, S5 and H4 in the flat cable-net without glass panes subjected to the failure of cable S4 anchorage*
Figure 5.36. Oscillation of the force in cable S3, S5 and H4 in the curved-2 cable-net without the glass panes subjected to the failure of cable S4 anchorage

Figure 5.37 shows the difference in the force in cables S5 and H4 in the flat cable-net both with and without glass panes. The glass panes on the flat cable-net have been shown to have a significant affect on the force in cables S5 and H4. The force in cable-net with glass oscillated with a lower frequency compared to that without glass panes is due to the mass of the glass. The increment of the force in the cables in the flat cable-net both with and without glass panes was approximately the same and is not critical. However, the force in the sagging and hogging cables of the curved-2 net as shown in Figure 5.38 were shown to be significantly different with glass on the structural systems. The force in sagging cable (S5) of the curved-2 cable-net with glass panes increased higher than that of the systems without glass panes. The increment of force in the sagging cable was approximately 21% for the first oscillation cycle compared to the systems without glass panes which only had an increase in force of approximately 15% of the initial pre-stressed force of 1500N. Moreover, the force in the sagging cable of the cable-net with glass panes oscillated for nearly 2 seconds which is four times longer than that of the systems without glass panes. Furthermore, the oscillation frequency of
the sagging cable of the curved-2 cable-net with glass panes is lower than that of the systems without glass panes. The amplitude of force in the hogging cable of the curved-2 cable-net with and without glass panes are approximately the same but the force in the latter oscillated and damped over a longer period than the former. In addition, the oscillation of the force in the sagging and hogging of the curved-2 net with glass panes remained in the opposite sense which was the same as for the oscillations in force in the cables of the curved net without glass panes.

Figure 5.37. Oscillation of the force in cables S5 and H4 in the flat cable-net (FCN) both with and without glass panes, subjected to the failure of cable S4 anchorage
Figure 5.38. Oscillation of force in cables S5 and H4 in the curved-2 cable-net (CCN) both with and without glass panes, subjected to the failure of cable S4 anchorage.

Figure 5.39. Oscillation of force in cables S4, H3 and H5 in the curved-2 cable-net with glass panes subjected to the failure of cable H4 anchorage.
Figure 5.39 shows the oscillation of the force in cables S4, H3 and H5 of the curved-2 cable-net with glass panes. The oscillation was due to the failure of one of the cable anchorages which used to hold cable H4. The force in the sagging cable (S4) initially decreased by 11% and finally damped down to approximately 105% of the initial pre-stressed cable force. While the force in the hogging cables (H3 and H5) initially increased by about 7% and settled down at about 103% of the initial pre-stressed cable force. Based on the results reported above, either the loss of a sagging or hogging cable in the curved cable-net did not result in a major failure event such as progressive collapse or glass breakage. The changes of force in the flat cable-net was small compared to the initial pre-stress force in the cables.

5.5 Summary

All of the key findings in this chapter are summarised as follows.

(i) The oscillations of the glass are influenced by the rigidity of the load bearing structure. In addition, the oscillations of the glass pane and the cable-net when attached together are the same. Because the glass on the cable-net oscillated the same as the cable-net it is evident that the glass remains intact with the flexible structure. The force that was created by the impact load was also absorbed by the cable-net structure. This characteristic is considered to be one of the factors that reduce the risk of glass breakage. The deflection of glass that was supported by the cable-net structure has an advantage over the deflection limit of the individual glass panes. The glass supported by the cable-net structure deformed approximately the same as the cable-net structure when subjected to the impact load. The actual deformation of the individual glass is very small and easily fulfils the deflection limit criteria of a glass facade. Unlike the glass supported by the rigid structure, the deflection of a glass pane under an impact load may be an
issue as the glass deflected by nearly 80% of the allowable deflection. In design, the thickness of the glass pane is determined based on the wind pressure and not by considering the effects of impact. Based on this study, the thickness of a glass pane could possibly be reduced when it supported by the cable-net structure. Moreover, the same concept used to design the force in the cables in the cable-net system to fulfil the deflection criterion of the cable-net must be used. In order to design the glass facade that may be subjected to an impact load, all components of the structural glass facade must be considered. This is to ensure that all possible behaviour scenarios of a cable-net glass facade under impact will be taken into the design consideration.

(ii) It is known that the glass edge is the weakest area of a toughened glass pane. As expected the glass broke immediately after the ball bearing touched the edge of the glass pane. Although the glass pane supported by the cable-net structure is considered safe under impact, the flexible structure has no capability to prevent glass breakage should the impact hit at the edge of the glass. However, in most of the impact tests, the glass did not break when hit by the ball bearing. This is because the impact force exerted on the surface of the glass is reduced by the large deformation of cable-net structure under impact. The deformation of glass that is almost the same as the deformation of the cable-net under impact, is equivalent to the distance travelled by the impactor during the impact. This has reduced the impact force on the glass panes.

(iii) The failure of a cable anchorage was not found to be very significant to the performance of the flat cable-net. The force in the cables in the flat cable-net are not interacting with each other because both planes of cables are initially horizontal. Small changes of force in the cables in the flat cable-net was expected as the boundary structure deformed during the pre-stressing of the cables. However, the loss of one of cables in the curved-2 cable-net, particularly a sagging cable was crucial. The force in the sagging and hogging cables in the curved-2 cable-net for the
first period of the force oscillation changed by about ±21% and ±10%, respectively. Although the curved cable-net is stiffer compared to the flat cable-net, based on its deflection criteria as reported in Chapter 4, the loss of a sagging cable also affected the force in hogging cables. However, for the particular nets investigated most importantly, the loss of a cable did not lead to glass breakage or any other major failure event such as progressive collapse of the structure.
CHAPTER 6

NONLINEAR FINITE ELEMENT ANALYSIS OF CABLE-NET SUPPORTED GLASS FACADE SYSTEMS

6.1 Introduction

In this chapter, the finite element modelling that was performed using Abaqus/Explicit v6.9-1 is carefully explained. Three configurations of cable-net, with and without glass, as explained in Chapter 3 are modelled. The results obtained from the FE model of the cable-net glass facade systems have been calibrated with the experimental results reported in Chapters 4 and 5.

6.2 Finite Element Modelling

Finite element analyses were performed to investigate the structural behaviour of the flat cable-nets both with and without glass panes subjected to static and impact loads. ABAQUS v6.9 was used to develop the FE model of the cable-net glass facade systems. Many finite element software packages have developed and implemented the same methods for solving structural problems with almost the same solution procedures. ABAQUS is one of the most advanced finite element software packages available in the market today. The numerical analyses were carried out in three stages namely pre-processing, analysis, and post-processing. The finite element model of the cable-net glass facade systems was, first, modelled and the elements that were used in the modelling were assigned with an appropriate mesh, element type, geometric and material properties. The boundary conditions and loading were also defined in the first stage. The FE-model developed is then solved to find an approximate solution using an appropriate numerical technique.
6.2.1 Implicit and Explicit Analysis

There are two main types of approaches in numerical analysis namely, implicit and explicit methods. Both methods are supported in the Abaqus v6.9-1. Implicit methods are usually used in finite element analysis where structural problems are relatively stiff. The implicit solver has automatic load and time steps which result in taking less computational time. However, cable-net structures are flexible and geometrically nonlinear. Undertaking the analysis for this kind of structures using implicit methods may result in convergence difficulties. Thus, the explicit method has been chosen to solve this flexible structural problem. The numerical model is updated for changes in geometry at the end of each load increment. Using the explicit method to analyse the cable-network was very time consuming as a very small load increment was necessary for accurate results.

6.3 Description of the Experimental Model

The layout of the chosen experimental model is illustrated in Figure 6.1. There are three main elements in the cable-net glass facade system, namely the cable-net structure, the glass panes and the glass support attachment. The cable structure was formed by 14 cables, which are pre-stressed to the desired pre-stress force. The diameter of the wire cable is 4mm. The details of each of the experimental models considered in this research are described in detail in Chapter 3.
6.4 Finite Element (FE) Modelling of the Experimental Model of the Cable-net with and without Glass Panes

The FE model of the flat cable-net without glass panes subjected to static loading at four points is first developed. In the next section, the development of the FE model that was modelled with clamped fittings and glass panes is also described.

The FE-model consists of a supporting structure and a 7 by 7 flat cable-net systems. The geometry of the structure was modelled as one part, but defined by different elements. In general, the cables were modelled using truss elements T3D2 which stands for a 2-node linear 3-D truss. The shape or profile of the truss element of the cable was defined by the cross sectional area of the cable. In addition, the truss element has no bending stiffness but it does have compression stiffness however, with careful use it is suitable for representing a cable element. The geometrical properties of the truss element were set to be nonlinear in the analysis steps. The pair of 180 x 90 x 90 parallel flange channel (PFC) used in the support system were not modelled. Furthermore, the pair of 150mm by 250mm of
12mm thick steel plates with four spacers that were used to hold the cable end fittings were also not modelled. These parts formed part of the boundary structure and because of their very high stiffness they were not considered in this particular FE modelling. The boundary structure had sufficient stiffness and only very small deformations were observed when the cables were undergoing pre-stressing. A complete FE geometry of flat cable-net without glass panes is shown in Figure 6.2.

![Figure 6.2. Finite element geometry of the flat cable-net without glass panes](image)

### 6.4.1 Material Properties

The response of the cables in the cable-net were assumed to be linear elastic, although the whole structure was geometrically nonlinear. The Young’s modulus and Poisson’s ratio of the cables were defined as 82 kN/mm² and 0.3, respectively. This value was obtained from the tests as reported in Chapter 3. Homogeneous sections were also assumed. In reality the cable structures were tension only structures but the element which was used when defining the wire cables cannot be set to be a tension only element as the procedure is not allowed in Abaqus/Explicit analysis.
The damping used for the models is as follows. Rayleigh damping is defined by two factors such as mass proportional damping, \( \alpha_R \), and stiffness proportional damping, \( \beta_R \). The definition of Rayleigh damping is given in equation 6.1.

\[
\xi_i = \frac{\alpha_R}{2\omega_i} + \frac{\beta_R\omega_i}{2}
\]

Equation 6.1

Only mass proportional damping, \( \alpha_R \), was introduced to define Rayleigh damping in the cable-net systems while stiffness proportional damping, \( \beta_R \), was ignored. \( \alpha_R \) damps the lower frequencies while \( \beta_R \) was used to damp the higher frequencies. In addition, a small amount of numerical or artificial damping was introduced by default to control high frequency oscillations. The artificial damping was defined by default as linear and quadratic bulk viscosities which were 0.06 and 1.2, respectively. The assignment of the mass proportional damping parameter was to stabilize the cable that experiences a small oscillation during loading.

6.4.2 Boundary Conditions

The cable is clamped to the steel plate of the anchorage which is clamped to a pair of steel girders forming part of the self-reacting frame (supporting structure). However, only the geometry of the cable-net is modelled. The supporting structure and the cable anchorages are not included in the FE modelling as the cable-net was assumed to be pinned supported. The cable-net was restrained in three translational directions at the cable ends, as shown in Figure 6.3.
Figure 6.3. The cables are restrained in three translational directions at their ends

6.4.3 Pre-stress Force

The pre-stressing of the cables was defined by applying an initial force in the cables. An initial stress is introduced in the cables using a set of command (known as keywords) in the input file. The input for the keywords is in the format as shown in Figure 6.4.

*Initial conditions, Type=Stress
“Set name”, “Pre-stress value”

Figure 6.4. The keywords for pre-stress

The cables were assigned with an initial pre-stress and were grouped and given a set name as reference for use in the keywords. The value of pre-stress is given by Equation 6.2.
\[ \sigma = \frac{4F_{\text{initial}}}{\pi D_{\text{cable}}^2} \]  

Equation 6.2

The value of the pre-stress force was input in the keyword in the form of a stress. The diameter of the cables, \( D_{\text{cable}} \), used in the experimental model was 4 mm. The initial pre-stress value was taken from the experimental values recorded before each test.

### 6.4.4 Loading

The experimental model for the series of static tests was loaded by a concentrated load imposed at four nodes in the gravitational direction as shown in Figure 6.5. Thus, the loading attributes were assigned to four nodes of the FE model of the flat cable-net in a negative global \( z \)-direction as shown in Figure 6.6. Each node was loaded with a force of 207.5 N resulting in a total load of 830 N. The actual loading system that was used in the experimental tests to apply the loads to the nodes was not modelled. However, the self-weight of the loading frame which was approximately 3 kg was considered in the numerical model. Such self-weight contributes 7.5 N approximately for each loading point of the cable-net systems, in addition to the load applied. The self-weight of the loading frame was considered in the loading stage because the frame was hung on the cable-net systems at four nodes before it was attached to the scissor jack used to apply the displacement loading. The load was defined at each loading node in a single step for a total of 207.5 N. The increment of the applied load was defined using tabular amplitude toolset in Abaqus 6.9.1.
Figure 6.5. The loading frame was hung at four nodes of the cable-net systems and the load was applied by lowering the platform of the scissor jack.

Figure 6.6. A complete FE model of the flat cable-net without glass panes that was pinned supported at each cable’s end and was subjected to a set of concentrated loads at four nodes.
6.5 Solution Procedure

The FE model was first solved using the standard implicit procedure. The results obtained from this run are shown in Figure 6.7. Although the maximum deflection of the cable-net at node 1 and 4 have shown good agreement with the experimental results, the nonlinear relationship profile of load–displacement between the experiment and FE analysis are not in agreement at all. Thus the explicit solver ABAQUS/Explicit with a direct sparse linear equation solver (Full Newton-Raphson iteration procedure) as a numerical technique was used to solve the nonlinear equilibrium equations. The load was ramped linearly (increased monotonically) in time in a single step. The initial increment was set to 1% of the total nodal load while automatic incremental steps were used throughout the analysis. Large displacement theory was adopted. The simulations were performed under load control. The FE results obtained from the explicit solver agrees well with the experimental results but a small oscillation is observed. The cable has an issue of stability as the analysis converges. Consequently, the cable-net has been stabilized by material damping as explained in section 5.4.1.
Figure 6.7. Various solution procedures used for the FE model of the flat cable-net without glass panes. The vertical load - displacement response at node 4 of the flat cable-net without glass panes has been shown.

6.6 Convergence Study of the FE Model of the Flat Cable-net without Glass Panes

The mesh density for each segment of the cable-net was first studied to determine the optimum number of elements for each segment. Each segment was divided into a uniform number of divisions, as illustrated in Figure 6.8. Local mesh refinement improves convergence. Figure 6.9 shows the maximum deflection of the flat cable-net without glass panes that was subjected to four points of concentrated load for various numbers of elements. Figure 6.10 shows maximum force in cable H4 and SF as the number of elements is increased. Mesh convergence tests show there was no significant different between the coarser and finer meshes of each segment of the cable-net. Thus, four elements for each segments of the cable-net were deemed to be sufficient.
Figure 6.8. Each segment of the cable-net was divided to four elements.

Figure 6.9. Maximum deflection of the flat cable-net without glass for various numbers of elements used for each segments of the cables.
Figure 6.10. Maximum force in cables H4 and S4 of the flat cable-net without glass panes for various numbers of elements used for each segment of the cable

6.7 Validation of FE Model

Calibration of the FE model of the flat cable-net without glass panes is made by comparing the load-displacement response, the force in the cable-load response and the maximum displacement of the flat cable-net without glass panes. The load-displacement responses of the finite element and experimental model of flat cable-net without glass pane are presented in Figure 6.11. Both numerical and experimental results show good agreement and nearly mimic each other. The displacement at all nodes of FE model showed good agreement with the measured values with a good level of accuracy. Furthermore, the accuracy of the numerical analysis can also be seen as the cable-net is pre-stressed at three different pre-stress levels as shown in Figure 6.12. The maximum displacement of node 4 of the flat cable-net without glass pane is taken for comparison and the results are tabulated in Table 6.1. The percentage error in the maximum nodal displacement between the numerical and experimental model is less than 1%.
Figure 6.11. Load-displacement responses at nodes 1 to 8 from the numerical and experimental model of the flat cable-net without glass panes

Table 6.1.

Maximum deflection of the flat cable-net without glass panes.

<table>
<thead>
<tr>
<th>Pre-stress level (N)</th>
<th>Maximum deflections (mm)</th>
<th>Different (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experiment, $U_{Exp}$</td>
<td>ABAQUS, $U_{FEA}$</td>
</tr>
<tr>
<td>1000</td>
<td>36.07</td>
<td>36.34</td>
</tr>
<tr>
<td>1500</td>
<td>29.24</td>
<td>29.44</td>
</tr>
<tr>
<td>2000</td>
<td>23.88</td>
<td>24.11</td>
</tr>
</tbody>
</table>
In addition, the comparison between the finite element (FE) analyses and experiments is also reported considering the force in cable to load responses. Figure 6.13 shows the response of the force in selected cables to the applied load obtained from both the FE analysis and experiments. The response of both models is very similar. The force in cables H4 and S4 of both models have good agreement with each other. Although the difference in the response between the force in cables S3, S5, H3 and H5 obtained from the numerical analysis and the experiment investigation was approximately 2.5%, the error is considered sensible within a reasonable range of error. The maximum force in cables S4 and H4 obtained from the FE and experimental models that were pre-stressed at various pre-stress levels are presented in Table 6.2. The percentage difference in the maximum force in the cables between both models is less than 1%. Figure 6.14 shows the response of the force in cable S4 from both models that are pre-stressed at various pre-stress levels. Based on the results presented in the respective figures and tables, the finite element model of the flat cable-net without glass panes is acceptable and is used to develop the FE model with glass panes.
Figure 6.13. The force in cables S3, S4, H3 and H4 to the applied load responses from the finite element and experimental model of the flat cable-net without glass panes. The cables were pre-stressed to approximately 1500N.

Table 6.2.
The maximum force in cables S4 and H4 in the flat cable-net without glass panes. The cables were pre-stressed at three levels of pre-stress.

<table>
<thead>
<tr>
<th>Pre-stress level (N)</th>
<th>Force in cable (N) H4</th>
<th>Difference (%)</th>
<th>Force in cable (N) S4</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Experiment ABAQUS</td>
<td></td>
<td>Experiment ABAQUS</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>1417.49 1415.15</td>
<td>0.17</td>
<td>1396.83 1409.02</td>
<td>0.87</td>
</tr>
<tr>
<td>1500</td>
<td>1762.70 1768.44</td>
<td>0.33</td>
<td>1759.24 1764.33</td>
<td>0.29</td>
</tr>
<tr>
<td>2000</td>
<td>2191.00 2178.63</td>
<td>0.56</td>
<td>2187.22 2175.84</td>
<td>0.52</td>
</tr>
</tbody>
</table>
6.8 **Finite Element Model of Flat Cable-net with Glass Panes**

Previously, the numerical response of the flat cable-net without glass panes was calibrated with the experimental results. In the next section, another two components of cable-net systems namely the glass panes and glass support attachment are considered in the FE modelling. The gap between glass panes which was 5mm was left empty without any element as it was not filled with any material in the experiments. Silicone sealant which is usually used as weather sealant was not modelled as it does not affect the integrity of the glass panel as well as the final load bearing capacity of the whole structure (Feng et al., 2007; Wang et al., 2007). In addition, the elastic modulus of the sealant is much lower than that of the glass. The load-displacement and the force in cable-load responses from the FE model of the flat cable-net with glass panes are presented below.

*Figure 6.14. Force in cable S4-load response from the numerical and experimental model of the flat cable-net without glass panes, subjected to various pre-stress levels*
6.8.1 Finite Element Model of a Glass Pane

The glass was modelled using shell elements (S4R) and was assumed to be a homogeneous elastic material with a Young’s modulus of 70 kN/mm² and a Poisson’s ratio of 0.2. The element is a four-noded doubly curved thin shell as shown in Figure 6.15. The thickness of the glass is 4 mm with zero eccentricity and is integrated using Simpson’s rule prior to the analysis. The thickness of the element follows the positive normal direction which was given by the right-hand rule about the nodes of the element. Furthermore, the direction of the right-hand rule also defined the top and bottom surface of the shell element. The top and the bottom surface of the element follow the positive (SPOS) and negative (SNEG) of the normal direction. These surfaces are important in specifying contact definitions such as a connection between the bottom surface of the glass element and the top surface of the steel plate of the glass support attachment.

![Figure 6.15. Shell element used in modelling the glass pane in Abaqus (Abaqus 6.9-1 manual, 2009)](image)

6.8.2 FE analysis of the Glass Support Attachment.

The glass support attachment (GSA) used in the flat cable-net system was a clamped fitting type. The GSA comprised of a pair of 75mm square of 3 mm thickness steel plate and a set of three, 25 mm square, steel blocks as shown in Figure 6.16. The steel plate was used to hold the glass pane
at its edges while the block was used to hold the cables together at its intersection. A pair of steel plates was represented by a single 3D deformable shell element which was modelled using shell element (S4R). The outer part of a pair of steel plates was not considered in the FE modelling of the GSA. The glass was assumed to be perfectly clamped by a pair of steel plate using a 3 mm diameter screws. The interface between the glass and steel plate was a single layer rubber pad which was not considered in the FE model of GSA. The steel plate was modelled without using the geometry of the set of three steel blocks of the GSA. The later part was replaced and defined using constraints element of the coupling element type. The intersection of a cable and the centre of the steel plate at the respective node have the same deflection criterion. Thus, the constraint coupling is sufficient to represent the characteristics of the steel block which moved together with the steel plate when subjected to loading.

![Figure 6.16](image)

*Figure 6.16. Glass support attachment which comprises of a pair of steel plate and a set of four steel blocks at each loading node. The glass is clamped in between two steel plates using 3mm diameter screws*

Initially, the steel plate of the GSA and the steel blocks were defined as one part and were modelled using a homogeneous shell element (SR4) as shown in Figure 6.17(i). However, the geometry of the steel block was simplified to a single line of 12mm length and was modelled using a
truss element (T3D2) as shown in Figure 6.17(ii). The geometry of the truss element was defined with a cross-sectional area of 625 mm$^2$ which was equivalent to the cross-sectional area of the set of three 25 mm square steel blocks. The steel plate was represented by a single homogeneous shell element. The interaction between the glass pane and GSA as well as the connection between the GSA and the cable-net are explained in section 6.9.3. In addition, the simplification of GSA element is also explained in that section.

![Figure 6.17. The FE-model of the glass support attachment (GSA). The steel block of the GSA was modelled as (i) shell element (SR4) and, (ii) truss element (T3D2)](image)

6.8.3 Constraint Elements

The definition of the constraint elements between the glass panes, glass support attachment (GSA) and flat cable-net are crucial to simulate the behaviour of the FE model of the cable-net glass facade systems. The GSA is an assembly that holds the glass at its edges via a pair of steel plates and it clamps the cables at their intersection. The assembly of glass and the steel plates of the GSA was modelled using a constraint tie element. The constraint pair acts according to the master-slave
formulation, in which the steel plate of the GSA was chosen as the master as it is composed the stiffest material (ABAQUS, 2010). The discretization type is surface-to-surface.

A pair of steel plates and a set of three 25 mm square cubes were assembled as a unit which was known as the GSA which translate with the cables with the same vector under loading. Thus, the constraint element that was defined between the two parts must reflect those characteristics. The geometry of the GSA was initially defined with and without a set of three steel blocks. The geometry of the later was modelled using a truss element (T3D2) as explained in 6.8.2. The connection that was defined to comply with all the geometry of GSA considered is of a constraint and connector type. The connection between the GSA and the cable’s intersection was made using a connector element which was defined between the free end of the truss/beam element of the GSA and the respective intersection node of the cable-net systems. The rotary inertia of the connectors was mismatched and has been augmented automatically to solve the convergence problem encountered. However, the additional rotary inertia is not suitable for strong dynamic analyses. The assembly between the GSA without the steel blocks and the cable-net were made using a constraint coupling element. The constraint element was defined between the centre of the steel plate and the respective cable’s intersection. A simple study to determine the most appropriate constraint/connector elements located between the geometry of GSA and cable-net has been carried out and is reported in 6.8.4.

6.8.4 Sensitivity Study on the Type of Connection Elements

A simple FE model of a flat cable-net with glass pane was developed to choose the most appropriate FE model of the GSA and its constraint to the respective cable’s intersection. A FE model of a simple flat cable-net with 2 by 2 configurations supported a single glass pane as shown in Figure 6.18 was chosen for this study. The connection between the glass pane and GSA under consideration
was modelled using constraint coupling element as explained in section 6.8.3. Three types of FE model of the GSA were considered, these were Models C1, C2 and C3 as summarised in Table 6.3. Model C1 – the geometry of the GSA comprises of a single steel plate with a set of three blocks. Model C2 and C3 – a single steel plate without a set of three blocks geometry. Models C2 and C3 have the same geometry but differ in the region of the slave element definition. Figure 6.19 shows the definition of models C1, C2 and C3.

![Figure 6.18](image.png)

Figure 6.18. FE model of a flat 2 by 2 configuration of a cable-net with a single glass pane that is held by four glass support attachments at its corners

Table 6.3.

*Constraint master-slave formulation between the cable-net to glass support attachment.*

<table>
<thead>
<tr>
<th>Model</th>
<th>Component of GSA</th>
<th>Constraint formulation</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steel plate</td>
<td>A pair of three steel blocks</td>
<td>Master</td>
</tr>
<tr>
<td>C1</td>
<td>/</td>
<td>/</td>
<td>Cable-net</td>
</tr>
<tr>
<td>C2</td>
<td>/</td>
<td>-</td>
<td>Cable-net</td>
</tr>
<tr>
<td>C3</td>
<td>/</td>
<td>-</td>
<td>Cable-net</td>
</tr>
</tbody>
</table>
The constraint coupling element was defined between the GSA to the respective cable’s element, according to the master-slave formulation. The cable-net at the specified node is always chosen as the master or control point of the constraint element. The slave element for each GSA model considered differs for each model considered. The slave element defined in model C1 was defined at the free end node of a set of steel blocks that was modelled by the truss element of the GSA. While models C2 and C3 define the slave element at the bottom surface of the steel plate of GSA and the centre node of the steel plate of GSA, respectively. Furthermore, for all GSA models considered, two conditions of constraint degree of freedom were defined as follows (i) restrained in all directions, and (ii) restrained in translational directions only. It was found that the deflection of the FE model considered has no significant effect on the different GSA models and constraint types. Thus, the simplest model of the GSA which was modelled without a set of three block element is chosen for the following study. A set of three blocks was not modelled as the definition of constraint coupling element is adequate to simulate the response of the movement characteristics of GSA under loading and constraint conditions.
6.8.5 Convergence Study: FE Mesh of Glass Support Attachment and Glass Pane

A convergence study to determine the optimum number of elements for the FE mesh for the glass panes and the GSA was carried out. The 2 by 2 FE model of the configuration of the flat cable-net with a single glass pane was again used to determine the mentioned objective. The connection between the glass pane and the GSA was modelled using a constraint tie element based on a master-slave formulation. The mesh density for the slave element was recommended to be finer than the master. This recommendation was made to avoid penetration of the master element onto the slave element which will influence the results. The FE mesh of the GSA was defined by dividing its edges into a certain number of divisions and the mesh was set as structured which ensures uniform mesh elements. Figure 6.20 shows the finite element mesh used for the GSA whereby each of its edges was divided to three divisions giving a total of 24 elements.

![Figure 6.20. The finite element mesh used for the glass support attachment](image)

The FE mesh of the GSA remains the same throughout the process to determine the optimum number of meshes used for the glass pane. In addition, the FE mesh of the GSA used for this preliminary study was assumed coarse enough on the master element compared to slave element on
the glass at its corners. Figure 6.21 shows the FE mesh of a glass pane that was divided into 15 elements at its edges with dual bias ratio of 15. There are no specific rules in choosing the bias ratio for this particular exercise but it was set to remain the same throughout the process for convenience. The number of elements was increased accordingly to find the optimum number of elements for the glass panes that constraint the GSA by constraining the tie element. Furthermore, the double bias option was set to obtain a finer mesh near the corners of the glass pane.

Figure 6.21. The FE mesh used for a glass pane

Figure 6.22 shows the nodal displacement of the 2 by 2 flat cable-net with a single pane in regards to the number of elements. The optimum density of the mesh for the glass was 12 with a doubly bias ratio of 5 and this was assumed to be sufficient for the FE model of the flat cable-net with glass panes. A complete FE model of 7 by 7 configurations of the flat cable-net with glass panes is shown in Figure 6.23.
Figure 6.22. Nodal displacement of the 2 by 2 flat cable-net with a single glass pane for various numbers of elements considered

Figure 6.23. The geometry and its associated FE mesh for the flat cable-net structure with glass panes
6.8.6 Validation of the FE Model of the Flat Cable-net with Glass Panes

The experimental model of test S5 was used to verify the numerical model of the flat cable-net with glass panes. The cable-net was pre-stressed to approximately 1500N. Figure 6.24 shows the load-displacement response at node 4 of the flat cable-net with glass panes. The percentage difference of the maximum deflection of the cable-net with panes between the experimental and finite element models is 4.6%. Consequently, the numerical model is within acceptable agreement with the experimental results.

![Figure 6.24. Load-displacement response at node 4 of the numerical and experimental model of flat cable-net with glass panes](image-url)
6.9 Summary

The finite element (FE) models of cable-net with and without glass panes were established and analysed using ABAQUS 6.9.1 software. The FE model was validated using the experimental models reported in Chapters 3 and 4. The cable-net was modelled using truss elements which included the definition of the geometric nonlinear properties of the cable. The pre-stress force in the cable in the flat cable-net both with and without glass panes was defined using a set of commands (called keywords) in an input file. The boundary structure that was used to support the cable-net system was not modelled. The cable-net was restrained in three translational directions at each cable end. The cable-net was defined as one part without the definition of joint elements between the cables. The FE used to model the glass was defined as homogeneous shell elements used with an optimum FE mesh density. The glass was connected to cable-net via glass support attachments (GSA) which comprised of two parts, namely a pair of steel plates and a set of three steel blocks. The former was used to hold the glass at its corners while the later was used to couple the cables at its intersection. Only a single plate of a pair of steel plate was modelled and the steel block was defined by a constraint coupling element. The flat cable-net with and without the glass panes was subjected to a set of four concentrated loads. Each concentrated load of 207.5N was applied at the selected loading points which were acting perpendicular to the flat cable-net plane.

The FE results have a very good agreement with the experimental results. The percentage difference in deflection between the experimental and finite element results for the flat cable-net with and without glass panes was 4.6% and less than 1%, respectively. Furthermore, the difference between the force in the cables in the FE model and the experimental model of the flat cable-net without glass panes was less than 1%. The FE model of the flat cable-net both and without glass panes that was modelled using ABAQUS 6.9.1 was equivalent to the experimental model. Thus the
modelling technique with all attributes defined in the FE numerical model can be used to predict the
deflection and distribution of force in a cable-net under different parameters such as thickness of
glass, size of cable-net, loading conditions, size of cable etc.
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

This thesis presents a comprehensive study of a cable-net supported glass facade system which comprises of three main elements namely, pre-stressed cables, glass panes and glass support attachments (GSAs). The glass is supported by the cable-net via the GSAs. The cable used in the experiment is 4 mm in diameter, 7 by 7 wire strand core (WSC) and three levels of pre-stress were considered namely, 1000N, 1500N and 2000N. Two main types of cable-net configurations were considered, namely flat and curved cable-net systems. A doubly-curved net considered in this research comprised of sagging and hogging cables which were the load bearing and the supporting cables, respectively. In addition, two shapes of curved cable-net namely, curved-1 and curved-2 were considered which have different levels of curvature. The central cables of the sagging and hogging cables were key for this configuration. The end fitting of the flat cable is considered as a reference for the curved cable-net. In general, the end fitting of the sagging and hogging cables were positioned below and above the reference lines, respectively. The central cable of the sagging and hogging cables of the curved-1 and curved-2 cable-nets were positioned 30mm and 45mm, respectively, from the reference line. Each configuration of cable-nets was tested with and without glass panes.

The glass pane used in the experiment is 300mm by 300mm square and 4mm thick; and made of toughened glass. The flat glass is used with the GSAs to accommodate the curved cable-net to form doubly curved glass facade systems. The GSAs used to hold the glass pane and the cable-net at their intersections are point-clamped fittings which comprised of two parts namely glass fittings and
cable fittings. The former was used to hold the glass and the latter was used to clamp the cable-net at its intersection.

Two types of test were considered namely static and dynamic test. A series of static tests on the experimental model of the cable-net was subjected to a total load of 830N which was applied at four nodes on the cable-net system. Each of the concentrated loads is approximately 207.5 N. The deformation of the cable-net both with and without glass panes under the four concentrated loads was monitored. In addition, the changes in the force in the cables were also monitored.

A series of dynamic tests comprised of two sets of test namely an impact test and the simulation of a cable anchorage failure were conducted. Flat and curved cable-nets with glass panes were subjected to the impact of a steel ball bearing that was dropped from various heights on carefully selected glass panes. In addition, a series of sensitivity tests was also carried out. The ball bearing was dropped at several points onto the selected glass pane. This test was performed to investigate the capability of cable-net structure to prevent glass breakage should the impact hit at the most sensitive or critical point on the glass pane. Another set of dynamic tests carried out is a simulation of a cable anchorage failure. This test was performed by suddenly releasing a pre-stressed cable from its anchorage. The objective of the static and dynamic tests was mainly to study the performance of cable-net supported glass facade systems.

In addition, a finite element model of the cable-net with and without glass panes was also developed and the results obtained from the finite element analysis carried out using the ABAQUS v6.9.1 were calibrated with the experimental results. This chapter summarises the findings from the static and dynamic tests and the numerical analysis of cable-net glass facade systems.
7.2 Conclusion

The key findings of this research are summarised as follows.

7.2.1 Experimental Studies: Static Tests

Glass in cable-net system contributed to the overall stiffness of the structural system. The glass stiffness contribution is the ratio of the difference in the deflection at the selected nodes of the cable-net with the glass panes to the deflection of the cable-net without glass panes. It is known that the pre-stressed cable is the main structural component that contributed to the overall structural stiffness. By increasing the pre-stress force in the cables in the cable-net systems, the percentage contribution of the glass to the overall structural stiffness is reduced. In this research, the glass stiffness contribution on the structural glass facade was varied with two dependent factors studied which are the configuration of cable-net and the initial stiffness of the cable-net structure.

The glass stiffness contribution on the flat cable-net is higher at the beginning of the loading stage which is at about 30% and reduced before steadying in the range of 15% to 20% as the load is increased. This is due to the increase in the force in the cable and the stiffening of the cable-net structure. Whereas, the glass stiffness contribution on the curved cable-net gradually increases as the load is increased. This is because the force in sagging and hogging cables in curved cable-net gradually increases and reduces, respectively, when the load is increased. Only sagging cables contributed to the stiffness of the cable-net structure. Moreover, the introduction of the curvature in the cable-net structural system increases the stiffness of the structural system and correspondingly reduces the deflection of the cable-net systems. The maximum deflection of the curved-1 and curved-2 cable-nets are approximately between 12% and 20% lower than the deflection of the flat cable-net.
The stiffness of the cable-net system can be further improved by considering a curved cable-net such as a doubly curved net to support flat glass panes. The curved cable-net can be designed to accommodate the same deflection criterion as a flat cable-net but with a lower pre-tension force required in the cables. The reduction of pre-stress force in the cable will reduce the reaction force needed for restraining by the supporting structure. Therefore, the geometry of the supporting structure which is designed based on the same reaction forces can be used to accommodate higher reaction forces should the cable-net be subjected to extreme loading conditions. However, a small adjustment on the position of the cable anchorage along the supporting structure is essential to configure the curved cable-net. Note that the supporting structure that is used to support the sagging cables of the cable-net systems must be designed accordingly by considering the fluctuation of force in the sagging cables. Flat glass panes can be used in curved cable-net systems but only to a certain limit in the curve configuration. Unfortunately, this research did not investigate the sensitivity of using flat glass panes in a curved cable-net system.

The deflection of cable-net with glass pane is lower than that of cable-net without glass pane. This is because the addition of glass increases the stiffness of the structural glass facade. This effect can also be seen from the percentage of glass stiffness contribution mentioned above. The increment of force for the same cables in the flat cable-net is just 17% of initial pre-stress force. The force in sagging cable of curved cable-net increases because of the decrement of force in the hogging cable when the load is increased. The force in the sagging cables in the curved-1 and curved-2 cable-nets increased approximately 36% and 38% of their initial pre-stress force, respectively. The force in the sagging cables in the curved-1 cable-net at the maximum applied load is just 2% lower than that for the curved-2 cable-net. The force in the sagging cables in the curved cable-net increases to more than...
double when compared to the same cables in the flat cable-net which was pre-stressed to approximately the same pre-stress level.

Moreover, the percentage of changes of the force in the sagging cables in the curved cable-net with and without glass are 12% and 20% higher, respectively, than that of the cables in the flat cable-net although the deflection of the curved cable-net is lower than the flat net. The contribution of glass in the stiffness of the structural glass facade slightly reduces (8%) the increment of force in sagging cable in the curved cable-net.

These advantages are not taken into consideration in the design of cable-net structure. The force in cable-net is usually designed by only considering the cable-net structure without glass pane. Whereby the wind pressure retained by the glass pane is transmitted at nodes of the cable-net structure. The thickness of glass pane is determined based on wind pressure and according to the established standards. Based on this research, there is a possibility to reduce the force in the cable used in the cable-net structure up to 50% after considering glass contribution in the analysis of structural glass facade. In other words, lower initial pre-stress force in the cable could be designed to accommodate the deflection criterion of the cable-net structure. This is based on the deflection of the cable-net without glass and the cable-net with glass that were pre-stressed at lower pre-stress force level. It was found that the deflection pattern between these two setups are approximately the same.

Glass is usually ignored in the analysis of cable-net supported glass facade systems. The results reported in this research show that glass has been proven to have a significant contribution to the stiffness of the cable-net systems. The analysis of the cable-net system supported glass facade should consider the contribution of the glass in the overall stiffness of the structural system.
7.2.2 Experimental Studies: Dynamic Tests

Two types of dynamic test were carried out in this research namely, the impact tests and the simulation of a cable anchorage failure. A series of impact tests were carried out on the flat and curved-2 cable-nets with glass panes. A 760g steel ball bearing was used as an impactor which was dropped onto three different glass panes located at the centre of the corner of the glass facade. The ball bearing was released from heights of 1.0m, 1.5m and 2.0m. The dynamic impact load had a greater impact on the deflection of the cable-net glass facade systems than the applied static loads. In a few impact tests carried out in this research, the target glass was broken by the impact of the ball bearing which was dropped from a height of 1.5m. The breakage of the glass did not have any impact on the performance of the cable-net systems. The glass breakage was due to an existing flaw from a previous impact test.

The impact of the ball bearing which was dropped even from a 2.0m height did not break the target glass, however it did result in a slight increment of force. The force in the cable in the flat cable-net oscillated during the impact at about $\pm 3\%$ of the initial pre-stress force which is considered insignificant. The boundary structure for the flat cable-net may not be affected by such increment of force. However, the force in sagging cable in the curved cable-net oscillated at $\pm 13\%$ of the initial pre-stress force. The maximum amplitude of oscillated force in sagging cable in the curved cable-net due to the impact is almost one third of the result obtained in the static tests. In the static tests, the force in sagging cable in the curved cable-net increased approximately 36% of the initial pre-stress force at the maximum applied load. In addition, the maximum deflection of the cable-net under impact is almost one third of the deflection of cable-net in the static test. The deflection of cable-net under impact load is not significant. Although this value is not comparable because of the difference in intensity and type of loading, the impact has shown great features on the deflection of glass pane.
The deflection of cable-net and the glass pane struck by the impact is approximately the same. Whereas for the case of a single glass pane supported by rigid structure, the deflection of the glass pane is slightly greater (1.1%) than the deflection limit of the glass pane which is 1% of the edge length of the glass. However, the glass did not break although the deflection limit of glass was exceeded. The deflection limit of the glass is rather conservative but important as a guideline to prevent glass breakage. In addition, the glass may break should larger impact pressure hit the glass. The deflection limit of glass may not be applicable for the glass used together with the cable-net structure. Moreover, there is the possibility of using thinner glass pane with the cable-net structure.

Based on the advantages of the cable-net to absorb the impact force on the glass, another set of impact tests was undertaken. The tests were carried out to determine the capability of the cable-net structure in resisting the glass pane when the impact hit the most sensitive region on the glass pane. The same ball bearing was used and dropped from a 1.5m height on the selected targets on the selected glass panes. The target was set approximately near the edge of the glass, which is near to a pair of plate glass support attachment (GSA) and exactly on the GSA. It is known that the edge of glass is the most sensitive region of a glass pane. The glass was immediately damaged as soon as the ball bearing hit the edge of the glass. The rest of the glass targets were not damaged. However, the structural cable system oscillated for a short period of time because the ball bearing hit the cables after the impact.

In another set of dynamic tests, the cable that was instantly detached from the anchorage released a significant amount of energy into the cable-net systems. The cable-net oscillated for a short period of time and the force in the cable adjacent to the released cable changed significantly. This was due to the released cable which lost more than 95% of its pre-stress force. This event was studied
to investigate the effect of sudden failure on the performance of the cable-net. The increment of force in the cables in the cable-net with glass panes is lower than that of the cable-net without glass panes. However, in the dynamic tests simulating cable anchorage failure, the rate of changes of the force in the cables were higher in the cable-net with glass panes compared to that in the structure without glass panes. This is due to the mass of glass which drove the oscillation amplitude and frequency.

However, the impact of cable loss is not significant on the flat cable-net system when compared to the curved cable-net. The force in the cable that was nearest to the cable with the damaged anchorage only increased by 3.5% of the initial pre-stress force and fluctuated in the range of 3% to 4% of the initial pre-stress force for a short period of time. The impact of the instant cable loss affected the rate of change in the force in the curved cable-net, especially the ones with glass panes. The force in the sagging cable in the curved cable-net with and without glass panes oscillated in the range of 9% to 20% and 6% to 15% of the initial pre-stress force, respectively. Furthermore, the force in the hogging cables in the cable-nets with and without glass panes was reduced and oscillated in the range of 2% to 10% and 0 to 11% below the initial pre-stress force, respectively. The failure of a cable anchorage has no significant impact on the flat cable-net. However, the impact is critical on the curved cable-net especially if the anchorage of a sagging cable, which is a load bearing cable, in cable-net system failed. In addition, neither the flat nor curved cable-net structures are prone to progressive collapse. The intensity of force in the sagging cables increases the reaction force on the boundary structure via the cable end fittings. From the static tests, it was found that the oscillation of force in the sagging cable in the curved cable-net is lower than the changes of force in the same cables in curved cable-net. The curved cable-net system can be designed according to the same deflection criterion as the flat cable-net system but with a lower pre-stress force in the cables.
7.2.3 Finite Element Analysis

The finite element model of the cable-net with and without glass panes was successfully constructed and calibrated with the experimental models. The numerical results obtained from the finite element analysis were in very good agreement with the experimental result. The analysis was carried out by explicit approach rather than implicitly as the behaviour of FE model of the cable-net has been simulated over geometrical nonlinear when the load was increased. Despite the maximum displacement at the maximum applied load obtained from the implicit and explicit analysis being the same, the load-displacement responds of the cable-net obtained from the implicit approach is not the same. The deflection of the FE model of the cable-net is not simulated correctly. Moreover, the implicit approach encountered convergence problem when the glass was considered in the FE modelling approach. By using the explicit approach, the percentage difference in the deflection and force in the cables in flat cable-net without glass panes was found to be less than 1%. In addition the FE model of the flat cable-net with glass panes also showed good agreement with the experimental results. The percentage difference in the deflection in this case was approximately 4.6%.

In addition, the type of glass fittings should be modelled accordingly in the finite element modelling. Only a single steel plate of the glass support attachment with constraint coupling element is adequate to simulate the clamped fittings. It is important to include the plate as to closely represent the actual deformation of glass under loading. Coupling the corner of glass to the node of cable-net structure is not the best option to model the connection. This is because the element is used as the medium to transmit the load from the glass panes to the cable-net structure. The distribution of force might be different depending on the type of glass fittings used in the structural system.
7.2.4 Recommendations for Future Research

(i) To study the performance of cable-nets with different glass support attachments namely point-fixed bolted and clamped fittings. The distribution of stress in the glass may be different with different types of glass fittings. Moreover, the glass fittings may influence the distribution of load from the glass pane to the cable-net system and then to the support structure.

(ii) To use different sizes and thickness of glass pane with cable-net structure. The design of glass pane is determined individually using established standards and based on the designed wind loading. However, the glass deforms differently when supported by cable-net structure under loading. These characteristics are not taken into consideration in the design of glass thickness. Moreover, the glass of different thicknesses behaved differently when subjected to impact. Therefore, the optimum glass thickness can possibly be determined.

(iii) To cut the cable at the intermediate part of the cable-net using appropriate tools such as an explosive bolt and more than one cable failure should also be considered. In the current research work, only one cable was released immediately from the cable anchorage which means that the cable failed at the boundary structure. Different locations of cable failure should also be considered in future studies. In addition, there will be a probability of more than one cable failing in the structural system. These events may create more serious effects which might lead to a progressive collapse.

(iv) To load the cable-net with a glass facade on top of the glass panes with a uniformly distributed load and to consider unsymmetrical distributed load whereby only a quarter or half of the systems is loaded. The load acting on the cable-net supporting glass facade systems is usually
assumed to be uniformly distributed. In reality, the load such as a wind load may be extreme on certain region of the facade which will create a condition of unsymmetrical loading.
REFERENCES


**BIBLIOGRAPHY**


Institution of Structural Engineers (1999). Structural Use of Glass in Buildings. The Institution of Structural Engineers (IStructE), London.


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APPENDIX A

Derivation of the Catenary by Differential Equations

Figure A1.

Equilibrium equation,

\[ \Sigma H = 0, \quad T_0 = T \cos \theta \]  \( \text{(i)} \)

As \( \mu \) is mass per unit length of the cable and \( s \) is length of cable from A to B, thus:

\[ \Sigma V = 0, \quad mg = \mu sg = T \sin \theta \]  \( \text{(ii)} \)

By referring to Figure A1(b),

\[ \tan \theta = \frac{\mu gs}{T_0} = \frac{s}{a} \]

\[ s = a \tan \theta \]  \( \text{(iii)} \)

Where, \( a = \frac{T_0}{\mu g} \) is introduced in \( \text{(iv)} \) as a constant that having the dimensions of length.

And,

\[ \tan \theta = \frac{dy}{dx} \]  \( \text{(iv)} \)
From (iii) and (iv),

\[ s = a \frac{dy}{dx} \]  

\[ \frac{ds}{dx} = a \frac{d^2 y}{dx^2} \]  

... (v)  

... (vi)  

By referring to Figure A1(c)

\[ ds^2 = dy^2 + dx^2 \]

\[ \left( \frac{ds}{dx} \right)^2 = \left( \frac{dy}{dx} \right)^2 + 1 \]

\[ \frac{ds}{dx} = \sqrt{\left( \frac{dy}{dx} \right)^2 + 1} \]  

... (vii)  

From (vi) and (vii),

\[ a \frac{d^2 y}{dx^2} = \sqrt{\left( \frac{dy}{dx} \right)^2 + 1} \]  

... (viii)  

Let, \( y' = \frac{dy}{dx} \),

\[ a \frac{d(y')}{dx} = \sqrt{(y')^2 + 1} \]

\[ d(y') = \sqrt{1 + (y')^2} \cdot \frac{dx}{a} \]

\[ \frac{dx}{a} = \frac{d(y')}{\sqrt{1 + (y')^2}} \]

Integrate both sides,

\[ \int \frac{dx}{a} = \int \frac{d(y')}{\sqrt{1 + (y')^2}} \]  

... (ix)
But \( \frac{du}{\sqrt{1+u^2}} = \sinh^{-1} u \), thus from (ix)

\[ \frac{x}{a} = \sinh^{-1}(y') + C; \quad \text{when } x = 0, y' = 0 \text{ and thus } C = 0 \]

\[ \frac{x}{a} = \sinh^{-1}(y') \]

... (x)

Taken sinh function of both side for (x)

\[ \sinh \frac{x}{a} = (y') \]

\[ \int y' = \int \left( \sinh \frac{x}{a} \right) dx \]

Once again we can define the coordinate axes so that \( C=0 \), thus

\[ y = k \cosh \left( \frac{x}{a} \right) \]

... (xi)
APPENDIX B

Deflection Formulae for Loaded Parabolic Cable (Source: Bridon International Ltd)

<table>
<thead>
<tr>
<th>Cases</th>
<th>Type of Load</th>
<th>Description</th>
<th>Formulae</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level Span</td>
<td>Uniformly loaded</td>
<td>Vertical deflection at any point in span</td>
<td>( y = \frac{WS(S-x)}{2t} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Horizontal tension</td>
<td>( t = \frac{WS^2}{8y_c} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum tension</td>
<td>( T = \frac{t}{\cos \theta} ) where, ( \tan \theta = \frac{4y_c}{S} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Length of wire rope</td>
<td></td>
<td>( L = S + \frac{8y_c^2}{3S} )</td>
<td></td>
</tr>
<tr>
<td>Single load at centre</td>
<td></td>
<td>Vertical deflection at centre</td>
<td>( y_c = \frac{S(2P+WS)}{8t} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Horizontal tension</td>
<td>( t = \frac{S(2P+WS)}{8y_c} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Maximum tension</td>
<td>( T = \frac{t}{\cos \theta} ) where, ( \tan \theta = \frac{P+WS}{2t} )</td>
<td></td>
</tr>
<tr>
<td>Inclined Span</td>
<td>Uniformly loaded</td>
<td>Vertical deflection at any point in span</td>
<td>( y = \frac{W(S - x)}{2t} )</td>
<td></td>
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<tr>
<td>---------------</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal tension</td>
<td>( t = \frac{WS^2}{8y_c} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum tension</td>
<td>( T_1 = \frac{t}{\cos \theta} ) where, ( \tan \theta = \frac{4y_c - h}{S} ) and ( T_2 = \frac{t}{\cos \alpha} ) where, ( \tan \theta = \frac{4y_c + h}{S} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Length of wire rope</td>
<td>( L = \left(1 + \frac{8y^2}{3S^2}\right)\sqrt{S^2 + h^2} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single load at centre</td>
<td>Vertical deflection at centre</td>
<td>( y_c = \frac{S(2P + WS)}{8t} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal tension</td>
<td>( t = \frac{S(2P + WS)}{8y_c} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum tension</td>
<td>( T_1 = \frac{t}{\cos \theta} ) where, ( \tan \theta = \frac{P + WS - h}{2t} - \frac{h}{S} ) and ( T_2 = \frac{t}{\cos \alpha} ) where, ( \tan \theta = \frac{P + WS + h}{2t} + \frac{h}{S} )</td>
<td></td>
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</tr>
</tbody>
</table>
**Figure C1.** Vertical displacement at the selected nodes of the flat cable-net systems without glass panes that is pre-stressed to approximately 1000N. The test was repeated three times.

**Figure C2.** Vertical displacement at the selected nodes of the flat cable-net systems without glass panes that is pre-stressed to approximately 1500N. The test was repeated three times.
Figure C3. Vertical displacement at the selected nodes of the flat cable-net systems without glass panes that is pre-stressed to approximately 2000N. The test was repeated three times.

Figure C4. Vertical displacement at the selected nodes of the flat cable-net systems without glass panes that is pre-stressed to approximately 1000N.
A 0.76kg ball bearing drops 1.0m down onto a glass pane. The ball bearing travelled a further 10mm vertically which is equivalent to the deflection of glass pane due to impact.

Velocity during impact,

\[ v = \sqrt{2gh} \]

where \( g \) is the acceleration of gravity and \( h \) is the drop height

\[ v = \sqrt{2(9.81)(1)} \]

\[ v = 4.43 \text{ m/s} \]

Impact force,

\[ F = 0.5mv^2/d \]

Where \( m \) is mass of the ball bearing, \( v \) is the velocity during the impact and \( d \) is the distance of the ball bearing travels during the impact. In the experiment, \( d \) is the deflection of glass pane during the impact which was measured using the LVDT.

\[ F = 0.5(0.76)(4.43^2)/0.01 \]

\[ F = 746 \text{ N} \]
APPENDIX E

Figure E1. Vertical displacement oscillation for all nodes on flat cable-net of Test D2.

Figure E2. Vertical displacement oscillation for all nodes on flat cable-net of Test D3.