Fibre Optic Sensors for Smart Structures

A Thesis submitted for the Degree of
Doctor of Philosophy

By:
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Abstract

"Smart Structures" or "Smart Skins" will require structurally integrated sensing systems that can operate in practical situations. Optical sensing techniques are receiving considerable attention for the monitoring of such systems. Single ended polarimetric sensors were utilized with a large dynamic range for strain measurements as surface mounted and embedded strain sensors in composite materials (glass fibre and carbon fibre reinforced polymers). They were also used to monitor the strain and the formation of microcracks in the glue line of carbon fibre reinforced polymer (CFRP) concrete beams. The intrinsic Fabry-Pérot was also used as a surface mounted sensor to monitor axial strain of GFRP coupons.

Finite Element (FE) modelling was used in order to investigate the stress/strain distributions within the composite material and the embedded optical fibre. The modelling results show excellent agreement with the experimental results and suggest that the soft acrylate coating is debonding, thus reducing the sensor's dynamic range.

Actuators and/or Sensors embedded into a host material will disrupt the physical properties of the host. Finite element analysis was used to determine and to minimise the stress concentrations which arise in a "Smart" material system due to the embedded optical fibre sensor. A parametric study was undertaken to determine the theoretical mechanical and thermal properties of the interface coating that minimises the disruption of the polymer composite host material properties due to the optical fibre inclusion.

The effects of transverse tensile and thermal loading were studied, and also the residual thermal stress concentrations due to the manufacturing process were taken into consideration. The stress concentrations in the composite host are affected by the dimensions, mechanical and thermal properties of the interface coating. The results show that with careful selection of the interface coating properties the stress concentrations in the host material caused by the optical fibre inclusion can be reduced and be similar to those of the pure host material.
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To my parents Andreas and Tasoulla,
and my wife Alexia,

without whose enduring support and understanding this could never have been achieved.
Author's Publications


# Glossary of Symbols and Abbreviations

## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>AFRP</td>
<td>Aramid Fibre Reinforced Polymer</td>
</tr>
<tr>
<td>AOTF</td>
<td>Acousto Optic Tunable Filter</td>
</tr>
<tr>
<td>AWDS</td>
<td>Active Wavelength Demodulation System</td>
</tr>
<tr>
<td>BBS</td>
<td>Broad Band Source</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fibre Reinforced Polymer</td>
</tr>
<tr>
<td>NDE</td>
<td>Non-Destructive Evaluation</td>
</tr>
<tr>
<td>EFPI</td>
<td>Extrinsic Fabry-Pérot Interferometer</td>
</tr>
<tr>
<td>EMI</td>
<td>Electro-Magnetic Interference</td>
</tr>
<tr>
<td>ER</td>
<td>Electrical Resistance</td>
</tr>
<tr>
<td>FE</td>
<td>Finite Element</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Model</td>
</tr>
<tr>
<td>FGB</td>
<td>Fibre Bragg Grating</td>
</tr>
<tr>
<td>FFP</td>
<td>Fibre (Optic) Fabry-Pérot</td>
</tr>
<tr>
<td>FOS</td>
<td>Fibre Optic Sensor</td>
</tr>
<tr>
<td>FRP</td>
<td>Fibre Reinforced Polymer</td>
</tr>
<tr>
<td>FSK</td>
<td>Frequency Shift Keying</td>
</tr>
<tr>
<td>GFRP</td>
<td>Glass Fibre Reinforced Polymer</td>
</tr>
<tr>
<td>HiBi</td>
<td>High Birefringence</td>
</tr>
<tr>
<td>IFFPI</td>
<td>In-Fibre (Optic) Fabry-Pérot Interferometer</td>
</tr>
<tr>
<td>LoBi</td>
<td>Low Birefringence</td>
</tr>
<tr>
<td>OPD</td>
<td>Optical Path Difference</td>
</tr>
<tr>
<td>PEEK</td>
<td>Poly Ether Ether Ketone</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SOP</td>
<td>State of Polarisation</td>
</tr>
<tr>
<td>TF</td>
<td>Transfer Function</td>
</tr>
<tr>
<td>WDS</td>
<td>Wavelength Demodulation System</td>
</tr>
</tbody>
</table>

## Scalars, Vectors and Tensors

- $A(\psi)$: Airy shape function
- $F$: Finesse
$I$ Optical intensity
$I_0$ Maximum optical intensity
$i_d$ Photodetector current
$\phi$ Phase shift
$\beta$ Wave propagation constant
$n$ Refractive index
$k$ Optical wave number in vacuum
$\lambda$ Optical wavelength
$L$ Physical fibre length
$\alpha$ Coefficient of thermal expansion
$N$ Number of fringes
$T$ Temperature
$T_c$ Primary coating thickness
$\varepsilon$ Strain
$\sigma$ Stress
$\sigma_{rr}$ Radial stress
$\sigma_{\theta\theta}$ Hoop stress
$\tau_{\text{max}}$ Maximum shear stress
$\sigma_{\text{max}}$ Maximum principal stress
$E$ Elastic modulus
$\nu$ Poisson ratio
$S$ Interferometric strain sensitivity
$G$ FP strain gauge sensitivity
$p_{ij}$ Strain-optic tensor
$\rho_i$ Density
$V_i$ Fibre volume content
$NA$ Numerical aperture
$CL$ Centre Line
$t$ transmission coefficient
$U_i$ Complex amplitude of interfering electro-magnetic waves
$\alpha$ Fibre core radius
$L_p$ Beat length
$B$ Normalised modal birefringence
$\lambda_B$ Bragg grating centre wavelength
$\Lambda$ Bragg grating periodic spacing of the refractive index perturbation
$\bar{\varepsilon}$ Average longitudinal strain along the fibre path
$\beta(z)$ Local birefringence at position $z$
$E$ Electric field amplitude
$\hat{E}$ Electric field vector
$J$ Jones vector
$V$ Contrast, depth of modulation, fringe visibility
$\theta$ Splice angle
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Chapter 1

Introduction

1.1 General Background

Civil structures must resist environmental and in service loads such as those due to winds, earthquakes, traffic, people, thermal effects and construction. It is often of interest to measure in real time such external loads, as well as the response of the structure to these loads and any damage that has occurred. Such information can be very useful in establishing the overall condition of the structure and for the future design of similar structures. A wide variety of transducers and data acquisition systems have been used to sense structural loads and responses; These include strain gauges, accelerometers, tiltmeters, meteorological instruments and electrical meters.

In situ monitoring of strain is of particular value for real structural components which could be subjected to excessive loading and corresponding stresses, leading to weakening or sudden failure. The long term effects of continuous low stress loading conditions may also result in weakening or failure of the structure. In this cases, strain measurement devices can provide advance warning of such degradation in performance.

It has become increasingly important to determine the safety of a structure by the non-destructive evaluation (NDE) technique of its strength and integrity. The field of civil engineering although highly advanced in materials and structural analysis and design, is comparatively deficient in its evaluation techniques. Many of the methods used are destructive. There is clearly a need for alternative sensors which can provide non-intrusive, real time, long term monitoring information. Fibre optic sensors are a possibility as they have many features which are attractive for sensing purposes.
[Medlock 1986]. Furthermore their use as embedded sensors in composite materials for the measurement of strain and the detection of structural damage has shown to be an effective NDE technique.

1.2 The “Smart Structures” Concept

Materials with structurally integrated sensors and/or actuators represent the first step toward ‘Smart Structures’ [Measures, 1992; Turner et al., 1990]. Monolithic load-bearing structures with built-in fibre-optic sensing systems, could continuously monitor their internal strain, loading, vibration state, temperature and structural integrity. An important class of materials providing a high compatibility with smart structures and the most scope for the implementation of these ideas are structural composites with polymeric matrices. These materials can themselves be tailored by lay up of plies and by hybridization of the reinforcing fibres. Since the materials are often made at the same time as the component, it is possible to embed sensors and/or actuators during the fabrication process. Fibre-optic sensors are extremely small and light weight, resistant to corrosion and fatigue, immune to electromagnetic interference, safe and are compatible with composite materials. They are consequently suitable for embedding within composite materials providing internal monitoring of the material.

In the case of advanced composite materials, this intrinsic sensing system could be capable of improving quality control during fabrication [Measures, 1992]. In even more advanced Smart Structures the information provided by the built-in sensor could be used for controlling some aspect of the structure, such as its stiffness, shape, position or orientation. These systems are designated ‘Adaptive’ smart Structures [Wada et al., 1990]. These prospects clearly have both safety and economic ramifications as they can lead to greater confidence in the use of advanced composite materials and weight savings through the avoidance of overdesign. This technology could lead to a reduction in maintenance, repair and downtime of future aircraft and should be of particular interest to the aerospace community because of the substantial effect of weight savings in aircraft and space structures.
1.3 Project Objectives

- To investigate the feasibility of using fibre optic sensors to monitor the structural behaviour of composite plates and composite concrete structures.
- Develop, manufacture and test fibre optic sensors for structural monitoring of composite and composite reinforced concrete beams.
- Study the local interaction mechanisms between the embedded optical fibre and the composite host.
- Develop a finite element model for predicting the structural behaviour of the sensor under loading.
- Develop a finite element model for optimising the mechanical and thermal characteristics of the fibre coating in order to reduce the embedded sensors obtrusivity.

1.4 Composite materials

Advanced Composites based on glass, aramid or carbon fibre reinforced thermosetting or thermoplastic polymers have seen a rapid growth in recent years. In most applications these materials are used in the form of laminates consisting of individual layers of unidirectional continuous fibres, discontinuous fibres or woven cloth. Reinforcing fibres based on carbon, aramid and glass are typically 8-10µm in diameter. Composite structures can be built up by stacking plies of reinforcing layers at varying angles through the thickness of the material. When heat and pressure are applied the composite is consolidated to produce a laminated structure of low density containing around 60% volume fraction of fibre. Most of the techniques currently utilized in assessing flaws introduced during processing and fabrication of composite laminates are time consuming and are sometimes impossible to perform after a composite structure has been installed. There is clearly a need for a fast reliable test/monitoring method that can be used from the manufacturing process through the service life of the composite material. The effects of the orientation and placement of the embedded optical fibre will be discussed later.
1.4.1 Fibre-reinforced polymer materials

Fibre-reinforced polymer composites essentially consist of two components; a low modulus, low strength isotropic matrix material, and a high stiffness, high strength reinforcing fibre material such as glass, carbon or aramid. These distinct phases are combined on a macroscopic scale to produce a heterogeneous composite with desirable characteristics that exceed those of the individual components. The fibres are the principal load-bearing elements. The functions of the matrix are to bind and disperse the fibres giving integrity to the system, to protect the fibre surfaces from damage and to transfer stress to the fibres through adhesion and/or friction. The matrix material must also be thermally and chemically compatible with the fibres.

The strength and stiffness of the composite material can be manipulated by varying the type, position, orientation and volume fraction of the fibres. The mechanical properties of the composite are also affected by the method of manufacture, for which a range of techniques have been developed. These are considered in detail by Hollaway, 1990 and 1993a. Of particular significance to the present study is the pultrusion technique, in which continuous strands of the reinforcing fibre are pulled through a resin tank and then through a heated die to form continuous lengths of a desired cross-sectional geometry. The shaped composite is pulled through the die at a predetermined rate to enable curing of the composite to take place. Alternatively, prepreg materials may be utilised, in which laminates are built up from fibres impregnated with the required polymer in an uncured state, then cured under pressure in an autoclave. Detailed characteristics of fibres for composite materials, and the key factors which affect the performance of FRP are considered by Mufti et al., 1991.

Fibre-reinforced products can be formed into rods, grids, sheets and winding strands which have the beneficial characteristics of being non-corrosive, generally resistant to chemicals, non-magnetic and non-conductive, and of possessing high stiffness and strength-to-weight ratios, and low linear thermal coefficients of expansion in the fibre direction. They therefore offer unique advantages for solving many civil engineering problems effectively and economically in areas where conventional materials fail to provide satisfactory performance and service life. For many years their high price and unknown long-term performance limited the use of FRP materials in structural applications. However, considerable advances over the last twenty years in the field
of polymers and polymer composites [Mufti et al., 1991; Hollaway, 1993a] have resulted in the development of high strength materials based on carbon (CFRP), aramid (AFRP) or glass fibres (GFRP) that surpass many of the mechanical and physical properties of steel, in particular its tensile strength. The successful use of composites in structural applications is directly related to the use of adhesives. The emergence of high strength epoxies and other structural adhesives has enhanced the feasibility of the use of composites in civil engineering.

Several survey papers have been written discussing the uses of FRP materials with application to a variety of civil engineering structures [McCormick, 1988; Ballinger, 1991 and 1992; Bank, 1992; Head, 1992; McElhaney and Schlup, 1994; Saadatmanesh, 1994; Ohama, 1996], including load-bearing and infill panels, skeletal structures, geotextiles, pipework, cables, ropes, reinforcing bars and grid reinforcement, as well as complete structural members. Composite materials have been used for wrapping and confining concrete columns to provide increased axial capacity and strength in seismic regions, and beams to provide additional shear strength. Rizkalla and Erki, 1991 have presented a state-of-the-art report on the use of composite materials for bridge applications.

1.5 Fibre-Optic Sensors

Optical fibre sensors have been considered to be the prime candidate for internal structure and condition monitoring of composite materials. If fibre optic sensors are incorporated into the composite structure the basis of an embedded sensor is formed, potentially capable of sensing strain and temperature variations throughout the composites service life. Fibre-optic sensors have several inherent advantages over conventional (resistive strain gauge) sensors rendering them compatible with composite materials. These include:

- Electromagnetic (EMI) and hazardous environment insensitivity
- Similar shape to the reinforcing fibres: geometric compatibility
- Comparable size to the reinforcing fibres\(^1\): dimensional compatibility

\(^1\) At present optical fibres are one order of magnitude larger (~100\(\mu\)m) in diameter but they can be made smaller by sacrificing only attenuation performance and ease of handling.
- Thermally and chemically stable in the host composite: environmental compatibility

These properties render them compatible with most composite fabrication routes and allow, with some prior considerations, the structural integrity of the host to be maintained.

1.5.1 Fibre-optic Sensors

Light propagating along an optical fibre is guided through the "core" of the fibre by means of internal reflection. The index of refraction of this core is slightly larger than that of the surrounding "cladding" region, which supports the waveguide structure whilst also when sufficiently thick, substantially reducing the radiation loss into the surrounding air. In general optical fibres are classified to be "multimode" or "single mode", depending primarily upon the modal volume of the fibre. This volume depends on the radius of the fibre core and refractive index and the wavelength of the propagating source. Single-mode optical fibres have a small core, of the same order as the wavelength of light, and have a distinct advantage of forming the most sensitive strain sensors.

Optical fibre sensors are the means whereby the properties of light guided within an optical fibre can be modified in response to an external physical, chemical, biological or some similar influence. A basic distinction that can be made between fibre-optic sensors is between "extrinsic" and "intrinsic" sensors. In "intrinsic" sensors the physical parameter being measured directly affects the intensity, spectral distribution (colour), phase or polarization of the light passing through a fibre. Consequently the properties of the fibre itself are very important. In an "extrinsic" sensor the measurand affects these properties of light, but in a medium external to the fibre. The fibre only acts as a flexible transparent link to and from the affected medium. The fibre properties are not as important as in intrinsic sensors because here light is only a means to transport information.
Interferometric Fibre Optic Sensors

- Mode Coupling
  - Strain
  - Temperature

- Sagnac
  - Rotation
  - Acceleration
  - Strain
  - Acoustics
  - Wavelength Measurement
  - Magnetic field
  - Current

- Mach-Zehnder
  - Acoustics
  - Magnetic fields
  - Electric field
  - Acceleration
  - Strain
  - Temperature
  - Current

- Michelson
  - Acoustics
  - Magnetic fields
  - Electric fields
  - Temperature
  - Strain

- Ring
  - Rotation
  - Acceleration

- Fabry-Perot
  - Acoustics
  - Strain
  - Temperature
  - Pressure
  - Index of Refraction

- Polarization
  - Acoustics
  - Acceleration
  - Pressure
  - Temperature
  - Strain

- Multimode
  - Temperature
  - Pressure
  - Index of Refraction

- Single Mode
  - Acoustics
  - Temperature
  - Pressure
  - Strain

---

**Figure 1.1** Interferometric Fibre-optic Sensors and Associated Applications [Udd 1991]

Of the many existing fibre-optic sensing techniques [Dakin and Culshaw 1989, Turner *et al*. 1990, Jackson and Jones 1986], interferometry has proved to be the most sensitive. Since the first demonstration of the Mach-Zehnder type fibre-optic interferometric strain sensor by Butter and Hocker (1978), several authors have investigated a variety of interferometric sensors. A diagrammatic representation of this important type of fibre-optic sensors with associated applications can be seen in Figure 1.1. The fibre Bragg grating sensor [Meltz *et al.*, 1989] is not included in this diagram but it is one of the most promising types of sensors for either "point" or "quasi" distributed measurements and is particularly suitable for multiplexed networks [Kersey, 1992; Kersey *et al*. 1992; Kersey and Morey 1993a,b].
Many types of interferometric sensors are being fabricated in both extrinsic and intrinsic form. From Figure 1.1 it is apparent that most environmental effects that can be conceived of, can be converted to an optical signal to be interpreted. The usual case is that each environmental effect can be measured by many fibre-optic sensor approaches. The key is often to design the sensor so that only the desired effect is sensed.

1.6 Fibre Optic Sensor Types and Configurations

There are a large number of sensing mechanisms possible with fibre-optic sensors [Dakin and Culshaw, 1989, Jackson and Jones, 1986]. The types of sensors reviewed are mainly directed towards the area of strain, pressure and/or temperature measurements, and with the most scope of implementations within the “Smart Structures” concept. Specifically, the following sensing mechanisms are considered:

- Interferometric sensors [Mach-Zehnder, Michelson and Fabry-Perot (intrinsic and extrinsic)]
- Polarimetric sensors
- Modal interferometers [2-mode elliptic core, twin core]
- Bragg grating sensors

The typical schematic diagrams for the sensor types above can be seen in Figure 1.2. Although the Bragg fibre sensor [Meltz et al. 1989] is directed towards a multiplexed system, it can also be utilized for “single-point” measurements.

1.6.1 Intrinsic sensing mechanism

The sensing mechanisms listed above are all intrinsic in nature with the exception of the extrinsic Fabry-Pérot interferometer (EFPI). The strain is coupled to the fiber directly, either by some form of adhesive or (for embedded sensors) by the material matrix. Optical fibres which satisfy the “intrinsic” criterion are single mode, with the exception of the 2-mode elliptic core fibre. In the polarimetric sensor, the intrinsic birefringence of the sensing fibre must be controlled, i.e. it must be well defined and constant.
Interferometric Sensors

(a) Mach-Zehnder

(b) Michelson 'Localized'

(c) In-fibre Fabry-Perot (Intrinsic)

Polarimetric Sensor

(d)

Modal Interferometric Sensors

(e) Two-mode elliptical core

(f) Twin core

Fibre Bragg Grating Sensor

(g) Broadband Source

Figure 1.2 Schematic diagrams of the major fibre-optic sensor types [Measures 1990]
1.6.2 Criteria for Structurally Integrated Fibre-Optic Sensors

The development of structurally embedded fibre-optic sensors has been driven by the smart structures technology. With this concept in mind a set of criteria that can serve as a guide for assessing the suitability of a fibre-optic sensor's use with smart structures have been established [Turner et al. 1990]. A suitable fibre-optic sensor would be:

1. Intrinsic in nature for minimum perturbation and stability.
2. Localized, so it can operate remotely with insensitive leads.
3. Able to determine changes in the direction of the measurand field and provide a well behaved, reproducible response.
4. Respond to the desired measurand field only (for example strain). Generally this is a difficult criterion to achieve. In the specific case of strain measurements, the sensitivity of fibre-optic strain sensors to temperature must be compensated.
5. Single ended for ease of installation and connection.
6. All-fibre for operational stability.
7. Generate a linear response. In the case of interferometric sensors, this response implies “quadrature” operation (i.e. maintaining the interferometer at the most phase-sensitive part of its TF).
8. Have suitable sensitivity and dynamic range for the particular measurand field studied. These parameters can be modified for each application.
9. Interrupt immune and capable of absolute measurement.
10. Non-perturbative to the structure and robust for installation.
11. Insensitive to phase interruption at the structural interface.
12. Suitable to be used in some kind of multiplexing [Kersey, 1992].

From the above it is unlikely that one single sensor will be able to meet all of the requirements. However if the idea of developing a single sensor for smart structures with the aim of keeping costs down is followed, then the sensor would have to exhibit a dynamic range adequate for monitoring the general loading of the structure while being sensitive enough so as to detect damage possibly through acoustic emission.
1.6.3 Two-beam Interferometry Principle

Two beam interferometry allows the measurement of extremely small differential phase shifts in the optical fibre generated by the measurand. The interference produced in two beam optical systems leads to a cosine modulation of the intensity of light arriving at the detector:

\[ I_{\text{out}} = I_{\text{in}} \cdot [1 + \cos(\phi)]/2 \]  

(1.1)

where \( \phi = \phi_s - \phi_r \). Here \( \phi_s \) and \( \phi_r \) represent the phase shift induced in the sensing and reference arms respectively. The phase retardation between the sensing and reference fields propagating along two paths with a difference in length \( L \) can be expressed in the form

\[ \phi = \beta \cdot L \]  

(1.2)

For an interferometric sensor, \( \beta = kn \). Where \( n \) is the refractive index of the fibre core, \( k \) the optical wave-number in vacuum \((2\pi/\lambda)\) and \( L \) the physical length of the fibre. In general, \( \phi \) depends on the length, temperature and operating wavelength of the sensor. The variation in \( \phi \) due to incremental changes in these parameters is given by the expression [Measures, 1992a]:

\[ \Delta \phi = \left(L \cdot \frac{\partial \beta}{\partial L} + \beta\right) \cdot \Delta L + \left(L \cdot \frac{\partial \beta}{\partial T} + \beta \cdot \frac{\partial L}{\partial T}\right) \cdot \Delta T + L \cdot \frac{\partial \beta}{\partial \lambda} \cdot \Delta \lambda \]  

(1.3)

For the more simple case of strain sensing [Butter and Hocker, 1978] where the temperature is kept constant and the wavelength is fixed equation 1.3 reduces to:

\[ \Delta \phi = \left(L \cdot \frac{\partial \beta}{\partial L}\right) \cdot \Delta L + \beta \cdot L \cdot \varepsilon \]  

(1.4)

where the path integrated strain \( \varepsilon = \Delta L/L \). Using \( \beta = kn \) equation 1.4 becomes:

\[ \Delta \phi = knL\varepsilon - \frac{n^3L}{2} \cdot \Delta \left(\frac{1}{n^2}\right) \]  

(1.5)

assuming \( \Delta (1/n^2) = -2(\Delta n/n^2) \). The strain-optic effect due to strain applied to the material appears as a change in the optical indicatrix \((1/n^2)\):
where $\varepsilon_j$ is the strain tensor and $P_{ij}$ are the strain optic coefficients of the medium. If a uniaxial longitudinal stress $\sigma_z$ is applied to an isotropic, elastic optical fibre oriented in the $z$ direction, the resulting strain from first-order elastic theory is:

$$\varepsilon_j = \begin{bmatrix} -\nu \varepsilon_z \\ -\nu \varepsilon_z \\ 0 \end{bmatrix}$$ \hspace{1cm} (1.7)$$

where, in the Butter and Hocker (1978) model, zero shear strain is assumed, $\varepsilon_z = \sigma_z / E$ is the longitudinal strain, while $-\nu \varepsilon_z$ is the corresponding transverse strain ($\nu$ is the Poisson's ratio) and $E$ is Young's modulus. Since the optical fibre is assumed to be homogeneous and isotropic it can be shown that,

$$\Delta n = \frac{n^2 \varepsilon_z}{2} \left[ (p_{11} + p_{12}) \nu - p_{12} \right]$$ \hspace{1cm} (1.8)$$

or

$$\Delta \phi = S L \varepsilon_z$$ \hspace{1cm} (1.9)$$

where $S$ is the interferometric phase sensitivity [Measures, 1992],

$$S = k n \left[ 1 - \frac{n^2}{2} \{ p_{12} - \nu (p_{11} + p_{12}) \} \right]$$ \hspace{1cm} (1.10)$$

where $k = \frac{2\pi}{\lambda}$. For fibres with a pure silica core and $B_2O_3$ doped cladding, $p_{11}=0.113$ and $p_{12}=0.252$, have been reported by Bertholds and Dandlinker (1988), values that are about 7% lower than for bulk silica. Substituting measured parameters in the above equation yields:

$$S = (1.151 \pm 0.006) \times 10^{-7} \text{ rad/m}$$ \hspace{1cm} (1.11)$$

or

$$S = (0.659 \pm 0.003) \frac{\text{deg}}{\mu \varepsilon \cdot \text{mm}}$$ \hspace{1cm} (1.12)$$
1.7 Mach-Zehnder Interferometer

The Mach-Zehnder fibre-optic sensor is perhaps the best known because it was developed first. This interferometer acts in the classic sense by optically interfering the light propagating in the sensing and reference arms (Figure 1.2a). The resulting intensity is modulated by a strain and/or temperature induced optical path length change, due to a change of the refractive index and/or change in the length of the fibre, which results in an induced optical phase shift. The first to develop a relationship between phase and strain were Butter and Hocker (1978) using a Mach-Zehnder sensor. The dynamical response of single mode fibre-optic sensors was later compared with traditional resistive strain gauges in a frequency range of 25-250Hz [Martinelly, 1982]. It was confirmed that fibre-optic sensors have no practical limitations on the mechanical frequency range and measurement lengths. The Mach-Zehnder is the easiest conceptual configuration of a fibre interferometer which it is why is often chosen as an example. Sirkis and Haslach (1991) developed a theory for surface-mounted interferometric fibre-optic strain sensors. They presented design techniques for selecting the path of a curved fibre-optic sensor required to isolate predetermined strain components. The Butter and Hocker model primarily verified the scientific feasibility of such sensors, since the sensing and reference fibres were laid in a straight line axially along a tip loaded cantilever beam. They also derived equations for a strain rosette and from experimental results, the resistive strain gauge and fibre gauge agree within 3%. The phase change in a surface-mounted fibre-optic strain sensor is affected only by the strain component tangential to the fibre path so there is no transverse sensitivity in the resistance strain gauge sense. However a transverse sensitivity arises from the finite diameter of the optical fibre. The design equations presented were derived under the assumption that the only transverse strain experienced by the fibre is Poisson contraction.

Mach-Zehnder sensors possess high sensitivity and are generally easy to set up in a laboratory environment. Additionally passive quadrature operation can be achieved [Turner et al., 1990] which reduces the complexity of control and data analysis electronics [Liu and Measures, 1992]. However, the sensor is two-fibre, implying larger physical size (important for embedding), and greater noise sensitivity. Localization is difficult to achieve since the standard configuration is to have one
“arm” in the sensed field and the other isolated from the field. This difficulty implies that isolation of the external “arm” must be guaranteed or actively compensated to prevent significant noise problems. Also, unless both 2x2 couplers are embedded in the structure being monitored, it is very difficult to isolate the lead-in/lead-out fibres from the external strain and temperature field. These non-identical “lead-in” paths (two fibres) in the two arms result in additional phase noise. The ‘lead-sensitivity’ is the greatest drawback of Mach-Zehnder fibre-optic sensors [Sirkis, 1993; Turner et al., 1990]

1.7.1 Michelson Interferometer

A Michelson sensor can be thought of as a Mach-Zehnder sensor acting in reflection. The Michelson interferometer shown in Figure 1.2b is another fibre implementation of a classical interferometer configuration. The light travelling from the source is split into the sensing and reference arms. After traversing the length of the arms the light is then reflected back through the same arms by reflectors. The optical path is therefore doubled, so that the phase-change function will be multiplied by two.

Kashyap and Nayar (1983) were the first to demonstrate an all fibre Michelson interferometer using single mode fibres. Considering the similarities of the Michelson and Mach-Zehnder sensors is obvious that in terms of optical loss budget both configurations are similar. Also the use of 3x3 couplers may be used for passive quadrature operation [Valis et al., 1990]. The setup can be seen in Figure 1.3. Recently however single-junction single-mode 4x4 directional couplers have become available which are the most direct method of obtaining optical quadrature outputs since selected pairs of output have a \(\pi/2\) phase relationship [Liu and Measures, 1992]. The localised michelson configuration also exhibits excellent localisation and unidirectional sensitivity. Also the sensor length can be adjusted down to millimetre range making this an excellent sensor for “point” strain applications [Hogg et al., 1989]. On the other hand the two-fibre nature of this interferometer makes it physically larger (causing more disruption of the material when embedded) and requires the use of two connectors for installation purposes [Valis et al., 1991]. Furthermore both arms require intimate mechanical bonding to achieve the necessary common mode rejection for true lead-in/lead-out insensitivity [Hogg et al., 1989]. Michelson fibre sensors have been adhered to small (2.5x25cm) aluminium cantilever
beams and their performance and characteristics have been determined over a strain range of \( \pm 2000 \mu e \) [Valis et al., 1989]. The following conclusions were drawn:

- The gauge sensitivity was \( 2 \times [6.510 \pm 0.085] (\mu e - \text{cm}) \).
- The gauge sensitivity was independent of gauge length for lengths between 3 and 12 mm.
- The same sensitivity was observed for both tension and compression.
- Transverse strain sensitivity was 0.5 (±1.5)%.

They then embedded the sensors in graphite/PEEK (thermoplastic) laminates. The sensors survived the material consolidation process for both collinear and orthogonal orientations of the optical fibres with respect to the material fibres. The coupons were cantilevered and loaded in flexure with the fibre sensors one ply deep in the 12-ply unidirectional lay-up. The conclusions matched those for the surface adhered sensors. The embedded sensitivity (using linear beam theory) was \( 2 \times [6.930 \pm 0.535] (\mu e - \text{cm}) \). The high sensitivity of the Michelson fibre-optic sensor permits it to detect acoustic energy released as a result of matrix cracking, fibre breakage or interlaminar debonding within composite materials. The sensor reported by Liu et al., (1990), comprised a pair of unbuffered optical fibres with mirrored ends embedded within the composite material. Signal recovery was achieved by a low-frequency piezoelectric (PZT) phase modulation feedback system [Active Homodyne, Liu and Measures,
1992] that also eliminated drifts and slowly varying strains. Operating the sensor using damage-sensitized optical fibres they have been able to correlate the occurrence of an acoustic signal with its concomitant matrix crack.

The greatest weakness of the Michelson sensor lies in the need for two mechanically coupled fibres. If this coupling degrades, the locality of the sensor degrades. Also the problems of common mode rejection and the problem of interfacing to the structures exist, as well as a problem that is common to all of the interferometric sensors are that they measure phase relative to some initial phase. Use of phase division or up/down counting can extend the tracking range well beyond $2\pi$. However if the signal is interrupted, the required phase is ambiguous and must be reset. Another common problem is the thermally induced apparent strain sensitivity.

### 1.7.2 Intrinsic Fabry-Pérot Interferometer

The Fabry-Pérot interferometer is a single fibre sensor with excellent localization and unidirectional sensitivity, and does not require phase preservation across any connector. In principle, sensors of virtually any length (within the restrictions of the source coherence length) may be manufactured [Hogg et al., 1989].

The Fabry-Pérot cavity is formed by two mirrors, the first is an internal mirror formed by fusing two mirrored ends of an optical fibre together. The second mirror is often formed on the end of the optical fibre as shown in Figure 1.4. Also indicated in the figure are the basic components of such a sensor. For a practical fibre-optic Fabry-Pérot sensor for structural monitoring the pair of reflectors which form the cavity should be mechanically strong to endure thermal mechanical stresses experienced during the embedding process. Lee et al. (1989) demonstrated the Fabry-Pérot based fibre optic sensors can be fabricated with reflective fusion splices. They formed the internal mirror of the sensor by fusion splicing two single mode fibres one of which was coated on the end with a TiO$_2$ film. Measures et al. (1992) have formed the sensor using a reflective fusion splice based on a metal evaporation technique.

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2. Apparent strain sensitivity is discussed in more detail in “Apparent Strain and Thermal Sensitivity” on page 36.
However the manufacture of the sensor itself requires carefully controlled and well understood splicing to obtain a Fabry-Pérot cavity. The ‘mirror’ splices at the ends of the F-P cavity are of reduced physical strength relative to normal fibre splices. The breakage strength is of the order of 50% of that of non-mirrored splices [Lee et al., 1989]. Furthermore quadrature operation of the sensor requires an “active” technique (such as source wavelength switching), making control and signal processing more involved [Lee et al., 1989; Liu and Measures, 1992]. They also suffer from interrupt ambiguity (i.e. if the phase-demodulation electronics are interrupted, the new value of the phase becomes non-unique and must be re-initialized). Mason et al. (1992) used a pseudo heterodyne phase demodulation technique with quadrature fringe tracking to determine the strain of the sensor. The system is capable of demodulating FFPI sensors with gauge lengths from 5 to 50mm by adjusting the wavelength modulation of the laser diode source. It can achieve sensitivities from 20 to 2με, with associated maximum strain rates from 2.5x10⁶ to 2.5x10⁵ μεs⁻¹. The system can also be used for two-mode and polarimetric sensors, since all of these sensors exhibit a periodic intensity transfer function which is dependent on the optical path difference. The system had low noise characteristics and was able to track dynamic strain using a
19mm FFPI sensor. The system was also able to simultaneously demodulate the signals from two separate 20mm FFPI sensors.

1.7.2.1 Strain Sensing
The response of the phase shift of Fibre Fabry-Pérot Interferometer (FFPI) sensor to axial strain can be described as:

\[ \Delta \phi = K \left( \frac{4\pi n}{\lambda} \right) \Delta L \]  

(1.13)

where \( K \) is a constant. If the fibre is not constrained in the radial direction, \( K \) is determined by the strain-optic coefficients of the silica fibre. The value of \( K \) for silica fibre is 0.8 [Hocker, 1979]. Assuming a phase measurement detectability of 1.0\( \mu \)rad and a wavelength of 633nm for the laser source, it follows from equation 1.13 that the minimum measurable strain is 4.3\( \times \)10\(^{-5}\)\( \mu \)e for a 1cm FFPI. From a practical standpoint, such a performance can only be achieved for dynamic strain measurements at frequencies above 100Hz [Lee et al., 1992]. When the FFPI is embedded the effect of the surrounding material on the radial strain in fibre must be taken into account [Lee et al., 1989]. The strain sensitivity of a graphite/PEEK embedded sensor which utilized an internal mirror and an end-coated reflector FFPI was reported as 1.9\( \times \)10\(^7\)\( \mu \)rad m\(^{-1}\) [Lee et al., 1992].

Measures et al. (1992) have shown that the FP strain gauges have similar sensitivity to the Michelson sensor. They also showed that the strain response is linear when embedded within several different composite materials; Kevlar/epoxy; graphite/epoxy and graphite/PEEK, and that is free of hysteresis during loading and unloading cycles. The reinforcing-fibre direction was always along the long axis of the coupons. The sensor had gauge lengths between 4 and 9mm (FP region). All sensors were embedded bare: no buffer, no coatings. The graphite/PEEK laminates were 12 plies thick and consolidated in a hot press, while the Kevlar/epoxy laminates were 10 plies thick and cured in an autoclave.

1.7.2.2 Temperature Sensing
The optical phase shift of the FFPI sensor is affected by a temperature change according to:

\[ \Delta \phi = \frac{4\pi n L}{\lambda} \left( \frac{1}{n dT} + \frac{1}{L dT} \right) \Delta T \]  

(1.14)
For a silica fibre, $dn/dT = 7.0 \times 10^{-4}/^\circ C$ and $dL/LdT = 3.0 \times 10^{-7}/^\circ C$ near room temperature [Hocker, 1979]. Thus the effect of the refractive index change is fourteen times larger than the effect of the length change in determining the temperature sensitivity. A FFPI temperature sensor with a 1.5mm long cavity has been operated from -200°C to +1050°C [Lee et al., 1988]. No significant changes in the optical properties of the FFPI were discerned after several heating and cooling cycles and no hysteresis in the sensor response was seen. Immersion in liquid nitrogen did not affect the sensor performance. However exposure to temperatures approaching 1000°C did cause the fibre to become brittle. Lee et al. (1989) embedded a FFPI in a graphite-epoxy composite material and demonstrated its performance from 20 to 200°C. The change in relative phase shift with temperature, $\Delta \phi/\Delta T$, was measured to be $8.0 \times 10^{-6}/^\circ C$ for this sensor. This value is 4% lower than for one employing a similar fibre in an air ambient. A thermal expansion coefficient for the composite material in the direction of the fibre axis was estimated from the data to be $2.1 \times 10^{-7}/^\circ C$.

1.7.3 Extrinsic Fabry-Pérot Interferometer

The extrinsic Fabry-Pérot sensor differs from its intrinsic counterpart in that the cavity is often formed in air instead of a glass waveguide. Figure 1.5 shows one popular Fabry-Pérot configuration, where a hollow core optical fibre is used to maintain the alignment of the two fibres forming the cavity. A single mode fibre used as the input/output fibre and a multimode fibre used purely as a reflector, form an air-gap that acts as a low finesse FP cavity. The far end of the hollow core fibres fused to the multimode fibre to accurately define the right-hand limit for the gauge length. The hollow core fibre is then attached to the single mode fibre with epoxy. The gauge length is defined by the distance between the fused section and the left end of the hollow core minus the length of epoxy which may wick into the tube. The value is measured using a translation stage microscope with an accuracy of ±5µm. Sensors with typical lengths of the order of 3mm have been fabricated [Lesko et al., 1992]. The Fresnel reflection from the glass/air interface at the front of the air gap (reference reflection) and the reflection from the air/glass interface at the far end of the air gap (sensing reflection) interfere in the input/output fibre. The interference of the two wave interferometer can be evaluated in terms of a plane-wave approximation. Assuming that the reference reflection coefficient $A_1=1$, the sensing reflection coefficient $A_2$ can be approximated by the following expression [Keiser 1983]:
\[ A_2 = A_1 \left( \frac{ta}{a + 2s \tan(\sin(NA))^{-1}} \right) \]  \hspace{1cm} (1.15)

The observed intensity at the detector is shown to be [Murphy et al., 1991]

\[ I_{\text{det}} = |U_1 + U_2|^2 = A_1^2 + A_2^2 + 2A_1A_2 \cos(\phi_1 - \phi_2) \]  \hspace{1cm} (1.16)

which can be recast in the form

\[ I_{\text{det}} = A^2 \left( 1 + \frac{2ta}{a + 2s \tan(\arcsin(NA)) \cos\left( \frac{4\pi s}{\lambda} \right) + \left( a + 2s \tan(\arcsin(NA)) \right)^2 } \right) \]  \hspace{1cm} (1.17)

where it is assumed that \( \phi_1 = 0 \) and \( \phi_2 = 2s(2\pi/\lambda) \), and \( \lambda \) is the wavelength of operation in free space. \( U_i \) in equation 1.16 represents the complex amplitude of the interfering electromagnetic waves, \( a \) is the fibre core radius, \( t \) is the transmission coefficient of the air-glass interface, \( s \) is the end separation and \( NA \) is the numerical aperture.

Murphy et al. (1991) demonstrated the operation of a quadrature phase-shifted extrinsic FP fibre-optic sensor for the detection of the amplitude and the relative polarity of dynamically varying strain. Strain sensitivities of 5.54° phase shift/microstrain cm\(^{-1}\) are obtained. The signal to noise ratio of the sensor decreases if a large air gap is introduced since the fringe contrast starts to drop. Lesko et al. (1992) demonstrated that extrinsic FP strain sensors can be accurate and precise means of making local internal strain measurements in and around damage events, when embedded within a macromodel composite.
The EFPI has also been demonstrated as a strain rosette which is necessary for the measurement of the internal strain state of materials or structures for an arbitrary set of applied loads [Case et al. 1994, Valis et al. 1989, 1990]. Case et al. (1994) used the extrinsic FP unlike Valis who used the intrinsic FP; this means that each arm of the EFPI monitors a phase shift which is only related to a single strain field, unlike intrinsic sensors that are a function of the full strain field. The results showed good agreement for the axial (0°) and transverse (90°) strains, but differences were noted between strain measured by the embedded EFPI and externally mounted strain gauges at 45°. The biggest drawback however is the obtrusivity of the rosette which caused a reduction of the compressive strength of ~300%.

An advantage of extrinsic FP strain sensors is that they are immune to transverse sensitivity error (because the refractive index of the air gap is independent of strain induced birefringence, strain dependence occurs only through the change in cavity length.) and their thermal apparent strain error remains within tolerable limits [Sirkis, 1992].

1.7.4 Polarimetric Sensors

Polarimetric fibre-optic sensors detect the presence of some physical field via a change in the state of polarization of the light propagating through the fibre. This polarization state change is the result of the phase velocities of the two polarization modes of the single mode fibre being altered unequally by the action of the field [Rashleigh, 1983]. In order to sense an external measurand by the modulation of the polarization state of the fibre, birefringent fibre sensors are needed. Polarimetric sensors utilise the relative change in optical path length which occurs between the two orthogonally polarised modes of a fibre. They exhibit excellent lead-in insensitivity (using Hi-Bi fibre with “on-axis” launching) and possess relatively moderate sensitivity [Hogg et al., 1989; Turner et al., 1992]. It has been shown that the variation in birefringence caused by stretching a high-birefringence (Hi-Bi) fibre is the result of a mismatch in Poisson’s ratio [Varnham et al., 1983].

1.7.4.1 High-Birefringent Fibres

Hi-Bi fibres have axes of stress built in so that the otherwise orthogonal but degenerate polarization modes become separated and propagate at different velocities. The required anisotropy is created either by fabricating a fibre with an elliptical core.
or by selectively doping the cladding region around the core to create the stressed axis as in the “bow-tie” fibre [Dakin and Culshaw 1989]. Some common expressions and parameters used for high-birefringence fibres are:

**Beat Length:** This is a fundamental measure of the polarisation maintaining performance of the fibre. When light is launched into HiBi fibre with a linear component in both axis, the difference in velocities of the two modes causes the resultant polarisation to vary along the length of the fibre. The beat-length $L_p$ is now the length over which this polarisation rotates through, $2\pi$, i.e. the greater the birefringence, the shorter the beat-length. It is given by equations 1.17 and 1.18 [Dakin and Culshaw, 1989], where the fibre cross section is independent of the fibre length $L$ in the $z$ direction:

$$B = n_x - n_y = \frac{\lambda}{2\pi} (\beta_x - \beta_y) \quad (1.18)$$

now substituting $B$ gives:

$$L_p = \frac{\lambda}{B} \quad (1.19)$$

where $B$ is the normalized, modal birefringence, $n_x$, $n_y$, and $\beta_x$, $\beta_y$ are the refractive indices and the phase, or propagation, constants of the two polarisation modes respectively. The anisotropy of HiBi fibre is introduced in the preform [Payne et al. 1982], and a variety of configurations are possible (see Figure 1.6 for some common configurations). As the same birefringence may be achieved by different configurations, the main differences between them lie in their ease of fusion splicing (elliptic core or cladding fibres are difficult to fusion splice, unlike bow-tie fibres).
Sometimes HiBi fibres are also misleadingly referred to as *polarisation-preserving* or *maintaining fibres*; this is only true if they are launched and connected on-axis.

In a polarimetric sensor, linearly polarised light is launched at 45° with respect to the birefringence axis of the core of the polarisation maintaining fibre such that both axes are excited with equal power. The relative phase delay may be measured by observing the output light through a correctly-orientated polarizer (specifically, one with its transmissive axis at 45° to the Hi-Bi fibre birefringent axes). The concept is illustrated above (Figure 1.7), where the birefringent axes have been labelled as “fast” and “slow” due to their different optical propagation speeds. A single-ended configuration can be constructed by using a mirrored end as illustrated in Figure 1.2d. A single lead fibre now serves as both the lead-in and lead-out fibre.

The strain sensitivity of an inline polarimetric sensor was determined by bonding a 2.5cm sensor to a cantilevered aluminium beam [Hogg *et al.*, 1989]. All fibre used was York HB600. The beam was deflected and strains of over 8000µε were induced in the sensor in both tension and compression. Excellent response and repeatability were obtained. An average strain sensitivity of 0.065±0.005°/(µε·cm) was determined for a
Figure 1.7 Operating principle of the high-birefringence polarimetric sensor. The sensor’s temperature response or thermal gauge factor was determined by using a temperature controlled oil bath. The sensing region was freely suspended in the bath and the resulting phase change was recorded as the temperature increased from 0°C to 100°C. A linear temperature response was found to exist from 3 to 90°C. A thermal gauge factor of 2.49±0.2 Deg/°Ccm was determined for the HB600 optical fibre.

Good linear response for most of the interferometric type sensors (including the polarimetric sensor) requires quadrature operation. Loss of sensitivity occurs in regions that are away from the quadrature condition. Optical techniques that are suitable for polarimetric sensor applications have included laser diode current (and hence wavelength) ramping [Jackson et al., 1982], laser diode frequency switching (by square-wave current modulation), [Kersey et al., 1983] and dual wave-length operation with two distinct laser diode sources [Kersey et al., 1984]. Specifically, for short sensing lengths the quadrature operation requires a large wavelength difference between optical sources, so distinct sources must be used. However, with the advent of distributed-feedback semiconductor lasers, which have a much larger tuning range than standard devices, current ramping may become more favourable approach to achieving quadrature in a polarimetric system. Tsuchida et al., (1988) demonstrated a demodulation scheme using a derivative technique. The method has the following advantages over the schemes mentioned before: the required laser frequency deviation is small, precise adjustment of the modulation depth is not necessary and finally it is applicable to a multiplexed sensor system.
Turner et al. (1992) developed a single-ended, all-fibre polarimetric strain sensor. Linear response is achieved by using a dual-wavelength technique, with modified pseudoheterodyne signal recovery. The arrangement is similar to the approach of Kersey et al. (1984). Single-valued multiple fringe phase tracking is obtained by using a binary signal division technique. Figure 1.8 illustrates the experimental arrangement. The system was operated single-ended using a 3dB coupler and silver-coating of the cleaved end of the sensing fibre. York HB800 fibre and York FP850 fibre polarizer were used. Operation of the sensor using pigtailed laser diode sources at 815.7nm and 835.3nm provided the desired 90° phase shifted responses. An average strain sensitivity of 0.050±0.02 deg/µε cm is found. The sensor was successfully applied to the measurement of the local orientation of a 1m structural beam, with an accuracy of ±0.02 deg of beam slope.

Figure 1.8  Schematic of the dual-wavelength all-fibre polarimetric strain sensor

Polarimetric sensors are temperature sensitive [Turner et al., 1992] something which may restrict the application of this sensor to local orientation measurements on real
flexible structures. Compensation of the sensor for ambient temperature variations is required to make the sensor a practical device. Since the relative/strain sensitivity ratio for York HB600 fibre is an order of magnitude larger than for a standard interferometric sensors [Hogg et al., 1989], there is a need for the simultaneous measurement of temperature so that variations in temperature during strain measurements may be compensated. The problems of polarisation scattering effects due to impurities of the fibre or microbending are an additional disadvantage.

Narendran et al. (1993) presented a fibre-optic sensor, using a combined interference and polarimetric technique. The main advantage of this sensor is that it possesses the sensitivity of an interferometer and at the same time the sign of the strain can be determined without any electronic logic circuits. The light intensity variation detected at the photodiode will be the sum of the light intensities produced by each technique separately. To determine whether the fibre is undergoing tension or compression, one has to look at the overall envelope of the signal. In order to reproduce the actual strain from the IP sensor, the optical signal was Fourier analysed using a fast Fourier transform package. Taking the first five Fourier components and inverse transforming produces a curve that is similar to the shape of the strain variation. The sensor configuration is primarily suited for strain measurements that produce a relative phase retardation much greater than $2\pi$, so that several fringes are spatially shifted. Also the phase shift caused by the strain has to be much greater than that produced by thermal and other external effects along the fibre.

Michie et al. (1991), have used a combined polarimetric and dual-mode sensor in a polarization maintaining fibre for the separation of temperature and strain. Both techniques were employed simultaneously with, the polarimeter operated at a wavelength greater than the cut-off, while the dual-mode technique was operated below cut-off. An elliptical core polarization maintaining fibre with a single mode cut-off wavelength of $\lambda_c$ can support two modes $LP_{01}$ and $LP_{11}^{\text{even}}$ when operated at a wavelength of $\lambda<\lambda_c$. Such a fibre can therefore be used simultaneously as a dual mode and polarimetric sensor if interrogated with two suitably chosen sources. A dual mode sensing scheme makes use of the dispersion between the $LP_{01}$ and the $LP_{11}$ modes. These modes interfere as they propagate down the fibre length. External perturbations modulate the delay between the two modes resulting in a shift in the intensity profile across the fibre core. These intensities can be measured in the far field of the fibre.
output and characterised in terms of sensitivity to the measurands of interest, \( \alpha_{\text{edual}} \text{rads} \mu \epsilon^{-1} \) and \( \alpha_{\text{Tdual}} \text{rads} \text{K}^{-1} \). Similarly the polarimeter can be characterised in terms of the necessary strain and temperature variations required to produce a \( 2\pi \) phase shift to the polarization state and thus the sensitivity of the fibre to temperature and strain variations \((\alpha_{\text{epol}} \text{rads} \text{K}^{-1} \) and \( \alpha_{\text{epol}} \text{rads} \mu \epsilon^{-1} \)), can be determined. The application of a temperature and/or strain change to the sensing region produces a phase change in the dual mode and polarimetric signals corresponding to the relation:

\[
\begin{bmatrix}
\delta \phi_{\text{pol}} \\
\delta \phi_{\text{dual}}
\end{bmatrix} =
\begin{bmatrix}
\alpha_{\text{epol}} & \alpha_{\text{Tpol}} \\
\alpha_{\text{edual}} & \alpha_{\text{Tdual}}
\end{bmatrix}
\begin{bmatrix}
\delta e \\
\delta T
\end{bmatrix}
\]

where the matrix \([\alpha]\) termed the characteristic matrix of the fibre and \( \delta e \) and \( \delta T \) are the measurands of interest. The experimental arrangement used to interrogate the sensor is shown in Figure 1.9. Linearly polarized light from a laser diode (\( \lambda = 820 \text{nm} \)) is combined with the output of a He-Ne laser (\( \lambda = 633 \text{nm} \)) and launched into the polarisation maintaining fibre. The fibre was epoxy bonded between two glass fibre reinforced plastic end tabs and threaded through a brass tube around which a heating element was coiled. The arrangement was located between the grips of an Instron 1185 tensile testing machine such that the fibre could be subjected to strain and temperature cycles.

**Figure 1.9** Experimental arrangement for dual-mode/polarimetric sensor.

The technique is capable of resolving simultaneously temperature and strain variations to within 20\( \mu \epsilon \) and 1K over a strain and temperature range of 20\( \mu \epsilon \) and...
Measurement errors are discussed in the paper in detail. Vengsarkar et al. (1994), extended the above concept and reported strain and temperature resolutions of 10μm/m and 5°C, respectively.

A method for eliminating the temperature dependence of phase sensitivity in polarimetric sensors has been recently presented [Wong and Poole, 1992]. They reported on a novel fibre design which is intrinsically temperature stable when used in a fibre polarimeter and which is shown to have a temperature dependence of <2.5 x 10^{-3} \text{rad(°Cm)}^{-1} over a range of 30 to 210°C, compared to around 3 \text{rad(°Cm)}^{-1} for a 'Bow-Tie' fibre. They have introduced a new fibre structure which gives zero stress-birefringence, by balancing the stresses generated in the core of an elliptical-core fibre (which are temperature dependent and hence give rise to the temperature dependence of the birefringence) with stresses generated by the inclusion of stress-applying sectors in the cladding.

### 1.8 Comparison of Fibre Optic Strain Sensors

The individual strengths and weaknesses of each of the sensor types can be summarised with respect to the criteria mentioned in Section 1.6.2. Table 1.1 summarises the strain and temperature sensitivities of the various sensors.

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>HI-Bi Polarimeter</th>
<th>Interferometer</th>
<th>Dual-mode</th>
<th>Twin-core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain (°/με·cm)</td>
<td>0.064</td>
<td>6.5</td>
<td>0.02</td>
<td>0.00035</td>
</tr>
<tr>
<td>Temperature (°/K·cm)</td>
<td>2.5</td>
<td>23</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>T/ε (με/K)</td>
<td>39.1</td>
<td>3.5</td>
<td>10</td>
<td>111</td>
</tr>
</tbody>
</table>

### 1.8.1 Mach-Zehnder Interferometer

Advantages: Passive quadrature operation may be achieved using a 3×3 fibre coupler, which reduces the complexity of control and data analysis electronics. The freely accessible reference arm of this sensor readily allows direct or active mechanical modulation, and therefore permits the use of phase modulation and matching techniques.
Disadvantages: The sensor is two-fibre, implying larger physical size, important for embedding, a need for two connecting leads and greater noise sensitivity. The sensor is difficult to localise, since the standard configuration is to have one “arm” in the sensed field (the sensor), and the other isolated from the field. Also non identical “lead-in” paths (two separate fibres) in the two arms results in additional phase noise.

1.8.2 Michelson Interferometer

Advantages: The 3×3 fibre coupler can be used for passive quadrature operation. The “localised” Michelson configuration exhibits excellent localisation and uni directional sensitivity. The sensor length can be easily adjusted to the millimetre range, making this an excellent sensor for “point” strain applications.

Disadvantages: As with the Mach-Zehnder the two-fibre nature of this interferometer makes it physically larger (problem with the embedded version) and requires the use of two connectors for installation purposes. Significant sensor noise as a result of non common path length of the lead-in arms.

1.8.3 Fabry-Pérot interferometer

Advantages: The sensor is single fibre and requires a single intensity only connector for installation. The sensors can in principle be of virtually any length (within the restrictions of the source coherence length). The sensor has excellent localisation and uni directional sensitivity.

Disadvantages: The manufacture of the sensor requires carefully controlled and well understood splicing to obtain a Fabry-Pérot cavity. The spliced mirrored ends that form the cavity are of reduced strength relative to normal fibre splices [Lee at al.1989]. Quadrature operation of the sensor requires an “optically active” technique (such as source wavelength switching, currently commercially available), making control and signal processing somewhat more involved.

1.8.4 Polarimetric, High Birefringence Sensor

Advantages: The sensors are single fibre and exhibit excellent lead-in insensitivity (using Hi-Bi fibre with “on axis” launching). The sensor possesses moderate sensitivity, a factor of 100 lower than standard interferometric sensors, making it
suitable for long sensing lengths or larger unambiguous strain ranges. The long sensing lengths possible can also be used to advantage for path-integrating applications, such as differential slope measurements on a beam.

Disadvantages: The reduced sensitivity of the sensor makes it less suitable for "point" strain measurements. In addition it has a poorer strain/temperature sensitivity than a standard interferometric sensor, which implies a greater need for simultaneous temperature measurement so that variations in temperature during strain measurement may be compensated.

1.9 Bragg Grating Sensors

Fibre Bragg gratings (FBG) sensors have attracted considerable interest over the past few years because of their intrinsic nature and wavelength-encoded operation. The gratings are holographically written into Ge-doped fibre by side exposure to a pair of overlapping coherent UV beams [Meltz et al., 1989]. The gratings are permanent up to temperatures of less than 350°C, and have a small gauge length. The technique has allowed the customizing of the filter wavelength, permitting the manufacture of gratings at useful wavelengths, such as 830nm, 1300nm and 1550nm. A Bragg grating based system has several advantages [Melle et al., 1992] over sinusoidal response interferometric, polarimetric, or modalmetric systems. These include:

- **Linear output behaviour**: The change in the Bragg grating centre wavelength as a function of the measurand being sensed (strain or temperature) is linear. There is thus no measurand direction ambiguity.

- **Absolute output**: The wavelength of the Bragg grating sensor is entirely determined by the measurand-induced state of the sensor and its determination allows the absolute value of the measurand to be determined.

- **Environmental insensitivity**: The sensor output is encoded into wavelength, which is an absolute quantity and the sensor output is therefore not affected by intensity fluctuations in the system.

- **Strength**: Fabrication of the FBG sensor using non-invasive techniques does not degrade the inherently high strength of the optical fibre.
• **Defined sensing length:** The Bragg grating sensor can be precisely localised in the optical fibre, making the sensor immune to environmental perturbations along the lead-in/out fibre.

• **Ideal for multiplexed networks** \(^3\) [Kersey, M30, 1992].

These advantages make these sensors suitable for use in a fibre-optic strain gauge system, and particularly suitable for embedded sensor applications for smart structures, as the sensors can survive the processing temperatures of polymer/graphite/epoxy fibre composites, integrate well with the composite matrix and behave as quasi-point sensors [Kersey and Berkoff, 1992].

### 1.9.1 Bragg grating strain sensitivity.

Figure 1.2 on page 9 shows the sensing concept involved for a single sensor element. The FBG sensor is illuminated using a broadband source (BBS), such as an edge-emitting LED, superluminescent diode or superfluorescent fibre source. The centre wavelength of the back reflected spectrum from a Bragg grating, \(\lambda_B\) is given by [Meltz et al., 1987]:

\[
\lambda_B = 2n_{core} \Lambda
\]  \hspace{1cm} (1.21)

where \(\Lambda\) is the periodic spacing of the refractive index perturbation in the core of the optical fibre which creates the Bragg grating and \(n_{core}\) is the effective index of the core. Measurand-induced perturbation of the grating sensor changes the wavelength returned, which can be detected and related to the measurand field (e.g. strain) at the sensor position. The grating wavelength is therefore dependent on the periodic spacing, as well as the refractive index of the core, and will therefore be tuned by changes to either of these quantities due, for example, to strain or temperature. For low-birefringent fibre the longitudinal strain sensitivity of the bragg grating can be shown to be:

\[
\left( \frac{\Delta \lambda_B}{\lambda_B} \right)_i = (1 - p_{ei}) e_i, \quad i = 2, 3
\]  \hspace{1cm} (1.22)

---

3. Alavie et al., (1994) reported on a multiplexed Bragg grating fibre laser (erbium) sensor system. Two and three Bragg elements were successfully multiplexed with very little crosstalk. However the number of sensors in series is likely to be limited by avoidance of laser line crossover.
where $\Delta \lambda_g$ is the change in the centre wavelength of a grating at $\lambda_g$, $\varepsilon_x$ is the longitudinal strain on the grating and $p_e$ is an effective photoelastic constant defined as

$$p_e = \frac{n_{core}^2}{2} [p_{11} - \nu_1 (p_{13} + p_{23})]$$

For low-birefringent optical fibres the strain-optic tensor is isotropic, so that $p_{11} = p_{22} = p_{33}$, $p_{13} = p_{12} = p_{23}$, and $\nu_2 = \nu_3$. For a typical low-birefringent optical fibre $p_{11} = 0.113$, $p_{12} = 0.252$, and $\nu = 0.16$ [Bertholds and Dandliker, 1988] at 633nm.

### 1.9.2 Applications

The sensitivity of the grating wavelength to the strain or temperature state of the fibre grating permits its use in a fibre-optic strain gauge system. However, such a system must be capable of detecting and resolving small shifts in the Bragg grating centre wavelength, of the order of hundredths of a nanometer. The wavelength of a Bragg grating sensor can be determined with monochromators or spectrum analysers. Another approach uses an unbalanced fibre-optic Mach-Zehnder interferometer in an active homodyne configuration [Kersey et al., 1992]. The system is capable of sub-nanostrain resolution (0.6$\text{nm}/\text{Hz}^{0.5}$ at 500Hz) sensing. The output from such a system has a high sensitivity to strain, but the lack of common mode rejection from the Mach-Zehnder arms limits the usefulness of this demodulation method at low frequencies. Furthermore, the absolute strain sensing possible with Bragg gratings, because of the wavelength encoding of the strain state, is lost when the signal is converted to phase information by an interferometer. Kersey et al., (1993), extended the idea further by introducing a referenced configuration that can provide high-resolution quasi-static strain sensing by using a local stable (shielded) reference grating in conjunction with the sensing element. The drift-compensated FBG sensor system can be seen in Figure 1.10.
Figure 1.10 Compensated Bragg-grating sensor system with sensing and reference grating elements and interferometric wavelength-shift detection.

The sensing and reference fibre-optic grating elements are placed in the output legs of an unbalanced fibre Mach-Zehnder interferometer. The broadband source used was a diode-pumped Er-doped fibre superfluorescent source, producing approximately 300μW of output power with a 35nm bandwidth (1530nm-1565nm).

As can be seen from Figure 1.10, the phase difference between the two interferometer outputs was monitored with pseudo-heterodyne [Jackson et al., 1982] signal processing. A strain induced change in reflected wavelength, $\delta \lambda_s$, from the grating sensor element induces the change in phase shift $\delta \psi_s$,

$$\delta \psi_s = \frac{2\pi nd}{\lambda_s} \xi \delta \varepsilon$$  \hspace{1cm} (1.24)

where $\delta \varepsilon$ is the change in strain subjected to the grating and $\xi$ is the normalized strain-to-wavelength shift responsivity of the grating, i.e.,

$$\xi = \frac{1}{\lambda_s} \cdot \frac{\delta \lambda}{\delta \varepsilon}$$  \hspace{1cm} (1.25)

which has a reported numerical value of 0.74 [Morey et al.,1991]. The system is capable of resolving sub-μstrain changes in the quasi static strain (three point bending test), applied to a grating and has a resolution of $\approx 6 \times 10^{-3}$ μstrain/√Hz at a strain perturbation frequency of 1Hz.
Melle et al., (1993), used a passive, ratiometric, wavelength demodulation system (WDS), [Melle et al., 1992], to determine the wavelength of the narrowband reflected spectrum from the grating sensor. The fibre-optic strain gauge permits the measurement of both static and dynamic strains with a noise-limited resolution of 0.44 microstrain/√Hz, a measurement dynamic range of 27.8dB and a bandwidth of 250Hz. The system architecture of the Bragg grating sensor can be seen in Figure 1.11. Melle et al., (1993) provide a detailed description of the system. Two different WDS systems were used, two filters with different filtering slope, a high pass coloured glass filter (WDS-1) and an interference filter (WDS-2). Strain resolution of the system is 98 and 28με for the WDS-1 and WDS-2 configurations respectively.

![System architecture for the Bragg grating strain gauge system.](image)

The strain resolution of the system is limited however by the use of Bragg grating sensors manufactured in Hi-Bi fibre with lo-bi lead-in/out fibres and couplers. The prominent modal spectrum of the superluminescent diode source therefore creates a non-linearity in the system output. This can be remedied through the use of Bragg gratings manufactured in lo-bi fibres or by the use of polarizing fibre in line with the Hi-Bi Bragg gratings.

The system splits the back-reflected light from the Bragg grating into two beams. One beam is filtered in proportion to its wavelength, while the other beam is used as a reference to compensate for any intensity fluctuations of the back reflected light. If
the back-reflected light power is split evenly between the two beams, and a filter with a linear filter function is used, the ratio of the filtered to the reference outputs can be determined. The system is therefore inherently self-referencing with respect to intensity variations from the broadband source, connector alignments, coupler and microbend losses. The wavelength of the sensor, \( \lambda_b \), can be determined by the following relationship:

\[
\frac{I_F}{I_R} = A\left(\lambda_B - \lambda_0 + \frac{\Delta \lambda}{\sqrt{\pi}}\right)
\]

where \( I_F \) and \( I_R \) are the filtered and unfiltered optical signals, \( A \) and \( \lambda_0 \) are constants determined by the filter characteristics, and \( \Delta \lambda \) is the laser linewidth. The sensor configurations mentioned above [Melle et al., 1993; Kersey et al., 1992; Melle et al., 1992] all use wavelength demodulation schemes. A common disadvantage of the WDS developed to date is the use of a broadband source to interrogate the Bragg grating sensor. This method is inefficient, as only a small fraction of the total power will be reflected back as the sensor signal due to the narrow-band nature of the Bragg reflection. The low power of the reflected light limits the signal-to-noise ratio and bandwidth of the demodulation system, and thus affecting the strain resolution.

Another area of research is fibre-grating based laser sensor concepts [Kersey & Morey, 1993; Melle et al., 1993]. Kersey and Morey (1993) reported the operation of a novel approach for addressing a series of Fibre Bragg grating sensor elements configured as feedback elements of an Er-doped fibre laser. This configuration provides improved interrogation efficiency over broadband systems, increasing the signal to noise characteristics of the system. By tuning a wavelength selective filter within the laser cavity over the gain bandwidth, the laser selectively lases at each of the Bragg wavelengths of the sensors, thus allowing strain induced shifts in the Bragg wavelengths to be monitored. Melle et al., (1993), used such a system in conjunction with a passive WDS [Melle et al., 1992]. The sensor provided interrupt immune sensing of static and dynamic strains with a resolution of 5.4\( \mu \)e and a bandwidth of 13.0KHz.

Simonsen et al., (1992), have tested fibre-optic Bragg grating sensors built into glass fibre reinforced polyester. A destructive test demonstrated strain measurements up to 16000\( \mu \)e and the mean sensitivity was 0.40nm/1000\( \mu \)e. The results showed good
linearity and reproducibility. Xu et al., (1993), constructed a high pressure fibre-optic sensor using in-fibre Bragg gratings. Although the Bragg wavelength shift observed (3.04x10^-3nm/MPa), is two orders of magnitude lower than a measured value from a hollow microsphere pressure sensor under similar conditions, the sensor is expected to be an attractive, simple and robust miniature sensor for measuring ultrahigh pressure.

Kersey and Berkoff (1992), described a differential temperature sensor based on fibre-optic Bragg grating elements. A high sensitivity to thermally induced Bragg wavelength shifts is obtained using an interferometric detection approach. The phase difference between the two interferometer outputs was monitored using pseudo-heterodyne [Jackson et al., 1982] signal processing. The results show a temperature resolution < 0.05°C, corresponding to a Bragg wavelength shift resolution of <6x10^-4nm.

Xu et al. (1996, 1995) have used an electronic lock-in system [Geiger et al. 1995], using an acousto-optic tunable filter (AOTF) for the interrogation of in-fibre Bragg grating sensors. The technique uses frequency shift keying (FSK) of the RF drive to the AOTF to track the wavelength shifts of a Bragg grating. Measured strain resolution was 0.4με and a temperature tuning coefficient of 2.68KHz/°C or 0.03nm/°C was determined. That implies that a temperature change of 1°C in the AOTF would give a signal equivalent to a strain of 27.7με, or a temperature change of 2.4°C in a typical grating. Therefore a reference with constant wavelength has to be introduced to the system.

Coroy et al. (1995) also used an AOTF to demonstrate an active wavelength demodulation system (AWDS). The system uses an intensity self-referenced edge locking technique to track the reflected signal of the Bragg sensor. The system had a linear wavelength response with a 2.62pm wavelength resolution, corresponding to a strain resolution of 2.24με.

1.10 Apparent Strain and Thermal Sensitivity

The two most important structural parameters required to be measured by embedded fibre-optic sensors are the strain and temperature. Invariably, any embedded fibre-optic sensor that can measure strain will also respond to temperature. The stresses due
to thermal cycling may compromise the performance of embedded fibre-optic sensors because of differential thermal expansion of the fibre and the composite material. Measurements of strain for a given load as a function of temperature indicated that the strain increased with temperature [Rogowski et al., 1989]. This is a serious problem and is referred to as apparent strain [Hogg et al., 1991]. Many of the early fibre-optic sensor designs used for structural monitoring applications were tested in uniaxial tension by mounting geometrically linear sensors on the surface of loaded structures. Under these loading conditions the equations presented by Butter and Hocker (1978) and Hocker (1979) provided good correlation between the observed and predicted sensor response.

Sirkis (1993) considerably extended the Butter and Hocker phase-strain model. Implicit in the use of the Butter and Hocker model with embedded sensors are the assumptions that:

- The presence of the fibre does not affect the local strain field in the host structure.
- The phase change in the sensor is independent of the host material properties.

Both of these assumptions are clearly incorrect because the fibre is a cylindrical elastic inclusion. However in many cases the model shows good agreement with optical phase changes. The phase-strain-temperature model [Sirkis, 1993] in response to the above relates the integrated strain and temperature strain along the structurally embedded fibre optic sensor path to the optical phase change. Sirkis (1993) also showed that the phase strain model of Butter and Hocker is a special case of the phase-strain-temperature model. The relation between the retardation in an embedded fibre optic Mach-Zehnder sensor and the strain and temperature state along the fibre is given by [Sirkis, 1993]:

\[ \Delta \phi = n_0 k_0 \int \left[ S'_1 - \frac{1}{2} n_0^2 \left( P_{12} S'_2 + \frac{1}{2} (P_{11} + P_{12}) (S'_2 + S'_3) \right) + \xi T \right] ds \]  

(1.27)

where the reference fibre is taken to be strain free and degenerate birefringence is assumed. In equation 1.27, \( \Delta \phi \) is the relative phase change by the light propagating in the fibre-optic sensor, \( S'_1 \) is the nominal fibre strain everywhere tangential to the fibre longitudinal axis, and \( S'_2 \) and \( S'_3 \) are any perpendicular normal fibre strains in the
plane of the fibre cross section (see Figure 1.12), \( \Gamma \) is the path traversed by the fibre, \( \mathbf{P}_{11} \) and \( \mathbf{P}_{12} \) are Pockel's constants and \( \xi \) is the thermo-optic constant. It is important to emphasize \( S_j \) is the sum of the thermal and mechanical strain states. Similar expressions have been derived for all of the type of sensors seen in Figure 1.2 [Sirkis, 1993].

![Fibre-optic sensor path and co-ordinate system](image)

**Figure 1.12** Fibre-optic sensor path and co-ordinate system

The analysis results showed that the extrinsic Fabry-Pérot fibre-optic sensor is immune to transverse sensitivity error and the thermal apparent strain error remains within tolerable limits over a wide temperature range. The level of error experienced by the extrinsic Fabry-Pérot fibre-optic sensor is a factor of 20 less than that experienced by Mach-Zehnder-type sensors, and a factor of 500 less than that experienced by the polarimetric sensor. The polarimetric sensor is most prone to thermal apparent strain error mainly because its transverse sensitivity coefficients are larger than those for the other sensors. This result does not mean that the polarimetric sensor experiences a greater phase change per unit temperature and gauge length than the other type of sensors. It simply means that the level of thermally induced phase changes that will be interpreted as ideal phase changes is greatest in polarimetric sensors. The Mach-Zehnder and polarimetric sensors however are prone to both transverse sensitivity error and thermal apparent strain error. In general the transverse apparent strain error can be eliminated under certain loading environments. The principle finding of the paper is that transverse strain sensitivity error in sensors experiencing isothermal transverse loading completely dominates the embedded sensor behaviour.
On comparison the Butter and Hocker model takes no account of the effects of the interaction between the sensor and the host material, which can apply radial, axial and shear loading on the fibre, instead of only axial loading [Butter and Hocker, 1978; Hocker, 1979]. The essential simplification made were that the strain in the optical fibre in the 1-direction matches that of the host, while zero host strain is coupled to the optical fibre in the 2- and 3-(transverse) directions (Figure 1.12). However the Butter and Hocker model can be used in embedded cases if the stiffness ratio is greater than 10 so that the fibre reinforces the host material, or when the fibre experiences Poisson-like load cases [Sirkis and Mathews, 1993]. This finding can be important since Butter and Hocker’s model relates the optical phase change only to the normal strain component tangent to the fibre path. The phase-strain-temperature model of equation 1.27 relates the phase change to all normal strains. Extracting the individual strain components or the temperature from the recorded intensity therefore becomes a nontrivial task when fibre-optic sensors are embedded in host materials of appreciable stiffness [Sirkis and Dasgupta, 1992].
2.1 Introduction

The principle of the polarimetric fibre sensor was introduced in section 1.7.4 on page 21. The polarimeter takes advantage of high-birefringence (HiBi) optical fibre to convert strain into a change in the state of polarisation (SOP). It can be considered as a single fibre 2-beam interferometer in which the two distinct optical paths are defined by the birefringent eigenaxes. Due to the different propagation velocities along these two axes, a phase difference will develop between orthogonal polarisation components of the incident light having their \( \hat{E} \) fields aligned to these eigenaxes. Varnham et al. (1983a) explored the origins of intrinsic optical birefringence, while Rashleigh et al. (1983b) provides a comprehensive discussion of the sources of externally induced birefringence in optical fibres.

For an isotropic fibre, with zero birefringence, applied longitudinal stress will induce no birefringent effects [Rashleigh et al. 1983b]. For an optical fibre with a well defined finite birefringence, either intrinsic or externally produced (by techniques such as bending) an application of longitudinal stress results in a change in the polarimetric phase shift \( \phi = \beta \cdot L \) which is proportional to the fibre extension \( \Delta L \). It follows that,

\[
\Delta \phi = \Delta (\beta \cdot L) = \beta \cdot \Delta L + L \cdot \Delta \beta = A \cdot \Delta L
\]  

(2.1)

where \( A \) is a constant, must be true, the relation,

\[
\frac{\Delta \beta}{\Delta L} = CONSTANT
\]

(2.2)
must be true for such fibres.

2.2 Theory

The theoretical sections that follow are based upon work previously published in the literature by various authors and are relevant to the experimental portion of this work.

2.2.1 The Strain-Optic Effect in a HiBi Fibre

The effect of longitudinal strain on a homogeneous, isotropic optical fibre was introduced in section 1.6.3 on page 11. The full theoretical analysis of the effects of longitudinal stress on a birefringent fibre would be too complex and beyond the scope of this discussion. In this case fibres having a well defined high intrinsic birefringence will be assumed. For such a case it is necessary to make the following assumptions: firstly that the strain optic tensor \( P_{ij} \) contains unequal off-diagonal terms and secondly that the Poisson's ratios \( \nu_{xy} \) in the two transverse directions are distinct, see Figure 2.1. For the Bow-Tie fibre structure in Figure 2.1 it is reasonable to assume that the differences in the \( P_{ij} \) off-diagonal terms are small, but that \( \nu_x \neq \nu_y \) [Varnham et al. 1983a].

\[
\Delta n = n_y - n_x > 0
\]

For the orientations shown

If we consider a short length \( L \) of HiBi fibre in which the local external strain along the fibre axis \( \varepsilon(z) - \bar{\varepsilon} \) is constant, then the general relation for integrated sensor phase is given by,
where $\beta(z)$ represents the local birefringence at position $z$ within the sensor region, and it reduces to the known form,

$$\phi = \beta L$$

(2.4)

where

$$\beta = \Delta \Lambda k = \Delta \Lambda n = 2 \pi / \lambda_0 (n_y - n_x)$$

(2.5)

using $\Delta n = n_y - n_x$ and taking the differential of both sides

$$\Delta \phi = \beta \Delta L + L \Delta \beta$$

$$= \beta \Delta L + k_0 L \left[ \Delta n_y - \Delta n_x \right]$$

(2.6)

For this case the assumption that $\frac{\partial k_0}{\partial L} = \frac{\partial (2 \pi / \lambda_0)}{\partial L} = 0$ is valid, since $k_0$ is a constant defined by the optical source. Using the strain optic tensor $P_{ij}$ and the strain tensor $\varepsilon_j$,

$$P_{ij} = \begin{bmatrix} p_{11} & p_{12} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{11} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{12} & p_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{44} \end{bmatrix}$$

$$\varepsilon_j = \begin{bmatrix} -\varepsilon_x \\ -\varepsilon_z \\ \varepsilon_z \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

(2.7)

for $\nu_x \neq \nu_y$ we obtain values for $\Delta n_x$ and $\Delta n_y$ of:

$$\Delta n_{x,y} = \frac{p_{12} \varepsilon_z}{2} [(p_{11} + p_{12}) \nu_{x,y} - p_{12}]$$

(2.8)

Now substituting into equation 2.5 we obtain

$$\Delta \phi - \beta_0 \Delta L - k_0 \Delta L \left( \frac{L}{2} \right) [p_{12} (n_y^3 - n_x^3) + p_{11} + p_{12}] [\nu_x n_x^3 - \nu_y n_y^3)]$$

(2.9)

where $\varepsilon_\tau = \frac{\Delta L}{L}$. The term relating $\Delta \beta$ may be then be expressed as a constant $\alpha'$,

$$\alpha' = (p_{12} (n_y^3 - n_x^3) + p_{11} + p_{12}) (\nu_x n_x^3 - \nu_y n_y^3)]$$

(2.10)
therefore,
\[
\frac{\Delta \phi}{\varepsilon L} = \beta_0 (1 - \alpha) = C \beta_0 \tag{2.11}
\]

where \( a = \frac{a'}{2 \Delta n_0} \), \( C = 1 - a \) and \( \Delta n = n_y - n_x \). The results indicate that the longitudinal strain sensitivity \( \frac{\Delta \phi}{\varepsilon L} \) of a HiBi polarimetric sensor should be linear, with a proportionality factor (gauge factor) of \( C \beta_0 \), which can be expressed in deg/mm. The linearity of the polarimetric sensor has been experimentally verified [Varnham et al. 1983a, Ohtsuka et al. 1987]. The gauge factor of a HiBi fibre is linearly proportional to the length of fibre embedded or adhered to the host i.e. the gauge sensitivity is independent of gauge length.

Sirkis et al. (1994) developed a phenomenological based phase-strain model for structurally embedded polarimetric sensors. The model is developed by postulating the existence of a fictitious residual strain state in the optical fibre and then following standard model development techniques. The model applies to all types of fibre, includes contributions from the axial and transverse strains and yields a non-zero phase change for pure uniaxial loading. The final form of the phase-strain model for a polarimetric sensor is given by,
\[
\Delta \phi = \frac{2 \pi}{\lambda} \int [K_1 \varepsilon_{11} + K_2 \varepsilon_{22} + K_3 \varepsilon_{33}] dz \tag{2.12}
\]

where
\[
K_1 = B + \frac{1}{2} \left[ (n_3^r)^3 - (n_2^r)^2 \right] P_{12}
\]
\[
K_2 = \frac{1}{2} \left[ (n_3^r)^3 P_{12} - (n_2^r)^2 P_{11} \right]
\]
\[
K_3 = \frac{1}{2} \left[ (n_3^r)^3 P_{11} - (n_2^r)^2 P_{11} \right]
\]

Equation 2.12 can then be used to predict the phase response of the polarimetric sensor experiencing uniaxial tension by letting \( \varepsilon_{22} = \varepsilon_{33} = -\nu \varepsilon_{11} \) where \( \nu \) is the Poisson’s ratio in the fibre so that the phase shift becomes,
\[
\Delta \phi = \frac{2 \pi}{\lambda} \int [K_1 - \nu K_2 - \nu K_3] \varepsilon_{11} dz \tag{2.13}
\]

which for a straight sensing fibre reduces to,
A numerical procedure was used to determine the model parameters, shown in Table 2.1.

Table 2.1 Model parameters for Bow-Tie, E-core and LoBi fibres, [Sirkis et al. 1994]

<table>
<thead>
<tr>
<th></th>
<th>K1</th>
<th>K2</th>
<th>K3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bow-Tie</td>
<td>-0.197</td>
<td>-0.714</td>
<td>-0.618</td>
</tr>
<tr>
<td>E-core</td>
<td>-0.223</td>
<td>-0.722</td>
<td>-0.730</td>
</tr>
<tr>
<td>LoBi</td>
<td>-0.233</td>
<td>-0.771</td>
<td>-0.771</td>
</tr>
</tbody>
</table>

2.2.2 Polarised Light representation in a Single Mode Fibre

An optical fibre can display single transverse-mode behaviour if sufficient guided-wave confinement of the electromagnetic radiation exists. This can be described by setting indices $m$ and $n$ in equation 2.15 (which describes the spatiotemporal evolution of the electric field vector as it propagates down an optical fibre in cylindrical coordinates) to unity.

\[
\hat{E}(r, \theta, z, t) = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=2}^{3} \hat{E}_{i,j,k}(r, \theta) \exp[i \beta_{i,j,k}(z)]
\]  

(2.15)

where $i$ and $j$ are transverse modal indices, $k$ is the polarisation index, $\omega$ is the optical frequency, $\beta_{i,j,k}$ is the modal propagation constant and the sign refers to forward and backward spatiotemporal propagation respectively. This results in the following dependence of the electric field,

\[
\hat{E}(r, \theta, z, t) = \sum_{k=2}^{3} \hat{E}_{k}(r, \theta) \exp[i(\omega t - \beta_{k} z)]
\]  

(2.16)

where a forward travelling wave is assumed.

The field distribution $\left| \hat{E}_{k}(r, \theta) \right|$ is to a good approximation Gaussian. It is also degenerate ($\left| \hat{E}_{k}(r, \theta) \right| = \left| \hat{E}_{k}(r, \theta) \right|$) for circular core fibres. This implies that when the two polarisation modes are mixed their overlap integrals are unity. As a result, the transverse field distributions are ignored in the context of interferometry and

\[
\frac{1}{L} \frac{d(\Delta \phi)}{d\varepsilon_{11}} = \frac{2\pi}{\lambda} [K_{1} - \nu_{2} K_{2} - \nu_{3} K_{3}]
\]  

(2.14)
polarimetry, such that the propagation equations become equivalent to those describing infinite plane waves. Equation 2.16 represents the linear superposition of two polarisation base states to the two independent photon spins of magnitude \( h \). One may choose basis polarisations \( \hat{x} \) and \( \hat{y} \) corresponding to the two orthogonal directions transverse to the fibre (2 and 3). Assuming complete polarisation\(^1\) and using the spatial degeneracy the propagation equation becomes,

\[
\hat{E}(z, t) = E_2 \exp[i(\omega t - \beta_2 z)] \hat{x} + E_3 \exp[i(\omega t - (\beta_3 z))] \hat{y}
\]

where \( E_2 \) and \( E_3 \) are transverse field amplitudes in the appropriate directions. Associating the temporally and spatially varying terms of equation 2.17 with a phase \( \phi_n \), leads to the complex vector description,

\[
J = \begin{pmatrix} E_2 e^{i\phi_2} \\ E_3 e^{i\phi_3} \end{pmatrix}
\]

where \( J \) is referred to as a Jones vector [Jones 1941]. In many cases one is only interested in the orientation and not the magnitude of the Jones vector so that the normalised form \( (J \cdot \bar{J} = 1) \) is adequate. When used in the context of optical fibre interferometry (polarimetry) the phase terms \( \phi_2 \) and \( \phi_3 \) are exclusively associated with \( \beta_2 l_2 \) and \( \beta_3 l_3 \) respectively, as the interfering signals are detected at the same time.

Figure 2.2  Bulk photoelastic setup used in experimental stress analysis [Valis et al. 1990].

---

1. All the input light used in fibre polarimetry is polarised, either at the source or shortly after.
2.2.3 Polarimetric Strain Sensor: Jones Calculus

2.2.3.1 Non-Local Polarimetric Strain sensor
The non-local polarimetric sensor is shown in Figure 2.2, which uses a crossed polariser and analyser to observe polarisation fringes; It is widely used in experimental stress analysis using photoelastic techniques. An optical fibre equivalent setup would simply replace the bulk medium with a HiBi fibre, keeping the polariser and analyser crossed (at 45° relative to the birefringence axes of the fibre), see Figure 2.3.

![Diagram of fibre-optic polarimetric sensor setup.]

Figure 2.3 Fibre-optic polarimetric sensor setup. The laser and polarising beam splitter are aligned to the HiBi fibre either by using rotatable λ/2 plate or launching stage.

The Jones matrix description of the system (Figure 2.3) is:

\[
[M_{sys}] = [P][R^{-1}(45°)][HiBi][R(45°)][P]
\]  
(2.19)

where the system frame is aligned with the polariser (see Appendix B for a detailed explanation of the terms). The system can be written as follows [Valis 1989],

\[
[M_{sys}] = \begin{bmatrix}
\frac{1}{2} & \frac{1}{2} e^{i\phi_\Delta} \\
\frac{1}{2} & e^{i\phi_\Delta}
\end{bmatrix}
\]  
(2.20)

if the first polariser is aligned along the \( \hat{x} \) axis (\( \phi_\Delta \) is the differential phase) or, 

\[
[M_{sys}] = \begin{bmatrix}
0 & 0 \\
0 & \frac{1}{2} \pm \frac{1}{2} e^{i\phi_\Delta}
\end{bmatrix}
\]  
(2.21)
if the first polariser is aligned along the $\hat{y}$ axis. The ± sign indicates an analyser (i.e. the second polariser) collinear or perpendicular to the first polariser respectively. When light of arbitrary SOP is launched into the system, the normalised (to the transmitted power through the first polariser) output power, $I$ is of the form:

$$I = \frac{1}{2} + \frac{1}{2} \cos(\phi_\Delta + \partial \phi_\Delta)$$  \hspace{1cm} (2.22)

The sinusoidal response is common to any interferometric system.

In practice it is unlikely that the 45° relative rotation of the birefringent axes between two HiBi fibres at fusion splice will be obtained exactly. The HiBi fibre is aligned at a general angle, $\theta$, relative to the polariser/analyser (i.e. slightly misaligned or with an imperfect 45° splice). This results to a reduction in the signal depth of modulation also referred to as fringe visibility, $V$, and a change in the dc offset. The normalised intensity is now,

$$I = (\sin(\theta) + \cos(\theta)) + 2\sin(\theta)\cos(\theta)^2 \cos(\partial \phi_\Delta)$$  \hspace{1cm} (2.23)

From the above equation the maximum and the minimum values of the intensity as a function of $\theta$ can be determined. Minima will occur for $\partial \phi_\Delta = \phi_\Delta - 2\pi m$ and maxima for $\phi_\Delta = (2m+1)$, where $m=0,1,2,...$, see Figure 2.4. The depth of modulation is defined as

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$  \hspace{1cm} (2.24)

and for an ideal response the value is unity. For this case the visibility may be expressed as

$$V(\theta) = \frac{\sin(2\theta)^2}{1 + \cos(2\theta)^2}$$  \hspace{1cm} (2.25)

and is shown in Figure 2.5.
Figure 2.4  Polarimetric sensor response for different splice angles.

Figure 2.5  Visibility as a function of the splice angle.
2.2.3.2 Localised Polarimetric Strain Sensor

Varnham et al. (1983) were the first to build a local polarimetric strain sensor using the technique for localising a strain sensitive region along a HiBi fibre implemented by Dziedzic et al. (1983). Corke et al. (1984), developed the sensor to its final form, with a mirrored end and a fusion splice.

The Jones matrix description for the local polarimeter is given below [Valis et al. 1990],

\[
[M]_{sys} = [P][HiBi][R^{-1}(45^\circ)][HiBi][R(45^\circ)][HiBi][P]
\]  \tag{2.26}

The difference between the above equation and equation 2.19 is the addition of two HiBi fibres aligned with the polariser and analyser (acting as the lead fibres). By choosing polarisers aligned with the \( x \) (rather than the \( y \) ) axis, the matrix product is explicitly written as,

\[
[M]_{sys} = \begin{bmatrix}
1 & 0 \\
0 & 1 \\
0 & 0 \\
e^{i\phi_{A1}} & 1 \\
e^{i\phi_{A2}} & 1 \\
1 & 1 \\
1 & 1 \\
0 & 0 \\
0 & 0
\end{bmatrix}
\]  \tag{2.27}

where \( \phi_{A1} \) and \( \phi_{A2} \) represent lead-in and lead-out phases and \( \phi_{A2} \) corresponds to the sensor (the strain sensitive length) phase. Multiplication yields the system matrix:

\[
[M]_{sys} = \begin{bmatrix}
1/2 + e^{i\phi_{A1}}/2 & 0 \\
0 & 0
\end{bmatrix}
\]  \tag{2.28}

which, significantly, does not contain any lead phase terms, and is identical to equation 2.20. The normalised output can be related in the same way as the nonlocal polarimeter.

In the Poincaré representation, the incident light propagates along an eigenaxis (stationary state) and therefore traces no evolution path (see Figure 2.6a). At the first 45° splice the polarisation eigenaxes undergo a 90° equatorial rotation. In the new eigenframe, the two eigenmodes are equally excited and the SOP describes a meridional trajectory (Figure 2.6b). Beyond the second 45° splice the SOP evolves along a circular trajectory about the lead-out eigenaxis (coincident with the lead-in axes, Figure 2.6c). Finally the SOP traces a radial arc to the analyser eigenaxis (coincident...
with the lead-in/out eigenaxes), such that the arclength, independent of lead-out phase, is proportional to the transmitted optical field (Figure 2.6d).

![Figure 2.6 Poincaré trajectories.](image)

The optical fibre can have either a transmissive or reflective form. The former consists of a gauge length section of HiBi fibre spliced at 45° relative to the lead polarisation axes (polarisation eigenaxes) which act as the lead-in/out fibres (Figure 2.7a). For the reflective system the sensor fibre is fusion spliced at 45° to a single
HiBi fibre which acts as both the lead-in/out fibre and mirroring the other sensor fibre-end (see Figure 2.7b, Appendices A and B describe the splicing and mirroring processes).

![Birefringence axes](image)

**Figure 2.7** Localised Polarimetric Sensor, (a) Transmissive and (b) reflective.

The Jones matrix now includes a mirror such that,

\[
[M]_{sys} = [P][HiBi][R^{-1}(45^\circ)][HiBi][FR][HiBi][R(45^\circ)][HiBi][P] \quad (2.29)
\]

Since the fibre reflector adds a constant (i.e., strain dependent) phase, there is no functional difference between the two modes of operation apart from the doubled optical path length. The sensitivity of the output to splice deviations from 45° can be evaluated by substituting an arbitrary angle into equation 2.26 and 2.27. The resultant output intensity takes the same form as in equation 2.23. Since the resulting change in contrast and dc offset does not affect the period of the phase-strain relation (see Figure 2.4), the accuracy of a ‘fringe-counting’ (measuring strain interval at every phase cycle) technique will not be changed. More sophisticated interfringe techniques require compensation for contrast and dc offset drifts.
Experimental Procedures and Results

This section provides details of the experimentally obtained results for HiBi polarimetric sensors subject to free-fibre tension, surface adhered and embedded in a composite structural system. The first two stages of testing can be referred to as the characterisation of the HiBi polarimetric sensor for strain measurements using a single-ended configuration; The third stage of testing was the application of a HiBi polarimetric sensor for strain measurements embedded in a structural composite structure, in particular reinforced concrete beams flexurally strengthened using carbon fibre reinforced plates (CFRP).

2.3 Free Fibre Polarimetric Strain Measurements

The strain response of a freely suspended optical fibre was experimentally determined using a calibrated 'straining rig' shown in Figure 2.8. The rig mainly consists of perspex blocks fixed with screw on four steel bars. A vernier (10mm scale) on one of these blocks provides accurate movement of one of the blocks in which the optical fibre is fixed, by gluing it in small perspex cylinders drilled in the centre using a two-part 5-Minute epoxy (UV curable glue was also tried but with very poor results).

![Free-space tensioning rig and experimental setup.](image)

Figure 2.8  Free-space tensioning rig and experimental setup.
The fibre coating was stripped from the gluing regions to avoid hysteresis effects due to fibre coating slippage under strain. The rig has a total length of 450mm and is capable of straining optical fibres of up to 300mm in length. The block movement was also recorded by a linear potentiometer connected to a data logger. The ‘fringe’ counter was also connected to the data logger for storage of the data on an HP machine. The software was designed in such a way so that every phase cycle change (1 fringe=\pi) would trigger the data logger to interrogate the linear potentiometer and obtain the associated change in length. A 1mW HeNe polarised laser source was used (UNIPHASE) operating at 633nm, and the polarimetric sensor (see Appendix A for a detailed description of the manufacturing procedure), was manufactured using Bow-Tie HiBi fibre (HB600 by Fibercore). Lead-in/out insensitivity was achieved by aligning the polarising beamsplitter axes with the birefringent axes of the lead-in fibre using a rotatable micropositioner. Sensor localisation is achieved by using the single 45° fusion splice.

The experimental results determined using this straining ‘rig’ were found to be reproducible and in good agreement with other reported values for HB600. Figure 2.9 shows a typical phase/elongation response curve for an increasing tensile load on a HiBi sensor of length 132mm. The change in length was recorded by a calibrated linear potentiometer and data was obtained at every \pi phase change. The fibre was strained up to -5000\muε and four different gauge lengths were tested. The phase/strain relation was linear (r² > 0.997) and the sensitivity was found to be independent of the gauge length. A mean phase/strain sensitivity of 0.42±0.01 deg \muε⁻¹ mm⁻¹ was obtained which is in very good agreement with work reported by Hogg et al. (1989) who determined a free fibre strain sensitivity of 0.46±0.02 deg \muε⁻¹ mm⁻¹. However, the sensitivity differs among different fibre types and different spools of the same fibre type [Hogg et al. 1989 (Bow-Tie), Kikuchi et al. 1984 (PANDA), Leilabady et al. 1985 (Bow-Tie), Ohtsuka et al. 1987 (ell. cladd., PANDA), Varnham et al. 1983 (Bow-Tie)]. This means that each sensor batch may have to separately calibrated.
2.4 Surface Adhered HiBi Polarimetric Sensor Strain Sensitivity

The HiBi polarimetric strain sensor was surface adhered onto CFRP coupons in order to investigate the phase/strain response of the sensor under controlled uniaxial tension on the same material as the one used for reinforcing the concrete beams using plate bonding.

2.4.1 Fibre-reinforced polymer materials

In plate bonding applications, the external reinforcement acts essentially as a longitudinally stressed tensile member. Unidirectionally reinforced composites are ideal in this situation since all of the strength and stiffness of the material can be placed longitudinally in the direction to be loaded. Three types of unidirectionally aligned fibre-reinforced polymer (FRP) materials were used in this project; Pultruded
E-glass fibre/vinylester produced by Kobe Steel Europe Ltd., carbon fibre/epoxy prepreg, supplied with a peel ply on both faces, and pultruded carbon fibre/vinylester, also supplied with a peel ply. Both carbon composites were manufactured by Techbuild Composites Ltd. The prepreg material was supplied by Cytec (‘CYCOM’ 919HF-42%-HS-135-460 (P/N 02098)) and contained high strength Toray T300 carbon fibres. These fibres were also used for the pultruded carbon composite.

The pultrusion technique, in which fibres are passed through a resin bath into a heated mould for shaping and curing, is an ideal method for producing the continuous lengths of unidirectionally aligned, high fibre content material of constant section and properties required for plate bonding. The lengths of material which can be produced by prepreg techniques, in which laminates are built up from fibres impregnated with the required polymer in an uncured state then cured in an autoclave, are limited by the size of the available autoclave. Production costs are also higher than for the pultrusion technique which is a fully automated, continuous process.

Both vinylester and epoxy are thermoset resins which harden irreversibly on curing. Epoxies are generally considered to be superior with regards to strength and elastic properties. They also have a much lower shrinkage on curing, a lower coefficient of thermal expansion and produce a higher interface bond strength between fibre and resin. However, epoxies are more expensive and have a high viscosity before curing, making it a difficult material to pultrude. The strength properties of the resin are relatively unimportant for the application considered here since the resulting composites are unidirectionally reinforced with a high fraction of fibres. Vinylester was used rather than polyester because of its superior weathering resistance.

The proportion of reinforcing fibre by weight contained in each of the FRP materials used was determined by burn-off for the glass composite, in which samples of the material were heated to temperatures around 550 °C in order to remove the resin, or, in the case of the carbon composites, by treatment with hot concentrated sulphuric acid, again to remove the resin component.

The longitudinal modulus of elasticity and Poisson’s ratio in tension, tensile strength and tensile strain to failure were determined for each FRP material using specimens of the dimensions shown in Figure 2.10.[Quantrill 1996]
Soft aluminium end tabs, 2.0 mm thick

Figure 2.10 FRP tensile specimen dimensions.

These specimens are in accordance with Part 3 of BS 2782, 1976 for obtaining tensile properties of reinforced polymers. All coupons were gauged longitudinally and transversely on both faces at the centre of the specimen, and loaded at 1.0 mm/min. for the glass composite and 0.5 mm/min. for the carbon, reflecting the relative stiffnesses of the materials. The derived material properties given in Table 2.2. Each value represents the average of three tests; the variance around the average is given in each case [Quantrill 1996].

All of the composites behaved linearly to failure, which occurred by sudden rupture of the fibres for the glass composite and by a combination of longitudinal splitting and fibre breakage in the specimens reinforced with carbon. Table 2.2 shows that all three composite materials had similar tensile strengths, the pultruded carbon fibre/vinylester producing the highest value. The carbon composites were found to have considerably higher stiffness than the glass, but greatly reduced strain to failure.

Table 2.2 Derived engineering properties for composite materials [Quantrill 1996].

<table>
<thead>
<tr>
<th>Composite material</th>
<th>Thickness (mm)</th>
<th>Weight fraction of fibre (%)</th>
<th>Modulus of elasticity (N/mm²) ±%</th>
<th>Ultimate tensile strain (µS) ±%</th>
<th>Tensile strength (N/mm²) ±%</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass/vinylester</td>
<td>1.2</td>
<td>83.0</td>
<td>$48.9 \times 10^3 \pm 0.8%$</td>
<td>$22000 \pm 9.1%$</td>
<td>$1017 \pm 8.6%$</td>
<td>0.29</td>
</tr>
<tr>
<td>Carbon/epoxy</td>
<td>1.2</td>
<td>57.0</td>
<td>$118.5 \times 10^3 \pm 2.1%$</td>
<td>$8330 \pm 1.4%$</td>
<td>$968 \pm 3.4%$</td>
<td>0.33</td>
</tr>
<tr>
<td>Carbon/vinylester</td>
<td>1.3</td>
<td>75.0</td>
<td>$135.0 \times 10^3 \pm 3.7%$</td>
<td>$7540 \pm 2.0%$</td>
<td>$1226 \pm 4.0%$</td>
<td>0.31</td>
</tr>
</tbody>
</table>

2.4. Surface Adhered HiBi Polarimetric Sensor Strain Sensitivity
2.4.2 Experimental Setup and Results

The HiBi polarimetric sensors were surface adhered onto CFRP coupons with the same dimensions as those shown in Figure 2.10. A similar optical setup to the free space tests was used but now the sensor is adhered to a CFRP coupon which is located in an Instron tensile machine (see Figure 2.11).

Figure 2.11 Experimental arrangement for surface adhered polarimetric sensor under uniaxial loading/unloading.

Figure 2.12 Instrumentation arrangement for tensile CFRP coupons.
Electrical resistance strain gauges were attached in the centre of the coupon on either side. The Sensor was also adhered along the centre line using cyanoacrylate adhesive, see Figure 2.12.

Four different sensor gauge lengths were tested and the results were found to be consistent and reproducible. A typical experimental response (phase/strain and Load/strain for a HiBi polarimetric sensor of length 140mm is shown in Figures 2.13, 2.14.

**Figure 2.13** Adhered HiBi (HB600) polarimetric sensor phase/strain response.

**Figure 2.14** Load strain plot for tension/relax cycles (extension rate 0.5mm/min).
Figure 2.13 shows the linear response of the embedded polarimetric sensor ($r^2>0.998$). The strain sensitivity was $0.44\pm0.02$ deg/µm, which is slightly higher than the free fibre strain sensitivity; but compatible with the zero transverse strain sensitivity hypothesis. The lead-in fibre was also found to be insensitive to any applied strain as expected. In Figure 2.14 the polarimetric sensor strain (for tension and relax cycles) is plotted against the results obtained from the electrical resistance strain gauges, in a load/strain plot, for direct comparison. The results are in excellent agreement and no hysteresis effects are observed for the polarimetric sensor. Figure 2.15 shows the load/strain response of the polarimetric sensor when tensioned to failure. The failure point was identified as being the fusion splice in all cases and the mean failure strain was found to be $6800\pm3\%$ µε.

![Figure 2.15 Load/strain plot for a HiBi polarimetric sensor tensioned to failure.](image)

2.4. Surface Adhered HiBi Polarimetric Sensor Strain Sensitivity
2.5 HiBi Polarimetric Strain Sensor Embedded in a Composite Concrete Structure

This section provides details on the experiments performed for monitoring the strains that develop in a composite structure, using HiBi polarimetric strain sensor. The composite structure is a reinforced concrete beam which is flexurally strengthened by a CFRP plate. The plate is bonded to the concrete beam using a two-part cold-cure epoxy (Sika 'Sikadur 31 PBA). It is this thin layer of glue line that the polarimeter was used to monitor the internal strain condition of the concrete beam when subjected to four point bending loading. The externally bonded plates have been employed solely to provide additional tensile reinforcement. Quantril R.J (1996) and Garden H (1997) provide an extensive study into the effects of ‘plate bonding’ techniques and applications. The introduction that follows is based on their work.

2.5.1 Introduction

Reinforced concrete structures may, for a variety of reasons, be found to be unsatisfactory. In the design and construction phase, causes of deficiency include marginal design/design errors causing inadequate factors of safety, the use of inferior materials, or poor construction workmanship/management, causing the design strengths not to be achieved. In service, increased safety requirements, a change in use or modernisation causing redistribution of stresses, an increase in the magnitude or intensity of the applied loads required to be supported, or an upgrading of design standards may render all or part of a structure inadequate. Increased loading may also result from a less favourable configuration of existing loads. In addition, the load-carrying capacity of a member may be compromised by material deterioration, such as corrosion of the internal reinforcement particularly in marine or industrial environments, carbonation of the concrete or alkali-silica reaction, or structural damage, caused by fire, impact, explosion, earthquake or overloading. On highway structures, corrosion of the internal reinforcement is exacerbated by the application of de-icing salts. For prestressed concrete beams, strengthening measures may be required to prevent further loss of prestress.

These inadequacies may manifest themselves by poor performance under service loading in the form of excessive deflections and cracking, or through inadequate fatigue or ultimate strength. When maintenance or local repair will not restore a
deficient structure to the required standards, there are two possible alternatives; complete or partial demolition and rebuild, or the commencement of a programme of strengthening. In this context, strengthening is defined as rehabilitation to restore the original structural performance, or upgrading to attain higher strength or stiffness requirements. The choice between strengthening or demolition depends on many factors, such as material and labour costs, time during which the structure is out of commission, and disruption of other facilities. However, the financial and environmental implications of strengthening as opposed to demolition can often be considerable, particularly if a simple, quick strengthening technique is available. In addition, if the structure in question has historical importance, the possibility of demolition may be precluded.

2.5.1.1 Possible strengthening techniques [Quantrill, 1996]

Strengthening operations are usually difficult because of the inaccessibility of the works, and can involve a great deal of labour and plant, as well as disruption to the use of the structure itself and surrounding facilities. Strengthening can be carried out by several techniques to achieve the desired improvement. These include increasing the size of the deficient members through the provision of additional reinforced or prestressed concrete layers using stapling and pressure grouting, the introduction of additional supports, beams or stringers, the replacement of non-structural toppings with structural toppings or lighter materials, overslabbing, or polymer impregnation. For bridge structures, traffic management measures may be imposed to relieve loading on weak members. Costs of the methods of strengthening vary considerably depending on the size of the structure, the extent of the strengthening work required and, in the case of bridges, the volume of traffic carried over and under. In techniques where additional material is applied to the original member, the main problem is that of ensuring adequate connection and composite action between the reinforcing element and the existing structure. External post-tensioning by means of high strength strands or bars has been successfully used to increase the strength of beams in existing bridges and buildings. However, this method does present some difficulties in providing anchorage for the post-tensioning strands, maintaining the lateral stability of the girders during post-tensioning and protecting the strands against corrosion.

The development of structural adhesives has lead to the evolution of a further method of structural repair in which steel plates are externally bonded to the structure in situ,
effectively increasing the area of reinforcement provided. The plates then act compositely with the original member, producing a section with improved flexural strength and stiffness. If propping is used during the bonding operation, the plates can help to support dead as well as live loading; otherwise, additional live loading capacity only is provided.

The success of this strengthening method depends critically on the performance of the adhesive used. When bonded to the tensile faces of concrete members, the plate is in a position where it can have the maximum effect on the ultimate strength, stiffness, and hence deflections, and also on the initiation and development of cracks. The effect of the additional material in the tension zone is to lower the position of the neutral axis in the section. This reduces the stress in the existing internal reinforcement but increases the compressive strains in the concrete. The method is thus constrained in its scope for strengthening by limits imposed on existing material stresses under working load. At the ultimate limit state, the strengthened section should remain under-reinforced to ensure that failure occurs in a ductile manner. The possible structural enhancements are therefore governed by the amount and distribution of internal reinforcement, geometry of the section and properties of the concrete. Although it is usually areas subjected to excessive tensile stress that require strengthening, bonded plates may also be used to provide additional shear or compressive reinforcement.

For bridge structures, external plating can be used to enhance the load-carrying capacity either in the short-term to support the passage of an abnormal load, or for longer-term service under design-imposed loading. In the context of bridge strengthening, the speed of application means that plate bonding is particularly favourable when heavily trafficked roads are involved, where restrictions or diversions could seriously affect local and national traffic patterns.

Despite the obvious advantages of plate bonding, the technique in general has several shortcomings. Since the plate is bonded to the surface of the concrete and not enclosed by it, there is a possibility that the plate may debond. Unless there is careful scrutiny of the development of crack patterns, there is likely to be little advance warning that such failure is imminent. The technique is sensitive to standards of workmanship and hence personnel with special polymer-related skills are necessary during the bonding operation, and particularly tight quality control must be
implemented. However, although the adhesives used are expensive compared to concrete and steel, in many situations economic solutions are possible to rectify inadequate structural performance and, sometimes, to avoid demolition. The technique is being increasingly adopted on both concrete buildings and bridges.

2.5.1.2 Sikadur 31 PBA Adhesive Characteristics

Sikadur 31 PBA is a two part, cold-cure epoxy resin system composed of a bisphenol ‘A’ resin which is mixed with one-third of its own weight of a polyamine-based hardener. Inert fillers are also included in the formulation. It is specifically designed for the external bonding of structural plate reinforcement to concrete and cast iron substrates and complies fully with Department of Transport requirements for plate bonding. The resin is supplied as a white paste, the hardener as a black paste; a mid-grey thixotropic paste should be obtained after correct mixing. The adhesive has a pot life of 30 minutes and an open assembly time of about 5 hours at 25 °C, and is said to have reached its fully hardened state by 24 hours.

The resin and hardener of Sikadur 31 PBA are supplied in separate containers produced for site use such that the correct proportioning is achieved when the entire contents of the containers are mixed together to give 5 kg of the adhesive. In this project only relatively small quantities of the material were required at any one time. Although part-mixing of the containers is not recommended by Sika, who then will not guarantee the properties obtained, using a ratio of resin: hardener of 3:1 is said to be the most appropriate. Hence, each time an amount of adhesive was required, proportioning by hand in this ratio was used.

The technical data supplied with the adhesive claims a moisture resistance of less than 0.5% by weight uptake at 28 days. Such a high water resistance combined with a large proportion of fillers is aimed at increasing the material’s resistance to creep. The flexural modulus of the hardened adhesive is said by the manufacturers to be 8600 N/mm².

Quantrill (1996) provides detailed material characterisation tests for the adhesive. The adhesive has a linear response up to about 50% of the ultimate stress, at which point the ductility of the tensile specimens used increased and the material strained to failure, which occurred in a brittle manner. The tests produced the following material properties. Each value is the average of three tests; the variance around the average is also given:

Tensile modulus of elasticity, $E_u = 7.85 \times 10^3$ N/mm² ± 3.1%

Tensile strength, $f_u = 26.78$ N/mm² ± 2.9%
Tensile strain to failure, $\varepsilon_t = 5140 \, \mu e \pm 12.5\%$

### 2.5.2 Specimen Preparation Procedures

#### 2.5.2.1 Concrete 1.0m Length Beams

The dimensions and reinforcement arrangements used for the 1.0 m length beams cast at the University [Garden 1997], and the beams cast by Grecon Ltd. are shown in Figure 2.16. As can be seen, both beam types had a longitudinal tensile reinforcement ratio, $A_g/b_d$, of 1.0%. In both cases the sections were well under-reinforced, with plenty of scope for studying the effects of flexural strengthening.

As can be seen from Figure 2.16, all 1.0 m length beams were provided with shear reinforcement in the form of 3 mm diameter mild steel wire links. Adequate shear capacity was provided for the unplated 1.0 m length beams to ensure flexural failure preceded failure due to shear. All 1.0 m length reinforcing cages were prepared at the University and, except for a batch of beams cast in-house, delivered to Grecon for beam manufacture.

#### 2.5.2.2 Test beam preparation

The programme of beam testing commenced after the initial bond tests and material characterisation had been completed, and the methods of surface preparation had been verified.
2.5.2.3 Beam Surface preparation

The procedures adopted for preparing the concrete beam surface were as follows.

The concrete was gritblasted with copper slag at a working pressure of 75 psi. to remove dirt and laitence and to expose, but not undermine, the coarse aggregate which provides a sounder bonding medium. The abraded surface was then blown free of dust using compressed air. The glass fibre/vinylester composite was not supplied with a peel ply and therefore surface treatment was necessary. Many authors have concluded that the subsequent strength of joints fabricated from treated FRP is dependent on the extent to which contaminants, in particular release agents, are removed prior to bonding, and not the severity of abrasion. In view of this, the procedure adopted for the programme of bond tests was to expose the CFRP bond surface to a very light gritblasting followed by degreasing with methylated spirit to remove surface contamination and produce a surface more receptive to bonding.

Both treatment procedures were carried out immediately prior to application of the adhesive, and at all stages great care was taken not to re-contaminate either bond surface with grease or dust.

For the carbon fibre composites, both of which were supplied with a peel ply, surface treatment was simply a case of removing this layer immediately prior to bonding to produce a clean, textured surface. Again, the surface treatment procedures were carried out immediately prior to application of the adhesive to prevent re-contamination of the bond surfaces.

2.5.2.4 Bonding procedure

After surface preparation, the epoxy resin and hardener were mixed by hand in their separate containers before being transferred to the mixing beaker in the correct proportions, mixed and applied to both the concrete and composite surfaces. In all cases, the concrete beams were inverted to be bond face up and the bond areas were bordered with masking tape so that clearly defined edges could be attained. Minimising the effects which variable size fillets of adhesive along the plate edges might have on the bond performance. The adhesive applied to the concrete was profiled so that excess would be extruded from the centre outwards, thereby dispelling air. The thickness of the adhesive was controlled as far as possible with ballotini of either 1.0 mm or 2.0 mm diameter. The plate was then positioned centrally on the beam and dead weights applied during the cure period, nominally 24 hours, after which the beam was instrumented and tested. Typically, the period between application of the adhesive and testing of the beam was around 3 days.
**2.5.2.5 Beam instrumentation and testing configuration**

Instrumentation of the plated 1.0 m length beams consisted of ER strain gauges on the underside of the CFRP plate to indicate the longitudinal strain distribution along its length. The positions of the strain gauges on a typical beam arrangement are shown in Figure 2.17. The 1.0 m beams were loaded in four point bending at the third points over a span of 900 mm as shown below. Steel plates covering the full width of the beam were used at the points of load application (50 x 10 mm) and also at the reaction points (30 x 10 mm) to aid distribution of stress into the concrete, reducing stress concentrations. Such a configuration gave a shear span/effective depth ratio, $a/d$ of 3.5. The beams were incrementally loaded to failure with strains recorded automatically at the required load interval, or in this case every phase cycle change. The data logger was again programmed to interrogate the strain gauges when a 'fringe' count occurred.

![Diagram of beam instrumentation and loading arrangement](image)

**Figure 2.17** Instrumentation and loading arrangement for 1.0 m length beams.

Three polarimetric sensors were embedded in each beam tested with excellent results, as only one fibre sensor was damaged during the manufacturing procedures.

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* The protective coating buffer was stripped from the sensor region of the fibre-optic sensor in order to avoid discrepancies due to coating slippage.
polarimetric sensor was also surface mounted on the CFRP plate as an additional monitoring sensor in case all the embedded sensors were lost. Prior to the application of the adhesive and the attachment of the CFRP the fibre optic sensors were accurately positioned as shown in Figure 2.18; 1mm adhesive pads were created upon which the fibre was adhered and slightly tensioned so that it would not lose its shape or position once the CFRP plate was bonded. Extra care was needed to avoid any damage to the sensors. The steel end plate was drilled so that the optical fibres could pass straight through thus avoiding any bending force on compressive force on the lead-in HiBi fibre.

Figure 2.18 Embedded Polarimetric sensor arrangement.
2.5.3 Experimental Results

The experimental setup used is shown in Figure 2.19. The data was again recorded every phase cycle and the load was applied using a hydraulic pump.

Figure 2.19 Experimental Setup for the embedded polarimetric sensor in a composite structure subjected to four-point bending loading
The load was slowly applied using the hydraulic pump and the embedded fibre optic sensor response was recorded. Figure 2.20 is a load strain plot for an embedded HiBi polarimetric sensor of length 206mm (the advantage the polarimetric sensor has for long gauge lengths is of particular benefit for the structural monitoring of such a structure). As mentioned before three sensors were embedded into each beam, but only the one positioned along the centre line was interrogated thus avoiding any possible data discrepancies because the sensor was positioned too close to the CFRP edge.

![Load/Strain plot for a CFRP plated 1m concrete beam, with an embedded fibre sensor monitoring the adhesive strain state.](image)

Figure 2.20 Load/Strain plot for a CFRP plated 1m concrete beam, with an embedded fibre sensor monitoring the adhesive strain state.

The beam was loaded to failure with the sensor failing (no backreflected signal) just prior to the failure of the beam. It can be seen that the fibre sensor strain is between the strains obtained from the strain gauges adhered to the surface of the CFRP plate. The strains are higher for the ER strain gauge located at mid-span. However the fibre sensor seems to deviate away from the strain gauges, experiencing higher strains. Looking at the phase/strain plot (Figure 2.21) it can be clearly seen that on two occasions the fibre sensor experienced rapid phase changes which did not seem to effect the surface adhered electrical resistance strain gauges. When the beam was
loaded for the first two times (Figure 2.22) a similar pattern was observed but at much lower strains.

Figure 2.21 Phase/Strain response for the embedded polarimetric sensor.

Figure 2.22 Phase/Strain response for the first two loading cycles. (LP: Load Point, MS: Mid Span)
Similar responses where obtained from all the beams (3) tested. The results suggest that the 2mm thick glueline is experiencing micro-cracking which is picked up by the path-integrating polarimetric sensor (206mm in length) and translated to phase changes. It seems that once the cracks have occurred on one load cycle then if the beam is unloaded and loaded again the abnormality in the data is not visible. Of course the other possibility is that the experimental setup and technique is at fault, but that is very unlikely since the same experimental methods and setups have been successfully used in our laboratory for a very extensive beam testing programme [Quantrill 1996, Garden 1997]. Clearly further investigation is required, but the results obtained clearly indicate that possible microcracks are forming in the glueline for strains as low as 600µε.

2.6 Summary

The HiBi polarimetric sensor was successfully manufactured and characterised. The free fibre and surface adhered phase/strain characteristics of the sensor were established and were found to be in good agreement with the theory presented and work reported by other authors.

The HiBi polarimetric sensor was then successfully used to monitor the structural behaviour of a composite structure (with reference to the reinforced concrete beam with a CFRP plate bonded to it). The sensor was successfully embedded into the adhesive used to bond the CFRP plate to the concrete beam and monitored the strain state of the adhesive during loading. Almost all of the embedded sensors survived the manufacturing process with only one failure.

The results suggest that micro cracks are forming in the glueline which are picked up by the embedded fibre optic sensor and translated to phase cycle changes. The sensor can be used to continuously monitor the structural integrity of the adhesive thus providing useful information about the state of the bond between the CFRP plate and the concrete beam and the overall structural integrity of the structure.
Chapter 3

Finite Element Modelling of an Embedded Hi-Bi Polarimetric Strain Sensor

3.1 Introduction

The finite element (FE) method was first introduced in the 1950's, and it is now an extremely sophisticated tool for solving numerous engineering problems. It has been extensively described in the literature, for example by Zienkiewicz and Taylor, 1989, and only a summary of the basic principles will be given in the following paragraphs.

The basic principles underlying the FE method are simple. The distribution of an unknown variable over a body, such as displacement or temperature, is required. The region under consideration is firstly divided into an assembly of sub-divisions called elements, which are considered to be interconnected at joints, known as nodes. A given distribution of the unknown variable through each element is assumed. The equations defining the approximating distribution are known as interpolation functions, usually defined by a polynomial (for example, linear or quadratic), or a trigonometric function. The number and type of elements are chosen so that the variable distribution through the whole body is adequately approximated by the combined elemental representation.

After the problem has been discretised, the governing equations for each element are calculated and then assembled to give the global equations which describe the behaviour of the body as a whole. The element equations for a specific type of problem, such as a stress analysis, have a constant format. Thus, once the general format of the equations of an element type is derived, the calculation of the equations for each occurrence of the element in the body is straightforward; it is simply a
The question of substituting the nodal coordinates, material properties and loading conditions of the element into the general format.

The global equations generally take the form

\[ [k] \{U\} = \{F\} \]  \hspace{1cm} (3.1)

where \([k]\) is the stiffness matrix, \([U]\) is the vector of unknown nodal displacements and \([F]\) the vector of applied nodal forces. The boundary conditions of the problem are then incorporated into the global equations and the relationship given in equation 3.1 is inverted to solve for \([U]\). After solving for the unknown nodal values, it is then possible to use the displacements to find the strains and then the elemental stresses.

Equilibrium analysis, in which a body under equilibrium conditions is analysed and its distortion predicted, is the most common use of the FE method. It is rare for an FE model to represent the unknown displacement field precisely, and the results will therefore invariably only approximate the true solution. The amount of error obtained depends primarily on the representation chosen to best resemble the continuous behaviour of the actual structure and the size of the elements employed. As such, the accuracy of a model can be improved in two ways; either the mesh density can be increased, or the accuracy of the elements themselves can be improved by using higher-order interpolation functions. As the number and complexity of the elements increases, so the approximation should improve and eventually converge to the 'true' solution. However, the gains in accuracy decrease as the number of elements increases, and increasing the element order leads to a significant increase in the computer time needed to analyse the structure.

If the geometric interpolation function, used to describe the geometry of a particular element, and the displacement interpolation function are of the same order, then the element is known as isoparametric. The two functions then prove to be similar to each other which simplifies their application significantly. Using quadratic elements with mid-side nodes allows curved boundaries to be modelled, of particular use in bending problems. This implies not only an improvement in the geometric accuracy of the model, but also an increase in the order of the interpolation function used for the element, thus leading to a significant increase in the complexity of the model.

The FE method potentially offers a powerful and general analytical tool for studying the behaviour of reinforced concrete. The initial aim of the FE investigation carried out in the present study was to obtain a model, verified in terms of overall and local response and mode of failure by a limited number of basic experimental tests. The model could also be used in conjunction with further experimental testing; the critical parameters and locations within the system which govern overall failure could be
identified so that measures could be taken to prevent their occurrence in actual tests. In this way the number of experimental tests could be reduced, thereby saving time and money.

3.2 Modelling of a Hi-Bi Polarimetric Sensor

Materials with structurally integrated sensors and/or actuators represent the first step toward "Smart Structures". Monolithic load-bearing structures with built-in fibre-optic sensing systems, could continuously monitor their internal strain, loading, vibration state, temperature and structural integrity. An important class of materials providing a high compatibility with smart structures and the most scope for the implementation of these ideas are structural composites with polymeric matrices. These materials can themselves be tailored by lay up of plies and by hybridization of the reinforcing fibres. Since the materials are often made at the same time as the component, it is possible to embed sensors and/or actuators during the fabrication process. Fibre optic sensors (FOS) have been considered to be the prime candidates for internal structure and condition monitoring of composite materials [Davidson 1993, Measures 1990]. If fibre optic sensors are incorporated into the composite structure the basis of an embedded sensor is formed, potentially capable of sensing strain and temperature variations throughout the service life of the composite. Fibre optic sensors have several inherent advantages over conventional (resistive strain gauge) sensors which render them compatible with composite materials. These include:

- Electro-magnetic (EMI) and hazardous environment insensitivity
- Similar shape to the reinforcing fibres: geometric compatibility
- Comparable size to the reinforcing fibres: dimensional compatibility
- Thermally and chemically stable in the host composite: environmental compatibility

A single-ended polarimetric strain sensor was used for strain measurements. The sensor was embedded in a GFRP coupon and was loaded in tension. A 2-dimensional FE model of the structure was also used to study the stress/strain concentrations of the material system (composite host, glass fibre and coating).
3.3 Single Ended Polarimetric Sensor

Although a more comprehensive theoretical analysis for the polarimetric sensor has been presented in Chapter 2, what follows is a brief summary of the polarimetric sensors concepts.

3.3.1 Principle

The applied principle for this kind of sensor is Polarisation Interferometry. Interferometry measurements are well known, and there are numerous examples in the literature [Dakin 1989, Butter et.al. 1978, Hogg et.al. 1989, Kashyap et.al. 1983]. Polarimetric fibre-optic sensors detect the presence of some physical field via a change in the state of polarization of the light propagating through the fibre. This polarization state change is the result of the phase velocities of the two polarization mode of the single mode fibre being altered unequally by the action of the field [Rashleigh 1983]. In order to sense an external measurand by the modulation of the polarisation state of the fibre, birefringent fibre sensors are needed. Polarimetric sensors utilise the relative change in optical path length difference which occurs between the two orthogonally polarised modes of a fibre. They exhibit excellent lead-in insensitivity (using Hi-Bi fibre with “on-axis” launching) and possess relatively moderate sensitivity [Hogg 1989, Measures 1990]. It has been shown that the variation in birefringence caused by stretching a high-birefringence (Hi-Bi) fibre is the result of a mismatch in Poisson’s ratio [Varnham et.al 1983].

Hi-Bi fibres have axes of stress built in so that the otherwise orthogonal but degenerate polarisation modes become separated and propagate at different velocities. The required anisotropy is created either by fabricating a fibre with an elliptical core or by selectively doping the cladding region around the core to create the stressed axis as in the “bow-tie” fibre [Dakin and Culshaw 1989].

3.3.2 Simplified Strain Sensitivity Theory

A single ended polarimetric sensor was used for strain measurements embedded in glass fibre polymer (GFRP). Simple fringe counting was employed for signal conditioning of the results. Therefore it is necessary to find a relationship converting the number of fringes to micro strains. Varnham et.al. [Varnham et.al 1983], derived
an expression relating the extension or elongation $\Delta l$, that is required to induce a $2\pi$ phase shift between the interfering modes in a HiBi fibre, to its beat length $L_p$ ($L_p = \lambda / B$):

$$\Delta l = \frac{(a_2 - a_1) T}{(v_2 - v_1)}$$

(3.2)

where $\lambda$ is the wavelength, $T$ is the difference between ambient temperature and the lowest fictive temperature of the glasses within the fibre, $\alpha_t$, $v_1$ and $\alpha_2$, $v_2$ are the expansion coefficients and Poisson’s ratio in the different regions of the Hi-Bi fibre (silica cladding and stress applying bows) respectively. An approximate difference between Poisson’s ratio for borosilicate glasses and silica is given as $v_2 - v_1 = 0.02$ and $(\alpha_2 - \alpha_1) \delta \lambda / T = -10^{-3}$. The beat length for the Hi-Bi fibres used varied from $L_p = 1$ to $1.1 \text{mm}$. The above values suggest that the elongation required for a $2\pi$ phase change is:

$$\Delta l = 0.05 \cdot \delta \lambda L_p$$

(3.3)

Therefore by interfering the two modes, a fringe should pass a maximum every time the fibre is stretched by $\Delta l$. By counting these interference fringes ($N$) the total elongation $\Delta l_{\text{total}}$ can be determined. Consequently the relative extension of the fibre with reference to the original length of the fibre $L_{\text{OL}}$, in micro strain can be calculated as follows:

$$\mu\varepsilon = \frac{\Delta l_{\text{total}}}{L_{\text{OL}}} \times 10^6$$

(3.4)

Due to the fact that the electronic fringe counter was triggered twice by each fringe and the light beam travels through the sensing fibre twice in Figure 3.1 because the sensor works in reflection and thus travels a distance of $2\Delta l$, equation 3.3 has to be further divided by a factor of 4, thereby increasing the resolution.

$$\mu\varepsilon = \frac{N \times 0.05 \times L_p \times 10^6}{4 \times L_{\text{OL}}}$$

(3.5)
3.4 Experimental Techniques and Results

3.4.1 Sample Preparation

The test structure was a fibre/matrix composite tensile specimen into which an optical fibre was bonded. The strains developed in the bonded specimen when subjected to tensile loading, were monitored by a High Birefringence fibre (York HB600, at 633nm) operated as a polarimeter and by electrical resistance strain gauges; the latter were bonded to the opposite flat surfaces of the test specimen, the experimental layout is shown in Figure 3.1.

![Figure 3.1 Experimental lay-out of the embedded Hi-Bi sensor](image)

The test specimen consisted of two identical GFRP coupons which when bonded together formed a composite member of 300×25×4mm. The two half specimens were manufactured from randomly orientated glass fibre of 30% by weight, in a polyester matrix and fabricated by the hand lay technique. One of the half beam units had a V-groove (1-2mm deep) machined into it. To locate the optical fibre inside the groove several of its individual points were bonded to the composite by an adhesive.

Epoxy resin was applied to the two half surfaces of the specimen and these were brought together and bonded. It was necessary to ensure that all air-bubbles had escaped from the joint and this was achieved by squeezing the two halves of the beam
from the centre through to the free edges; the coupons were then firmly clamped together for approximately 12 hours. Aluminium tabs were bonded to the composite sample to prevent stress concentrations from developing in the optical fibre and the GFRP coupon, when placed in the jaws of the INSTRON test machine.

### 3.4.2 Experimental results

#### 3.4.2.1 Introduction

The experimental procedure for manufacturing the polarimetric sensor are detailed in Appendix A. Potential scattering centres caused by localised strain did not cause a problem. The monochromatic laser light was passed through a polarising beam splitter which was aligned to only one of the high birefringence eigenaxes thus carrying the linearly polarised light to the sensing region. Using a HiBi fibre as the feeding fibre excellent lead-in insensitivity to the measurand was achieved [Hogg et al. 1989]. The splice at the start of the sensing region introduces a 45° relative rotation of the eigenaxes between the feeding and sensing (embedded) fibres, so that light is coupled vectorially into the two axes of the sensing fibre equally.

Travelling with a continuously varying phase difference due to the different refractive indices seen by each mode, both modes are reflected at the mirrored end of the sensing fibre. Mirroring of the fibre end was achieved by immersing the cleaved and cleaned fibre sensor end into a rochelle solution (see Appendix B) and coating it with silver, the technique yielded reflectivities of up to 85%. (an aluminium evaporation technique was also used but it proved to be too time consuming without a big performance benefit, so the much faster silvering method was used). The light now emerging from the sensing fibre becomes measurand dependant, because the phase difference between the two propagating modes is affected by the applied strain. The reflected light is then coupled back into both axes of the feeding fibre at the splice, forcing common polarisations to interfere. The light in the axis perpendicular to the light input axis now travels through the polarising beam splitter in free space to the photo-diode detector for signal processing.

#### 3.4.2.2 Results

The output light power from the laser was 1mW and a reflected power of 12μW was received at the detector. The resolution of the electrical resistance strain gauge used in this system was in the range of ±5με; the load was applied by means of an INSTRON
test machine and the results are shown in Figure 3.2. Using equation 3.5 the results are expressed in microstrain and are plotted on the same graph as those obtained from the electrical resistance strain gauges, for direct comparison of the values acquired from each sensor. It can be seen that the electrical resistance strain gauge and the fibre-optic sensor (FOS) results are in good agreement, the mean deviation of the FOS with respect to the electrical resistance strain gauge results is 2.92% for values up to 2000µε.

![Figure 3.2 Load-strain plot for the tensile test (extension rate = 0.02cm/min)](image)

Slight discrepancies are expected, because the optical fibre sensing region extends throughout the sample (path integrating sensor) and it is thus affected by end-effects, whereas the resistive strain gauge records the uniform strain value in the middle of the specimen. The fibre optic sensor failed at approximately 2200N(≥2000µε), which may be due to either de-lamination between the optical fibre and the primary coating and/or between the primary coating and the GFRP host (in section 2.4 on page 54 the HiBi sensors were subjected to strains >7000µε. The finite element (FE) modelling...
results which are presented in the following section suggest that the soft acrylate coating is dedonding thus causing the failure of the FOS.

3.4.3 Stress/Strain Field Distributions Study using FE Analysis

From the experimental results reported above it was necessary to establish what caused the FOS to deviate at a certain load. Therefore, FE analysis was used to provide an insight into the behaviour of the fibre inclusion (core/cladding and primary coating) and the GFRP host. The analysis also provided an understanding of the local interaction mechanisms between the embedded fibre and the composite host.

3.5 Finite Element Model

In order to study the stress/strain distributions of the system under consideration a 2-D finite element model was developed. The boundary and loading conditions applied to the model are shown in Figure 3.3. The conditions applied represent, as close as possible, the method by which the specimen was loaded under tension in the INSTRON test machine.

![Figure 3.3 Geometry and boundary conditions of the FE model](image)

**Figure 3.3** Geometry and boundary conditions of the FE model
The model was created using 2D solid elements under the plane stress assumption [Timoshenko], the underlined condition for plane stress can be seen in Table 3.1, and the mesh was formed using the pre-processor of the FE package Patran P3. The mesh was formulated using 8-noded quadrilateral and 6-noded triangular quadratic elements (CPS8, CPS6). The mesh developed can be seen in Figure 3.4a, and a close up of the refined mesh used to enable the modelling of the coating and core/cladding of the optical fibre is also shown in Figure 3.4b. The coating of the optical fibre used in the experiment was a very soft acrylate (DeSolite 950-131), used in most telecommunication purpose fibres. All materials in the study were assumed to be isotropic and their properties as used in the model are given in Table 3.2, where $E_x$ and $E_y$ are the elastic modulus in directions X and Y respectively and $\nu_{xy}$ is the Poisson's ratio. The analysis of the structure system (Linear Static with time incrementation) was performed using the FE package ABAQUS (ver. 5.4) [Abaqus 1994]. The model was subjected to the same loading scenario as the GFRP coupon with the embedded optical fibre. The stress and strain distributions of each material (core/cladding, coating, composite host) obtained from the analysis were then studied.

The faces of the model when a load of 2200N was applied, were constrained to remain planar. Some disturbance to the stress/strain fields was expected to appear at points A and B (see Figure 3.3) due to end-effects.

### Table 3.1 Plane Stress and Plane Strain Conditions

<table>
<thead>
<tr>
<th>Plane Stress</th>
<th>Plane Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_z=0$, $\tau_{zx}=0$, $\tau_{zy}=0$</td>
<td>$\tau_{zx}=0$, $\tau_{zy}=0$</td>
</tr>
<tr>
<td>$\sigma_x, \sigma_y$ and $\tau_{xy} \neq 0$</td>
<td>$\sigma_x, \sigma_y, \sigma_z$ and $\tau_{xy} \neq 0$</td>
</tr>
<tr>
<td>$\gamma_{xx}=0$, $\gamma_{yy}=0$</td>
<td>$\varepsilon_x=0$, $\varepsilon_y=0$, $\gamma_{xy}=0$</td>
</tr>
<tr>
<td>$\varepsilon_x, \varepsilon_y, \varepsilon_z$ and $\gamma_{xy} \neq 0$</td>
<td>$\varepsilon_x, \varepsilon_y, \varepsilon_z$ and $\gamma_{xy} \neq 0$</td>
</tr>
</tbody>
</table>

3.5. Finite Element Model
Slices cut along the specimen.

Refined mesh region for the GFRP close to the optical fibre.

(a) Part of the mesh used in the FE model

(b) Close-up of the refined mesh region showing the coating and core/cladding layers

Figure 3.4 Finite element model generated mesh
Table 3.2 Material properties used in the analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_x$ (GPa)</th>
<th>$E_y$ (GPa)</th>
<th>$v_{xy}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core/Cladding</td>
<td>70.7</td>
<td>70.7</td>
<td>0.17</td>
</tr>
<tr>
<td>Acrylate Coating</td>
<td>0.045</td>
<td>0.045</td>
<td>0.35</td>
</tr>
<tr>
<td>Polyimide Coating</td>
<td>2.23</td>
<td>2.23</td>
<td>0.35</td>
</tr>
<tr>
<td>GFRP</td>
<td>10.9</td>
<td>10.9</td>
<td>0.34</td>
</tr>
</tbody>
</table>

3.5.1 FE Analysis Results

Figure 3.5 is the longitudinal Stress/Strain ($\sigma_{xx}$ and $\varepsilon_{xx}$) of the FE analysis at point C (see Figure 3.3). Subscript “xx” refers to stress or strain in the direction of the X-axis and on the face of the element in that direction, similarly for “yy”. The results obtained from the FE analysis are plotted in Figure 3.5 and are compared with those obtained from the electrical resistance strain gauge; the comparison also serves to verify the validity of the FE model. It can be seen that the results show excellent agreement between the numerical and experimental results.

![Figure 3.5 Stress ($\sigma_{xx}$) versus Strain ($\varepsilon_{xx}$) plot for the FE model](image-url)

3.5. Finite Element Model
By plotting the stress and strain field distributions along the X-axis of the material system and studying each material entity within the system it is possible to show whether the strains, hence stresses have been successfully transferred from the composite host to the glass core/cladding of the optical fibre through the primary coating interface material. The curve shown in each of the graphs (Figures 3.6, 3.7, 3.8, 3.9, 3.10, 3.11, 3.13, ) is the field distributions at maximum load (2200N).

In Figures 3.6, 3.7, all the stress and strain components for the composite host near the interface with the fibre’s primary coating material are shown. As expected the stress/strain axial components (e_xx and $\sigma_{xx}$) start to build-up immediately between points A and B (see Figure 3.3), where the specimen is constrained, to a uniform strain value when the composite is subjected to a tensile load. The transverse stress component ($\sigma_{yy}$) is zero within the uniform region but two peaks appear at points A and B due to end-effects, the transverse strain (e_yy) developed in the uniform region being due to the Poisson’s ratio effect. Shear stress and strain components are, as expected, zero within the uniform strain region but again at points A and B high values arise due to end effects. Figures 3.8, 3.9, show the stress and strain components for the core/cladding of the optical fibre; the stress and strain field are similar in shape and the transverse and shear components are zero in the uniform region with the disturbance in the core due to end effects negligible. The results indicate that stress/strain is successfully transferred to the optical fibre from the composite host. However, looking at the normal components (e_xx and $\sigma_{xx}$), the two small peaks at points A and B, which appear on the normal components of the host, have disappeared. This may be due to a buffering/absorbing effect caused by the primary coating of the optical fibre which acts as the interface. Figure 3.9(a) shows the normal strain distribution for the coating and the two peaks exist thus supporting the assumption made above.

Figures 3.10, 3.11, show the stress/strain components of the primary coating which acts as the interface between the core/cladding of the optical fibre and the composite host. From the results it can be seen that although the normal strain (e_xx) field is as expected the normal stress field ($\sigma_{xx}$) (Figure 3.10(b)) is distorted with high peaks at points A and B (see Figure 3.3). However, when the shear stress/strain components for the coating material are observed it can be seen that the interface experiences extremely high values of shear at points A and B. The transverse components are also
extremely high, thereby causing large deformations of the interface elements. It must be noted that the shear and transverse components are as expected zero within the uniform region. The high shear and transverse values, in effect, suggest that at points A and B the elements forming the coating are moving in opposite directions and therefore inducing massive distortions to the elements, consequently the normal stress field is also affected.

The results obtained clearly suggest that debonding is occurring at points A and/or B between the coating material and the host and/or between the coating and the core/cladding of the optical fibre. Figure 3.12 shows the deformed mesh of the FE model at point A and the deforming coating elements are indicated on the plot. The large deformation experienced by the coating interface can be clearly seen as well as the high transverse effects causing an expansion of the coating elements. However, interface debonding is difficult to investigate using FE analysis unless precisely defined. It has been suggested that debonding between the GFRP and the coating interface can be limited by using polyimide coated optical fibres instead of the usual acrylate coatings [Difrancescia 1991, Melvin 1991]. Other researchers have also shown that the acrylate coating generally experiences failures at the core/cladding-primary coating interface [Melvin 1991, Roberts 1991].

The analyses were repeated to investigate the stress strain characteristics when the stiffer polyimide coating material for the optical fibre was utilised, the results are shown in Figure 3.13. The strain field remains the same as expected, but now the stress field is also behaving as expected and the shear and transverse components are also significantly reduced. It is clear that the polyimide coating is superior to its acrylate counterpart. Melvin et al., performed high cycle tension-tension fatigue tests on unidirectional graphite/epoxy specimens with embedded optical fibres coated with either a single layer of polyimide or a dual layer of acrylate coating. Scanning electron microscopy showed interface debonding in the acrylate coated system but not in the polyimide coated system, in agreement with the finite element modelling results presented here.
Figure 3.6 Stress distributions for the GFRP next to the coating interface
Figure 3.7 Strain distributions for the GFRP next to the coating interface
Figure 3.8 Stress distributions for the core/cladding
Figure 3.9 Strain distributions for the core/cladding
Figure 3.10 Stress distributions for the coating interface (soft acrylate)
Figure 3.11 Strain distributions for the coating interface (soft acrylate)
Coating Elements for the soft acrylate material exhibiting large deformations

Figure 3.12 Exaggerated deformed mesh
Figure 3.13  Normal stress/strain components for the polyimide coating
3.6 Summary

A fibre optic sensor has been assembled, using low cost readily available components, exploiting the principle of polarisation interferometry and the properties of HiBi fibres. In this work the sensor was embedded with the protective coating in place and the experimental results obtained indicate that the sensor can operate reliably for strain values up to 2000με. A direct comparison of the FOS results with those from the resistive strain gauges shows excellent agreement between the two sensors. The fibre optic strain gauge in its present form will perform dynamic strain measurements up to values of 2000με. Although the polarimetric sensor possesses moderate sensitivity it offers an attractive alternative for the special case where large strain or integrated measurements are required.

A finite element model was developed in order to study and predict the behaviour of the stress/strain fields of the material system. The results of this analysis show that strain is successfully transferred from the GFRP host to the core/cladding of the optical fibre through the primary coating which acts as an interface. The modelling results also provided an insight into the reasons why the FOS deviated from linearity at a load of approximately 2200N. The analysis suggests that debonding is occurring at the coating interface (caused by end-effects), something which can be avoided by the use of polyimide coated optical fibres. Debonding of the soft acrylate coating was expected as this type of material is chosen mostly for use in the telecommunications industry because of the ease of stripping the coating from the cladding necessary for making connections. Polyimide coatings have the additional advantage of chemically bonding to the core/cladding of the optical fibre and would therefore permit sensors to operate at much higher loads than their acrylate counterparts. Their thermal stability also makes them more suitable for embedding in thermoset composite systems.
Chapter 4

Optimisation of Fibre Coating Properties

4.1 Introduction

"Smart Structures", with sensors and/or actuators embedded into or surface bonded on to a host material, are currently receiving attention worldwide. Monolithic load-bearing structures with built-in sensing systems could continuously monitor their internal strain, loading, vibration state, temperature and structural integrity. The development of smart polymer composite materials depends upon embedding the sensory system into the host material during the fabrication process. Fibre optic sensors (FOS) have been considered to be the prime candidates for internal structure and condition monitoring of polymer composite materials [Davidson 1993, Measures 1992, Hadjiprocopiou 1995]. If fibre optic sensors are incorporated into the composite structure the basis of an embedded sensor is formed, potentially capable of sensing strain and temperature variations throughout the service life of the composite.

For the embedded sensor or actuator systems, the issue of the obtrusivity of the sensor to the host material arises. Obtrusivity refers to possible structural strength degradation of the host material due to stress concentrations arising from the inclusion of the sensor. Optical fibres are typically 100-300μm in diameter and are considerably larger than the reinforcing fibres (5-10μm in diameter), and it is most important that the inclusion of these optical fibres does not alter the mechanical properties of the host composite material. The embedded optical fibres will, however, disrupt the composite host by causing local stress concentrations to arise when compared with
the stress levels had the fibre inclusion not been there [Davidson 1992]. The response of the material system, (host and sensor/coating), depends upon the material properties of the fibre and composite host and the condition of the interface between them [Davidson 1990, Roberts 1992]. The interface condition is important as it is the medium via which stress and strain are transferred from the host to the fibre sensor (thus directly affecting sensor “calibration”. Interface failure, fibre fracture, local microcracking and stiffness changes will also affect the performance and calibration of the embedded fibre optic sensor). Therefore, by careful selection of the material properties of the fibre primary coating which acts as the interface between the fibre core/cladding and the composite host, the obtrusive characteristics of the embedded fibre optic sensor can thus be minimised [Carman 1993, Das Gupta 1992].

Most of the work carried out by other researchers has concentrated on minimising the stress concentrations caused by the stiffness mismatch between the fibre/core and the composite host. In the work presented here the effects of temperature induced stresses during the service life of the host and the manufacturing residual thermal stresses were also taken into account, and the combined effect of thermal and mechanical loading cases was also considered. Finite Element (FE) modelling was employed to determine an “optimum” theoretical coating material stiffness, thickness and coefficient of thermal expansion for an optical fibre embedded parallel to the reinforcing fibres of a unidirectional glass fibre reinforced polymer (GFRP) in order to minimise the obtrusive behaviour of the optical fibre. This “optimum” interface material will create a system assembly (fibre/coating/host) which minimises possible degradations of the system’s transverse characteristic, by reducing the stress concentrations which arise due to the fibre inclusion.

The optimisation is achieved by minimising the stress concentrations which result in the composite host due to stiffness mismatch between the fibre and host and also due to the residual stresses resulting from mismatches in the thermal expansion coefficients.

4.1.1 Transverse Tensile Strength

Unidirectional laminae have very low transverse tensile strength and this does present a problem when embedding FOS. In general reinforcing fibres are orientated to lie parallel to the external loads but, transverse stresses cannot always be avoided and they
may lead to fracture failures of the composite. Unlike the longitudinal strength and stiffness and the transverse modulus, the transverse strength is reduced in the presence of the reinforcing fibres [Hollaway 1993]. Experimental results have also shown that the strength of composites are directly related to the micro-level composite properties, such as the presence of fibre surface treatments and fibre coatings [Madhukar 1991a, 1991b]. Therefore the transverse tensile strength of the composite host, with the embedded sensor running parallel to the reinforcement, is very sensitive to the presence and mechanical properties of the optical fibre, and failure is thought to initiate in the host close to the interface between the sensor and the host material [Roberts 1991, Jensen 1992]. Therefore, it is important to try and minimise the stress concentrations in the composite host, created by the optical fibre inclusion, and to maintain the transverse strength properties of the host, and as a result increasing the transverse strain to failure ratio of the composite host.

4.2 The F.E. model

The laminate/optical fibre geometry studied concentrates on a 125μm (diameter) silica fibre embedded parallel to the reinforcement in a unidirectional glass fibre (of 66% by weight) reinforced polymer (GFRP) plate. The composite plate under evaluation is to be used as reinforcement for a concrete beam, therefore, it is important not to perturb its structural characteristics by the inclusion of the optical fibre.

In order to study the stress concentrations of the system under evaluation a 2-D FE model was developed that considers both mechanical and thermal induced stresses under the plane strain assumption. The geometry and boundary conditions of the model are shown in Figure 4.1a and, since two planes of symmetry exist, only one quarter of the system was modelled. The mesh was formulated from 8-noded quadrilateral ABAQUUS [Abaqus 1994], elements (type DC2D8 for the thermal analysis and CPE8 for the structural analysis) using the pre processor of the FE package PATRAN from PDA Engineering; the mesh is shown in Figure 4.1b. The mesh was developed and carefully refined in such a way so as to enable the accurate modelling of the interface coating material properties and thickness. The material properties used in the analysis are shown in Table 4.1, where $E_x$, $E_y$, and $E_z$ are the elastic modulus values in directions X, Y and Z respectively, v is the Poisson’s ratio
and \( \alpha \) is the coefficient of thermal expansion. The GFRP density was calculated using the rule of mixtures [Hollaway 1993] as shown below:

\[
\rho_{\text{GFRP}} = \rho_f V_f + \rho_m V_m \tag{4.1}
\]

where \( \rho \) refers to density, \( V \) to the fibre volume content, and \( m \) and \( f \) refer to the matrix and reinforcing fibres respectively.

### Table 4.1 Material properties used in the analysis

<table>
<thead>
<tr>
<th>Properties</th>
<th>Core/Cladding</th>
<th>Interface Coating</th>
<th>GFRP host</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_x, E_y ) (GPa)</td>
<td>72.9</td>
<td>0.045 to 72.9</td>
<td>10.0</td>
</tr>
<tr>
<td>( E_z ) (GPa)</td>
<td>72.9</td>
<td>0.045 to 72.9</td>
<td>48.9</td>
</tr>
<tr>
<td>( \nu )</td>
<td>0.17</td>
<td>0.34</td>
<td>0.288</td>
</tr>
<tr>
<td>( \alpha_x, \alpha_y ) ( \text{C}^{-1} \times 10^{-6} )</td>
<td>0.45</td>
<td>10-400</td>
<td>13.38</td>
</tr>
<tr>
<td>( \alpha_z ) ( \text{C}^{-1} \times 10^{-6} )</td>
<td>0.45</td>
<td>-</td>
<td>8.60</td>
</tr>
<tr>
<td>Conductivity (W/m°C)</td>
<td>1.02</td>
<td>0.20</td>
<td>0.30</td>
</tr>
<tr>
<td>Density ( (10^3 \text{Kg/m}^3) )</td>
<td>2.56</td>
<td>1.11</td>
<td>2.139</td>
</tr>
</tbody>
</table>

The analysis of the structural system was performed using the FE package ABAQUS (ver. 5.4) [ABAQUS 1994]. The faces of the model were restrained to remain planar and the stress concentrations, from the embedded optical fibre were studied. The parametric study undertaken involved three design variables for the coating (stiffness, thickness and thermal expansion coefficient), and the design objective was the minimisation of stress concentration in the GFRP host (maximum principal \( \sigma_{\text{max}} \) and maximum shear \( \tau_{\text{max}} \)).

### 4.3 FE analysis results

#### 4.3.1 Transverse Tensile Load Case

A uniform tensile stress was applied to the model and the resulting stress distributions were analysed. The design variables in the material system studied are the properties of the interface coating; the Young's modulus \( E_z \), and the interface coating thickness \( T_i \). The interface elastic modulus value was varied from 45MPa to 70GPa thus including both a compliant ("soft") and a stiff interface; the thickness was varied from 5µm to 70µm including the thickness of commercially available coatings (e.g. polyimide \( \sim 8-15 \mu m \) and soft polymer \( \sim 65 \mu m \)), the uncoated case was also considered.
Figure 4.2 shows a comparison of the maximum principal stress ($\sigma_{\text{max}}$) concentrations in the host for five different interface elastic modulus values for an interface thickness of $T_c=10\mu m$ (a) and $65\mu m$ (b), as a function of angular position from point A to B (see Figure 4.1a). The stress concentrations are normalised to the maximum principal stress value obtained from the analysis of a pure host material (no optical fibre inclusion) under the same boundary and loading conditions. For the pure host the normalised value is 1.0, hence for the material systems under consideration, deviations from the ideal normalised value of 1.0 indicate stress concentration caused by the presence of the embedded optical fibre. The results show that the soft interface coating ($E_c=45\text{MPa}$) caused the highest stress concentrations in the composite host which increased as the interface thickness increased. However, it can also be seen that for both the interface thicknesses (for $T_c=10\mu m$ $E_c=2.0\text{GPa}$ and for $T_c=65\mu m$ $E_c=10.0\text{GPa}$), there is a certain coating material for which the material system behaves similarly to the pure host. Such an interface coating may be termed as “optimum”.

Figure 4.3 shows the stress concentrations arising in the host material at points A and B as a function of coating thickness and elastic modulus. Figure 4.3a shows the normalised stress concentration in the “xx” direction $\sigma_{xx}$ (where “xx” refers to the normal stress in the x-axis direction), and Figure 4.3b is the stress concentration in the “yy” direction $\sigma_{yy}$. The “optimum” coating thickness for a given elastic modulus is at the point where the respective curves for points A and B intersect satisfying the following criterion for selecting an “optimum” interface material proposed by other researchers [Case 1994, Tryson et al. 1981]:

$$\sigma_{rr}^{\text{host}}(r_i,0^\circ) = \sigma_{\theta\theta}^{\text{host}}(r_i,90^\circ)$$  \hspace{1cm} (4.2)

It can be seen that the “optimum” interface thickness increases as the elastic modulus is increased. As the coating thickness is increased ($E_c$ kept constant), and the combined stiffness of the core/cladding and coating decreases, the $\sigma_{yy}$ stress component reduces at point B but increases at point A. Furthermore both stress components ($\sigma_{xx}, \sigma_{yy}$) increase as the coating modulus ($E_c$) is decreased. Figure 4.3a indicates that for an optical fibre with a core/cladding diameter of 125$\mu m$ the optimised coating thickness is $\sim 12\mu m$ for $E_c=2.0\text{GPa}$, or $\sim 7\mu m$ for $E_c=1.0\text{GPa}$. For the case of $E_c=10.0\text{GPa}$ the result indicates that the optimum thickness is greater than

4.3. FE analysis results
70μm, thus making it unsuitable due to the large physical size the FOS will acquire. The very low modulus value of 45MPa exhibits the worst behaviour of all systems analysed.

To confirm the conclusion made for the “optimum” coating thickness the normalised maximum principal stress concentrations (σ_{max} in the GFRP host) against angular position, for E_c=2.0GPa and E_c=10.0GPa are shown in Figure 4.4a and 4.4b respectively. For the 2.0GPa interface the “optimum” thickness is again between 10 and 20μm whereas for the 10GPa interface the stress concentrations become constant and closer to 1.0 as the thickness is increased; this supports the conclusions made earlier.

The maximum shear stress (τ_{max}) in the host was also studied, normalised by the maximum shear stress in a pure host material. From Figure 4.5 it can again be seen that for the two interface thicknesses shown here, the worst concentrations are for the low elastic modulus interface, while the interface that now demonstrates a relatively constant variation of shear stress, and a value close to 1.0, is the 10.0GPa coating for both the 10μm and 65μm interface thickness. Again, this suggests that this coating material is the “optimum” material making this sensor/host combination resemble the behaviour of the pure host. However, the optimum for maximum principal stress σ_{max} was E_c=2.0GPa whereas for maximum shear stress τ_{max} was E_c=10.0GPa. This is significant since under certain loading conditions a material is much weaker in shear than in tension.

4.3.2 Thermal Load Case

The material properties used for the thermal analysis can be seen in Table 4.1. The analysis carried out is an ideal case as the residual stress concentrations, due to cooling down after the manufacturing process, were ignored in this section, but are discussed in more detail in the next section. The thermal analysis performed was primarily concerned with the service life of the GFRP plate and how it is affected by the temperature changes during a working day. The stress concentrations generated in the composite host due to the embedded optical fibre were studied for the case when the temperature changes from -20°C to +30°C (one day cycle, a total change of 50°C).
Stress concentrations will arise in the composite host due to the mismatch of the coefficients of thermal expansion between the material system components (core/cladding, interface coating and GFRP). For the case of the GFRP host without an embedded optical fibre, in an ideal thermal loading case the model is free to expand in all directions therefore no stress concentrations exist ($\sigma_{xx}, \sigma_{yy}=0$). A parametric study for the interface coating modulus of $E_c=2.0\text{GPa}$ is shown in Figure 4.6. Similar studies were also carried out for all elastic modulus values studied in the mechanical load case.

The thermal expansion coefficient of the interface coating was varied (from $10\times10^{-6}$/°C to $400\times10^{-6}$/°C) and two interface thicknesses were studied ($10\mu\text{m}$ and $65\mu\text{m}$). Figure 4.6a and 4.6b show the variation in the thermally induced radial stress ($\sigma_m$) along the x-axis away from the fibre centre and Figure 4.6c and 4.6d show the hoop stress concentrations ($\sigma_{00}$). It can be seen that for $T_c=10\mu\text{m}$ the stress components decrease (in the core/cladding region as well as the GFRP) as the coefficient of thermal expansion ($\alpha$) is increased, whereas for $T_c=65\mu\text{m}$, as $\alpha$ is increased, the stress concentrations in all regions increase. However, it can also be seen that for a certain value of $\alpha$ the radial and hoop stress components will be zero since, as $\alpha$ is varied, the stress components go from tension to compression and vice-versa. It may thus be concluded that for a particular value of $\alpha$ an “optimum” interface coating exists that makes the material system behave similarly to the pure host material. The thermal induced stresses in the core/cladding region of the fibre are also of particular interest as for some strain sensing techniques it is desirable to avoid thermally induced strains or in the case of cure monitoring, high thermally induced strains are desirable in order to achieve high sensitivity. Polyimide coatings are of particular interest and in Figure 4.7 the thermal stress concentrations for a polyimide coated fibre for varying interface thickness are shown ($E_c=2.0\text{GPa}$ and $\alpha=20\times10^{-6}$/°C). It can be seen that for $T_c=50\mu\text{m}$ the hoop and radial thermal stress concentrations in the GFRP host are minimised (almost zero), and the core/cladding stress concentrations are greatly reduced.

Following the conclusions made above a detailed thermal analysis was also performed to determine the variation of the radial and hoop stress concentrations in the GFRP host at point A (see Figure 4.1a) and the results are shown in Figure 4.8. The graphs obtained are for a coating thickness of $12\mu\text{m}$ which was one of the “optimum” geometries suggested in the previous section. It can be seen that, as the
interface coating elastic modulus is increased (thus increasing the effective rigidity of the optical fibre), the thermally induced stress concentrations increase. The stress concentrations also increase when the thermal expansion coefficient is increased. This is in opposition to the transverse tensile analysis results where the low modulus coating had the worst effect on the GFRP host. If the objective is only to minimise residual thermal stresses this may be achieved by making the interface coating as compliant as possible. Such a compliant coating however, will severely degrade the transverse performance of the host as shown in section 4.3.1

However, one significant observation is that for an interface coating thermal expansion coefficient, \( \alpha = 65 \times 10^{-6}/\degree C \) (±2.5%), the stress concentrations (\( \sigma_r \) and \( \sigma_\theta \)) in the composite host at \( r \) are minimum (almost zero) for all values of elastic modulus. This is significant as thermal stress concentrations are now almost eliminated but a very wide spectrum of coating stiffness values can be investigated for different optimization criteria. Clearly this value will vary for different coating thicknesses and is also a result specific to the material system under investigation in this work.

### 4.3.3 Effect of manufacturing induced thermal stresses

Thermal residual stresses are generated during the processing of glass fibre/epoxy composites, particularly during the final cool from the cure temperature. These result from the different mechanical and thermal expansion characteristics of the optical fibre and the surrounding epoxy/fibre composite host. The residual stresses are important in as much as they affect the overall mechanical behaviour of the composites. If these stress concentrations are significant failure may be initiated at external loads which are lower than predicted. In this section the effect of these residual thermal stresses is considered.

The material system was assumed to cool down from a curing temperature of 160°C to 20°C with a state of zero stress and strain at the start of the cooling process, simulating the conditions during the manufacturing of the pultruded GFRP plates, and was then subjected to a transverse tensile load, because, as mentioned previously, the objective is to minimise all stress counteractions not just thermal stresses. The glass transition temperature is assumed to occur just below the curing temperature so that elastic conditions apply over the whole time that cooling is occurring. The
conclusions made from the transverse tensile and thermal loading cases were combined and the material systems studied were the ones termed as "optimum".

Figure 4.9 shows the normalised maximum principal and maximum shear stress concentrations in the GFRP host against angular position at \( \theta \). The elastic modulus values of 45.0MPa, 2.0GPa and 10.0GPa were used for the interface; the uncoated case was also considered. The thickness used was \( T_c = 10 \mu m \) and the coefficient of expansion was set to \( \alpha = 65 \times 10^{-6}/^\circ C \); this is the "optimum" value for the 10\( \mu m \) coating thickness found in the thermal analysis. The analysis also included the coefficient of expansion for the polyimide coating (\( \alpha = 20 \times 10^{-6}/^\circ C \)) for two thickness values (\( T_c = 10 \) and 50\( \mu m \)).

It can be seen that the soft acrylate coating (\( E_c = 45 \)MPa) causes the highest stress concentrations in the host, although they are reduced by 1.2 times when compared to result shown in Figure 4.2; this result shows the effect of the thermal stresses. For the polyimide coating the thermal analysis suggested an optimum thickness of 50\( \mu m \) for the actual thermal expansion coefficient of \( \alpha = 20 \times 10^{-6}/^\circ C \) of the material. However, it can be clearly seen that the increased interface thickness in order to reduce thermal stresses, is not justified as the stress concentrations increase when compared to the 10\( \mu m \) coating thickness. Hence coatings of smaller thicknesses are favoured for embedded FOS applications. The stress concentrations are also reduced for the 10.0GPa coating when compared to the results of Figure 4.2 and Figure 4.5.

However for the combined effect of residual thermal stresses and transverse load the stress concentrations in the host (\( \sigma_{\text{max}}, \tau_{\text{max}} \)) are minimised by the proposed optimised coating, \( E_c = 2.0 \)GPa, \( T_c = 10 \mu m \), \( \alpha = 65 \times 10^{-6}/^\circ C \). Compared to the compliant coating the stress concentrations are reduced by 1.5 times, they also satisfy the condition given in equation 4.2.

### 4.4 Summary

The results obtained from the FE analysis indicate that an "optimum" interface coating exists such that the combined properties of the optical fibre coating and GFRP host minimise the stress concentrations in the material system. This "optimum" interface results in a system whose mechanical properties are similar to that of the pure GFRP host and this was shown to be the case with the minimisation of the maximum principle
stress (\( \sigma_{\text{max}} \)) and maximum shear stress (\( \tau_{\text{max}} \)) concentrations in the GFRP host. If a maximum principal stress failure criterion is used, the results suggest that the transverse strain to failure of the GFRP may be increased by 1.5 times by the use of the optimised coating.

The FE analysis model assumed that no resin eye exists around the optical fibre and that perfect bonding occurs between the core/cladding, interface coating and GFRP host, the latter because interface bonding is one of the most difficult effects to model accurately. The transverse loading case results indicate that an interface coating with an elastic modulus value of \( E_c = 2.0 \text{GPa} \) and a thickness of \( t_c = 12\mu\text{m} \) will minimise stress concentrations in the host. However, in the case of maximum shear stress concentrations the stiffer coating of \( E_c = 10.0 \text{GPa} \) gave the best results and the stress variations in the GFRP host around the coating were decreasing as the coating thickness was increased. The parametric study for a transverse tensile load showed that compromises need to be made according to the design requirements and the possible service life of the material system.

Initially the thermal analysis was performed assuming that no residual stresses develop in the material system during the cool down process after manufacturing. The thermal loading results indicate that stress concentrations in the GFRP host are affected by the coefficient of thermal expansion of the coating as well as its stiffness. Furthermore, by varying the thermal expansion coefficient, the residual stress concentrations in the GFRP host as well as the core/cladding region of the optical fibre can be minimised. A detailed analysis for a 12\( \mu\text{m} \) interface coating thickness suggests that, for a coating expansion coefficient of \( \alpha = 65 \times 10^{-6}/\text{°C} \), the stress concentrations in the GFRP host are minimum for all values of coating elastic modulus. This is significant as thermal stress concentrations are now almost eliminated but a very wide spectrum of coating stiffness values can be utilized for different optimization criteria, either reducing the fibre sensor obtrusivity or enhance the sensor performance. However the result is specific for the material system considered in this study.

Subsequently the effect of residual thermal stresses during manufacturing was also taken into consideration and was combined with a transverse tensile load. The "optimum" coating parameters established by the individual load cases were used,
and the stress concentrations in the composite GFRP host were minimised, as expected. The study also suggests that FOS may be designed for specific sensing techniques.

Figure 4.1  Model Diagrams

(a) Geometry and Boundary Conditions

(b) Detail of the finite element mesh
Figure 4.2  Maximum principal stress concentrations ($\sigma_{max}$), distribution in the composite host at $r_i$, for varying interface elastic modulus ($E_c$)
Figure 4.3 Stress concentrations in the composite host at point A and B as a function of the coating thickness ($T_d$) and elastic modulus ($E_c$)
Figure 4.4 Maximum principal stress concentrations ($\sigma_{\text{max}}$), distribution in the composite host at $\eta_i$ for varying interface thickness ($T_i$).
Figure 4.5 Maximum shear stress ($\tau_{\text{max}}$) concentrations distribution in the composite host at $r_1$ for varying interface elastic modulus ($E_i$)
Figure 4.6 Thermal induced stress concentrations due to a 50°C temperature change for the polyimide coating ($E_c=2.0$ GPa) for varying thermal expansion coefficients.
Figure 4.7 Thermal induced stress concentrations due to a 50°C temperature change for the polyimide coating ($E_c=2.0$ GPa, $\alpha=20\times10^{-6}/^\circ\text{C}$) for varying interface thickness ($T_e$)
Figure 4.8 Variation of thermal induced stress concentrations at $0^\circ$ (point A) due to a $50^\circ$C temperature change as a function of the coating elastic modulus and coefficient of thermal expansion.
Figure 4.9 Normalised stress concentration variation in the GFRP host subjected to a transverse tensile load taking into consideration manufacturing induced thermal stresses due to cooling down from 160°C to 20°C.
Chapter 5

Fabry-Pérot Strain Sensor

5.1 General Background

The motivation for building the fibre-optic Fabry-Pérot (FFP) was to be able to combine the single-fibre 'self-referencing' of the polarimeter with the high sensitivity of the Michelson interferometer. Although the FFP is conceptually simple in design, the manufacturing procedure required more effort to establish than the polarimetric sensor (see Appendix A).

As mentioned above, the aim was to remake the Michelson interferometer into a single fibre device. A naive, but entirely correct, solution is simply to put the two Michelson mirrors into a single fibre. The only problem in this approach is the fact that the first mirror must be partially transmissive for interference with the second mirror to occur. Such a device was first build in 1899 by Fabry and Pérot (using bulk optics) [Vaughan 1989]. In keeping with interferometric tradition, it was named after them. Interestingly, the mathematical description of its operation predated its construction by 68 years; being formulated by Airy. The characteristic that sets the Fabry-Pérot apart is that it is a multiple-beam (rather than two beam) device, and thus represents an entirely new class. Multiple beam interferometers differ from their two-beam counterparts in their optical transfer functions: rather than being sinusoidal, they exhibit sharp resonances. It is the resonance property of the Fabry-Pérot that has made the device by far the most commercially significant of all the interferometers, for it serves as the basis of all lasers; the Fabry-Pérot cavity does not act as an interferometer, but rather as a 'resonant filter' for a lasing medium. For use as a fibre-optic strain sensor this property is not essential and is often undesirable. For
heterodyne-type orthogonal phase demodulation the device is detuned to the point that its response is virtually sinusoidal (i.e., two beam).

The principles of the Fabry-Pérot interferometers (extrinsic and intrinsic) have already been described in Chapter 1, section 1.7.3 on page 19.

5.2 Characteristics of the Fabry-Pérot Output

5.2.1 Fibre interferometers as strain gauges

Strain on an optical fibre translates to a change of the optical path length through both the physical path length and the refractive index of the transmission medium as shown below:

\[ \Delta L = n \Delta l + l \Delta n \] (5.1)

where \( L \) is the optical path length, \( l \) is the physical path length and \( n \) is the refractive index of the fibre core. \( \Delta l \) and \( \Delta n \) are both strain dependent. \( \Delta l \) is directly proportional to strain, with the constant of proportionality being the gauge length of the sensor. The dependence of \( \Delta n \) on strain is through the strain-optic coefficients of the fibre.

From equation 5.1, we can define the phase strain sensitivity for the FFP sensor showing its dependence on the source wavelength. It has been shown experimentally, that the magnitude of the phase shift is approximately 0.65°/µε per mm of gauge length for a single pass fibre interferometer using a 633nm source (using York SM600) [Valis 1989]. This value doubles for reflective cases. So for example a 10mm gauge length reflective Fabry-Pérot with similar components will have a gauge sensitivity of ~13°/µε.

\[ G = \frac{2\pi}{\lambda} n \left( 1 - \frac{n^2}{2} \cdot (p_{12} - \sqrt{p_{11} + p_{12}}) \right) \] (5.2)

5.2.2 Fabry-Pérot output

The characteristic shape of the transfer function of a Fabry-Pérot cavity in transmission mode is given by the so called Airy function:

\[ A(\psi) = \frac{1}{1 + F \sin^2(\psi/2)} \] (5.3)
where \( F = \frac{4r_1r_2}{(1-r_1r_2)^2} \) (5.4)

and is referred to as the finesse.

The variation of the power phase relation due to finesse is shown in Figure 5.1. Naturally when the cavity is used in reflection mode, the transfer function becomes one minus the Airy function. The sharpness of the peaks in the Airy function is determined by the coefficients of reflection, transmission and absorption of the cavity mirrors. High finesse (\( F \approx 10000 \)), cavities exhibit comb like transfer functions making them unsuitable for decoding by any other than fringe counting, due to the ambiguity inherent in the function over the majority of its period. At moderate finesse, the relation resembles a harmonically distorted sinusoid, while in the low-finesse regime (e.g. \( F \approx 10 \)), the relation approaches a sinusoid.

![Figure 5.1 The Airy function shown on logarithmic and linear scales.](image)

5.2. Characteristics of the Fabry-Pérot Output
5.3 Uniaxial FFP strain sensor

5.3.1 Manufacturing procedure

The first reported intrinsic, local FFP were described by Lee et al. (1989), who used TiO$_2$ films, and by Leilabady, who used an air-gap, in 1987; although other designs that were either extrinsic or nonlocal preceded it. Lee et al. have used the device as both a free fibre and composite embedded (graphite/epoxy) temperature sensor.

The key to fabricating an intrinsic FFP lies in the ability to make semireflective fusion splices. Lee et al. succeeded in doing this by sputtering TiO$_2$ films on fibre endfaces, and fusion splicing them. A similar but simpler technique was used by the author. The ends of the two cleaved and cleaned fibre (York SM600, 3.5μm/125μm) ends were dipped in a Rochelle solution for one hour to coat them with silver, a film was deposited within the first five minutes, but experimentation with various dip times showed that one hour was the best result. The two ends were fusion spliced with the SUMITOMO ELECTRIC TYPE-35 fusion splicer, which was programmed to the fuse cycle listed in Table 5.1. This technique yielded usable semireflective splices, but with a very low probability of success of approximately 20%. The technique was then modified such that the fibres were silvered for only 30 mins, and fused with the cycle listed in Table 5.2. Because of the function of the fusion splicer an additional re-fuse cycle was not possible. This will generally reduce the reflectivity to a desired point, but also have the possibility of damaging the semireflective fusion splice. The latter technique yielded more usable and consistent sensors, approximately 50% of the splices were of use.

Power reflection, transmission, and loss coefficients for these splices were typically: $R=0.2$, $T=0.4$ and $A=0.4$. The lowest loss case was $A=0.3$ and the worst case corresponds to splice failure. The loss represents power coupled to cladding and radiation modes rather than true absorption. Valis (1989), has found that the tensile strength of the semireflective splice was greater than 1N, using a free fibre tensioning rig. If localised mirroring is used i.e. only the fibre core the splice strength should increase to the point where it is only marginally weaker than a typical fusion splice.
Critical to the successful fabrication is the ability to cleave fibre endfaces that are perpendicular. Because of this requirement the cleaves were made using the high precision cleaver FUJIKURA CT-07. The cleaver yielded endfaces perpendicular to within 0.1° consistently.

The Fabry-Pérot cavity was formed by cleaving and silvering one end of the fibre at a short distance (5-15mm) from the splice. A cleaved, silvered mirrored end (the secondary mirror) has a typical power reflectivity of 0.7-0.85. Assuming typical primary and secondary mirror reflectivities, the cavity has a nominal finesse of 0.4. The length of the cavity (the sensor gauge length) was measured using a travelling microscope. The reflective sensor was completed using bulk optics (in the absence of a 2x2, 3dB coupler). Light from a 1mW HeNe laser was launched into the fibre, and a photodiode was used to monitor the backreflected power, as shown in Figure 5.2.
5.4 Experimental Results

5.4.1 Power/Strain relation

To verify that the sensor was operating in the low finesse regime, the cavity was adhered to the surface of a GFRP coupon which was then loaded. The monitor photodiode and electrical resistance strain gauge outputs was recorded using a PC. This allowed the backreflected power vs strain (and hence power vs. phase) relation to be observed. A typical cavity output is shown in Figure 5.3. The horizontal scale is determined by the gauge length of the sensor and the vertical scale is determined by the optical efficiency of the system. The plot shows that the output response is virtually sinusoidal, indicating that the two-beam model is a good approximation.
In order to set usable contrast there is a need to adjust the input state of polarisation (SOP). The power-strain plot will go from minimum to maximum based on the input SOP. This can be easily solved by using HiBi fibre. Valis (1989) has experimentally shown that the contrast is only weakly dependant on the applied strain (the changes in output power are mostly due to laser amplitude-noise).

5.4.2 Surface Adhered Uniaxial IFFP Strain Sensor

5.4.2.1 Experimental Setup
The experimental setup is shown in Figure 5.4. Power from a 1mW HeNe laser source was launched into the fibre using bulk optic components (in the absence of a 2×2 coupler). The backreflected intensity was monitored using a PIN photodiode and the output was converted to digital form and fed into an HP data logging computer, which also controlled the INSTRON tensile machine and the strain gauges data logger. This was done so that phase cycles (π) could also be logged and referenced to a strain and load measurement.

The IFFP and the electrical resistance strain gauges were bonded in the middle of a glass fibre coupon (25×300×2mm) as shown in Figure 5.5, using a cyanoacrylate adhesive. Aluminium tabs were also bonded on the coupon ends to provide for a better grip in the Instron. After the fibre sensor and strain gauges were adhered the coupon was left undisturbed for a day before it was mounted on the tensile machine and tested.
Figure 5.4  Fabry-Perot strain sensor experimental setup using bulk optics.

Figure 5.5  Adhered IFFP strain gauge detail on the centre of the GFRP coupon.
5.4.2.2 Experimental results
The results obtained from the surface mounted IFFP strain sensors are plotted in Figure 5.6. 'Fringe' counting was used to record the output of the IFFP at $\pi$ intervals and the fibre gauge length was determined using a travelling microscope.

![Graph showing load/strain curves for two IFFP sensors.](image)

**Figure 5.6** Load/strain curves for two IFFP sensors.

The fibre optic sensor strain data is plotted for direct comparison against the results obtained from the electrical resistance strain gauges. It can be seen that the two are in
good agreement. The discrepancies on the curves was due to the fact that the GFRP coupon was slipping inside the Instron grips, efforts to avoid this proved unsuccessful. The sensors were loaded over a strain range of 2000με but the slippage of the coupon was too big and therefore data above 1000με was discarded.

The IFFP sensors yielded a linear phase strain relation ($r^2 > 0.996$) as shown in Figure 5.7. The phase cycles are plotted against the strain obtained from the electrical resistance strain gauges. The mean phase strain sensitivity was,

$$S = (0.640 \pm 0.005) \frac{deg}{\muε \cdot mm} \quad (5.5)$$

which is in good agreement with other reported phase strain sensitivities [Valis 1989, Bertholds et al 1987].

Figure 5.7 Phase Strain response for a surface adhered IFFP sensor.
5.5 Phase-demodulation techniques for the FFP strain sensor

Although the sensitivity is the same as the Michelson interferometer, the FFP’s optical behaviour as it relates to phase demodulation is closer to the local polarimeter. In both devices interference takes place at the fusion splice of the lead fibre and the gauge length. By analogy all the phase demodulators applicable to the polarimeter are also applicable to FFP.

The requirements of a FFP phase-demodulator to achieve performance comparable to an electrical strain gauge are:

- Be applicable to sensor gauge lengths of interest (1-20mm).
- Able to resolve 1με. This corresponds to 1° to 15° phase resolution.
- Have a wide strain range: typically ±10,000με. (This corresponds to a phase-tracking range of approximately 500 to 5000 radians.
- Cover a wide frequency range (dc to 1kHz).

The drive for the discussion that follows was to improve on the ‘fringe’ counting interrogation system used during testing. The work is based upon literature previously published.

5.5.1 Fibre Interferometer Output

Since the output of the low finesse Fabry-Pérot interferometer is sinusoidal, it can be represented by the standard form of the classical interferometers output as

\[ i_d = A [1 + K \cos(\phi_s + \Phi_m)] \] (5.6)

where \( i_d \) is the photo-detector current, \( A \) is related to the source power and photodetector characteristics, \( K \) is the fringe visibility, \( \phi_s \) is a measurand independent phase offset (ideally constant), and \( \Phi_m \) is the measurand induced phase shift.

The interferometer can be considered to be a linear phase output device rather than a periodic intensity output device. This makes the task of decoding interferometric output signals appear simple. The problem lies in the fact that optical detectors can detect only intensity and so translation of the output from intensity to phase...
information is necessary. Direct translation is not practicable for the following reasons.

Firstly the sensitivity of the output intensity to a phase shift is dependent on the total phase. Sensitivity is greatest at the so-called quadrature point, where $\phi_p + \Phi_m = (2n+1)\pi/2$, and $n$ is an integer. When $\phi_p + \Phi_m = n\pi$ the sensitivity is zero. This loss of sensitivity also causes directional ambiguity. As a peak or trough is traversed, it is impossible to tell whether the interferometer has maintained or reversed its direction of motion.

Secondly the DC offset of the fringe signal and its visibility both drift as a result of the random evolution of the state of polarization in ordinary single mode fibres. It is impossible to distinguish between an actual change in the phase of the signal, and an offset or amplitude drift. Assuming that the visibility never actually decreases to zero, visibility changes can be taken care of by amplifying and clipping the signal, or by passing it through a zero-crossing detector to convert it to a square wave. However both techniques are unreliable when applied to a signal that has a drifting DC offset.

### 5.5.2 Production of Quadrature Components

If two output signals separated by some known phase angle are available, then the problems of zero sensitivity at maxima and minima of the transfer function and directional ambiguity can be solved. Whenever one of the signals is at zero sensitivity, the other is usable. The best case is when the phase angle between the two signals is $90^\circ$. The signals can then be considered to be the sine and cosine of the measurand (both containing an offset), and said to be in quadrature. When one of the two signals in quadrature is at the point of zero sensitivity, the other is at maximum. Unfortunately, the extraction of phase information from these signals requires knowledge of the other signal parameters such as visibility and offset. Since only two signals are available, and the independent variables on which they depend are more than two, it is not possible to decode quadrature signals that have changing offsets and visibilities, without some form of extra information.

In the simplest case, if offset and visibility are constant, the quadrature components can be passed to a fringe counter system that has the ability to determine direction of fringe motion from these two signals. Fringe counters are relatively quick, but suffer
from resolution problems. One fringe corresponds to more than 27µe for a 10mm Fabry-Pérot sensor. Strain resolution improves with gauge length at the expense of spatial resolution.

There are a number of different techniques to produce quadrature components, but those based on couplers (e.g., 3x3 coupler) or differential modulation of one fibre arm relative to another are not applicable to the FFP sensor. Another way to create quadrature components is to switch the wavelength of the source between two values calculated such that they will create fringe patterns that are 90° apart. The photodetector signal must then be gated or sampled at the appropriate times to separate the two distinct outputs [Turner et al. 1992]. Alternatively two distinct sources can be used, but in general the wavelength separation necessary is so small that a single source can be used.

5.5.3 FFP Pseudo-heterodyne Systems

The recombination of quadrature components can be achieved with mixers and an adder as shown in Figure 5.8. This circuit is based on the equation:

\[
\sin(\omega t)\cos(\phi) + \cos(\omega t)\sin(\phi) = \cos(\omega t + \phi)
\]

The output of the adder is a carrier of frequency \(\omega\) phase modulated by the measurand. The phase of the signal is then compared to that of a reference carrier in order to retrieve the measurand. In other words, some form of phase sensitive detector is necessary to demodulate the signal, thereby extracting the measurand. Since the effect is that of translating the signal in the frequency domain, such a system is known as a pseudo-heterodyne system. The largest problem is that amplitude and visibility drifts at the input will cause large errors in the output.

There is a much easier way to arrive at a carrier phase modulated by the measurand. As already mentioned this method involves driving the interferometer over some portion of a fringe, or in some cases over more than a fringe. This means that any given sample of the signal can be processed with respect to its nearby local maxima and minima at any given time. This means that DC level shifts in the interferometer output can be made to disappear simply by AC coupling the signal at some intermediate stage in the processing. Any fringe visibility drift created by the optical system must still be taken care of by the demodulator system.
Figure 5.8 Recombination of quadrature components to produce an output signal, from [Turner et al. 1992].

The two common methods for creating a predictable variation in the output of a fibre interferometer are using a piezo-electric fibre stretcher in a sensitive part of the interferometer, and modulating the wavelength of the source. The PZT modulation method as mentioned before is not suitable for the Fabry-Pérot.

There are three modulation waveforms that have been used successfully to produce phase-modulated carriers. These are square, sinusoidal, and ramp (sawtooth) waveforms. The square wave modulation technique was briefly explained before as a method for the production of quadrature components which can be recombined to create the carrier.

The sinusoidal modulation method has been reported by Webb et al., and by Lewin et al. By recalling equation equation 5.6,

\[ i_d = A[1 + K \cos(\phi_s + \Phi_m)] \]  

Now if a source wavelength \( \lambda \) results in an output phase (in the absence of a strain signal),

\[ \phi_\lambda = \frac{2\pi n l}{\lambda} \]
where \( nl \) is the optical length of the interferometer path imbalance, then,

\[
\frac{d\phi_d}{dt} = -\frac{2\pi nl i_d}{\lambda^2} dt
\]  

(5.10)

So a sinusoidal wavelength modulation will result in a sinusoidal phase modulation of the output, i.e.,

\[
i_d = A\{1 + K\cos[\phi_d + \Phi_m + \phi_c \sin(\omega_c t)]\}
\]  

(5.11)

where \( \phi_c \) is the amplitude of the phase modulation, and \( \omega_c \) is the modulating frequency. Obviously it is important that \( \omega_c \) is much greater than the maximum frequency present in the measurand induced signal. Expanding the last result into its Fourier components and denoting \( \phi_d + \Phi_m \) by \( \Phi \) results in,

\[
i_d = A \cdot (1 + K\cos(\Phi_c)J_0(\Phi_c) + 2K\cos(\Phi_c)\sum_{n} J_{2n}(\Phi_c)\cos(2n\omega_c t) \\
-2K\sin(\Phi_c)\sum_{n} J_{2n+1}(\Phi_c)\sin((2n+1)\omega_c t))
\]  

(5.12)

Now if this signal is multiplied (gated) by a square wave,

\[
G(t) = \frac{1}{2} + \frac{2}{\pi}[\cos(\omega_c t)]
\]  

(5.13)

and filtered at the frequency \( 2\omega_c \), the results will be,

\[
R(t) = A(\phi_c)\sin(\Phi_c)\sin(2\omega_c t) + B(\phi_c)\cos(\Phi_c)\cos(2\omega_c t)
\]  

(5.14)

where \( A \) and \( B \) are defined as,

\[
A(\phi_c) = -\frac{8K(J_1(\phi_c))}{\pi} + \frac{J_3(\phi_c)}{5} - \frac{J_5(\phi_c)}{21}
\]  

(5.15)

and

\[
B(\phi_c) = KJ_2(\phi_c)
\]  

(5.16)

if \( \phi_c \) is now adjusted such that \( A(\phi_c) = B(\phi_c) \), then,

\[
R(t) = A(\phi_c)\cos(2\omega_c t + \Phi_d)
\]  

(5.17)
which is effectively a carrier at the frequency $2\omega_s$, phase modulated by $\Phi_s$. This can now be demodulated with a phase sensitive detector to produce $\Phi_s$, which is the signal of interest. Figure 5.9, shows the intermediate signals during the above operations.

![Intermediate signals](image)

**Figure 5.9** Intermediate signals in the creation of a phase modulated carrier using sinusoidal source wavelength modulation (in the absence of any disturbance to the interferometer): a) source wavelength modulation signal, b) interferometer output, c) square wave "gate", d) gated interferometer output, and e) carrier after filtering [Webb et al. 1988].

Lewin gives a good summary of the mechanics of the ramp modulation technique [Lewin et al. 1985]. If the wavelength of the source is ramped linearly over a complete fringe, then the phase of the interferometer output will also change linearly according to,

$$\Phi_c = \frac{\Phi_a \omega_c}{2\pi} t$$

(5.18)

and the photo-detector current will become,

$$i_d = A[1 + K\cos(\Phi_s + \Phi_e)]$$

(5.19)

In practice, $\Phi_a$ is usually set to $2\pi$ and so,

$$i_d = A[1 + K\cos(\omega_c t + \Phi_s)]$$

(5.20)

which is a carrier at the frequency $\omega_s$, phase modulated by $\Phi_s$. All of this assumes a continuously increasing ramp. In practice, the flyback of the ramp creates a spike in the carrier which must be filtered out before the carrier can be demodulated. Figure 5.10, shows the signals at various stages of the above process.
Figure 5.10 Intermediate signals in the creation of a phase-modulated carrier using linear ramp modulation of the source wavelength (in the absence of any disturbance to the interferometer).

The magnitude of the wavelength modulation necessary to produce a phase shift of one fringe is dependent on the nominal source wavelength and the optical path length of the sensing region. Pseudo-heterodyne scheme involves modulating the source wavelength to produce an orthogonal phase shift. Therefore, imposing the condition of phase orthogonality on the locally linear expression (see equation 5.1),

\[ |\Delta\phi| = \frac{\partial \phi}{\partial \lambda} |\Delta\lambda| \]  \hspace{1cm} (5.21)

results in the following expression for the required wavelength shift,

\[ \Delta\lambda_{orthogonal} = \frac{\lambda^2}{nOPD} \]  \hspace{1cm} (5.22)
Figure 5.11 shows the necessary wavelength shifts as a function of the optical path difference (OPD), for five common laser wavelengths. The marker indicates that a wavelength shift of approximately 0.0236nm is necessary to create a one fringe shift in the output of a 10mm FFP (the OPD is twice the gauge length as it operates in reflection), with an 830nm source. Note that to create the same output phase shift using the same FFP with a 1500nm source would require roughly three times the source wavelength shift.

5.5.4 Phase Tracking

Assuming that a phase modulated carrier has been generated, the next step is to extract the phase information. Simple phase comparators will measure the phase difference between two signals to a maximum of about ±90°. Phase-locked loops (PLLs) and conventional FM discriminators cannot be used because of the huge dynamic range of the signal. Remember that for a 10mm gauge length Fabry-Pérot with a 633nm source, a range of ±1000με corresponds to a phase of ±13000° or more than ±36 fringes.
If a range of only a few fringes is needed, the AD639 trigonometric chip can be used. This chip can be configured to produce a voltage proportional to the sine of the sum of the two input voltages. The system is shown in Figure 5.12, and was reported by Tveten et al. (1988). The laser and the AD639 are fed the same modulating signal, and the error signal created by comparison of the trigonometric chip output and the interferometer output is fed back to the chip in order to keep the phases equal. The result is that the error signal is proportional to the phase deviation caused by the measurand. The drawback to this circuit is that it will only track phases smaller than about ±540° which corresponds to ±40με for a 10mm gauge length Fabry-Pérot using a 633nm source.

Figure 5.12 Use of the AD639 trigonometric chip for carrier phase tracking. Modified from Tveten et al. (1988).

A phase tracker is a device that uses a phase comparator to compare the signal carrier to the phase of the reference carrier. In steady-state the two are in quadrature. When a phase shift is detected, the tracker creates an artificial phase shift in the reference carrier in order to bring it back into quadrature with the signal carrier. The general architecture is shown in Figure 5.13. The phase shift required for correction is equal to the signal phase shift.

Two such phase trackers have been reported in the literature and both are analog/digital systems. They differ mostly in how they create the phase shift on the reference carrier.
The tracker developed by Nokes (1978), uses the scheme shown in Figure 5.14. Four sinusoids of the same frequency but spaced in equal $90^\circ$ steps are created from a simple carrier by a four quadrant phase shifter. These are applied to four equally spaced taps of a resistor ring. The ring is comprised of 120 equal resistances with taps at all connections. The taps are connected to a multitap MOS FET multiplexer switch whose position can be controlled digitally by supplying the chip with a binary address. The addressing is done by a digital counter and so the value stored in the counter determines the switch position, and consequently the phase from the sweeper terminal of the switch, in $3^\circ$ steps. The amplitude of the output is kept constant by an automatic-gain-controlled (AGC) amplifier. The counting direction and speed are controlled by the error signal from the phase comparator. Thus when the signal phase changes, an error signal is generated which causes the counter to count, changing the reference phase until the phase error is again zeroed. The value in the counter, therefore, is a digital representation of the phase of the signal carrier. By using a large counter and addressing the MOS FET switch with only the least significant bits, phase differences much greater than one fringe can be tracked. In fact, since the resolution of this system depends only on the number of resistors in the resistor ring, the dynamic range is determined by the dynamic range of the digital counter, and can be made as large as necessary simply by adjusting the size of the counter.

Nokes et al., used their tracker to track out and eliminate unwanted drifts in the movement of small biological systems, and so they discard the counter value as drift
and use the error signal as a measure of relatively quick small-scale changes in optical path length.

Jackson (1981) also designed a phase tracker to track out unwanted drift. It is very similar in structure to Nokes', but uses a different phase shifting technique. In this system, the digital counter controls a pair of EPROMs which contain look-up tables of the value of sine and cosine for phases from zero to 360°. These values are fed to multiplying digital-to-analog converters (MDACs) and multiplied by quadrature components of the sinusoid at the carrier frequency. The outputs are then combined by an adder to produce the reference carrier. A more detailed discussion of the operation of the phase tracker will follow.

5.6 Interrogation System Implementation

5.6.1 Concepts of Operation of the Phase Tracker

As already mentioned the proposed phase demodulator is a modified version of a circuit presented by Jackson (1981) and is based upon work previously published in the literature. The circuit creates a reference carrier based on a stored digital representation of a phase angle. This reference is compared to the incoming (signal) carrier and an error signal is created which is proportional to the phase difference between the two. The error signal is used as a basis for correction of the reference phase. The error signal is then kept at (or very close) zero, and the reference phase is kept equal to the phase of the signal carrier. The reference phase is therefore the output of the tracker.
Figure 5.15 shows a block diagram of the system. The diagram also includes the optical system and the carrier generation system. The output of the phase detector, is a voltage proportional to the phase difference between the signal carrier and the reference carrier. This error signal also contains a large component at the carrier frequency, which must be filtered out before the error signal can be used further, thus the low pass filter directly after the phase detector. After filtering, the error signal is used to control a digital counter. The sign of the error, found using a zero crossing detector, controls the direction of the counting, while the magnitude of the error, found by an absolute value circuit is fed to a voltage-controlled oscillator to control the counting speed. The error signal is also fed through two threshold detectors. One switches when the error signal is significant enough to demand correction, and the other switches if the error signal gets so large that the output is unreliable. The result is that the counter is disabled when the input is changing so fast that the tracker can not keep up.

The value stored in the counter represents a phase, and so each step counted represents a phase step of some part of a cycle. The counter output, as well as being the tracker output, is used to address an EPROMs that contains the values of the sine and cosine of the counter phase. So, if for example, the counter contains a value 763°, then the values on the output of the EPROMs will be the sine and cosine of the 763°. These values are fed to the digital inputs of two multiplying digital-to-analog converters. The analog multiplying inputs to the converters are fed sinusoids at the carriers frequency which are 90° apart in phase. The value of the sine of the counter phase is multiplied by the cosine carrier, while the value of the cosine of the counter phase by the sine carrier. These two signals are then added using a summing amplifier to produce the reference carrier. This is better understood by recalling equation 5.7,

\[
\sin(\phi)\cos(\omega t) + \sin(\omega t)\cos(\phi) = \cos(\omega t + \phi)
\]

where \(\omega\) is the carrier frequency, \(t\) is time, and \(\phi\) is the value of the phase stored in the counter. The reference carrier is band-pass filtered to remove digital noise added by the digital to analog converters, before being fed back to the phase detector to close the feedback loop.

If the signal carrier is changed in phase by a disturbance applied to the interferometer, then the error signal will increase in either the positive or negative direction. The
counter will count in the appropriate direction in small steps, changing the phase of the reference carrier to bring the error signal back to zero. In this way, the system will track the phase of the signal carrier. The value in the counter will always be equal to the phase of the signal carrier, within the resolution of the system.
The resolution of the system is determined by the size of the phase steps stored in the EPROMs. The range is dependent on the size of the phase step, and by the size of the counter. If the counter is eight bit, and if the phase step is 20°, then the tracker would have a range of $2^8 \times 20°$, or 5120°. The maximum tracking speed is determined by the maximum frequency of the voltage-controlled oscillator, and by the size of the phase step.

### 5.7 Summary

An In Line Fibre Fabry-Perot interferometer has been assembled and tested. The IFFP sensor combines the single fibre self-referencing property of the polarimeter with the high strain-sensitivity of the Michelson interferometer. A simple manufacturing procedure was used for producing the semireflective fusion splices and endface mirrors. Once the right parameters had been established the sensor was fairly easy to produce. The IFFP sensors (adhered to GFRP) yielded a linear phase strain relation ($r^2 > 0.996$), and free of any significant hysteresis. The mean phase strain sensitivity was determined and is equal to $S = (0.640 \pm 0.005) \frac{deg}{\mu e \cdot mm}$. The strain range was however limited by the strength of the semireflective fusion splice (~2000μe). The discrepancies observed in the results obtained were due to the relaxation of the Instron grips.

An interrogation system was also produced for the IFFP sensor, based upon work previously published, capable of a strain resolution <1μe. Although the functionality of the interrogation system was verified unfortunately due to time constraints the system was not tested with a sensory system. This work is currently continuing at the University of Surrey.
Chapter 6

Conclusions

6.1 Summary

The objectives of the project have been listed in Chapter 1; these have largely been achieved.

The HiBi polarimetric sensor was successfully manufactured and characterised. The free fibre and surface adhered phase/strain characteristics of the sensor were established and were found to be in good agreement with the theory presented and work reported by other authors.

The need for monitoring the structural integrity of civil engineering structures led to the following experimental work being carried out. The HiBi polarimetric sensor was successfully used to monitor the structural behaviour of a composite structure (which reference to the reinforced concrete beam with a CFRP plate bonded to it). The sensor was successfully embedded into the adhesive used to bond the CFRP plate to the concrete beam and monitored the strain state of the adhesive during loading. Almost all of the embedded sensors survived the manufacturing process with only one failure.

The results suggest that micro cracks are forming in the glueline which are picked up by the embedded fibre optic sensor and translated to phase cycle changes. The sensor can be used to continuously monitor the structural integrity of the adhesive thus providing useful information about the state of the bond between the CFRP plate and the concrete beam and the overall structural integrity of the structure. Although the polarimetric sensor possesses moderate sensitivity it offers an attractive alternative for the special case where large strain or integrated measurements are required. The experimental results have demonstrated the long sensing lengths advantage of the polarimetric sensor and its possible applications in civil engineering structures.
A polarimetric sensor was also embedded with the protective coating in place in a GFRP coupon and the experimental results obtained indicate that the sensor can operate reliably for strain values up to 2000 με. A direct comparison of the FOS results with those from the resistive strain gauges shows excellent agreement between the two sensors. The fibre optic strain gauge in its present form will perform dynamic strain measurements up to values of 2000 με. A finite element model was developed in order to study and predict the behaviour of the stress/strain fields of the material system. The results of this analysis show that strain is successfully transferred from the GFRP host to the core/cladding of the optical fibre through the primary coating which acts as an interface. The modelling results also provided an insight into the reasons why the FOS deviated from linearity at a load of approximately 2200N. The analysis suggests that debonding is occurring at the coating interface (caused by end-effects), something which can be avoided by the use of polyimide coated optical fibres. Debonding of the soft acrylate coating was expected as this type of material is chosen mostly for use in the telecommunications industry because of the ease of stripping the coating from the cladding necessary for making connections. Polyimide coatings have the additional advantage of chemically bonding to the core/cladding of the optical fibre and would therefore permit sensors to operate at much higher loads than their acrylate counterparts. Their thermal stability also makes them more suitable for embedding in thermoset composite systems.

The results obtained from the FE analysis indicate that an "optimum" interface coating exists such that the combined properties of the optical fibre coating and GFRP host minimise the stress concentrations in the material system. This "optimum" interface results in a system whose mechanical properties are similar to that of the pure GFRP host and this was shown to be the case with the minimisation of the maximum principal stress (σ_max) and maximum shear stress (τ_max) concentrations in the GFRP host. If a maximum principal stress failure criterion is used, the results suggest that the transverse strain to failure of the GFRP may be increased by 1.5 times by the use of the optimised coating.

The FE analysis model assumed that no resin eye exists around the optical fibre and that perfect bonding occurs between the core/cladding, interface coating and GFRP host, the latter because interface bonding is one of the most difficult effects to model accurately. The transverse loading case results indicate that an interface coating with
an elastic modulus value of $E_c=2.0\,\text{GPa}$ and a thickness of $t_c=12\,\mu\text{m}$ will minimise stress concentrations in the host. However, in the case of maximum shear stress concentrations the stiffer coating of $E_c=10.0\,\text{GPa}$ gave the best results and the stress variations in the GFRP host around the coating were decreasing as the coating thickness was increased. The parametric study for a transverse tensile load showed that compromises need to be made according to the design requirements and the possible service life of the material system.

Initially the thermal analysis was performed assuming that no residual stresses develop in the material system during the cool down process after manufacturing. The thermal loading results indicate that stress concentrations in the GFRP host are affected by the coefficient of thermal expansion of the coating as well as its stiffness. Furthermore, by varying the thermal expansion coefficient, the residual stress concentrations in the GFRP host as well as the core/cladding region of the optical fibre can be minimised. A detailed analysis for a 12$\mu$m interface coating thickness suggests that, for a coating expansion coefficient of $\alpha=6.5\times10^{-6}\,\text{C}$, the stress concentrations in the GFRP host are minimum for all values of coating elastic modulus. This is significant as thermal stress concentrations are now almost eliminated but a very wide spectrum of coating stiffness values can be utilized for different optimization criteria, either reducing the fibre sensor obtrusivity or enhancing the sensor performance. However the result is specific for the material system considered in this study.

Subsequently the effect of residual thermal stresses during manufacturing was also taken into consideration and was combined with a transverse tensile load. The “optimum” coating parameters established by the individual load cases where used, and the stress concentrations in the composite GFRP host were minimised, as expected. The study also suggests that FOS may be designed for specific sensing techniques.

An In Line Fibre Fabry-Perot interferometer has been assembled and tested. The IFFP sensor combines the single fibre self-referencing property of the polarimeter with the high strain-sensitivity of the Michelson interferometer. A simple manufacturing procedure was used for producing the semireflective fusion splices and endface mirrors. Once the right parameters had been established the sensor was fairly easy to
produce. The IFFP sensors (adhered to GFRP) yielded a linear phase strain relation ($r^2 > 0.996$), and free of any significant hysteresis. The mean phase strain sensitivity was determined and is equal to $S = (0.640 \pm 0.005) \frac{deg}{\mu e \cdot mm}$. The strain range was however limited by the strength of the semireflective fusion splice (~2000$\mu e$). The discrepancies observed in the results obtained were due to the relaxation of the Intron grips.

An interrogation system was also produced for the IFFP sensor, based upon work previously published, capable of a strain resolution <1$\mu e$. Although the functionality of the interrogation system was verified unfortunately due to time constraints the system was not tested with a sensory system. This work is currently continuing at the University of Surrey.

### 6.2 Original work and contributions

The author considers the following as his original work and contributions:

- The development of a finite element model for optimising the mechanical and thermal characteristics of the fibre coating in order to reduce the embedded sensors obtrusivity.
- A parametric study using the finite element method to investigate the local interaction mechanisms between the embedded optical fibre and the composite host.
- The development of a finite element model for predicting the strain behaviour of an embedded sensor under loading, and the possible cause for sensor failure.
- The successful manufacturing, characterisation and application of fibre optic sensors (HiBi Polarimeter and Fabry-Perot) for the structural monitoring of composite materials and of a composite Civil engineering structure.
- Study into the feasibility of using fibre optic-sensor to monitor civil engineering structures and the successful structural monitoring of a civil engineering composite beam structure using an embedded polarimetric sensor.
6.3 Recommendations for future investigation

The author considers that the following areas warrant further investigation:

- Further investigation into the formation and the location of microcracks in the adhesive and alternative fibre-optic strain sensors for providing point load instead of distributed strain measurements.
- Methods for improving the strength of the FFP semi-reflective splice.
- A study into the effects of thermal loading and methods for compensating the apparent thermal strain measurements.
- A study into other sensor interrogation techniques for the polarimeter offering intrafringe resolution, and methods for eliminating interrupt ambiguity.

The long term durability of the embedded fibre optic sensor including:

- Further environmental exposure tests under accelerated or natural conditions, and in the presence of aggressive substances such as de-icing salts.
- Further sustained load tests over longer durations, particularly when combined with natural or accelerated environmental exposure.

More analytical work using finite element techniques,

- Further investigation into the finite element modelling of debonding mechanisms and the specific difficulties of the model.
- The development of a more generalised finite element model for optimising the optical fibre coating properties and the overall reduction of the sensor's obtrusivity to the host material, and capable of predicting strength or structural integrity reductions in the host material.

6.4 Conclusions

Commercially available optical fibres (single-mode) have been shown to be compatible with composite materials and structures and intrinsic and localised strain sensing has been successfully demonstrated. The polarimetric sensor was successfully embedded in a composite beam structure (reinforced concrete beam flexurally strengthened by a CFRP plate) and was used for the monitoring of strains in the adhesive layer of the structure. The formation of microcracks in the adhesive layer
was also detected by the polarimetric sensor, providing valuable information about
the structural status of the structure. Although the fibre-optic sensor focus has been
shifted towards sensors like the Bragg grating and the extrinsic Fabry-Pérot, the
polarimetric sensor offers a low cost alternative to the Civil Engineering world when
moderate strain resolution and sensitivity is required. The long sensor gauge lengths
possible for the polarimeter have been shown to be an advantage when an overall
view of the current structural status is required. The Fabry-Pérot sensor was also
successfully demonstrated and it’s high sensitivity and point sensor advantages can be
used in conjunction with the polarimeter to provide a more accurate representation of
the composite structure’s integrity.

The mechanical properties of the primary coating of the optical fibre can be optimised
in such a way as to minimise the disturbance caused by the optical fibre to the host
material. Other enhancements include the minimisation of concentrations caused by
thermal effects. Tailor-made coatings would have to be developed however for each
different type of composite material which is not a viable solution. However if a
standard is established for what material should be used in plate bonding for example
then the production of such an optical fibre would be beneficial to the structure and
development and production costs would gradually reduce.

Further development of local fibre-optic sensors with customised characteristics is
primarily held back by economic issues. A considerable amount of money is being
spent and will continue to be spent for the development of FOS; The Civil
Engineering world must also be convinced that fibre-optic sensors can provide
solutions for applications where the usage of conventional strain gauges is ineffective.
The issue to be resolved is whether the value of this applications justifies the cost of
development.

6.4. Conclusions
Appendix A: Hi-Bi Polarimetric Sensor manufacturing procedure

Experimental Procedure for a Single 45° Fusion Splice

The procedures described outline practical methods for achieving 45° eigenaxis rotation between two sections of HiBi fibre which are to be fusion spliced. It is important to note that misalignment of 45° splices in the PF sensor does not destroy either the sensor localization or the lead-in/lead-out insensitivity, if correct launch and detection optics alignment is employed: it does, however, reduce the absolute signal modulation depth available from the sensor.

In the sections that follow, we consider a simple in-line polarimetric sensor system of the form illustrated in Figure A.1 [Hogg et.al 1989]. We therefore assume that we have a linearly-polarized light source, with some means of rotating the polarized orientation to align it with the 'lead-in' section of the fibre sensor. For the bulk system shown here, this alignment is carried out using a half-wave plate. In the case of an all-fibre source, the output of the fibre polarizer (which is linearly polarized) must be aligned to the 'lead-in' fibre directly, and fusion spliced. Once this has been accomplished for a back-reflective system, the 'lead-out' and analyzer alignment is also complete.

![Figure A.1 Basic localised in-line Hi-Bi sensor system.](image)

At the output end of a transmissive (or in-line) system, we also assume that the analyser (or polarizer in front of the detector) can be rotated to give alignment with
the ‘lead-out’ eigenaxes. This is normally achieved for a bulk system using either a rotatable polarizer, or a polarizing beamsplitter (with fixed orientation) in combination with a half-wave plate.

**Single 45° Fusion Splice for HiBi Fibres**

Through the course of our experiments with launch and detection of light to and from HiBi fibres, we found that a very useful technique for testing axis alignment was to ‘shake’ (i.e. generally disturb by gentle pulling or plucking under tension) the fibre in question, while monitoring the output for intensity variations. If a null sensitivity was observed, then the launch (or detection, as appropriate) optics were determined to be aligned with one of the eigenaxes of the tested fibre. It constitutes an important part of the procedures described below.Linear laser light is launched into an unbroken length of HiBi fibre. At the output, an analyser-detector combination are set up, and the detected intensity monitored.

1. The input polarised light is aligned to one of the eigenaxes of the fibre. This is accomplished by slowly rotating the input state of polarisation SOP, (using the half wave plate in Figure A.1), while simultaneously ‘shaking’ continuously the fibre. The output intensity is monitored at the detector, and one continues the test until a minimum sensitivity of the output is observed. For maximum sensitivity of this method, the output half wave plate is then slowly rotated until the maximum intensity variation is achieved (this corresponds to 45° analyser orientation with respect to the fibre axes). The input SOP is then fine-tuned to minimise detected intensity sensitivity once again. The input SOP (half-wave plate orientation) is then recorded.

2. The orientation of the fibre eigenaxes is determined at the output end of the system. This has been partly accomplished in the previous step, since the output analyser is most sensitive to phase fluctuations for a 45° orientation with respect to the fibre axes. However, for more exact determination, the input SOP is rotated by 45° (22.5° rotation of the half wave plate) to give equal excitation of the two sensor eigenaxes. Then the analyser is adjusted for minimum sensitivity, corresponding to alignment with an output eigenaxis. Again the position of this axis is recorded.
3. Both input SOP and output analyser are aligned to the fibre eigenaxes (the same one if a signal is detected). The fibre is then broken in the desired location for the fusion splice. Protective buffer is removed and the end-faces of the fibre are cleaved and cleaned in preparation for fusion splicing. The two fibre sections are then placed into the fusion splicer; none of the launch/detection optics have been disturbed during this process.

4. The two fibre ends in the splicer are brought together and the detector intensity monitored. If a PFBS and detector pair are available, as shown in Figure A.1, one then rotates one of the fibre ends (in the fusion splicer) to give equal intensity at the two detectors. For a single detector with a rotatable polarising analyser, the analyser must be switched between the two eigenaxes of the output fibre (90° apart) to determine this ‘equal excitation’ condition. When equal excitation has been obtained, a 45° relative axes orientation at the splice point has been achieved.

5. The fibre ends are fusion spliced to finish the first 45° fusion splice. For a back reflective system, this completes fabrication of the sensor, except for trimming the sensor length and mirror coating of the end-face (see Appendix B).
Appendix B: Silvering Solution Preparation Description

The silvering solution used in our experiments to coat the fibre end-faces to produce single-ended fibre sensors is described below. The method yielded excellent results with reflectivities of up to 85%. The method was extracted from an old Chemistry Handbook and was prepared successfully in our labs with the help of Ian Rankin. Although the procedure described appears to be straightforward, from our exercise we noticed that extra care should be taken while preparing the solutions in order to achieve the best possible results.

The solution preparation requires the following components:

1. Ammoniacal Silver Nitrate
2. Sodium Potassium Tartrate
3. Ammoniacal
4. Rochelle Salt

**Solution A**

- Add 5gm of Silver Nitrate in 300cc of distilled water
- Add ammoniacal until the precipitates form. Add until is almost but not entirely dissolved. (Note: Always put some of the original mix aside in case you add too much ammoniacal. This is achieved through experience).
- Filter the solution and dilute it to 500cc of distilled water.

**Solution B**

- Add 1gm of Silver Nitrate in a small quantity of distilled water and add that into 1/2 litre of boiling water.
- Dissolve 0.83gm of Rochelle salt in a small quantity of water and add that to the boiling solution.
- Continue boiling for half an hour. Refill if necessary.
- Gray precipitates will form at the base.
- Filter while hot and add distilled water to make it 500cc.
Once produced the solutions must be stored in a dark environment for up to 8 weeks.

For silvering cleave the fibre ends and prepare them by thoroughly cleaning them using lint free tissues soaked with methanol.

Then simply mix equal amounts of both solutions and dip the fibre end in the mixture. It is better to have the fibre end-face in place and then add the solutions as a thin residue film forms on the surface of the mixture. This will produce a thin silver film within one minute. For the maximum thickness allow 1 hour.
Appendix C: Jones Matrices

The fibres and optical devices discussed in chapter 2 can be represented by matrices, \([M]\), that operate on Jones vectors; hence the name Jones matrices. Their utility becomes evident when cascading elements,

\[
J_{out} = [M_n]...[M_1]J_{in}
\]  \hspace{1cm} C.1

The matrix product can be replaced by a Jones system matrix so that the above equation becomes,

\[
J_{out} = [M]_{sys}J_{in}
\]  \hspace{1cm} C.2

Various relevant Jones matrices are given below [Fowles 1989]:

**LoBi Fibre**

\[
[LoBi] = \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\]  \hspace{1cm} C.3

**HiBi Fibre**

\[
[HiBi] = \begin{bmatrix}
1 & 0 \\
0 & e^{i\beta_{d}}
\end{bmatrix}
\]  \hspace{1cm} C.4

**Fibre polariser or Polarising Fibre**

\[
[P_x] = \begin{bmatrix}
1 & 0 \\
0 & 0
\end{bmatrix}
\]  \hspace{1cm} and  \hspace{1cm} C.5

**Fibre Quarter-wave device**

\[
[\lambda/4] = \begin{bmatrix}
1 & 0 \\
0 & \pm i
\end{bmatrix}
\]  \hspace{1cm} C.6
Fibre Half-wave device

\[ \frac{\lambda}{2} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \]  

Fibre Reflector (Mirrored Fibre End-face)

\[ [FR] = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} \]  

Rotation Matrix

Any of the above elements can be rotated with respect to some reference frame (usually the frame of the first element) using the standard rotation operation,

\[ [M(\theta)] = [R(\theta)][M][R^{-1}(\theta)] \]  

where the rotation matrix \([R(\theta)]\) is given by,

\[ [R(\theta)] = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \]  

Loss Element

Loss elements may be added to any of the above matrices,

\[ [\eta] = \begin{bmatrix} \eta_1 & 0 \\ 0 & \eta_2 \end{bmatrix} \]  

where \(\eta_1\) is the insertion-loss amplitude ratio.
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