

CRANFIELD UNIVERSITY

L. F. J. AIME

DEVELOPMENT OF AN OPTICAL FIBRE PRESSURE
SENSOR FOR F1 APPLICATIONS

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING

PhD

Academic Year: 2017–2021

Supervisors: Prof. S. W. James, Dr. A. A. Skordos, Prof. R.

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Abstract

This study investigated the development of optical fibre sensing technologies for the measurement of pressure in aerodynamic applications, in particular on F1 racing cars. The specific application placed constraints on the dimensions and geometry of the sensor, and provided the specification for a resolution of order 20 Pa over a range 0 to 35 kPa, with a requirement for means for compensation for the temperature response of the sensor. The light weight and minimally intrusive nature of optical fibres has aroused great interest for embedment in the thin composite structures that comprise the aerodynamic elements of F1 cars. The sensor design is based on a diaphragm that deflects under pressure, with an in-plane optical fibre sensor bonded to the diaphragm to measure the induced strain. The initial design was informed by analytical calculations, with Finite Element Analysis (FEA) subsequently providing information on the strain distribution over the diaphragm's surface and revealing a nonlinear response, which were key to the final design decisions. Two optical fibre sensing technologies were investigated: Fibre Bragg Grating (FBG) and Fibre Segment Interferometry (FSI). Experimental analysis of sensors of differing dimensions made from candidate materials and formed using different manufacturing and sensor integration processes allowed refinement of the material choice and sensor fabrication approach. A sensor of diameter 25 mm and thickness 0.27 mm with an FBG sensor mounted on its surface exhibited a sensitivity of 56.7 ± 7.6 pm/kPa, equivalent to a resolution of 17.6 Pa, over a pressure range of 0 to 35 kPa. The sensor diaphragm was made from Glass Fibre Reinforced Polymer (GFRP), fabricated using a press mould with the integration of the FBG during the cure.

The performance of FBG and FSI based strain sensing with the optical fibres bonded to the same GFRP diaphragm of diameter 21.5 mm and thickness 0.23 mm was analysed. This is the first reported use of FSI for pressure measurement. Over the pressure range of 0 to 35 kPa, the FBG sensor exhibited a sensitivity of 95 ± 4.4 pm/kPa, equivalent to a resolution of 10.5 Pa. The FSI sensor exhibited a sensitivity of 6.3 ± 0.3 rad/kPa, equivalent to a resolution of 0.61 Pa.

The strain distribution on the diaphragm surface revealed by the FEA highlighted an annulus of compressive strain around the edge of the diaphragm, which was exploited using an optical fibre with FSI segments that covered the regions of compressive and tensile strain with a view to demonstrating temperature compensation.

In addition to the measurement of pressure, there is an interest in the measurement of strain on composite suspension components using embedded optical fibre sensors. The process of embedding the fibre sensors and its influence on the signal quality were investigated, culminating in the calibration of the instrumented components and their testing on track. Several processes developed during this work are now in routine use at Mercedes AMG F1.

Keywords

Pressure Sensing ; Fibre Bragg Grating ; Fibre Segment Interferometry.

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List of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
CAD	Computer-Aided-Design
CAE	Computer-Aided-Engineering
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibre Reinforced Polymer
CPU	Computer-Aided-Engineering
CTE	Coefficient Thermal Expansion
DMF	Dimethyl Formamide
DoF	Degree of Freedom
EPT	Elastic Plate Theory
F1	Formula One
FBG	Fibre Bragg Grating
FC/APC	Fibre Connector/Angled Physical Contact
FEA	Finite Element Analysis
FEM	Finite Element Modelling
FLWB	Front Lower Wishbone
FP	Fabry-Perot
FPRD	Front Push Rod
FS	Full Scale
FS	Fibre Segment
FSI	Fibre Segment Interferometry

FTRD	Front Track Rod
FTWB	Front Top Wishbone
FWD	Forward
GFRP	Glass Fibre Reinforced Polymer
HF	Hydrofluoric (acid)
HNBR	Hydrogenated Nitrile rubber
HT	High Temperature
ID	Inner Diameter
LPG	Long Period Grating
MMF	Multi Mode Fibre
OBR	Optical Backscatter Reflectometer
OD	Outer Diameter
OTDR	Optical Time Domain Reflectometer
PDMS	Polydimethylsiloxane
PLA	Polylactic Acid
PMMA	Polymethyl Methacrylate
PTFE	Polytetrafluoroethylene
R&D	Research and Development
RWD	Rearward
SFG	Superstructure Fibre Grating
SMF	Single Mode Fibre
SS	Stainless Steel
TTG	Trivial Transfer Graphene

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Chapter 1

Introduction

The aerodynamic performance of an Formula One (F1) car is one of the most important research and development topics for an F1 team, and logging aerodynamic parameters in real time during races provides crucial information to allow optimisation of the performance of the car. Pressure measurement is currently performed using pitot tubes, which offer high resolution over a wide pressure range. However, pitot tubes are bulky, difficult to route inside the composite parts that comprise the majority of the F1 car, and have a slow response time. The work reported in this thesis explores the development of an alternative system for pressure measurement using optical fibres. The size, light weight and strength of optical fibres allow the possibility of measuring pressure where it is not accessible with pitot tubes. They also offer other significant advantages such as high bandwidth, immunity to electromagnetic interference, low loss and ease of multiplexing.

The use of optical fibre technology for pressure sensing has been widely investigated and two approaches have aroused interest in the last decades: Fabry-Perot interferometry (FP) and Fibre Bragg Gratings (FBG). Both technologies have their advantages and disadvantages and are discussed in Chapter 2. One of the greatest advantages of optical fibre sensing is the ability to sense multiple measurands along a single fibre using appropriate packaging and deployment, making it a versatile and compact technology. FBG sensors

have become the preferred technology in a number of industrial sectors due to the ease of multiplexing a number of sensors along a single fibre. FP, on the other hand require more cumbersome approaches if the multiplexing of sensors is required. FBG sensing technology was also the preferred method of the sponsor of this project, Mercedes AMG F1. Sensitivity to pressure is not an intrinsic property of FBG sensors so they require means of transducing the pressure into strain, and for compensation for the influence of temperature. A recent development in optical fibre sensing has been fibre segment interferometry (FSI), which provides a means for measuring the strain integrated over sections of fibre of length ranging from 10 mm to 1m using a simple optical configuration, exploiting the principles of range resolved interferometry. The approach can offer a resolution that is more than an order of magnitude higher than that offered by FBGs, while offering the same ease of multiplexing.

On an F1 car, the whole aerodynamic structure is made from composite materials, with strict attention paid to details regarding overall weight and strength. The use of embedded optical fibre sensors for the monitoring of strain, temperature and pressure at multiple locations within the car and providing data that were not accessible previously while using a single generic interrogation system, offers considerable potential benefits.

Analysis of the literature regarding optical fibre based pressure sensors allowed the identification of the research gap as being the absence of reports of FBG pressure sensors with characteristics appropriate for use in aerodynamic applications in F1, which should be capable of measuring low pressures (mbar), be suitable for embeddment within composite components, validated in a multiplexed installation and incorporate methods for compensating for their inherent temperature sensitivity. Novel approaches involving the use of FBG and FSI technology were explored.

1.1 Aim and Objectives

The aim of the research work was to develop an optical fibre based pressure sensor capable of measuring low pressures (0 to 35 kPa) with a minimum resolution of order 20 Pa, incorporating means for temperature compensated operation and being applicable to composite structures in a multiplexed installation. The pressure specifications are based on current capabilities of pitot tube based systems used by the aerodynamic department of Mercedes AMG F1.

The objectives to achieve the aim were:

1. Develop a means for transducing pressure to strain that will provide the required measurement performance when interrogating the sensor using a commercially available FBG interrogator (wavelength resolution of 1 pm, equivalent to a strain resolution of $0.83 \mu\epsilon$) or when using an alternative highly novel approach that employs FSI sensors using an in-house developed interrogation system.
2. Develop an analytical and numerical analysis prior to design and manufacturing
3. Define and implement an appropriate means for temperature compensation.
4. Develop the packaging such that it can be readily embedded within carbon fibre composite components using approaches that are compatible with current manufacturing processes.
5. Demonstrate the sensitivity gain by comparing FBG and optical fibre interferometry.

1.2 Methodology

To achieve the objectives, several methodologies were employed:

Methodology One: pressure sensor design, manufacturing and analysis

- Identify the most appropriate means to transduce the pressure into strain from the literature review.
- Perform an analytical analysis and Finite Element Analysis based on the pressure sensor design.
- Undertake an experimental analysis of the pressure sensor using FBG and FSI technologies.
- Correlate experimental results with the output from the FEA.

Methodology Two: temperature compensation

- Experimental analysis of strain free FBGs at various temperatures.
- Develop a temperature compensation approach by exploiting the strain distribution identified by the FEA over the diaphragm diameter.

Methodology Three: pressure sensor incorporation

- Study the manufacturing processes of composite components at Mercedes AMG F1.
- Design packaging for embeddment.

Methodology Four: pressure sensing enhancement

- Experimental comparison of sensors based on FBG and FSI technologies.

1.3 Thesis Outline

The individual chapters cover the following:

Chapter 2 reviews pressure sensing approaches and optical fibre sensing technologies such as FBG and FSI to establish the principles of the work reported in this thesis.

Chapter 3 describes the working principle underpinning the pressure sensor concept with

analytical and numerical analyses of the performance. Small and large deflections analyses of a clamped diaphragm under uniform pressure are presented with the associated strain in the optical fibre. A case study on a 25 mm diameter diaphragm is described.

Chapter 4 presents the design and processes used to manufacture various type of pressure sensors. The first section describes sensors made using an elastomer diaphragm, with diameters ranging from 6 mm to 30 mm. Then two manufacturing processes are presented, fabricating a composite diaphragm of diameter 25 mm, where different ways of incorporating of the optical fibre sensor are investigated. The chapter concludes with a manufacturing optimisation method using a press mould, incorporating the optical fibre during the composite laminate curing process. Limitations of each method are described. Chapter 5 presents the experimental analysis of the pressure sensors designed and manufactured using different methods and materials described in Chapter 4.

Chapter 6 presents an experimental analysis of a pressure sensor formed using the manufacturing optimisation process described in Chapter 4, that incorporates both FBG and FSI strain sensors, comparing their performances under pressure and temperature.

Chapter 7 presents a characterisation of the temperature response of strain free FBGs encapsulated in various capillary materials and dimensions for use in Chapter 8. A study to compare FBGs bonded to material used in the pressure sensors and the pressure chamber, arising from the thermal effect on pressure sensitivity described in Chapter 5 is also investigated.

Chapter 8 offers a collaboration with the sponsor of this thesis Mercedes Amg F1 on the instrumentation of the F1 suspension members. The challenges arising from the embedding of optical fibres in composite structures are investigated and data quality analysed. The FBG strain measurements are monitored using the same system as used for the pressure sensing.

Chapter 9 concludes by summarizing the project and results and provides an outlook for areas of future work.

Chapter 2

Pressure Sensing Technologies Review

This chapter reviews aerodynamic pressure measurement devices such as pitot tubes and those based on piezoresistive, piezoelectric and optical fibre approaches. The optical fibre pressure sensing technologies are detailed to aid the identification of the approach best suited to satisfy the requirements associated with their use on an F1 racing car, as detailed in Chapter 3. Pressure sensors and the underlying technologies used to transduce the pressure into an output signal are explored. A detailed review of pressure sensors formed using the most common optical fibres sensor technologies, FP interferometers and FBG, is presented, followed by a description of the working principles and methods used for the fabrication of sensors based on the chosen optical fibre sensing technologies. FSI is a novel optical fibre strain sensing approach that is used for pressure measurement for the first time in Chapter 6 of this thesis, and its working principle and fabrication are described in this chapter.

2.1 Pressure Sensors

Pressure sensors employ diverse technologies to transduce pressure into an output suitable for analysis and storage. Most commonly, a pressure sensor provides an output signal that is proportional to the applied pressure and requires calibration to convert it to a pressure reading. There are three main classifications of pressure measurement [1]: absolute,

gauge and differential, illustrated in Figure 2.1. In absolute pressure measurement, depicted in Figure 2.1(a), the pressure is measured relative to the pressure in a vacuum. This method is important in aerospace engineering where the pressure changes with altitude. The reference vacuum is created inside the sensor itself. Gauge pressure measurement, illustrated in Figure 2.1(b), measures the pressure relative to ambient atmospheric pressure. As both the reference and the pressure of interest are acted upon by the atmospheric pressure, the gauge method excludes the effect of the latter. Finally, differential pressure measurement, represented in Figure 2.1(c), is comparable to the gauge pressure method, with the difference that the reference is taken from a specific location, often with a fixed pressure, rather than the ambient atmospheric pressure. This type of measurement is currently used in F1 cars [2, 3], where the pitot tubes are connected to one side of the pressure transducer and the reference point inside the cockpit is connected to the other side for differential pressure measurements.

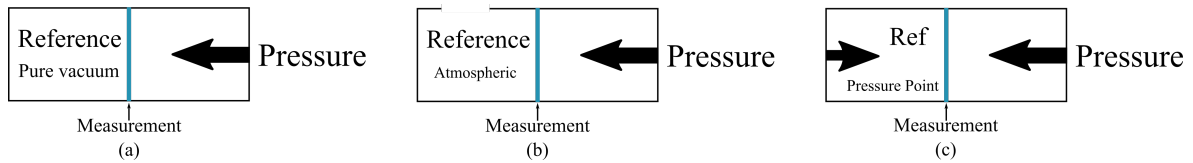


Figure 2.1: (a) absolute pressure measurement. (b) gauge pressure measurement. (c) differential pressure measurement.

2.2 Pitot Tube

Pitot tubes [1] are the most commonly used pressure sensors in racing cars. The specifications for the pressure sensor to be developed within the work described in this thesis are derived from the performance of the pitot tubes currently deployed to characterise the aerodynamics of an F1 car. A pitot tube is usually positioned so that the orifice faces the stream direction and the other side is connected to a manometer where a reference pressure is compared to the measured pressure. A schematic of a pitot tube is shown in

Figure 2.2

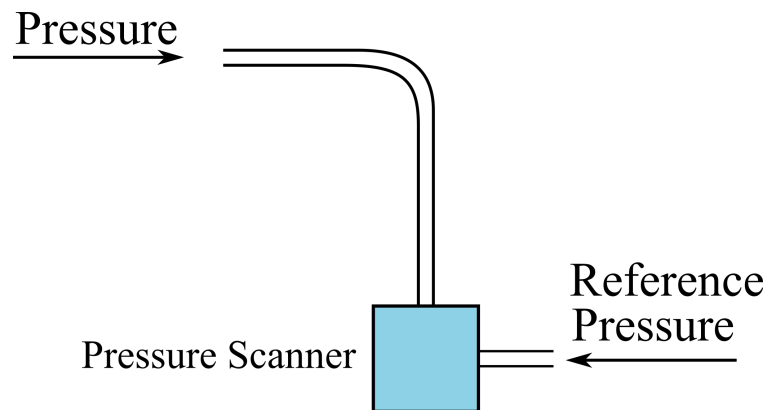


Figure 2.2: Typical Pitot tube schematic.

2.3 Piezoresistive Transducers

Resistive transducers are widely used for the measurement of static and low dynamic pressures. A piezoresistive transducer consists of a strain gauge bonded to a deflecting diaphragm. When the diaphragm deforms, the corresponding change of resistance in the piezoresistive strain gauge is converted into an electrical signal. In this type of pressure sensor, a full-bridge circuit is placed on the diaphragm, with two strain gauges in tension, placed in the centre on the diaphragm, and two in compression, placed at the edges of the diaphragm. However, the diaphragm needs to be formed from a flexible material due to the low gauge factor of metallic strain gauges. The sensitivity in resistive transducers is also influenced by the dimensions of the diaphragm, especially the thickness, which is discussed in Chapter 3.

Piezoresistive pressure transducers used for aerodynamic pressures are commercially available from Texense PDIF, defined as aerodynamic pressure scanners [4], with a range of ± 5 to ± 100 kPa and with accuracy of ± 0.5 % Full Scale (FS). These are the most widely used pitot tube pressure sensor interrogator in racing cars on track. The scanner consists of a single point of reference and a number of differential pressure points using

a Scanivalve manifold. On a similar principle, Kulite offers pressure scanners [5] but Texense is preferred for its CAN output signal. Other piezoresistive pressure transducers can be found in wind tunnel applications such as Endevco, with a sensor of diameter 2.3 mm and length 12.7 mm, operating over a pressure range of 0 to 100 kPa [6]. Also available from Endevco is a pressure sensor of diameter 6.3 mm, operating over a pressure range of 1.5 to 5 MPa [7]. Keller Druck offers sensors of diameter ranging from 4.5 to 6 mm, with pressure ranges up to 2 MPa full scale [8]. Although they are small size, these sensors require electrical signals which can introduce electromagnetic interference within the rest of the car and their maximum temperature range does not allow them to be embedded in the composite during the cure process.

2.4 Optical Fibre Sensing Technology

Optical fibre sensing arouses interest due to the various advantages that they offer over conventional sensors, such as small size and light weight, immunity against electromagnetic interference and corrosion resistance, allowing the sensors to be included within a structure without interfering with the properties of the material. This is of particular interest in harsh environments or when applied to structures where weight and intrusion are to be minimised, such as the application at the heart of this thesis.

Three technologies are considered in this thesis for pressure sensing; Fabry-Perot (FP), Fibre Bragg Grating (FBG) and Fibre Segment Interferometry (FSI). FBG and FSI technologies are defined as intrinsic sensors where the measurand impacts on the properties of the fibre directly, whereas FP are defined as extrinsic sensors. The light propagating in an optical fibre is inherently sensitive to strain and temperature. The sensing of other measurands such as pressure when using intrinsic optical fibre sensors generally requires the incorporation of an appropriate means to transduce the measurand into an elongation or compression of the fibre or into a modification of the effective refractive index of the

propagating mode.

Due to their physical length (4 to 10 mm) and sensitivity to strain gradient, FBG sensors are categorized as point sensors. Due to their design, FP are also categorized as point sensors. In comparison, FSI, is capable of integrating the strain over a longer length along the fibre providing a higher sensitivity. Typical FSI segments range from 10 mm to couple of meters.

2.4.1 Fabry Perot Interferometry

A typical FP interferometer takes the form of an optical cavity formed between two partially reflecting surfaces [9, 10, 11]. Light undergoing multiple reflections within the cavity interferes, such that the transmitted or reflected intensity varies with the separation between the reflectors [12]. In the case where the reflectors have high reflectivities, the interference between multiple reflections results in the transfer function has the form of the cyan curve (95%) shown in Figure 2.3, while a cavity with low reflectivity reflectors, such that the cleaved ends of on an optical fibre (4%) will behave like a two-beam interferometer, with a sinusoidal transfer function illustrated by the darker blue curve in Figure 2.3.

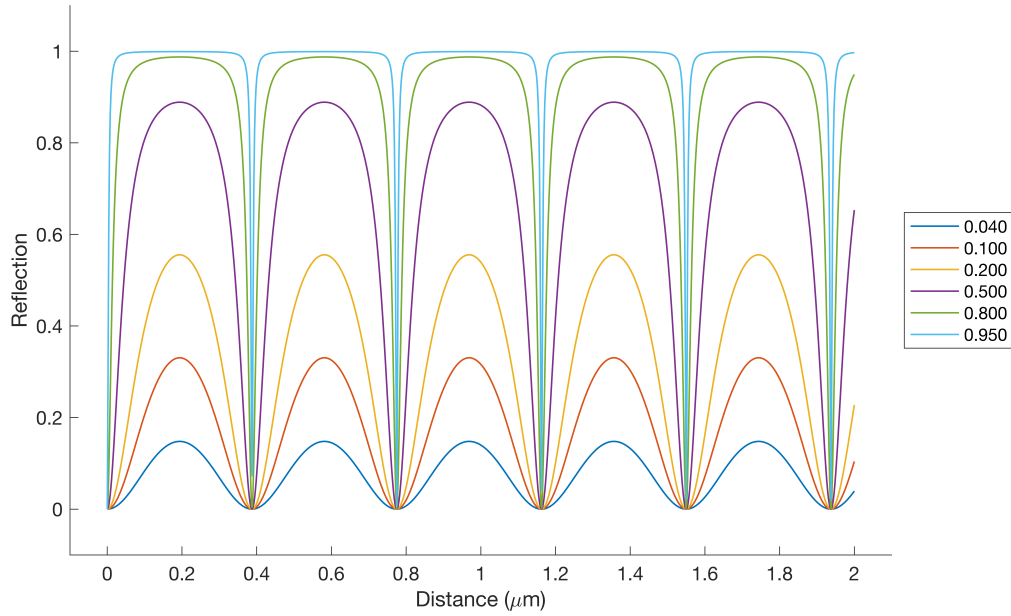


Figure 2.3: Changes in the reflection from an FP cavity in response to a change in the cavity length, determined assuming a laser wavelength of 1.55 microns. Mirror reflectivities provided in the legend.

In optical fibre based FP sensors, the cavity is generally formed between the end faces of two optical fibres, as shown in Figure 2.4 or between the end face of an optical fibre and a reflective diaphragm as illustrated in Figure 2.5.

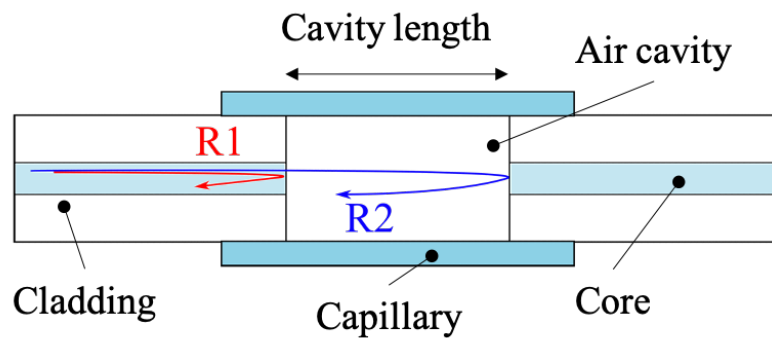


Figure 2.4: Schematic of a typical Optical fibre based Fabry-Perot interferometer.

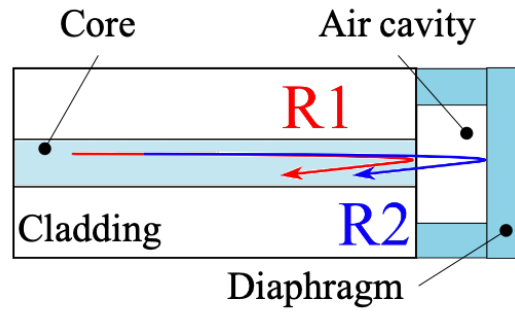


Figure 2.5: Schematic of a typical Optical fibre based Fabry-Perot interferometer.

An FP-based pressure sensor typically comprises a cavity formed between a deflecting diaphragm and the cleaved end of an optical fibre, allowing the measurement of the deflection of the diaphragm with interferometric resolution and providing high resolution pressure measurements from a compact probe that can be as small as the diameter of an optical fibre. The cavity length changes with applied pressure, creating a phase difference that can be measured by monitoring the optical path difference (OPD) from the change in the phase of the reflection spectrum shift using broadband illumination. The sensitivity of the sensor is determined by the mechanical proprieties of the diaphragm material and its dimensions.

A number of approaches to the interrogation of low finesse FP cavities have been reported [13]. Intensity measurement at a single wavelength can be employed, with the intensity changing with changes in the cavity length. However the sensitivity depends on the wavelength selected to interrogate the cavity, with the highest sensitivity at the quadrature point of the sinusoidal transfer function, where the sensitivity is highest. The quadrature point will change with changes in environmental parameters such as temperature, requiring the use of complex means to lock the laser wavelength to the quadrature point [14]. Such approaches have a dynamic range limited to a quarter of the illuminating wavelength. Quadrature phase demodulation approaches, which generate orthogonal signals via passive or active approaches to determine the arctangent of the phase can also be

employed [15]. White light based approaches, where the transmission or reflection spectrum is observed using a broadband source and spectrometer or a tuneable laser, can allow the movement peaks in the channelled spectrum to be tracked as they change in response to changes in the cavity length and can achieve absolute cavity length measurement with sub-nanometer resolution.

2.4.1.1 FP Fabrication

There are a number of techniques to fabricate FP cavities in optical fibres which take various form. Two methods have been categorised by researchers: with and without splicing. Most of the fabrication processes are reported in [16]. For pressure sensing, the most commonly used methods are chemically etching of the fibre core, followed by splicing of either a single or multimode fibre to fabricate a miniature sensor [17, 18, 19] or a diaphragm of various material and diameter greater than the fibre in order to increase the sensitivity [20, 21, 22]. Section 2.5.1 describes FP sensors with various diaphragm materials and geometries.

2.4.2 Fibre Bragg Grating Sensors

FBG sensors and their applications have been the topic of a great number of publications and experiments in the past years due to their well-established advantages (immunity to electromagnetic interference, high bandwidth, corrosion resistance, possibility to multiplex along a single fibre, etc.) over conventional electrical and mechanical sensors such as strain gauge and piezoelectric sensors. FBG sensors also have the benefits of easy multiplexing compared with other optical fibre sensing methods and have had an increasing commercial availability in the past decades, leading to a reduction in cost and improved specifications compared with electrical strain gauges. For the application of this thesis, strain gauges are expensive and time consuming, requiring parts to be sent to be instrumented and calibrated by the supplier as well as additional calibrations of the part itself for load measurements once back at the factory. Further work on strain sensing in sus-

pension members is presented in Chapter 8.

An FBG consists of a large number of partial reflectors (forming a grating) within a small length inside the core of a single mode optical fibre. The reflected Bragg wavelength is defined by the period of the grating and the effective refractive index of the mode propagating in the core of the optical fibre. Section 2.4.2.2 details the principle of the reflected wavelength.

2.4.2.1 FBG Fabrication

FBGs are fabricated by creating a permanent periodic modulation of the refractive index of the fibre's core. This can be achieved by exposing the photosensitive core of the optical fibre to a periodic pattern of intense ultraviolet light, or by exposing the optical fibre to the output from a femtosecond laser. The most common methods used to fabricate FBGs are the phase mask method using a UV laser and the point by point method using a femtosecond laser. A phase mask is a diffractive optical element that spatially modulates a laser beam [23, 24] and is illustrated in Figure 2.6.

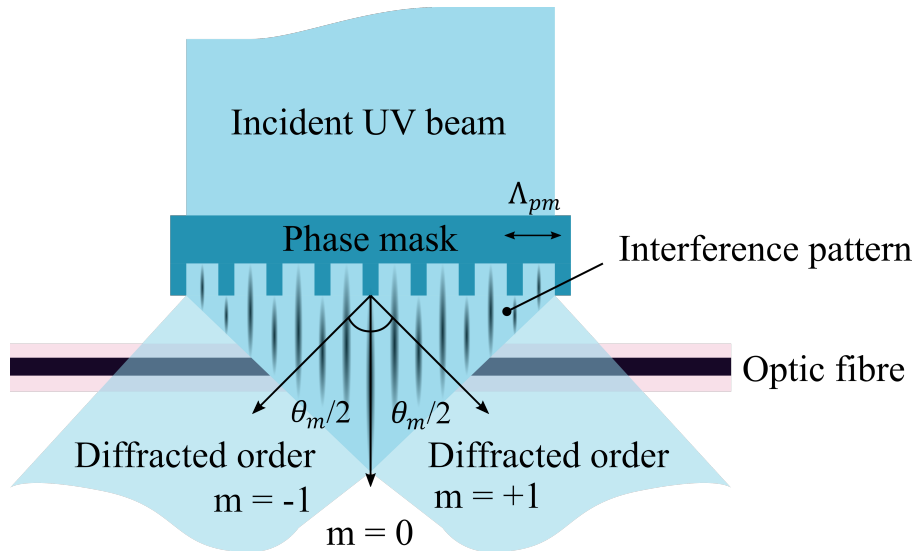


Figure 2.6: Schematic of the FBG writing method using a phase mask, with $\theta_m/2$ the diffraction angle and Λ_{pm} the phase mask period.

The phase mask diffracts the incident beam into several orders, creating in the near field where the diffracted orders overlap, an interference pattern (regions of alternating of high and low light intensity). The phase mask is design to ensure the majority of the UV radiation is diffracted into the first orders for an incident beam at normal incidence. The diffraction angle $\theta_m/2$ is related to the period of the interference pattern, Λ_g , by [25]:

$$\Lambda_g \frac{\lambda_{uv}}{2 \sin \frac{\theta_m}{2}} = \frac{\Lambda_{pm}}{2} \quad (2.1)$$

With Λ_{pm} the phase mask period, Λ_g the grating period and λ_{uv} the UV wavelength. In the system employed at Cranfield University, the fibre is positioned 1 mm away from the phase mask, with the UV cured acrylate coating removed from the section of fibre to be exposed. In general, while being UV irradiated through the phase mask, the reflection spectrum is monitored using an FBG interrogator, and the irradiation is stopped once the reflected signal has reached a desired level.

Point by point grating inscription is undertaken using a similar set up, with the differences being the use of a pulsed femtosecond laser, allowing the fabrication of the grating without removing the polymer coating and the use of translation stage to move the fibre relative to the focused laser beam to allow the FBG to be created one grating plane at a time [26, 27].

The Bragg wavelength is related to the grating period Λ_g and the effective refractive index of the fibre core n_{eff} according to:

$$\lambda_{Bragg} = 2n_{eff}\Lambda_g \quad (2.2)$$

A wavelength multiplexed array can be created by translating the optical fibre to the desired position and, in the case of UV irradiation, changing the phase mask or, in the case of femtosecond irradiation, changing the speed of movement of the translation stage

for a fixed laser pulse rate, allowing to the identification of each grating by its unique wavelength. Figure 2.7 shows a typical reflection spectrum of a wavelength division multiplexed array bought from FemtoFiberTec, with Bragg peaks at different wavelengths.

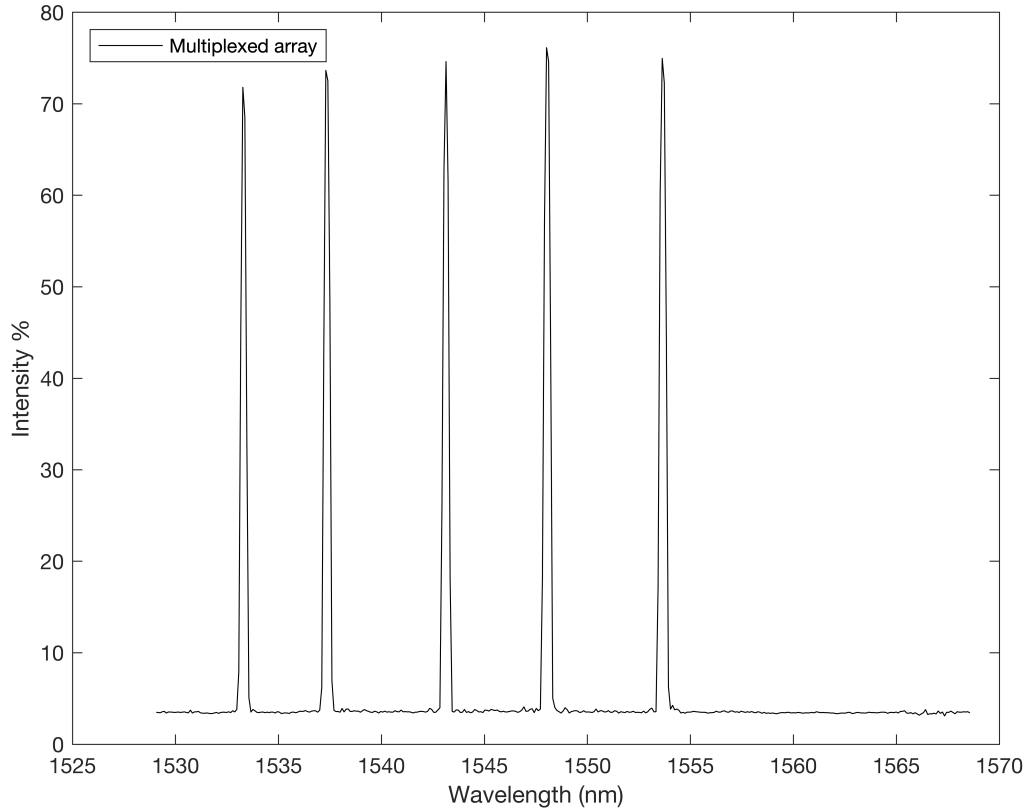


Figure 2.7: Typical reflection spectrum of a wavelength multiplexed array bought from FemtoFiberTec.

A typical FBG sensor has a length of 4-10 mm, narrow bandwidth and high intensity peak. The FBG working principle and intrinsic sensitivities of strain and temperature are described in Section 2.4.2.2 and 2.4.2.3.

2.4.2.2 Fibre Bragg Grating Sensing Principle

A model that is often used to understand the operation of an FBG is to consider that each grating plane acts to reflect a small amount of light, with the reflections being in phase and

interfering constructively at a wavelength where the optical separation of adjacent grating planes is $1/2$ of the wavelength creating a narrow-band spectral component, wavelength encoded and called the Bragg wavelength. The rest of the spectrum is transmitted through the fibre as illustrated in Figure 2.8. The Bragg wavelength depends on both the effective refractive index experienced by the propagating guided mode of the fibre and the spacing between the grating planes as seen in Equation (2.2) .

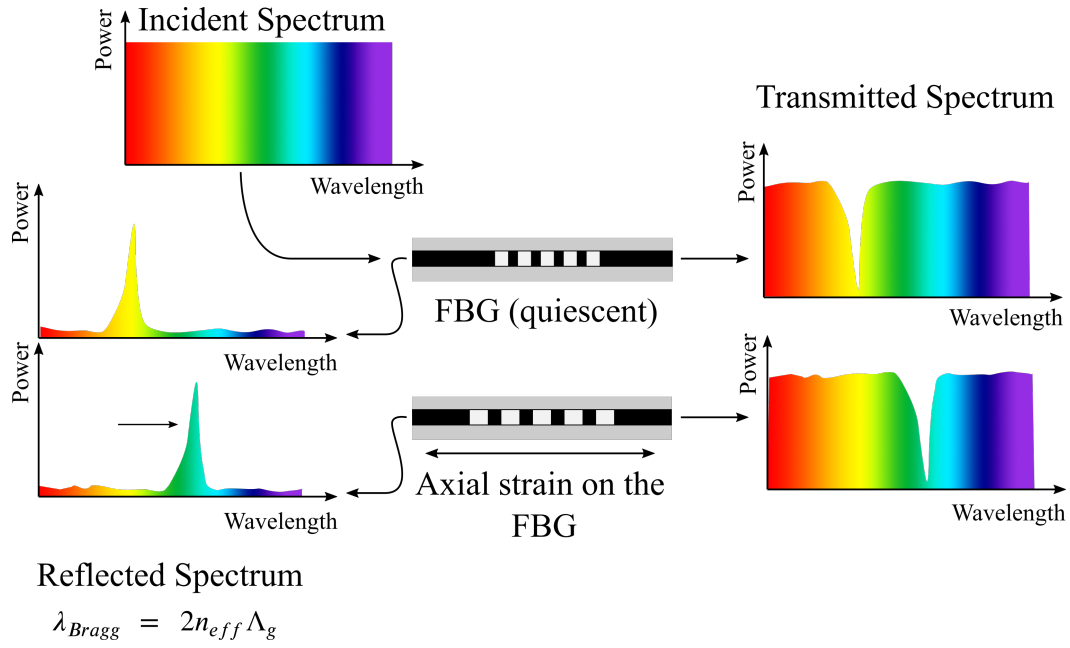


Figure 2.8: Schematic of the FBG working principle.

The physical period and effective index of the propagating mode are both affected by the local strain and temperature experienced by the optical fibre, inducing a change in the Bragg wavelength. The principle of operation of FBG sensors relies upon the measurement of the measurand-induced change in the Bragg wavelength.

2.4.2.3 Fibre Bragg Grating Strain and Temperature Sensitivities

Strain Sensitivity

The strain sensitivity of an FBG results from the physical change in length of the optical fibre and the strain induced refractive index change, and has a value of $1.2 \text{ pm}/\mu\epsilon$ for

an FBG fabricated with a Bragg wavelength of 1550 nm in SMF-28 optical fibre [28]. Equation 2.3 describes the strain sensitivity of an FBG [28].

$$\frac{\Delta\lambda_{Bragg}}{\lambda_{Bragg,initial}} = (1 - \rho_e)\Delta\varepsilon \quad (2.3)$$

The mechanical strength, and so strain range, of FBGs will vary significantly depending on several factors such as stripping methods, re-coating materials, reflectivity of the gratings and the wavelength of the UV laser beam [29]. Pristine FBGs have been reported to have a mean failure strength of 4.73 ± 0.1 GPa, compared with FBGs where the coating has been subject to stripping methods such as chemically stripped and mechanically stripped, which reduced the failure strength to 4.53 ± 0.4 and 1.87 ± 0.42 respectively [29], [30]. Stripping the coating prior to inscribing the FBGs is usually required for phase mask method, while draw tower gratings (DTG) [31] and gratings made point by point with femtosecond laser do not require the removal of the protective buffer coating, hence are mechanically stronger [30].

Thermal Sensitivity

The temperature sensitivity of FBGs is well-established, arising from a combination of the thermal expansion of the fibre and the thermally induced refractive index change and is given in Equation (2.4) [28].

$$\frac{\Delta\lambda_{bragg}}{\lambda_{bragg}} = (\alpha + \xi)\Delta T \quad (2.4)$$

With $\Delta\lambda_{bragg}$ representing the temperature, ΔT , induced change in the Bragg wavelength, λ . α represents the thermal expansion coefficient of the optical fibre ($0.55 \times 10^{-6}/^{\circ}C$) and ξ the thermo-optic coefficient approximately equal to $10^{-5}/^{\circ}C$ for silica core fibres doped with germanium [32]. For an FBG written with a Bragg wavelength of around 1550 nm in SMF-28 fibre, the thermal sensitivity has a value of approximately 10 pm/ $^{\circ}C$ [33].

The thermal response of the FBG is dependant on the temperature, with a decrease of sensitivity below -173°C (100K) [34], and a sensitivity approaching zero at -271°C (2.2K) [35]. This is particularly interesting for cryogenic applications, where there is no need for temperature compensation as the strain sensitivity stays unaffected. Flockhart *et al.* reported in 2004 the non-linearity on the temperature response of FBGs at ambient temperatures (-70°C to 80°C .) due to the temperature dependence of the thermo-optic coefficient of silica glass [36]. To allow operation at high temperatures, up to 1000°C , the FBGs require an annealing process to regenerate the refractive index modulation. Laffont *et al.* annealed the FBGs at 710°C for two hours and increased the temperature to 920°C , which triggered the regeneration of the FBGs [37].

Over their typical length of 4-10 mm, a large strain gradient can broaden or split the Bragg peak in several peaks [38], [39], [40], which as a result introduces increased errors and difficulties in resolving the FBG peaks. In comparison, the second optical fibre strain sensing technology used in this thesis, FSI, presented in Section 2.4.3, is capable of integrating the strain over a longer length of fibre, and offers higher sensitivity due to the use of an interferometric interrogation approach.

2.4.2.4 Fibre Bragg Grating Interrogation Techniques

Several interrogation techniques are available and are determined by resolution, cost and compatibility with multiplexing. The FBGs are illuminated by a light source with broad spectrum and the reflected wavelength can be monitored using various methods such as using an edge filter, a tuneable filter or interferometric scanner for instance [28]. The edge filter method measures the output intensity which is proportional to the wavelength shift while the tuneable filter measures the maximum output when the FBG peak matches the spectrum of the tunable filter. The shift in wavelength is detected by a scanned interferometer with the interferometric scanning method.

2.4.3 Fibre Segment Interferometry Strain and Temperature Sensitivities

Fibre segment interferometry refers to a long gauge length interferometric fibre sensing approach that integrates the strain over the entire segment length. The series of segments along a same fibre allows the capture of multiple strain variations. The reflective mirrors in this configuration take the form of ultra short and low reflectivity FBGs, usually in the order of 250 μm and 0.001-0.01 % respectively, with a maximum of 5 nm FWHM with identical wavelength. A typical fibre segment interferometry system is shown in Figure 2.9 [41]. The broadband FBGs reflect the light from the single wavelength illuminating laser source over a wide range of local strain and temperature conditions at the reflector that would otherwise cause the FBG to move out of the wavelength band of the laser [41]. The FSI phase resolution is given by [41], with quadrature bandwidth of 250 Hz and dependent on segment length:

$$1.2 \cdot 10^{-4} \text{ rad} \cdot \text{Hz}^{-0.5} \cdot \text{m}^{-1} \quad (2.5)$$

The strain and temperature sensitivities are dependent of the length of the segment and the fibre characteristics and are described below.

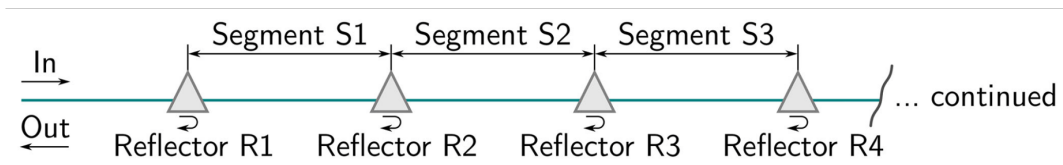


Figure 2.9: Typical fibre segment interferometry system [41]. Reflectors formed by short (0.5 mm), low reflectivity (in order of max 0.01%), identical wavelength FBGs.

Strain Sensitivity

The strain sensitivity of FSI is determined using Equation 2.6 and is dependent on the gauge length between two gratings, L , as shown in Figure 2.9 [42].

$$\varepsilon = \frac{d\phi \cdot \lambda}{4L \cdot \pi \cdot n_{eff} \cdot k} \quad (2.6)$$

where $d\phi$ is the strain induced phase change and n is the effective index of the propagating mode. The strain gauge factor k is calculated from the strain-optic coefficient of the optic fibre [43], which has a value of 0.795 for SMF-28 fibre.

Thermal Sensitivity

The temperature sensitivity of FSI is governed by the same glass properties as that of FBGs, but is dependent on the gauge length, L , and can be calculated using Equation 2.7 [32]. An additional factor of two is included as the light traverses the sensor gauge length twice in this configuration [42].

$$\frac{d\phi}{dT} = \frac{4\pi L}{\lambda} (n\alpha + \xi) \quad (2.7)$$

Assuming a value of 1.456 for the refractive index, n , at an operating wavelength $\lambda = 1521$ nm [28], we obtain:

$$\frac{d\phi}{dT} = L \cdot 89 \text{ rad/m}^\circ\text{C} \quad (2.8)$$

2.5 Optical Fibre Based Pressure Sensors

This section reviews optical fibre base pressure sensors based on FP and FBG sensors. As a novel technology, FSI is not reviewed here as this research project is the first reported use of FSI for pressure measurements and the technique is described further in Chapter 6.

2.5.1 Fabry-Perot Based Pressure Sensors

All silica FP pressure sensors, using a lead in fibre and a lead out fibre have been investigated up to recently. They offer the advantage of simple fabrication, few or no additional

component and miniature size. Cibula *etal.* [44] chemically etched a custom design fibre with germanium doped core for higher etching time compared to the cladding. Once the cavity was formed in the lead out fibre, they spliced the lead in fibre and the cleaved the lead out fibre to form the diaphragm. The schematic of their fabrication process is shown in Figure 2.10. The fibre tip sensor was fabricated in few steps, producing a miniature sensor of diameter 125 μm . Over a pressure range from 0 to 40 kPa, they achieved high resolution of 10×10^3 pm/kPa, however at higher pressure the sensor exhibited non linear response due to the large deflection. Also using an all silica fibre sensor, Ma *etal.* [45] used a femtosecond laser to inscribe a micro hole in the centre of a SMF and then spliced a lead out fibre with no core and finally cleaved the latter to create the diaphragm. The diameter of the sensor was also 125 μm but was tested it at higher pressures, up to 10 MPa. They achieved a lower sensitivity of 70.8 pm/kPa with a diaphragm thickness twice the size of [44]. Aref *etal.* [46] also based their sensor principle of a lead in lead out fibre, with a stainless tube bonding both fibres at a given air cavity length. However, when using the pressure transducer from [47], they replaced the lead out fibre by a metal wire to reduce thermal cross sensitivity the tube induced on the sensor due to the higher coefficient of thermal expansion of the stainless steel. The diameter of the sensor, including the tube was 6.5 mm and their sensor reached sensitivity of 25.5×10^3 pm/kPa over the largest pressure range of all three, with 0 to 53.8 MPa.

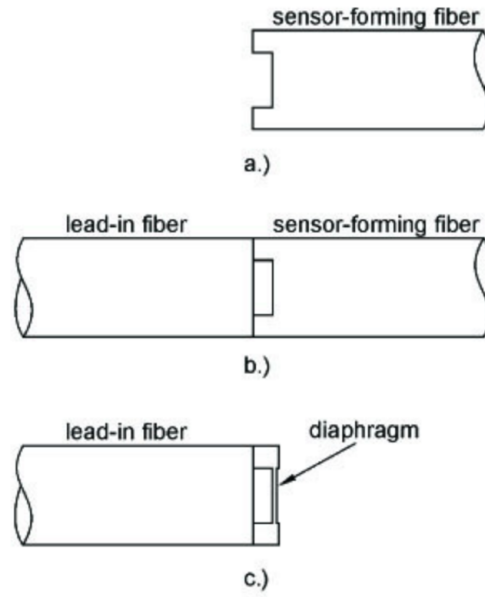


Figure 2.10: Schematic of the fabrication process of the FP proposed by Cibula *et al.* [44] (a) cavity formation by etching. (b) fusion splicing of both fibre. (c) diaphragm creation by cleaving.

The fabrication of in-fibre diaphragm has also been investigated where the lead out fibre is replaced by a diaphragm of other materials in an effort to increase the sensitivity, pressure range or temperature cross sensitivity. Wang *et al.* [19] chemically etched a SMF and thermally bonded a thin silica diaphragm to the tip of the fibre, while keeping an overall dimension of $125\text{ }\mu\text{m}$. Increased and decreased pressures from 0 to 140 kPa were applied to the sensor which exhibited a pressure sensitivity of $11 \times 10^3\text{ pm/kPa}$. Cibula *et al.* [17] spliced a small section of a multimode fibre (MMF) onto a SMF in which the core was doped with germanium. The etching of the MMF allowed a larger sensing area due to the larger fibre core size. The solution used for etching was Hydrofluoric (HF) acid. The thin polymer diaphragm was made by dipping the etched fibre into an elastic polymer P-1190A solution in dimethyl formamide (DMF). The cavity length measured to be $80\text{ }\mu\text{m}$ and the diaphragm thickness to be $4\text{ }\mu\text{m}$. The sensor was tested over a pressure range of 0 to 40 kPa and reported a pressure sensitivity of $7.5 \times 10^3\text{ pm/kPa}$. The schematic of the sensor is shown in Figure 2.11.

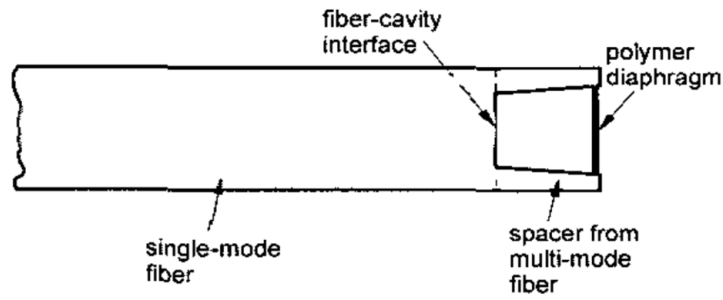


Figure 2.11: Schematic of the FP pressure sensor proposed by Cibula *etal.* [17].

Chen *etal.* [48] also chemically etched a MMF using HF acid. They dropped a small amount of UV adhesive at the bottom of the cavity and then formed an air cavity by sealing it with more UV adhesive, fabricating three reflective surfaces. The sensor was tested in a gas chamber where it achieved good linearity over a range of 20 to 980 kPa, with sensitivity of - 40.94 pm/kPa. The positive pressure induced a negative shift due to the reduction in the cavity length.

Increasing the sensitivity of the sensor can be achieved by increasing the deflecting diameter. In order to do so, several designs have been developed. Nesson *etal.* used a diaphragm diameter of 150 μm , slightly bigger than bare fibres. The diaphragm, made from polyimide and nickel/titanium, was bonded to a cleaved glass tube of outer diameter 366 μm . The tube with the diaphragm was then bonded onto a cleaved SMF, leaving an air cavity as shown in Figure 2.12. Over a range of 0 to 70 kPa, the sensor exhibited high sensitivity of 2×10^4 pm/kPa. Liu *etal.* [49] also used a glass tube and bonded a silver diaphragm of diameter 2.5 mm. Because of the larger inner diameter of the tube, they use a ferrule to transition between the tube and the SMF, using epoxy resin. The large diaphragm diameter allowed the sensor to achieve linear sensitivity over low pressures, from 2.5 to 268 mPa, with a sensitivity reaching 28.57×10^3 pm/kPa.

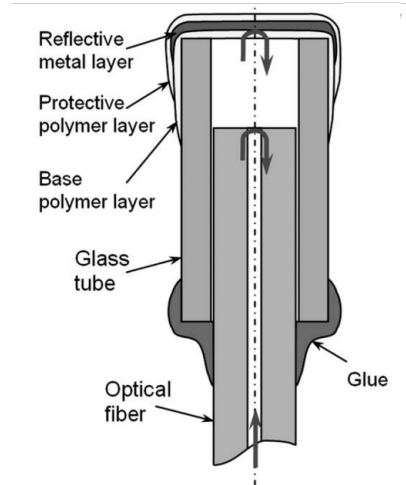


Figure 2.12: Schematic of the FP pressure sensor proposed by Nesson *et al.* [20].

The use of ferrules in FP pressure sensor has been widely investigated as it allows to construct a sensor with several off the shelf components with various diaphragm materials, while keeping a relatively small size. Lawson *et al.* [50] glued an optical fibre to a ceramic ferrule of diameter 2.43 mm. The ferrule and a 381 μm diameter tube were inserted in a zirconia sleeve. The tube acted as a vent to form a differential pressure sensor. A diaphragm made from a thin electret metallised Mylar film membrane was bonded to the tip of the sleeve. The schematic of the sensor and an image are shown in Figure 2.13. The sensor was tested in-flight over a pressure range of 0 to 0.7 kPa and the sensitivity of the sensor reached 750 pm/kPa.

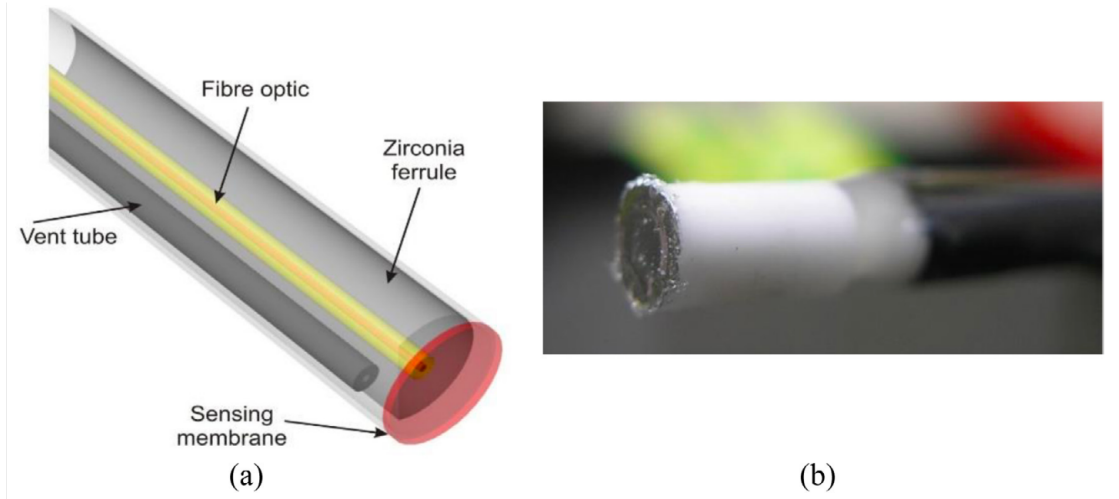


Figure 2.13: (a) schematic of the FP pressure sensor proposed by Lawson *et al.* showing the components and (b) an image of the sensor tip [50].

To increase the sensitivity of their sensor, Ghildiyal *et al.* [51] used a stainless steel ferrule in their design, with the difference of a larger diaphragm diameter. The stainless steel diaphragm had a diameter of 25 mm, making it more intrusive than other FP pressure sensors described previously. However, due to the size of the diaphragm, the sensor exhibited sensitivity of 26.6×10^3 pm/kPa, over a range of 0 to 5 kPa. Later, the same authors [52], reduced their sensitivity while reducing their diameter, with an overall diameter of 5 mm and a diaphragm diameter of 2 mm. A copper beryllium alloy diaphragm was bonded to a ceramic ferrule. A schematic of the sensor along with an image is shown Figure 2.14. The sensor reached 10×10^3 pm/kPa over a pressure range of 0 to 7 MPa. A sensitivity one order above was achieved by a smaller diameter sensor by Dong *et al.* [21]. Using a ceramic ferrule, they bonded a graphene diaphragm at the tip, made from 10-15 layers of commercial Trivial Transfer Graphene (TTG) covered with polymethyl methacrylate (PMMA). Although the overall diameter reached 2.5 mm with the ferrule design, the working diameter of the diaphragm was $125 \mu\text{m}$, formed by the inner diameter of the ferrule. The sensor was tested in a pressure chamber and achieved high sensitivity of 501.4×10^3 pm/kPa over a pressure range of 0 to 2 kPa.

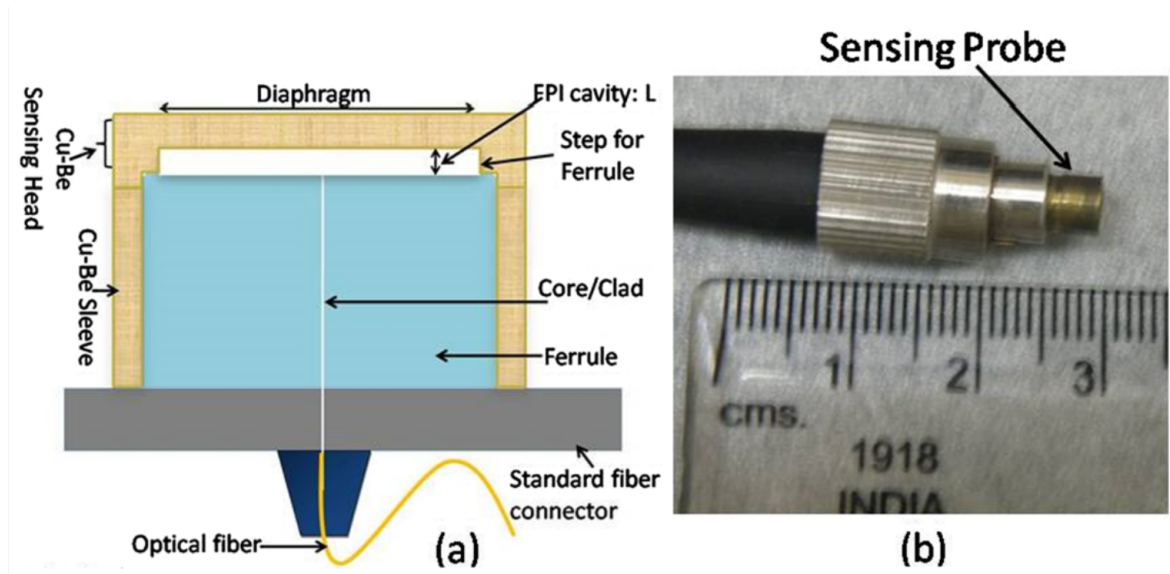


Figure 2.14: (a) schematic of the FP pressure sensor proposed by Ghildiyal *et al.* showing the components and (b) an image of the sensor tip with the ferrule [52].

Finally, a sensor of overall small size and high sensitivity is shown in Figure 2.15. Eom *et al.* [22] fabricated a FP pressure sensor by splicing a coreless fibre onto a SMF and formed a lens at the tip using arc discharger method. After placing the fibre in the ferrule, they bonded the polymeric diaphragm made from three-layer comprising of Polydimethylsiloxane (PDMS), parylene, and gold. The PDMS was used for its flexibility and so increased sensitivity to pressure, while the gold was used internally to improve the reflectivity of the light. The sensor showed high sensitivity of 1.41×10^6 pm/kPa over a pressure range of 0 to 4 kPa.

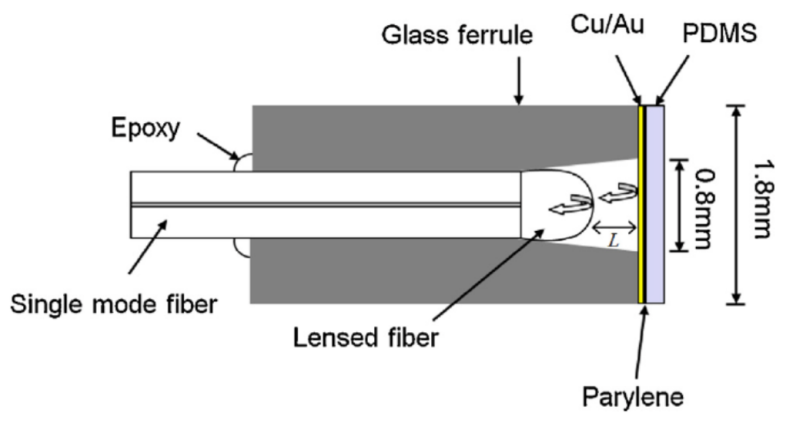


Figure 2.15: Schematic of the FP pressure sensor proposed by Eom *et al.*, with L the cavity length and a three-layer comprising of Polydimethylsiloxane (PDMS), parylene, and gold [22].

Recently, Liu *et al.* developed a differential pressure sensor using a silica diaphragm of diameter 5 mm, UV bonded to a silica tube of inner diameter 3.4 mm. To ensure concentric and simple manufacturing process, a second tube was inserted inside the first tube and a third tube was inserted inside the second, which inner diameter allowed the alignment of the SMF fibre with a dimension of $126\ \mu\text{m}$. A schematic and an image of the sensor is shown in Figure 2.16. The cavity was sealed by UV adhesive between each tube. A plastic tubule was inserted in the first tube and was connected to the static pressure of a pitot tube. The FP cavity was connected to the total pressure, allowing the whole sensor to measure differential pressure. The pitot tube was tested in a wind tunnel, with the FP differential pressure sensor connected to it. The sensor achieved a sensitivity of $826.975 \times 10^3\ \text{pm/kPa}$ over a differential pressure range of 0 to 11 kPa.

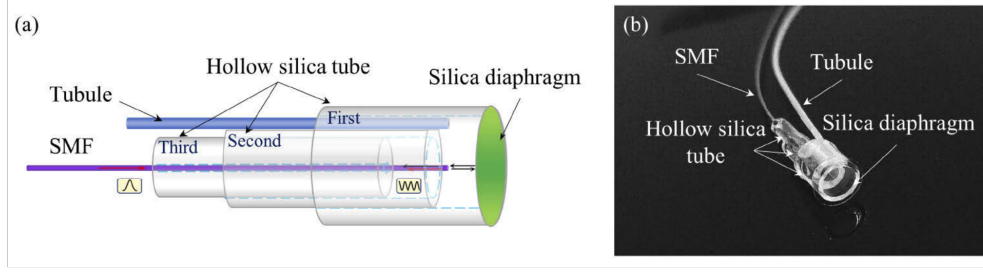


Figure 2.16: (a) schematic of the FP pressure sensor proposed by Liu *et al.* [53] and (b) an image of the sensor.

FP pressure sensors can be of ultra small size (of diameter 0.125 mm [44, 19, 17, 45]) while exhibiting high sensitivity, making them great candidates for numerous applications, including medical and oil and gas [54, 55, 56]. A summary of the performance of previously reported FP pressure sensors is provided in Table 2.1. However, the main disadvantage of FP pressure sensors is the difficulty of deployment, in particular the orientation of the cavity perpendicularly to the surface of the structure, which can limit its applicability in thin structures. The multiplexing in a single fibre is also complicated due to the fibre tip design and the difficulties to directly distinguish the sensors in the wavelength domain. Commercially available FP pressure sensors are available from Fos4X, where the orientation issue is taken into account by using an angle polished fibre which deflects the light perpendicularly in direction to the diaphragm [57]. Zhu *et al.* [58] achieved high sensitivity using a corrugated diaphragm with an angled fibre tip on the same principle as [57], with sensitivity of 7×10^5 pm/kPa over a large range of pressure from 0 to 100 kPa. The F-P cavity, shown in Figure 2.17, is formed between the surface of the diaphragm and the side wall of the fibre, which changes when the diaphragm deflects.

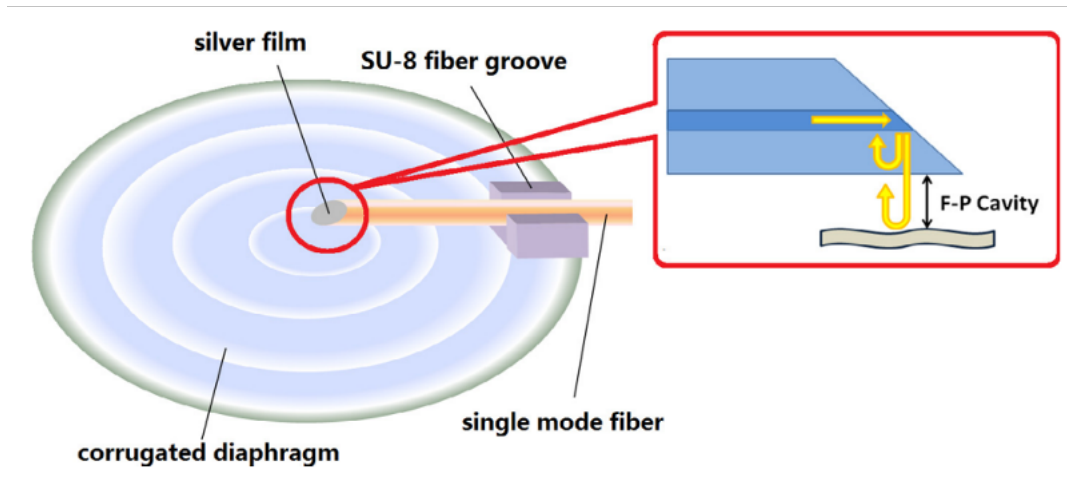


Figure 2.17: Schematic of the FP pressure sensor proposed by Zhu *et al.* [58] with epoxy-based photoresist groove (SU-8).

Although FP pressure sensors can achieve very high sensitivity, they are not ideal for the application, given the difficulty of deployment for aerodynamic pressure mapping, especially with multiplexing limitations and the intrusion to composite structures similarly to pitot tubes.

Table 2.1: Performance summary of reviewed FP pressure sensors

Design	Pressure range (kPa)	Pressure sensitivity (pm/kPa)	Size, ϕ	Reference
Stainless tube bonding two SMF forming a cavity	0 to 53.8 x 10 ³	25.5 x 10 ³	6.5 mm	[46]
SMF forming diaphragm to lead in fibre	0 to 40	10 ⁴	125 μ m	[44]
Silicon oxide thin film bonded to an etched SMF tip	0 to 140	11 x 10 ³	125 μ m	[19]
Coreless fibre forming diaphragm to machined SMF	0 to 10 ³	70.8	125 μ m	[45]
Polymer diaphragm bonded to an etched MMF spliced onto SMF	0 to 40	7.5 x 10 ³	125 μ m	[17]
UV adhesive formed diaphragm cured on an etched MMF	20 to 920	40.94	60 μ m	[48]
Polymer-metal composite diaphragm bonded on a glass tube at the tip of a SMF	0 to 70	2 x 10 ⁴	366 μ m	[20]
Silver thin diaphragm with glass tube bonded to ferrule at a SMF tip	2.5 to 268 x 10 ⁻⁶	28.57 x 10 ³	2.5 mm	[49]
Mylar film diaphragm bonded to ferrule at the tip of SMF	0 to 0.4	750	3.5 mm	[50]
Cavity between a stainless steel diaphragm and a sapphire window, at the tip of the SMF	0 to 5	26.6 x 10 ³	25 mm	[51]
Copper Beryllium diaphragm bonded to ferrule at the tip of SMF	0 to 70 x 10 ³	10 ³	5 mm	[52]
Graphene diaphragm bonded to ferrule at the tip of SMF	0 to 2	501.4 x 10 ³	2.5 mm	[21]
Polymeric diaphragm bonded to glass ferrule at the tip of SMF	0 to 4	1.42 x 10 ⁶	1.8 mm	[22]
Angled polished fibre tip with a corrugated diaphragm	0 to 100	7 x 10 ⁵	4.6 mm	[58]
Three hollow silica tubes with silica diaphragm at the tip of SMF	0 to 11	826 x 10 ³	5 mm	[53]

FBG sensors however, although they might achieve lower sensitivities, are easy to multiplex and can be less intrusive. A review of various types of FBG based pressure sensor is described in Section 2.5.2. The first report of the use of an FBG to measure pressure involved subjecting a bare optical fibre containing an FBG to hydrostatic pressure in a pressure chamber. The initial experiment assessed the intrinsic sensitivity of the fibre, varying the pressure from 0 to 70 MPa, revealing a sensitivity of 0.0032 pm/kPa [59]. The intrinsic pressure sensitivity of an FBG is low, especially for applications requiring resolution in the order of a few Pascal. Assuming a requirement for a resolution of 20 Pa when using a commercial FBG interrogator of resolution 1 pm, a pressure sensitivity of 50 pm/kPa is needed. This has been approached previously by transducing the pressure into a strain acting on the fibre, as will be discussed in the following section.

2.5.2 Fibre Bragg Grating Based Pressure Sensors

The following review of FBG based pressure sensors details the various methods that have been used to transduce the pressure into a strain acting on a section of optical fibre containing an FBG. Two categories have been identified, with the first one involving the transduction of pressure into axial strain (tension or compression) acting on the optical fibre and the second being the transduction of pressure into bending of the fibre.

2.5.2.1 Transduction of Pressure Into an Axial Strain Acting on the Optical Fibre

There are several transduction methods that have been used to transform pressure into and axial load acting on the FBG, ranging from embedding the optical fibre inside a tube filled with polymer to the use of complex mechanical systems.

Embedded FBG - Lateral Pressure

Embedding FBG sensors in a polymer filled tube has been investigated by researchers, where opportunities for temperature compensation have arisen by using the peak decoupling or two FBGs of different properties. Zhang *et al.* [60] filled a metal cylinder of inner

diameter 11 mm, length 30 mm and wall thickness 2.4 mm, with silicone rubber polymer and encapsulating an FBG. The cylinder was open at the fibre tip extremity, such that the pressure acted along the axis of the fibre only. Over the 0 to 450 kPa range tested, a pressure sensitivity of -5.28 pm/kPa was reported. Similarly, Liu *et al.* [61] manufactured a sensor where they used a copper tube of inner diameter 8.4 mm, length 25 mm and wall thickness 0.8 mm, filled with organic silica gel. The sensor schematic is shown in Figure 2.18. The FBG was only partially encapsulated, leaving half of the grating free. While the embedded side of the FBG was affected by the surroundings pressure, the other side was unaffected, resulting in the splitting of the reflected Bragg peak. The dual peaks were, however, sensitive to temperature change, which reduced the sensor cross sensitivity by having the same change in both peaks. However, over the same pressure range presented in [60], the sensitivity reported was lower, with -3.75 pm/kPa.

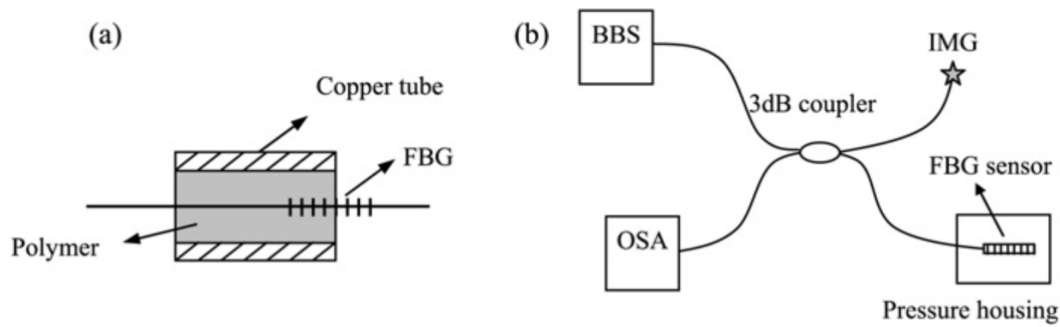


Figure 2.18: (a) schematic of the half polymer-coated FBG pressure sensor proposed by Liu *et al.* (b) experimental set up with the broadband source (BBS) launched into the sensor, connected to an optical spectrum analyser (OSA), and index matching gel (IMG) to avoid back reflection in the coupler [61].

Around the 2000s, similar designs arose consisting of a metal tube filled with polymer, encapsulating an optical fibre sensor with a circular plate attached to the tip. The pressure was applied through lateral holes, which induced a deformation of the polymer which as a result moved the circular plate, inducing an axial stretch to the optical fibre. A typical schematic from [38] is shown in Figure 2.19. Sheng *et al.* [38] encapsulated an FBG in

silicone rubber inside an aluminium tube of inner diameter 11 mm, length 20 mm and wall thickness 2 mm as depicted in Figure 2.19. The circular plate of diameter 10 mm and thickness 0.5 mm extended the FBG axially when the pressure was applied through the lateral hole. The sensor's performance over the range 0 to 200 kPa was assessed by placing it in a pressure chamber, revealing a sensitivity of 33.87 pm/kPa. Zheng *et al.* [39] exploited the splitting of the FBG's wavelength peak, by encapsulating half of the grating inside the polymer and fixing the other two extremities of the left part of the grating. As a result, only the right side of the grating is affected by the deformation of the polymer induced by a pressure change and the axial strain produced by the round plate. The thermal effects are different in each side of the grating due to polymer's intrinsically higher thermal sensitivity compared to metal, which allowed simultaneous measurements of pressure and temperature. The tube had an inner diameter of 11 mm, length of 20 mm and wall thickness of 2 mm. The round plate had a diameter of 10 mm and thickness of 0.5 mm. They reported a pressure sensitivity of 14.85 pm/kPa over a pressure range of 0 to 250 kPa.

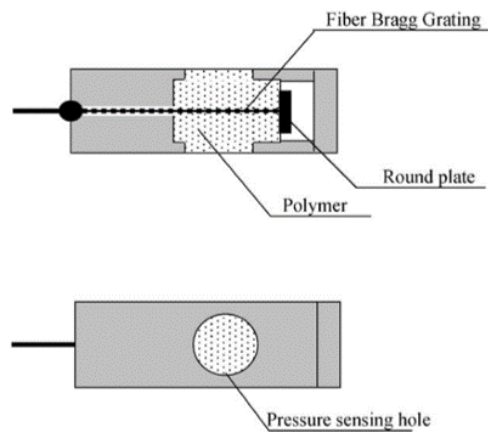


Figure 2.19: Schematic of the lateral polymer-coated FBG pressure sensor proposed by Sheng [38].

Chia Min Lin *et al.* [40] investigated the use of a superstructure fibre grating (SFG) consisting of an FBG and a long period grating (LPG). Figure 2.20 shows a schematic of the sensor. The use of the SFG allowed the measurement of both temperature and

pressure by means of different spectral and intrinsic sensitivities of the the gratings. The tube outer diameter was 15 mm, length 25 mm and round plate diameter 5 mm. They reported a pressure sensitivity of 45 pm/kPa over a pressure range of 0 to 160 kPa.

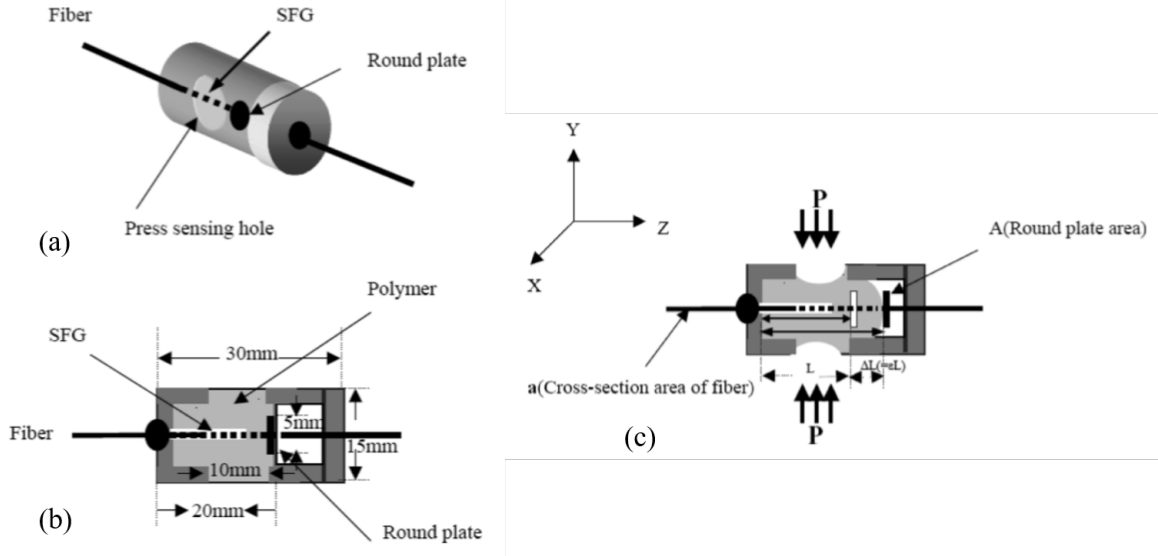


Figure 2.20: (a) schematic of the outer structure of the polymer-coated SFG pressure sensor proposed by Chia-Min *et al.* (b) schematic of the inner pressure sensor section view with dimensions. (c) schematic of the deformation of the polymer due to applied pressure [40].

Recently, Liu *et al.* [62] fabricated a liquid pressure sensor using an epoxy polymer filled cylinder, encapsulating an array of two FBGs, with one FBG embedded in the polymer and one FBG encapsulating in a metal case as shown in Figure 2.21. The FBG was placed in the metal case to remove the effect of pressure from the deformation of the polymer, thus only measuring temperature change. The diameter of the polymer was 8 mm and the overall diameter of the sensor was 20 mm with total length of 70 mm. Two sensors were considered, where the FBGs central wavelength differed as well as the elastic modulus of the polymer. Both were tested in a liquid chamber, with liquid pressure applied from 0 to 15.5 MPa and reported sensitivities of -46.1 pm/MPa and -51.3 pm/MPa.

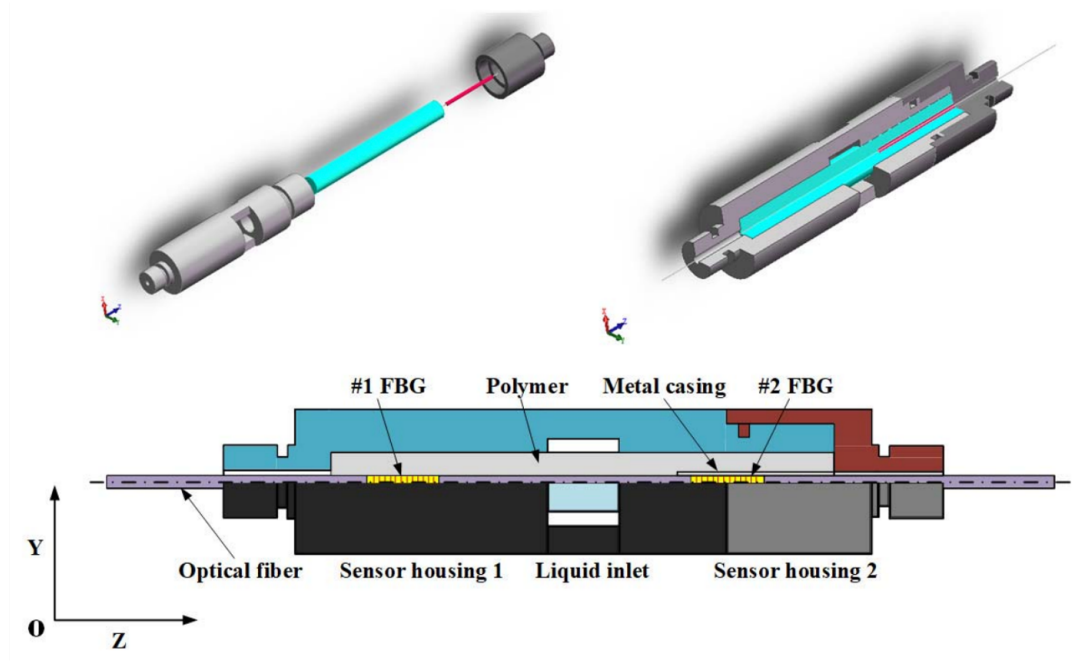


Figure 2.21: Schematic of the half polymer-coated FBG pressure sensor proposed by Liu *etal.* [62].

Polymer filled tube design has the advantage of compact sensors, protection of the optical fibre and most have pressure range covering the requirement of this research. However, most reported sensors are at least an order below the required sensitivity. Although compact, their cylinder-type design is not appropriate to be incorporated in thin composite structure. Table 2.2 summarises all axially stretched FBG with polymer filled tubes.

Table 2.2: Performance summary of reviewed FBG pressure sensors - Axial stretch with polymer filled tubes

Polymer	Tube ϕ (mm)	Plate ϕ (mm)	Plate thickness (mm)	Pressure range (kPa)	Pressure sensitivity (pm/kPa)	Reference
Silicone	11	/	/	0 to 450	-5.28	[60]
Organic silica	8.4	/	/	0 to 450	-3.75	[61]
Silicone	11	10	0.5	0 to 200	33.87	[38]
Polymer	11	10	0.5	0 to 250	14.85	[39]
Polymer	15	5	/	0 to 160	45	[40]
Epoxy	20	/	/	0 to 15.5×10^3	46.1×10^{-3}	[62]
Epoxy	20	/	/	0 to 15.5×10^3	51.3×10^{-3}	[62]

Mechanically Stretched FBG

This section report various designs which are based on the same following principle. The applied pressure is transduced into an axial stretch of the optical fibre which is bonded either side of an FBG. Xu *etal.* [59] attached an FBG to a hollow glass sphere of 5.5 mm diameter and 0.5 mm wall thickness. When the pressure is applied inside, the sphere increases its volume and induce an axial stretch on the FBG which is bonded either side of the sphere wall as shown in Figure 2.22. Over a pressure range of 0 to 14 MPa, they achieved sensitivity of 0.013 pm/kPa. Similarly, Lin *etal.* [63] embedded an FBG inside a printed structure made from acrylonitrile butadiene styrene (ABS). The FBG was placed half way through the printing of a 30 mm diameter cylinder of wall thickness 5 mm, where either side of the FBG was embedded and the FBG itself was free inside the pressure chamber. When the pressure sensor is under pressure, the chamber size increases, stretching the FBG. A pressure of 2.08 pm/kPa was reported over a pressure range of 0 to 40 kPa.

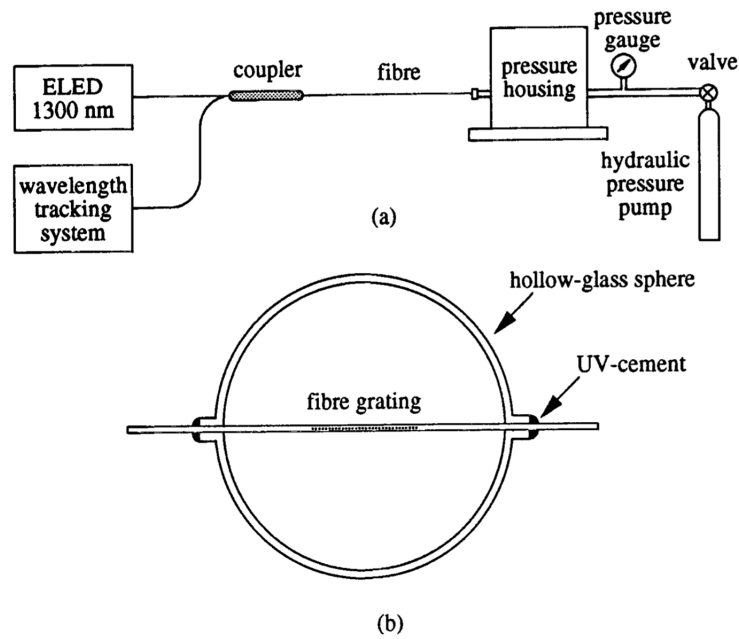


Figure 2.22: Experimental set up (a) of the glass bubble FBG pressure sensor (b) proposed by Xu *etal.* [59].

In 2009, Song *et al.* [64] proposed an axially stretched FBG-based pressure sensor using a carbon-fibre-ribbon-wound cylindrical shell, with the extremities of the optical fibre fixed to an iron cylinder. The sensor was tested over a pressure range of 0 to 800 kPa in a sealed pressure chamber, achieving a sensitivity of 0.452 pm/kPa. Pachava *et al.* [65] attached an FBG to the extremities of a stainless steel bellows which longitudinally expands with applied pressure. As a result of the expansion, the FBG is mechanically stretched in function of the pressure. Another strain-free FBG was installed in the structure for temperature compensation. Over a pressure range of 0 to 276 kPa, they achieved a sensitivity of 13.14 pm/kPa. Zhang *et al.* [66] reported a piston-like FBG based pressure sensor, where two rubber diaphragms bonded either side of an FBG located inside a cylinder induced an axial strain when water/oil entered the cylinder through a side hole, as illustrated in Figure 2.23. The diaphragms were 1 mm and 7 mm in diameter. To increase the diaphragms deformation, they bonded copper hard cores of diameter 3 mm, on the centre of the diaphragm which acted to increase the FBG's sensitivity to pressure. The configuration exhibited a sensitivity of 7 pm/kPa over a pressure range of 100 kPa to 200 kPa.

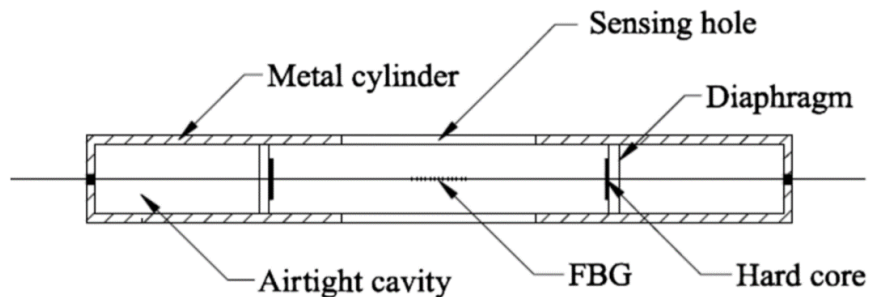


Figure 2.23: Schematic of the piston-like FBG pressure sensor proposed by Zhang [66].

Recently, Schenato *et al.* [67] reported the use of a Nylon 3D printed structure to transduce pressure to an axial strain acting on an FBG. The pressure applied on one side of the sensor through a 0.5 mm thick rubber diaphragm reduced the space between two plates by compressing two lateral arms, which resulted in the application of an axial load on the optical fibre, as shown in Figure 2.24. A simulation of the design allowed

the optimization of the response of the sensor, achieving a pressure sensitivity of 240 pm/kPa over a pressure range of 10 kPa. Sheng *etal.* [68] proposed a whole structure comprising an aluminium drum and two FBGs operating in a push-pull configuration, with one experiencing tension and the other compression in response to applied pressure. Both FBG are bonded to the drum wall and are separated by a silicone rubber diaphragm of diameter 25 mm and thickness 1 mm. This approach allowed the measurement of differential pressure and made the system temperature independent. Over a range of ± 5 kPa, a sensitivity of 822 pm/kPa was achieved. On a same principle but with a single FBG across the diameter of a steel cylinder and a temperature sensing along the wall, Zhang *etal.* [69] achieved sensitivity of 0.0937 pm/kPa over a pressure range of 0 to 4 MPa. The inner diameter of the cylinder was 30 mm, with wall thickness 1 mm.

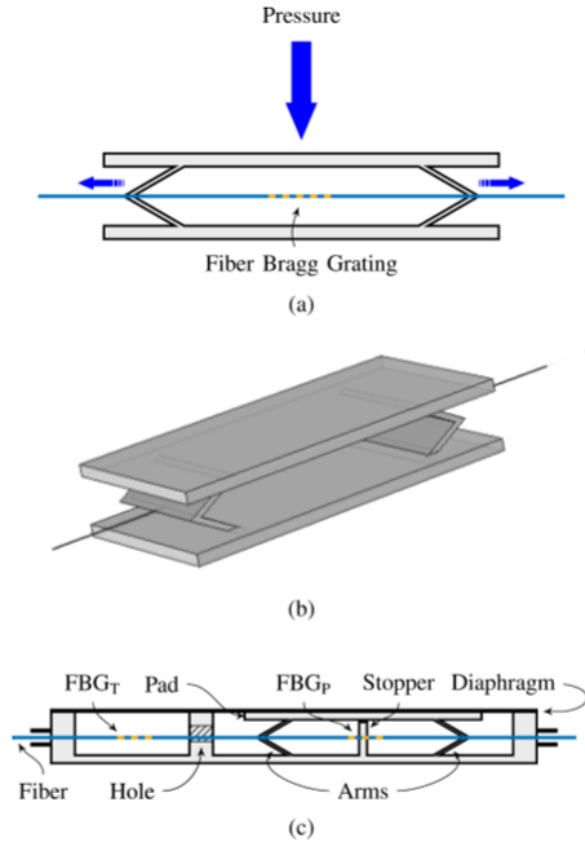


Figure 2.24: (a) working principle of the 3D printed transducer using an FBG proposed by Schenato *etal.* (b) schematic of the outer pressure sensor (b) schematic of the inner pressure sensor section view with FBG_T and FBG_P temperature FBG and pressure FBG respectively [67].

Hsu *etal.* [70] designed a complex system in which pressure applied on a silicone slice moved an aluminium plate through a spring which as a result induced an axial strain on an attached FBG. Over a range of 100 to 300 kPa, a sensitivity of 27.71 pm/kPa was reported. In 2019, Jia *etal.* [71] considered a square stainless-steel diaphragm with an FBG attached to two steel trusses that induced an axial strain on the FBG when the diaphragm deflected. The diaphragm made from stainless steel measured 15 mm x 15 mm and had a thickness of 0.5 mm. The sensor exhibited a sensitivity of 0.62 pm/kPa over a range of 0 to 2 MPa. Also using a diaphragm and inducing an axial stretch on an FBG has been developed by bonding the optical fibre perpendicular to a deflecting diaphragm.

Pachava *etal.* [72] bonded an FBG in the centre of a 10 mm diameter, 0.32 mm thick aluminium diaphragm, as illustrated in Figure 2.25. Fan *etal.* [73] used a square aluminium diaphragm that was 1.4 mm thick with sides measuring twice the size of [72]. Xiong *etal.* [74] bonded the FBG to a metal diaphragm of diameter 26.86 mm and thickness 0.6 mm. Liang *etal.* [75] bonded their FBG to a flat stainless steel plate with was attached to a 12 mm diameter, 1 mm thick diaphragm. All sensor principle induced an axial strain due to the maximum deflection of the diaphragm with applied pressure. Respectively, the sensors where tested over a pressure range of 0 to 207 kPa, 0 to 200 kPa, 0 to 500 kPa and 0 to 50 MPa. The sensitivities were reported at 37.56 pm/kPa, 3.4 pm/kPa, 3.56 pm/kPa and 0.0357 pm/kPa respectively. Thin diaphragms such as those used by [72] suggest the possibility to achieve higher sensitivities.

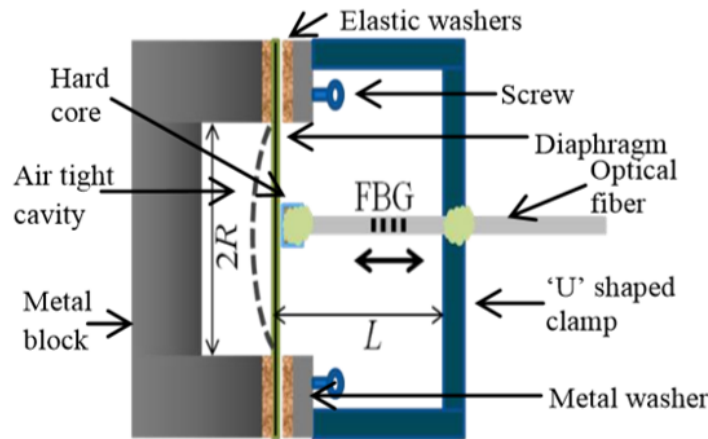


Figure 2.25: Schematic of the aluminium diaphragm based FBG pressure sensor proposed by Pachava *etal.* [72].

FBG mechanically stretched approached are interesting and some sensors achieved high sensitivity, outperforming the requirements of the project [67, 68]. However, these designs are bulky thus not appropriate for embedding, similarly to the polymer filled tube approach. The advantage of optical fibre small size is unfortunately affected with these designs. A summary of all mechanically stretched FBG designs is reported in Table 2.3.

Table 2.3: Performance summary of reviewed FBG pressure sensors - Mechanically stretched FBGs

Design	Material	Pressure range (kPa)	Pressure sensitivity (pm/kPa)	Reference
Hollow glass sphere	Glass	0 to 14×10^3	0.013	[59]
3D printed structure	ABS	0 to 40	2.08	[63]
Ribbon wound cylinder	GFRP	0 to 800	0.452	[64]
Bellow	Stainless steel	0 to 276	13.14	[65]
Piston and diaphragms	rubber	100 to 200	7	[66]
3D printed structure	rubber and Nylon	105 to 115	240	[67]
Drum	Aluminium	± 5	822	[68]
Cylinder	Steel	0 to 4×10^3	0.0937	[69]
Pulley-based system	Silicone and aluminium	100 to 300	27.71	[70]
Square diaphragm	Stainless steel	0 to 2×10^3	0.62	[71]
Diaphragm	Aluminium	0 to 207	37.56	[72]
Square diaphragm	Aluminium	0 to 200	3.4	[73]
Diaphragm	Metal	0 to 500	3.56	[74]
Flat plate and diaphragm	Stainless steel	0 to 50×10^3	0.0357	[75]

2.5.2.2 Pressure Transduced Into Bending of the Optical Fibre

Rather than applying an axial load directly to the fibre, a number of publications have reported systems that transduce the pressure into a bending of the structure to which the fibre is attached. The clearest example is the case where the fibre is bonded such that it lies in the plane of a diaphragm. Similarly, a diaphragm deflecting with pressure can induce bending to an attached cantilever. Embedding an array of FBGs between composite plies was also investigated, with the lateral load inducing a bending to the whole structure. Finally, another instance of a sensor based on the transfer of pressure into bending of the fibre can be conceptualised in the form of a pressure vessel that increases the bending of a fibre attached to its circumference. Several studies showing those concepts are discussed in the following sections. Correia *et al.* [76] tested an FBG in a three point bending rig where the lateral load was applied to a short section of the FBG, with the centre point of contact on the centre of the FBG and the outer points located outside the FBG as shown in Figure 2.26. Rather than monitoring the Bragg peak, the wavelength shift of the spectral hole created by the non-uniform strain on the FBG was measured. This technique provided a sensitivity of 50.8 pm/kPa over a range of 137 to 882 kPa. This approach was used on an aircraft wing [77].

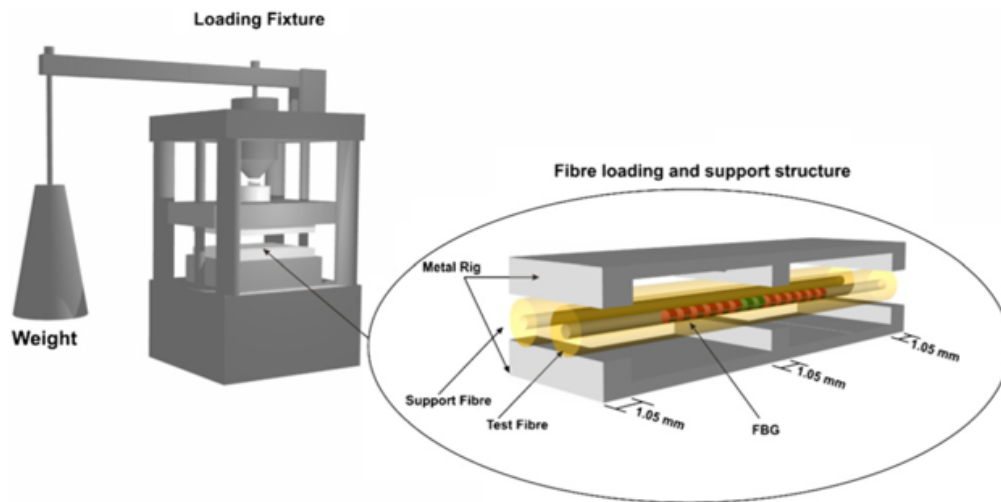


Figure 2.26: Schematic and set up of the transverse loading of the FBG based pressure sensor proposed by Correia *et al.* [76].

Pressure Vessel

Pressure vessels expand when pressure is applied inside, where the longitudinal and circumferential strain can be calculated. This is an area of research where FBG sensors can be applied. Gu *et al.* [78] designed a pressure probe consisting of a thin walled aluminium cylinder of inner diameter 10 mm and wall thickness 0.5 mm, with two FBGs bonded on the outer surface, measuring the circumferential strain. When hydraulic pressure was applied inside the probe, the cylinder deformed and bent the strain FBG. The temperature FBG, used as temperature compensation, was also bonded along the circumference of the probe but in an area that did not deform with applied pressure. The probe was characterised over a range of 0 to 16 MPa and a sensitivity of 0.069 pm/kPa was reported. Hong-Kun *et al.* [79] developed a similar sensor which was a beryllium bronze oval cylinder of length 7 mm, radius 4.5 and wall thickness 0.5 mm. Two FBGs were bonded on the outer surface to record the longitudinal strain with the first sensor bonded on the flat surface of the oval, and the second sensor bonded on the curved surface. The position of those sensors was used for temperature compensation, where the flat surface was expected to exhibit higher strain than the curve section. Over the pressure range of 0 to 1

MPa, a sensitivity of 1.198 pm/kPa was measured, an order of magnitude larger than that of their previous design. Recently, Stephens *et al.* [80] used a silicone cylinder of inner diameter 9.5 and wall thickness of 1.5 mm, to enhance the sensitivity of an FBG attached helically onto the outer surface, as shown in Figure 2.27. A second FBG inscribed in the same fibre was bonded either side inside a splice protector and acted as a strain free reference FBG, measuring changes in temperature only to provide a means for temperature compensation. Their blood pressure measurement device was placed in a heat bath and a custom made pump was used to vary the pressure from 33 to 166 kPa. A sensitivity of 34.5 pm/kPa was achieved, which is three orders of magnitude more than that achieved by the design exploiting a metal cylinder. While the three sensors have similar dimensions, their sensitivities are different, by several orders of magnitude. The elastic modulus of the material in which the vessel is made of greatly influence the strain response to pressure and as a result the sensitivity of the sensor.

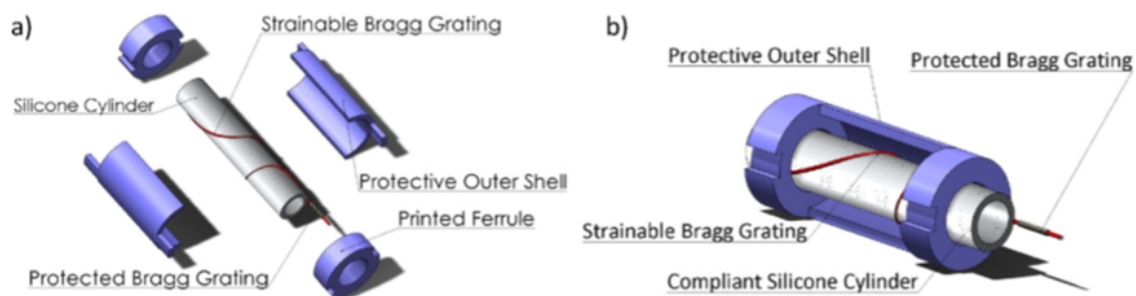


Figure 2.27: Schematic of the exploded FBG based cylinder pressure sensor (a) and assembled view with part of the outer cylinder removed for visibility of the inner components (b) proposed by Stephen *et al.* [80].

Pressure vessel approach has the advantage of high pressure range but has unfortunately low pressure sensitivity with the proposed designs. The sensitivity increase by using a silicone cylinder can be an area of further work however the intrusion of the design is still not appropriate for this application. Table 2.4 summarises the pressure vessel designs.

Table 2.4: Performance summary of reviewed FBG pressure sensors - Pressure vessels

Material	ϕ (mm)	Wall thickness (mm)	Pressure range (kPa)	Pressure sensitivity (pm/kPa)	Reference
Aluminium	10	0.5	0 to 16×10^3	0.069	[78]
Beryllium bronze	Oval: L: 7 x R: 4.5	0.5	0 to 1000	1.198	[79]
Silicone	9.5	1.5	33 to 166	34.5	[80]

Embedded FBG - Vertical Pressure

Additional optical fibre embedding designs have been developed using polymer, composite and 3D printing techniques. Liu *et al.* [81] embedded an FBG in a polycarbonate cube of size $10 \times 15 \times 50$ mm, achieving a pressure sensitivity of -0.0097 pm/kPa over a range of 10 MPa when placed inside a pressure chamber. The negative response indicates that the pressure was transduced into a compressive load acting on the FBG. Hao *et al.* [82] embedded an array of five FBGs between 10 plies of Carbon Fibre Reinforced Polymer (CFRP) to fabricate a foot pressure sensor for diabetic patients. The laminate, consisting of 8 plies before the array and 2 after, was cut into a pad with the shape of an insole. The pressure was applied as a lateral load, simulating body weight, with the aim of understanding the weight distribution of healthy and diabetic patients. The sensitivity of their sensor was shown to be 0.7 pm/kPa over a pressure range of 0 to 45 MPa. Tjin *et al.* [83] also embedded an FBG between 8 plies of CFRP after applying a perpendicular force to a bare FBG with a $10\text{ }\mu\text{m}$ thick polyimide coating, obtaining a non-linear response and observing permanent deformation of the FBG. To minimise damage and improve performance, the FBG was located 7 plies below the surface that was exposed to pressure. Pressures up to 230 kPa were applied and enhanced sensitivity and linearity were demonstrated, as well as better stability and increased operating pressure range. The embedded FBG exhibited a sensitivity of 0.5 pm/kPa. Recently, Hong *et al.* [84] embedded an FBG in Polylactic Acid (PLA) using 3D printing method. The printed sensor was 100 mm long and 100 mm wide with the FBG placed in the middle of the 10 mm height, as shown in Figure 2.28. The FBG was placed half way through the printing, requiring no additional bonding material. Vertical pressure from 0 to 2000 kPa was applied in a cycled series of single pressure load of 400 kPa, 800 kPa, 1200 kPa, 1600 kPa and 2000 kPa. A linear fit to the data revealed pressure sensitivity of 0.075 pm/kPa. The embedding method fits well within the requirement for reduce intrusion in the host structure however, the sensitivities achieved are too low for the application. Table 2.5 summarises the embedded designs.

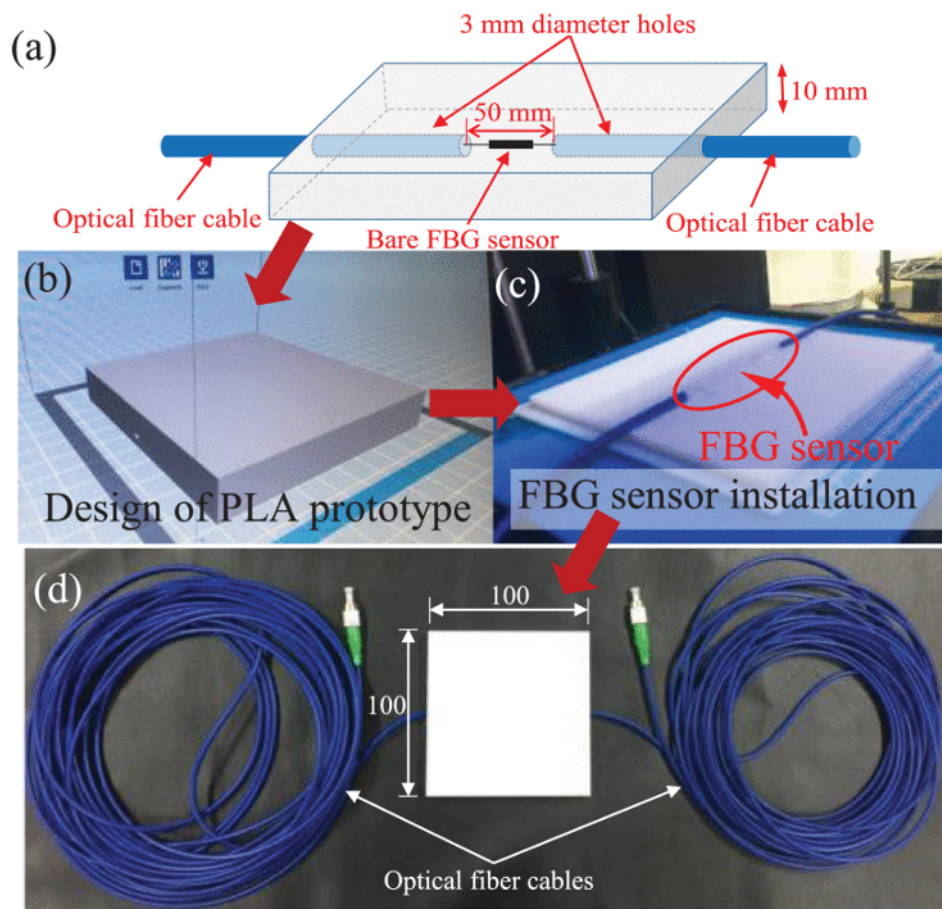


Figure 2.28: (a) schematic the FBG based pressure sensor proposed by Hong *etal.* [84], (b) 3D CAD model. (c) and (d) images of the sensor.

Table 2.5: Performance summary of reviewed FBG pressure sensors - Vertical pressure on embedded FBGs

Material	Pressure range (kPa)	Pressure sensitivity (pm/kPa)	Reference
Polycarbonate	0 to 10^3	-0.0097	[81]
CFRP	0 to 45×10^3	7	[82]
CFRP	0 to 230	0.5	[83]
PLA	0 to 2000	0.075	[84]

Diaphragm Based Approaches

A final approach for transducing pressure into strain is by bonding an FBG in-plane on a diaphragm. The FBG is often bonded in the centre of the diaphragm, where highest strain occur when the diaphragm deflects with applied pressure [85]. The sensitivity of the sensor can be tuned through material and dimensions and temperature compensation can be achieved using wavelength differential measurement. In most sensors, the FBG was bonded to the surface opposite to that which experiences the applied pressure, such that the fibre experiences tension in response to positive pressure. Amad *etal.* [86] bonded an FBG to a stainless steel sheet of thickness 0.4 mm and diameter 55 mm. The sensor did not exhibit hysteresis due to the material it is made of and achieved a sensitivity of 1.67 pm/kPa over a range of 0 to 690 kPa. Huang *etal.* [87] also fabricated their sensor with a stainless steel diaphragm of larger dimensions with a diameter of 60 mm and thickness 1.5 mm. They bonded an array of two FBG along the diameter of the diaphragm, with the first FBG in the centre and the second FBG closer to the edge, measuring positive strain and negative strain respectively. The wavelength difference and sensitivities of both FBGs is used for temperature compensation. This method has been investigated in Chapter 6. Over a pressure of 0 to 1000 kPa, they achieved a sensitivity of 1.57 pm/kPa, which is in the same order as [86], with larger diaphragm diameter and thickness. On the same principle of deflecting diaphragm, Jiang *etal.* [88] used an elastic metal film of thickness 2 mm and diameter 15 mm with the FBG bonded in the centre and achieved a sensitivity of 0.0238 pm/kPa over a pressure range of 0 to 60 MPa. Pachava *etal.* [89] designed a thin metal diaphragm of diameter 30 mm and thickness 0.5 mm, made from copper and bonded the FBG in the centre, as shown in Figure 2.29. Over a range from 0 to 1 MPa, they reported a pressure sensitivity of 3 pm/kPa.

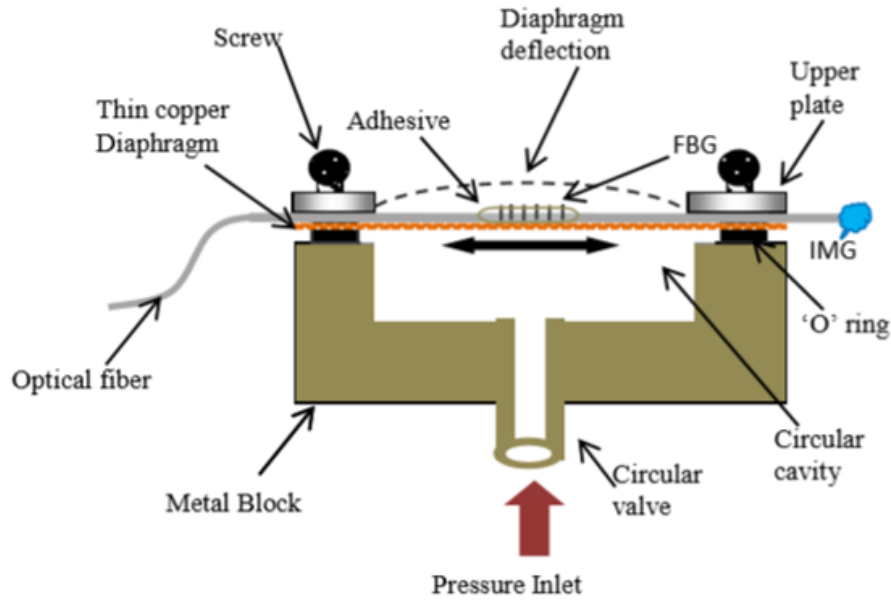


Figure 2.29: Schematic of the diaphragm based FBG pressure sensor proposed by Pachava *etal.* [89].

Polymer and rubber diaphragm can have the advantage of higher strain induced by the diaphragm deflection due to the low modulus of elasticity of these materials. In 2018, Diaz *etal.* [90] embedded an FBG in an epoxy diaphragm of diameter 19 mm and thickness 1.1 mm, as shown in Figure 2.30. The sensor was immersed in water and pressures of up to 100 kPa were applied. The sensor exhibited a nonlinear response over larger pressure range, suggesting that the sensor was operating in the large deflection regime for this range. The large deflection theory applies when the deflection is more than 20% of the diaphragm thickness. Chapter 3 of this thesis further develops this concept. A reference strain free FBG was used for temperature compensation. Designed to measure liquid level, the sensitivity of the sensor reached 2.8 pm/mmH₂O, equivalent to 285.6 pm/kPa over a pressure range of 0 to 97 kPa. Recently, Leal-Junior *etal.* [91] developed a temperature insensitive pressure sensor based on a polyurethane diaphragm of diameter 40 mm and thickness 1 mm, with two FBGs bonded to either side of the surface. When pressure was applied, one FBG was subject to tension and the second FBG was subject to compression, with the temperature influencing both FBG to a red shift. The subtraction

to one another offers temperature discrimination, assuming the position of the FBGs are exactly in the opposite positions. The temperature dependence of the polymer was found to influence the pressure performance due to the thermal expansion of the material, which induced additional strains. Further investigation of the same subject is presented in Chapter 7. At ambient temperature, the pressure sensitivity was reported at 571 pm/kPa over a range of 0 to 1.2 kPa.

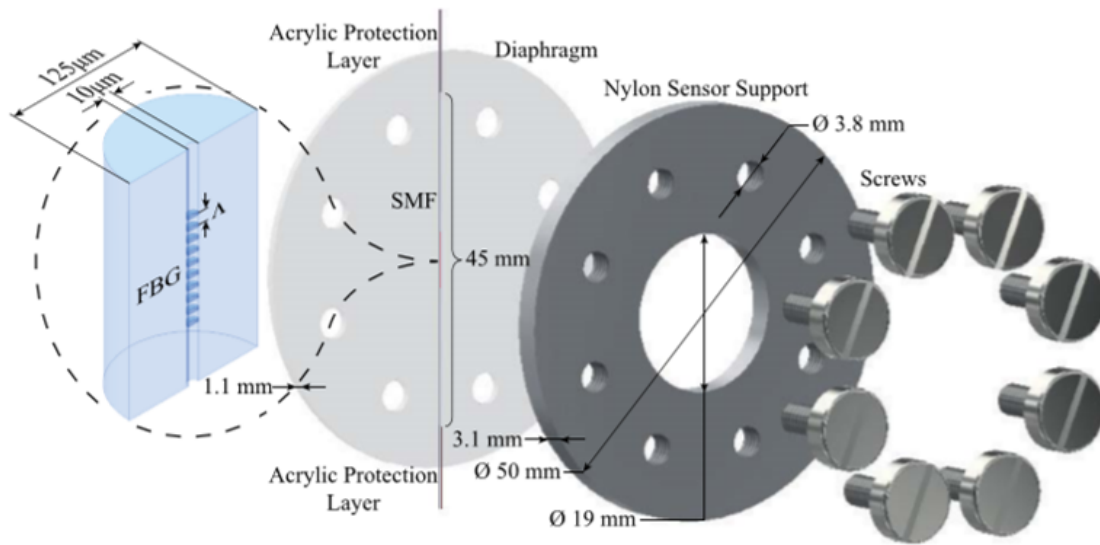


Figure 2.30: Exploded view of the liquid level diaphragm based FBG pressure sensor proposed by Diaz *et al.* [90].

Allwood *et al.* [92] design a sensor made from a rubber diaphragm of diameter 14 mm and thickness 0.125 mm. The sensor was tested over a pressure range from 100 to 115 kPa and achieved a sensitivity of 116 pm/kPa. The use of an edge filter FBG for temperature compensation was investigated. Vorathin *et al.* [93] bonded a 10 mm FBG onto a rubber diaphragm of diameter 45 mm and thickness 1.26 mm. Half the FBG was bonded to the diaphragm and half was free from the diaphragm but sandwiched between two aluminium sheets of length 5 mm, width 3 mm and thickness 1.3 mm to increase mechanical strength and thermal transfer. The split method, such as described in [61, 39], was used for temperature compensation due to the difference of thermal sensitivities between the two material. The sensor was tested over a pressure range of 0 to 10 kPa, with a reported

sensitivity of 117.7 pm/kPa. Although rubber materials have lower modulus of elasticity compared with composite materials, the latter have the advantage of thin ply thickness. The challenge with small thicknesses relate with the large deflections as explained previously. Song *etal.* [94] fabricated their sensor using a carbon fibre composite material. The FBG was bonded on the centre of a diaphragm of diameter 57 mm and thickness 0.2 mm, using epoxy. Over their pressure range of 0 to 100 kPa, a nonlinear response from their sensor can be observed but a linear fit sensitivity of 18.87 pm/kPa. Ambastha *etal.* [95] also bonded an FBG on the diameter of a glass epoxy diaphragm mounted on a conical flask that was attached to a pressure regulator. They reduced pressure in the flask via a tube on the opposite side of a diameter 25 mm, 0.5 mm thick diaphragm. The sensor also exhibited nonlinearity but a linear fit showed a pressure sensitivity of 14 pm/kPa over a pressure range of 2.4 to 100 MPa. Ameen *etal.* [96] fabricated their sensor using a 25 μ m thick graphene sheet of diameter 55 mm at the top of the cavity, and a sandwiched FBG between two sheets, forming a 44 mm diameter diaphragm at the bottom of the cavity as shown in Figure 2.31. The hydrostatic pressure was transferred from the 55 mm diaphragm to the 44 mm diaphragm through a plastic needle with hemispherical tip. A second FBG, free from pressure, acted as a temperature sensor for temperature compensation. The sensor achieved sensitivity of 248 pm/kPa over a pressure range of 0 to 10 kPa.

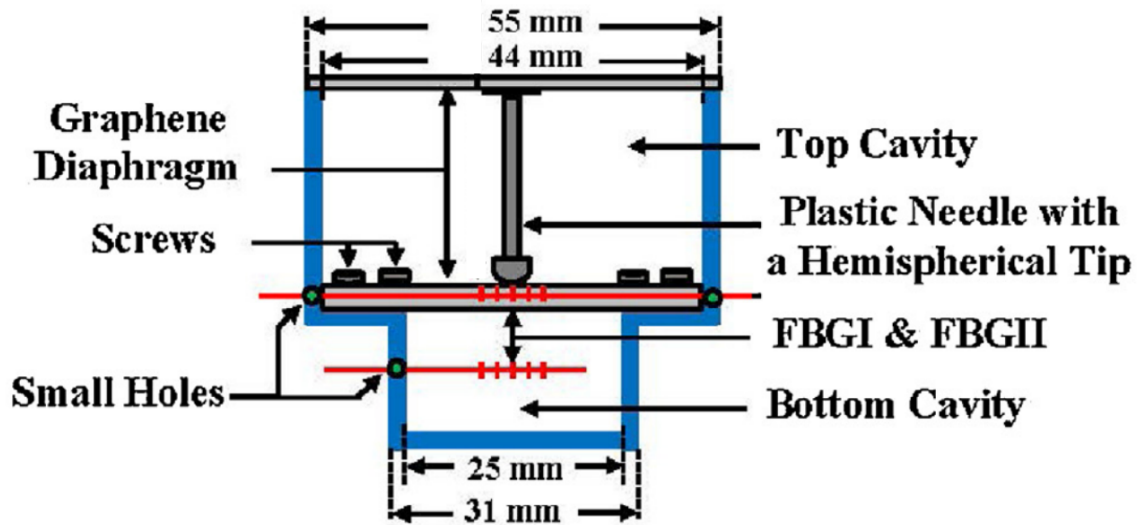


Figure 2.31: Schematic of the FBG based pressure sensor proposed by Ameen *et al.* [96].

Another method using a diaphragm was also investigated using a cantilever attached to the centre, where two FBG are bonded either side of the cantilever for wavelength differential, thus allowing temperature compensation. Liang *et al.*'s [97] sensor comprised of a dowel bar connected to a stainless-steel diaphragm of diameter 12 mm and thickness 0.5 mm. The thickness of the cantilever beam was 1.2 mm and was also made from stainless steel. Both FBGs, due to their positions on the cantilever, experienced opposite strains, with one FBG in compression and the other one in tension. Vorathin *et al.* [98] used a similar sensor and based their diaphragm on [93]. Their cantilever beam was made from a 0.009 mm thick aluminium sheet. Each sensor was placed in a pressure chamber and the pressure varied from 0 to 10 kPa. The metal diaphragm based sensor exhibited lower sensitivity, with 0.339 pm/kPa, than the rubber diaphragm based sensor, with 329.56 pm/kPa. The difference in sensitivity can be explained by the larger stiffness of the metal diaphragm. Zhao *et al.* [99] based their sensor on a similar design, with a triangular cantilever as shown in Figure 2.32. The diaphragm, of diameter 30 mm and thickness 1 mm and cantilever of thickness 0.5 mm were made from beryllium bronze and achieved a sensitivity of 258.28 pm/MPa over a pressure range of 0 to 2 MPa. Although

based on similar structure as previously described, Manuvinakurake *etal.* [100] bonded their FBGs such that both are placed on the cantilever on the same surface, with the first sensor closer to the centre of the diaphragm, experiencing tension, and the second closer to the edge, experiencing compression, according to the beam theory of a fixed-guided beam [101]. The 20 mm diameter diaphragm and cantilever were made from stainless steel, with thicknesses of 0.5 mm and 0.3 mm respectively. Over a range of 0 to 2 MPa, they achieved a sensitivity in the order of metal diaphragm, with 1.03 pm/kPa.

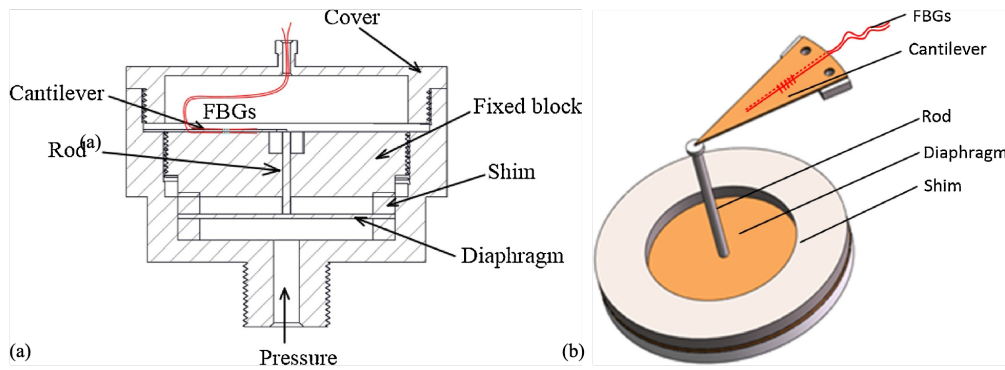


Figure 2.32: Section cut of the FBG based pressure sensor proposed by Zhao *etal.* (a) and (b) a schematic. [99].

Overall, FBG diaphragm based pressure sensors exhibit high sensitivities when used with rubber diaphragms. The large choice of materials and dimensions to tailor the sensitivity to the application is interesting and the use of cantilever can participate in increasing the sensitivity. However, the advantage of in-plane diaphragm approaches is the possibility of reduced intrusion when embedded in composite structure due to the small thickness dimension that can particularly be achieved with composite diaphragms. Table 2.6 summarises the pressure sensors diaphragm-based. Regarding the application targeted in this project, the ability to reduce intrusion and dimension on one axis and the possibility of tuning the sensitivity by changing material, thickness and diameter is an advantage, especially where different pressure resolution can be required in different area of the car.

Table 2.6: Performance summary of reviewed FBG pressure sensors - Diaphragm based

Material	ϕ (mm)	Thickness (mm)	Pressure range (kPa)	Pressure sensitivity (pm/kPa)	Reference
Stainless steel	55	0.4	0 to 690	1.67	[86]
Stainless steel	60	1.5	0 to 1000	1.57	[87]
Copper	30	0.5	0 to 100	3	[89]
Epoxy	19	1.1	0 to 97	285.6	[90]
Polyurethane	40	1	0 to 1.2	571	[91]
Rubber	14	0.13	100 to 115	116	[92]
Rubber	10	1.26	0 to 10	117.7	[93]
CFRP	57	0.2	0 to 100	18.87	[94]
Glass epoxy	25	0.5	2.4 to 100 10^3	14	[95]
Graphene	0.05	44	0 to 10	248	[96]
Stainless steel	12	0.5	0 to 10	0.34	[97]
Rubber	10	1.26	0 to 10	329.56	[98]
Beryllium bronze	30	1	0 to 2000	0.26	[99]
Stainless steel	20	0.5	0 to 2000	1.03	[100]

2.6 Conclusion

This chapter presented an overview of optical and non optical pressure sensors, applied to aerodynamic and other applications. For the requirements of the application targeted by, the main technology used to develop a pressure sensors for aerodynamic measurements on a racing car is the measurement of pressure induced strain on a diaphragm. This means of transducing the pressure has been chosen for its benefits regarding the requirements of high sensitivity and ease of deployment within the host composite structure. This design allow minimal intrusion with the optical fibre in-plan within the diaphragm and allow ease of multiplexing. The diaphragm based optical fibre pressure using FP is not adequate due to the location of the sensing part of the sensor which require the optical fibre to be perpendicular to the measurement surface. Two optical fibre technologies are highlighted to measure the deflection in-plane: FBG, which is commercially available and FSI, which is a new approach. Both technologies are used in this research project with experimental analysis in Chapters 5 and 6 and their working principles and sensitivities were described in this chapter.

Chapter 3

Sensor Principle: Small and Large Deflections Theory, Analysis and Simulation

In this chapter, the theory underpinning the sensor concept is developed. Section 3.1 presents the working principle of the sensor and the theory, based on the deflection of a circular plate in response to applied pressure, that was used to aid the design of the sensor and to predict its performance. Section 3.2 details the theory of thin plate deflection, which is fundamental to the working principle, where an analytical approach is used to analyse the small deflection case, while the large deflection case requires the use of Finite Element modelling (FEM), which is described in Section 3.3. In both approaches, the strain induced in an optical fibre mounted on the circular plate is considered. A case study of an optical fibre mounted on a 25 mm diameter circular plate, undertaken using FEM simulation is presented. The results are validated experimentally for the specific cases of a sensor of 25 mm diameter in Chapter 5 and of 21.5 mm diameter in Chapter 6. The theoretical tools developed are used subsequently in the design of the sensor to ensure that the performance specifications are met.

3.1 Working Principle of the Sensor

The operation of the sensor is based upon the strain induced in a circular plate, clamped around its circumference, that experiences deformation in response to pressure. The strain is measured by means of an optical fibre bonded to the surface of the diaphragm, aligned along its diameter. The strain that the fibre experiences could be monitored via a number of optical fibre sensing techniques, but here the focus is on the use of FBG technology. Figure 3.1 (a) shows an optical fibre containing a 4 mm long FBG bonded to a diaphragm, while Figure 3.1 (b) illustrates the influence of pressure on the diaphragm and on the optical fibre.

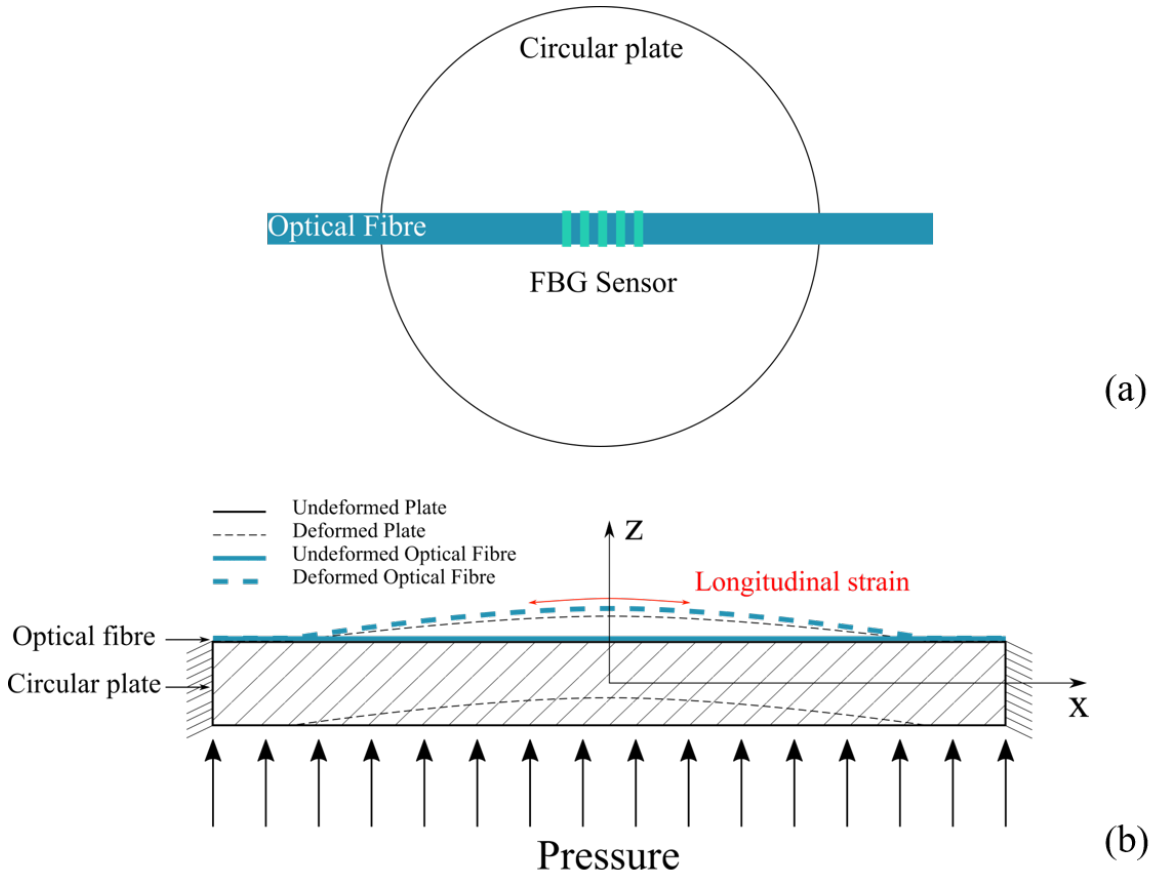


Figure 3.1: Schematic of a clamped circular plate with an optical fibre mounted on its surface. (a) presents a top view and (b) a section cut along the fibre longitudinal axis. Not to scale.

3.1.1 Optical Fibre Properties

The mechanical reliability of optical fibres was assessed by Komachiya *et al.* [102]. They proof tested optical fibres and determined their short term reliability at strains of 3-5 % and at 1 % for general reliability during long term mechanical deformations. To ensure long term operation of the sensor, the worst case scenario of 1 % was taken, equivalent to a strain of 10000 $\mu\epsilon$. The FBG interrogator used throughout the experimental investigations presented with this thesis (SmartScan, Smart Fibre, UK [103]) offers a wavelength resolution of 1 pm, equivalent to a strain of approximately 0.82 $\mu\epsilon$ and a 40 nm bandwidth, allowing wavelength multiplexing. With the resolution of 20 Pa required for the sensor in this study, the design was constrained such that a minimum sensitivity of 20 Pa/pm or 24.4 Pa/ $\mu\epsilon$ was defined.

3.2 Small Deflection: Analytical Solution

The equations governing circular plates are derived from the Poisson equation transformed from rectangular Cartesian coordinates to polar coordinates. The equation of equilibrium governing the linear bending of isotropic plates is given by [85], assuming that the plate is not supported on an elastic body:

$$D \nabla^4 w_0 = P \quad (3.1)$$

where $w_0 = w_0(r, \theta)$ is the transverse deflection, P the distributed transverse load and D the flexural rigidity. For axisymmetric deformation, $w_0 = w_0(r)$ and Equation (3.1) can be expressed in polar coordinates [85], more suitable for circular plates, as:

$$D \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial}{\partial r} \right) \right] \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial w_0}{\partial r} \right) \right] = P(r), \quad r < a \quad (3.2)$$

where r is measured radially outward from the centre of the plate and a is the radius of the plate.

The strain induced in an isotropic solid circular plate subject to an axisymmetric load with edge conditions that are also axisymmetric is a function of the radial coordinate r . The following treatment concerns the linear, static bending of clamped circular plates. The deflection of isotropic circular plates under uniform load can be calculated using Equation (3.3) and Equation (3.4) where the constants c_1 and c_2 are determined by the boundary conditions.

$$Dw_0(r) = H(r) + c_1 \frac{r^2}{4} + c_2 \quad (3.3)$$

$$D \frac{dw_0}{dr} = H'(r) + c_1 \frac{r}{2} \quad (3.4)$$

The boundary conditions of a clamped circular plate are given by $\frac{dw_0}{dr} = 0$ for $r = 0$ and $w_0 = 0$, $\frac{dw_0}{dr} = 0$ for $r = a$. Using these boundary conditions in Equation (3.3) and Equation (3.4) gives

$$c_1 = -\frac{2H'_0}{a}, \quad c_2 = -H_0 + \frac{H'_0 a}{2} \quad (3.5)$$

For an uniformly distributed load P , we have $c_1 = -Pa^2/8$ and $c_2 = Pa^4/64$, so the deflection becomes

$$w_0(r) = \frac{Pa^4}{64D} \left(1 - \frac{r^2}{a^2}\right)^2 \quad (3.6)$$

and the nonzero radial strains are given by

$$\varepsilon = z \frac{1}{r} \frac{dw_0}{dr}, \quad z = \frac{t}{2} \quad (3.7)$$

where t is the thickness of the membrane.

The classical small deflection plate theory is based on the Kirchhoff hypothesis which consists of:

- Straight lines perpendicular to the mid-surface before deformation, which remain straight after deformation.
- The transverse normals do not experience elongation.
- The transverse normals rotate such that they remain perpendicular to the mid-surface

after deformation.

However, these equations are true only for small deflections such that the maximum deflection does not exceed $1/5$ of the plate thickness. Beyond this deflection, the plate enters the large deflection regime, where the equations are nonlinear and the analytical solution more complex [104, 105, 100]. The requirements of the pressure sensor to be developed within this work, described in Chapter 1 and depending upon the properties of the plate material, are expected to fall within the large deflection range, which is described in the following section.

3.3 Large Deflection: Finite Element Modelling

FEM was used to simulate the deformation of the membrane and the optical fibre in a non-linear analysis. The model is detailed in this section. The FE solution offers a means for determining the deformation of the whole membrane, irrespective of thickness, revealing a different behaviour at the edge, not represented with the linear solution but seen in [87]. Chapter 6 experimentally investigates this particular edge condition to explore a means for the simultaneous and independent measurement of pressure and temperature.

The modelling of the fibre and glue line between the fibre and the membrane were performed using the Computer-Aided-Design (CAD) software CATIA V5 with both the pre and post processing and solver performed in the Computer-Aided-Engineering (CAE) software Abaqus CAE. The circular plate was modelled directly in the CAE. The model initially concerned the plate only, in order to perform a mesh sensitivity study, described in Section 3.3.3.2 using a linear static analysis comparable with the analytical solution. The nonlinear static analysis was then performed with the option "Nlgeom" (nonlinear geometry) in Abaqus, and included additional components such as the optical fibre. Although other materials have been experimentally tested during this study, the model described here is based on the use of a Glass Fibre Reinforced Polymer (GFRP) material to form

the circular plate. Material selection is detailed in Chapter 4, Section 4.2. The model detailed here is used for comparison with the experimental results that are presented in Chapter 5 and Chapter 6.

3.3.1 Properties and Design

3.3.1.1 Material

The "material card", in Abaqus, was created for the optical fibre, the circular plate and the glue line. The material cards are virtual materials for type of material configurations and contain information related to mechanical and thermal properties. The material configuration was the same for all components and was set as elastic homogeneous isotropic. Although composites are not isotropic materials, the laminate of this particular plate can be assumed to be, given the quasi-isotropic laminate layup with fibre orientations at $\pm 45^\circ$ with respect to the optical fibre's longitudinal axis.

The glue line, based on the improved manufacturing method presented in Chapter 4 is essentially formed by the resin of the prepreg material, with a Young's modulus of 26.5 GPa and a Poisson's ratio of 0.14. The material properties of the GFRP were provided by the project sponsor as a bespoke composite, but similar product is available here [106]. The optical fibre is fused silica with a Young's modulus of 72 GPa and a Poisson's ratio of 0.14 [107]. Material properties are summarised in Table 3.1.

3.3.1.2 Cell Partition

To simplify the calculation and reduce solver memory requirements and Central Processing Unit (CPU) time, the model comprised a mix of shell and solid sections, with the former used for the plate and the latter for the optical fibre and the glue line.

The plate was designed in Abaqus as a 32 mm diameter shell disc with a cell parti-

tion of the inner working diameter of the sensor, as depicted in Figure 3.2, used for the boundary conditions, presented in Section 3.3.2.3. The shell section was given a thickness depending on the working diameter of the sensor. The 32 mm diameter was chosen to allow a minimum of 2 mm annular section for clamping diaphragms up to 30 mm diameter, 30 mm being the maximum diameter tested in Chapter 4.

The optical fibre and the glue line were designed in CATIA V5 and imported to the model with no further modification and were independent of the circular plate design. Figure 3.3 (a) shows the model representing the sensor as faithfully as possible to the microscope picture (b) with shell and solid sections. Including the glue line provides a more representative contact between the fibre and the membrane. The contacts between each component are described in Section 3.3.2.1.

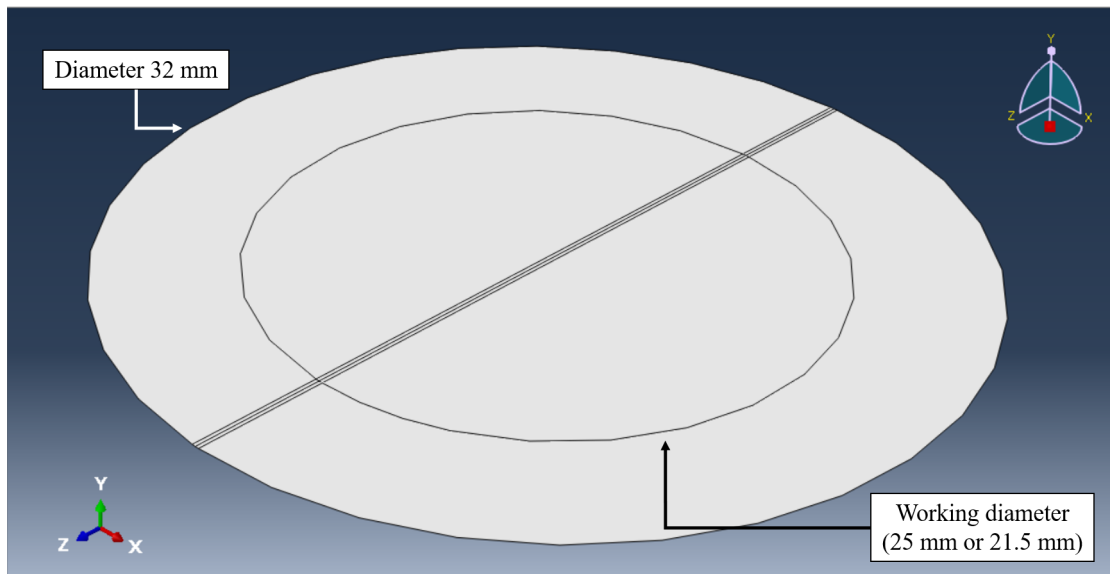


Figure 3.2: 32 mm diameter circular shell plate with annular partition for constraints application (load and boundary conditions).

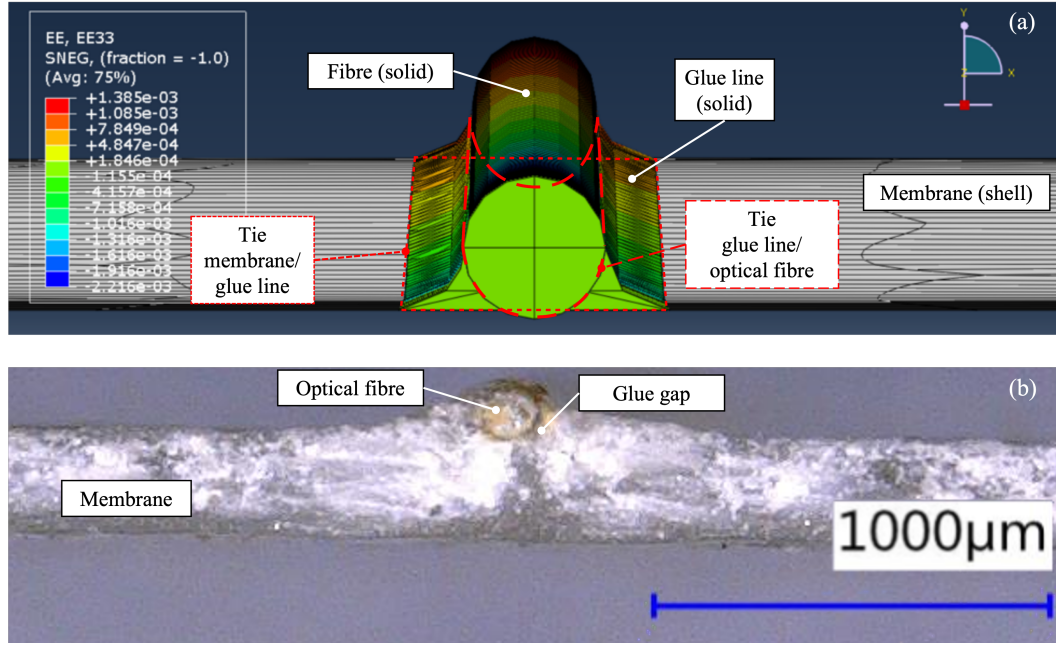


Figure 3.3: (a) FE model, representing the sensor with optical fibre, glue gap, circular plate and their associated ties. Image also showing the strain results in solid components only (optical fibre and glue gap). (b) microscopic picture of a manufactured sensor.

3.3.2 Constraints

3.3.2.1 Contact

The circular plate, fibre and glue line are separate entities that require contacts to allow the deformation of the plate to be transferred to the fibre. Similar to the material card, the constraint card contain several parameters, including the type of contact between the entities. The "surface tie" was selected so that there was no relative motion between the plate and the glue radially, along the 32 mm diameter. The tie between the glue and the optical fibre was made along the longitudinal axis of the fibre, on the lower half of the surface of the fibre as shown in Figure 3.3 (a).

3.3.2.2 Load

Figure 3.4 shows the distribution of the loads on the assembly, and, in particular, on the plate. The shell membrane, although represented as a single surface, has both its top and bottom surfaces defined by the shell thickness. The load was applied as pressure to the shell surface opposite that to which the fibre was attached on the inner diameter of the plate and along the positive Y-axis to simulate the pressure chamber presented in Figure 3.1 (b).

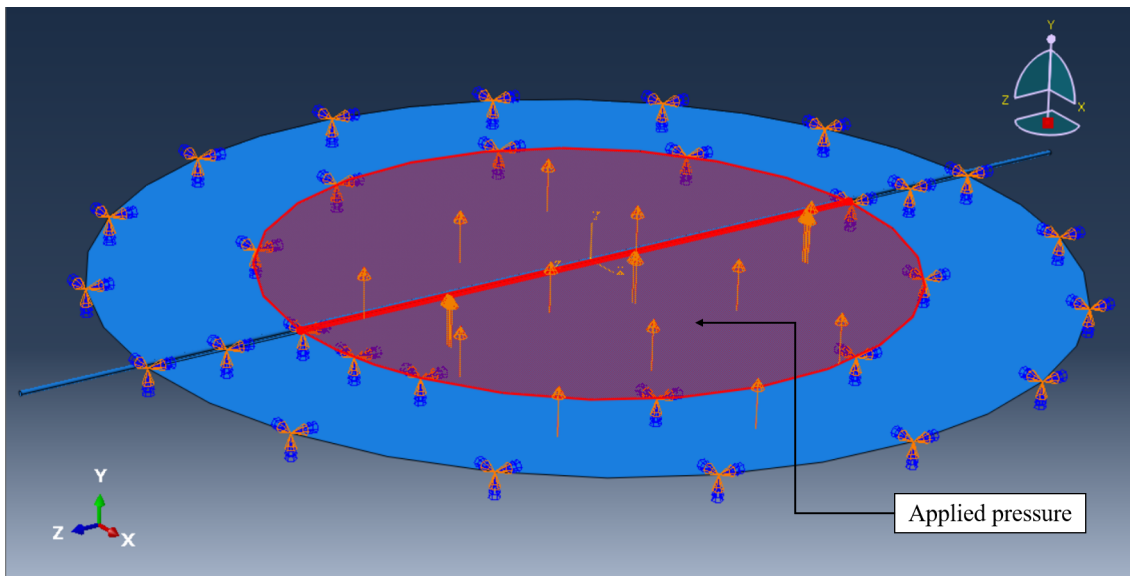


Figure 3.4: Pressure applied on the inner working diameter of the circular plate, in the Y-positive direction on the surface opposite the surface containing the fibre. The central area is highlighted to show the area prone to applied pressure, including the inner working diameter and part of the optical fibre.

3.3.2.3 Boundary Condition

The sensor design was based on the circular clamped plate as detailed in Section 3.1. To faithfully represent the sensor design, the circular plate had a diameter of 32 mm with an annular surface representing the bonded surface on the pressure chamber. The annular width depended on the sensor diameter that actually deflected with applied pressure from

the pressure chamber aperture. The annular surface was partitioned as per Section 3.3.1.2 and then used to simulate the bond by using the encastre boundary condition as shown in Figure 3.5. The encastre boundary condition locks all degrees of freedom (DoF), i.e. the three translations and the three rotations, and leaves the inner diameter free to deflect with applied pressure.

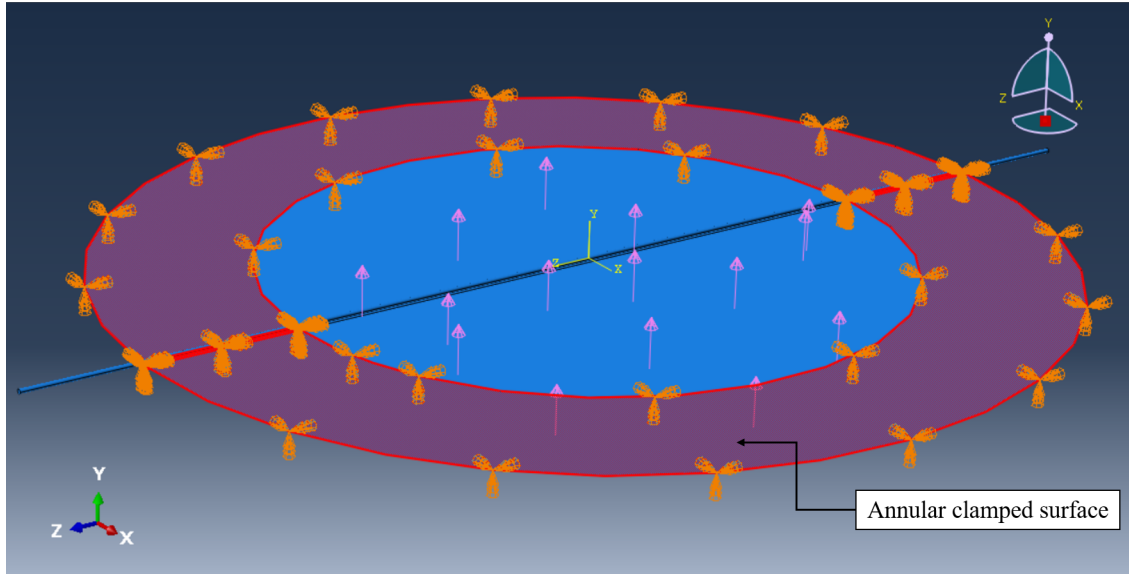


Figure 3.5: All degrees of freedom locked on the outer annular shell surface. The annular area is highlighted to show the area prone to the encastre boundary condition. Inner working diameter free to deflect with applied pressure, with all DoF unlocked.

3.3.3 Mesh

3.3.3.1 Properties

The mesh density of the circular plate was evaluated and is detailed in Section 3.3.3.2. The mesh of the circular plate was made primarily of quadrilateral elements at the annular section and a mix of quadrilateral and triangular elements over the inner diameter of the disc. The element type of the circular plate was the standard shell and the geometric order was selected as quadratic for its appropriate solving function for large deformations (nonlinear analysis). Both the fibre and glue line were solids and required different type

of elements. Hexahedra (hex) elements (cube) were used for the fibre, as they are known to have better accuracy [108], which was desirable for the fibre as it was the component of interest. These elements also reduced memory and CPU time compared to other type of elements such as tetrahedra (tet) (3-sided pyramids). However, due to the shape of the glue line (pointy pyramids), tet elements were required as hex elements were not appropriate for the 3D shape of the glue line. Mesh and material properties are summarised in Table 3.1.

Table 3.1: Case study model properties

	Membrane	Glue gap	Fibre
Material	GFRP	GFRP	Fused silica
Material	Elastic, isotropic	Elastic, isotropic	Elastic, isotropic
Young's modulus (GPa)	26.5	26.5	72
Poisson's ratio	0.14	0.14	0.14
Section	Shell	Solid	Solid
Dimensions (mm)	ϕ 25, t: 0.3	Groove from mould	ϕ 0.155
Mesh elements	Quad and tri	Tet	Hex
Mesh size (mm)	0.3	0.2	0.1

3.3.3.2 Mesh Sensitivity Study

The mesh of the plate was investigated to select the best refinement matching the analytical solution. To do so, the solver was run as a linear analysis in order to compare with the analytical solution described in Section 3.2.

The thickness of the plate, 0.25 mm, was defined using the analytical solution to achieve the required resolution on a ϕ 21.5 mm diameter sensor. Table 3.1 summarises the properties of the model.

The mesh, labelled #1, was very coarse with a 1 mm element size for a total of only 1070 elements, and was used for comparison with the analytical solution presented in Section 3.2. Refined meshes of 0.5, 0.3 and 0.1 mm element size, labelled #2, #3 and #4 respectively, were also solved and compared with the analytical solution. The properties are summarised in Table 3.2.

Table 3.2: Mesh sensitivity study of four meshes and their properties

Mesh	#1	#2	#3	#4
Element size (mm)	1	0.5	0.3	0.1
Total number of element	1104	4114	11603	105958
Max % error (at edge)	41	2	0	0
Time to solve (s)	13	29	72	1166

Figure 3.6 shows the different meshes of increasing refinement from (a) to (d). Although they all show the same response as that shown in Figure 3.7 (a), the thinner mesh shows a more representative analysis when compared to the analytical solution, especially at the edge which is where the differences are the highest with the coarser mesh as depicted in Figure 3.7 (b). Apart from the edge, the predicted strains, globally, are highly correlated with the analytical solution.

With the highest error at the edge, mesh #1 was not chosen for further use despite its fast solving time. The three other meshes, with low errors, were sorted depending on their solving time. Meshes #3 and #4 correlated 100 % with the analytical solution, but #4 was more than 10 times slower to solve, using more memory and CPU time. The solving time difference between meshes #2 and #3 was small but the accuracy was better with mesh #3, with no errors at the edge, so the mesh size for the plate was selected at 0.2 mm.

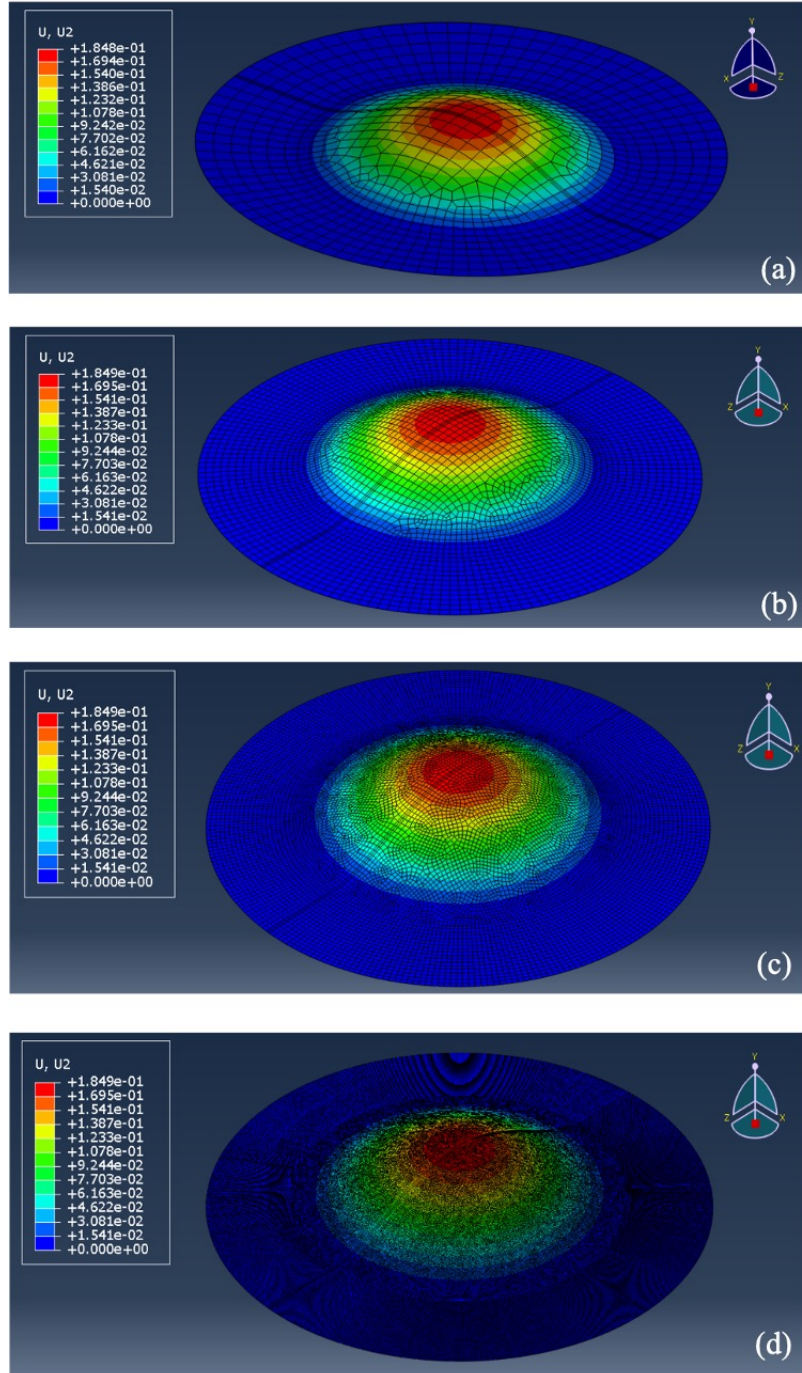


Figure 3.6: Mesh sensitivity study with (a) coarser mesh of 1104 elements, (b) refined mesh of 4114, (c) 11603 elements and (d) the thinner mesh with 105958 elements. The comparison of the meshes were taken from the results of deflection U , in mm.

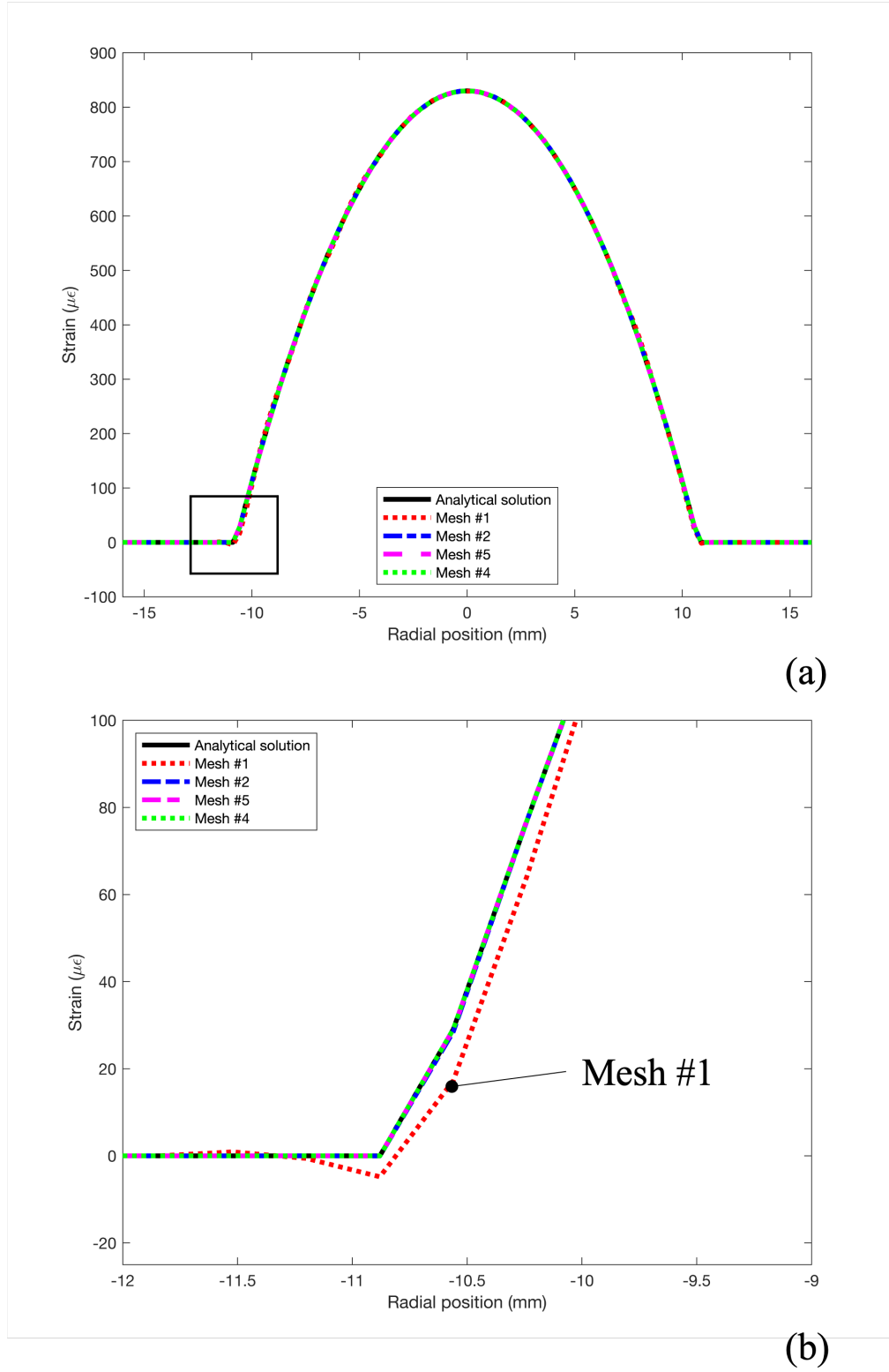


Figure 3.7: (a) strain responses of various mesh sizes and the analytical solution for comparison (b) with the emphasis on the edge where errors occur with mesh #1.

3.3.4 Case study - Nonlinear Analysis of a ϕ 25 mm Diameter Pressure Sensor

3.3.4.1 Model

The model of the circular plate was designed to be representative of the sensor based on a 7-ply laminate produced using the improved manufacturing method presented in Chapter 4, which produced a 0.3 mm thick diaphragm. The working diameter was set to ϕ 25 mm. The annular width of 3.5 mm was clamped as described in Section 3.3.2.3 and pressure was applied on the inner diameter as presented in Section 3.3.2.2. The properties and meshes are detailed in Section 3.3.3.1 and Section 3.3.3.2 respectively.

To optimize the model, the mesh sizes were chosen based on the volume and importance of the parts. For the optical fibre, being the subject of interest, a finer mesh was applied. The glue line volume had a secondary importance in the model (used to simulate contact between the circular plate and the optical fibre), which resulted in the choice of a medium size mesh. The mesh size of each component, reported in Table 3.1, was 0.3 mm, 0.2 mm and 0.1 mm for the circular plate, the glue line and fibre respectively. The materials used are described in Section 3.3.1.1 and reported in Table 3.1. The contact between the shell plate and the glue line is detailed in Section 3.3.2.1, along with the contact between the glue line and the fibre.

The whole assembly was analysed under a pressure load of 35 kPa using the nonlinear geometry solver "Nlgeom". Two paths were created longitudinally, in the centre of the fibre and radially, on the surface of the circular plate as depicted in Figure 3.8, in order to analyse the strain exhibited by both components. An additional, smaller path of length 4 mm was analysed in the centre of the fibre, to simulate the FBG sensor.

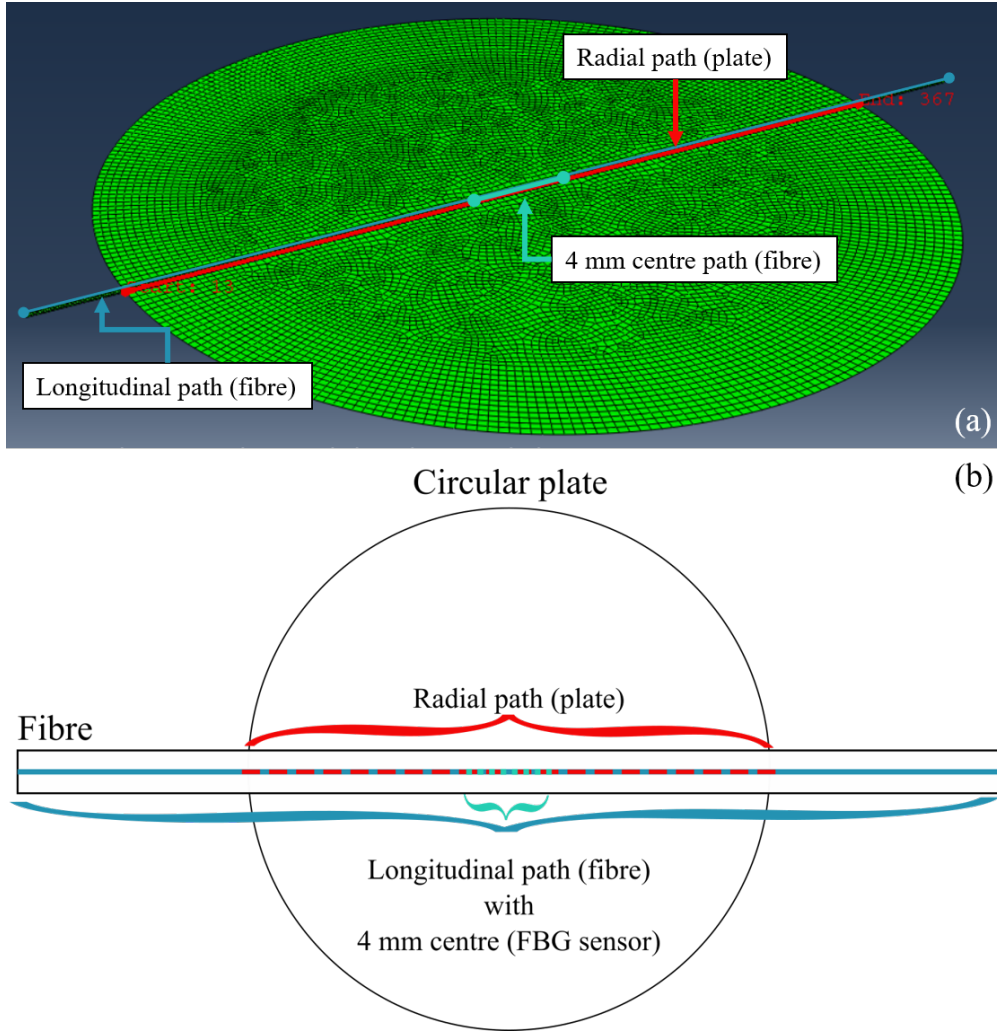


Figure 3.8: Paths created to analyse the strains longitudinally. (a) the FE model and (b) the schematic, representing the fibre, the 32 mm diameter plate and 4 mm FBG sensor.

3.3.4.2 Results and Discussions

Figure 3.9 shows the general trend of the strain over the full working diameter of the diaphragm, with compression at the edge and tension in the centre, and the longitudinal strain of the optical fibre and the radial strain on the surface of the plate at the maximum pressure of 35 kPa. The analytical solution and the mesh study solved with linear analysis did not show the edge behaviour, suggesting that the nonlinear analysis highlights the compression at the edge. Chapter 6 experimentally analyses and take advantage of the edge behaviour with FSI technology, which was also investigated by Huang *et al.* using

FBGs for temperature compensation [87].

Overall, the strains between the circular plate and the optical fibre show similarities and differences. At the edge, both show similar negative strains of around $1500 \mu\epsilon$. However, at the maximum positive strain in the centre, both exhibit consequent strain difference. The optical fibre exhibited about twice as much strain with a value of $1047 \mu\epsilon$ compared to $526 \mu\epsilon$ for the circular plate. This difference can be explained by the distance from the neutral axis of the plate, which, for the optical fibre, is including the thickness of the glue gap and the radius of the optical fibre if strain are taken at the core.

In the centre of the fibre, the strain over the highlighted 4 mm length has a low gradient with an average value of $1019 \mu\epsilon$. The highest positive strain, as suggested by Equation (3.7) and Figure 3.9, appear in the centre of the diaphragm/optical fibre. While the strains at the edge are higher than those in the centre and could potentially increase the sensitivity of the sensor, the high strain gradient would be expected to affect the response of the FBG sensor as it has been reported to result in a split in the peak [61]. A split in the peak could lead to erroneous results as the signal processing built into the FBG interrogator used in this research only expects a single peak. As a result, it was decided to locate the FBG in the centre of the circular plate.

The following paragraph describes the analysis of the strain, undertaken over the full pressure range, in the centre of the diaphragm/optical fibre and the average strain over the 4 mm length of the optical fibre. Figure 3.10 shows the comparison of analytical and FE results over the pressure range, from 0 to 35 kPa.

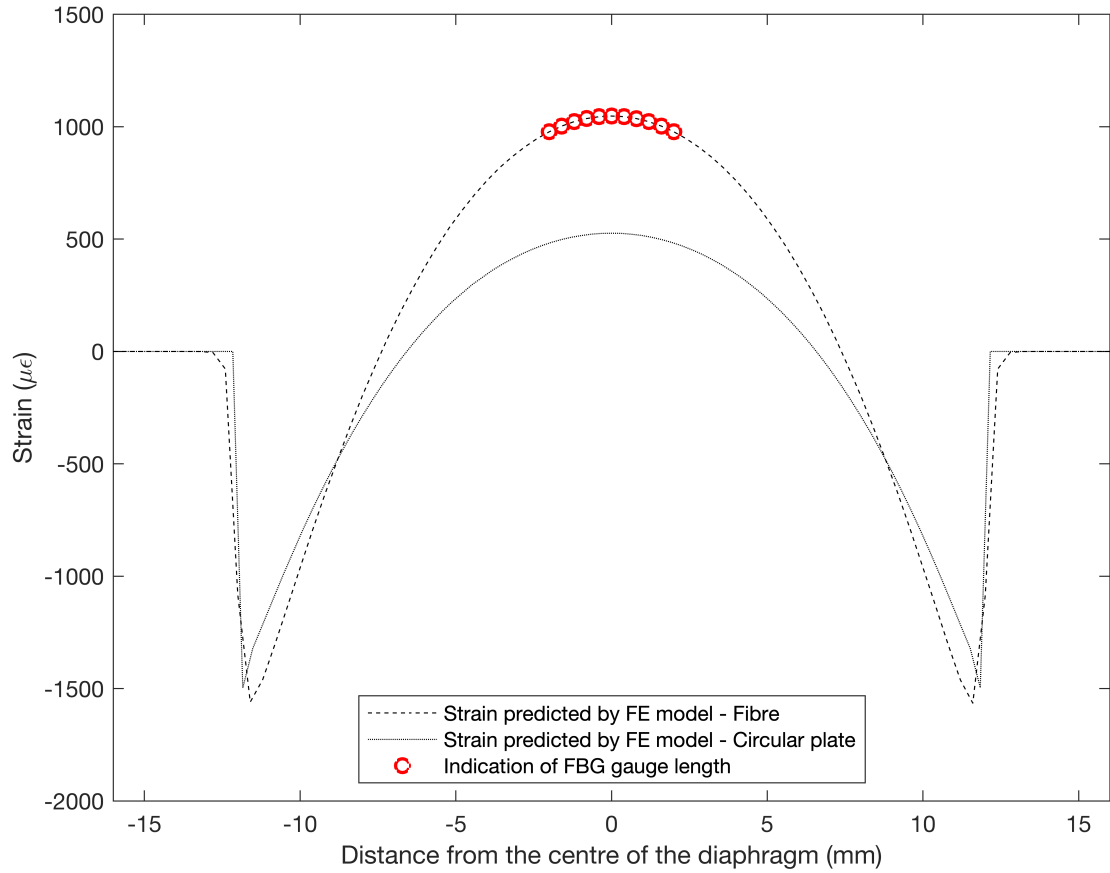


Figure 3.9: Radial response at 35 kPa with the indication of the FBG gauge length.

Figure 3.10 shows the results of the simulation of the ϕ 25 mm diaphragm, showing several maximum strain over the full pressure range, from 0 to 35 kPa. The strains were taken as follow: the maximum positive strain of the fibre, taken from the single point located in the centre of the sensor, shown in the middle of the 4 mm highlight in Figure 3.8 (a), the stain over the 4 mm, averaged as shown in Figure 3.8 (a), simulating the FBG and last, the maximum positive strain located in the centre of the diaphragm. The graph shows a similar response to that seen in Figure 3.9, with the maximum strain located in the centre of the plate and a low strain gradient over the 4 mm length, which is desirable for obtaining the best performance from the FBG sensor.

Figure 3.10 also shows the response of the diaphragm predicted by the FE analysis and the analytical solution for comparison. Unlike the optical fibre, the diaphragm exhibits nonlinear behaviour that starts around 15 kPa when compared to a linear fit. It also shows a lower strain than that exhibited by the fibre and the analytical solution. The analytical solution, as presented previously, considers the deflection of the diaphragm only, without the fibre mounted to it. In the literature [94, 89], the strain experienced by an optical fibre attached to a diaphragm is always assumed to be the same as that predicted by the analytical solution. However here, there are two effects that must be taken into consideration: the lower strain in the diaphragm compared to the analytical solution and the higher strain in the fibre compared to the diaphragm.

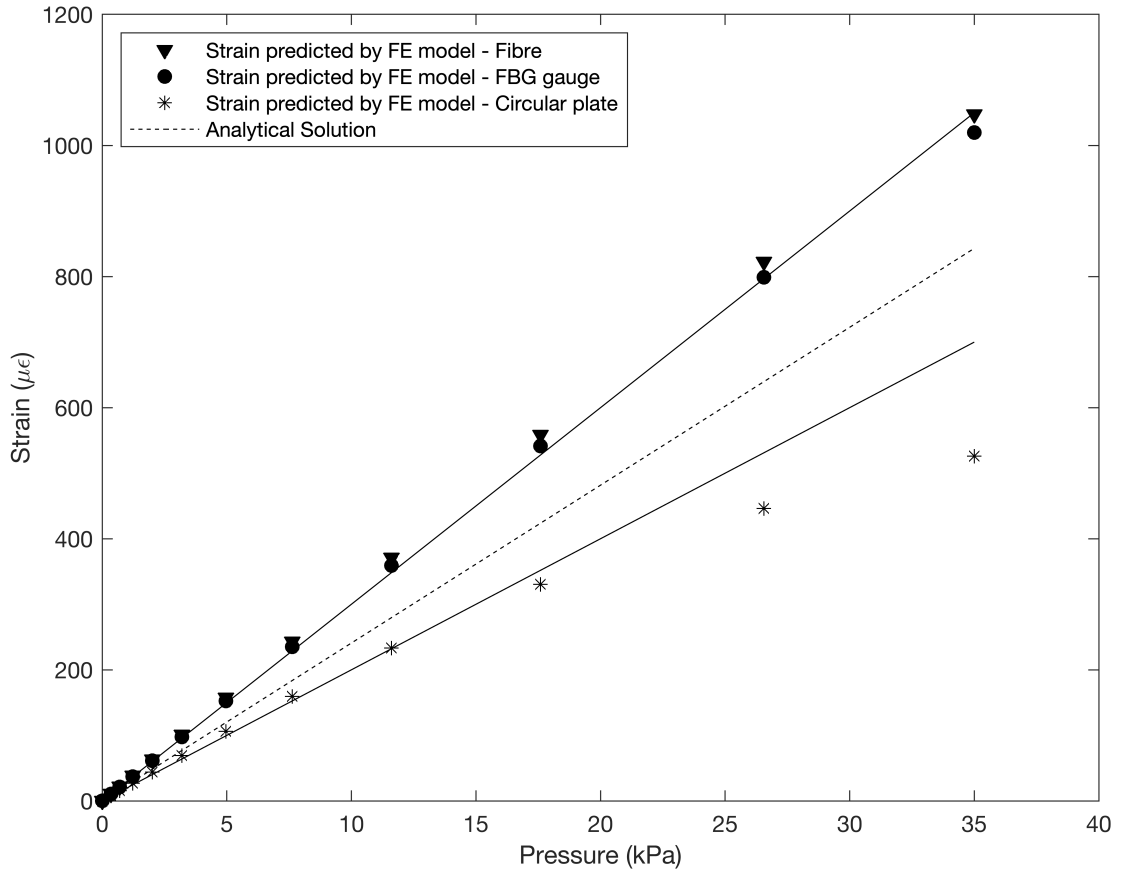


Figure 3.10: FE and analytical results of the maximum strains over the full pressure range (0 to 35 kPa) with ▼ the highest strain in the centre of the fibre, ● the maximum strain averaged over the 4 mm FBG section in the fibre and * the highest strain in the centre of the diaphragm with respective linear fits ($R^2 = 0.9994$, $R^2 = 0.9995$ and $R^2 = 0.9879$). Comparison with the analytical solution.

Firstly, the analytical solution does not consider the stiffness added by the optical fibre mounted on the surface of the membrane. Although the fibre is small (ϕ 0.125 mm where the coating is stripped, ϕ 0.250 mm for acrylate coated and ϕ 0.155 mm for polyimide coated) compared to the diameter of the circular plate, its diameter is about half the diaphragm thickness, which can explain the influence it has on the membrane's stiffness.

The nonlinear response exhibited by the diaphragm can be predicted using the rule of 1/5 the diaphragm thickness, described at the end of Section 3.2. The analytical solution suggests that a ϕ 25 mm, 0.3 mm thick circular GFRP diaphragm enters the large deflection regime at a pressure of 10 kPa, which is earlier than the simulation shows. With the optical fibre attached, the diaphragm experiences increased stiffness, which results in less deflection, delaying the effects of the large deflections.

Finally, the higher strain in the optical fibre can be explained by its position relative to the surface of the diaphragm. While the term z in Equation (3.7) concerns the thickness of the diaphragm, it does not take into consideration the location of the core of the optical fibre, dependent on its diameter and the thickness of the glue line. It can be seen from the same equation that the further away from the neutral axis of the diaphragm, the higher the strain. To predict the strain in the optical fibre with more accuracy, the term z can be re-written with $z = ((t_{membrane} + \phi_{optical fibre})/2) + t_{glueline}$. The linearity of the strain experienced by the optical fibre compared to that experienced by the diaphragm can be explained by its position relative to the neutral axis, which theoretically simulates a larger thickness with a stiffer material, hence delaying the large deflection response to the pressure.

3.4 Conclusion

The working principle of the pressure sensor has been developed with an analytical solution and an FE model, based on the elastic plate theory of a circular clamped plate under uniform load. The FE analysis revealed the importance of the position of the optical fibre relative to the neutral axis of the diaphragm, predicting a difference between the strain experienced by the optical fibre and by the surface of the diaphragm which is conventionally assumed to be the same. Compared to the analytical solution, the optical fibre exhibits higher strain due to its position further away from the neutral axis of the

diaphragm and the diaphragm exhibits lower strain due to the added stiffness from the optical fibre. The elastic plate formula has been rewritten, taking into account the fibre diameter. The FE analysis also highlights the behaviour of the membrane at the edge with the nonlinear analysis, which is of considerable importance in Chapter 6. The compressive strains at the edge and the overall modelling influenced the location of the FBG on the sensor to ensure the lowest strain gradient was experienced, as well as the position of the segments when using FSI technology to benefit the discrimination of temperature and pressure. The content of this chapter is used in Chapter 4, manufacturing and design, to design the associated manufacturing and experimental test tools such as the mould and the pressure chamber. It is also used in the experimental Chapters 5 and 6 to compare with experimental results.

Chapter 4

Design, Manufacturing and Analysis of Optical Fibre Pressure Sensors Using Rubber Diaphragms

Introduction

This chapter describes the manufacturing method, process and experimental results of nine pressure sensors based on FBGs attached to HNBR diaphragms. The manufacturing of the FBGs in Cranfield University Engineering Photonics laboratories is presented. This is followed by a discussion of the selection of materials suitable to use for the diaphragm. The process used for the manufacture of the diaphragm is detailed, describing the initial concepts for an elastomer diaphragm, followed by its limitations. The final section covers the characterisation of the performance of HNBR-based sensors, where the diaphragms took the form of circular discs of thickness 1 mm and diameters ranging from 6 to 30 mm.

4.1 Fibre Bragg Grating Manufacturing

The manufacturing of the FBGs was based on the phase mask method [25] detailed in Chapter 2. A schematic of the FBG fabrication system is depicted in Figure 4.1 (a) along with an image of the setup (b). Before writing the FBGs, a SMF-28 fibre is immersed in a hydrogen environment at 170 bar and ambient temperature for a minimum of 7 days to enhance the photo sensitivity of the core [109, 110, 111]. The optical fibre was then prepared by marking the required location of the FBG on the fibre, mechanically removing the UV cured acrylate coating with a fibre stripper to expose the cladding and finally cleaning the fibre with IsoPropyl alcohol.

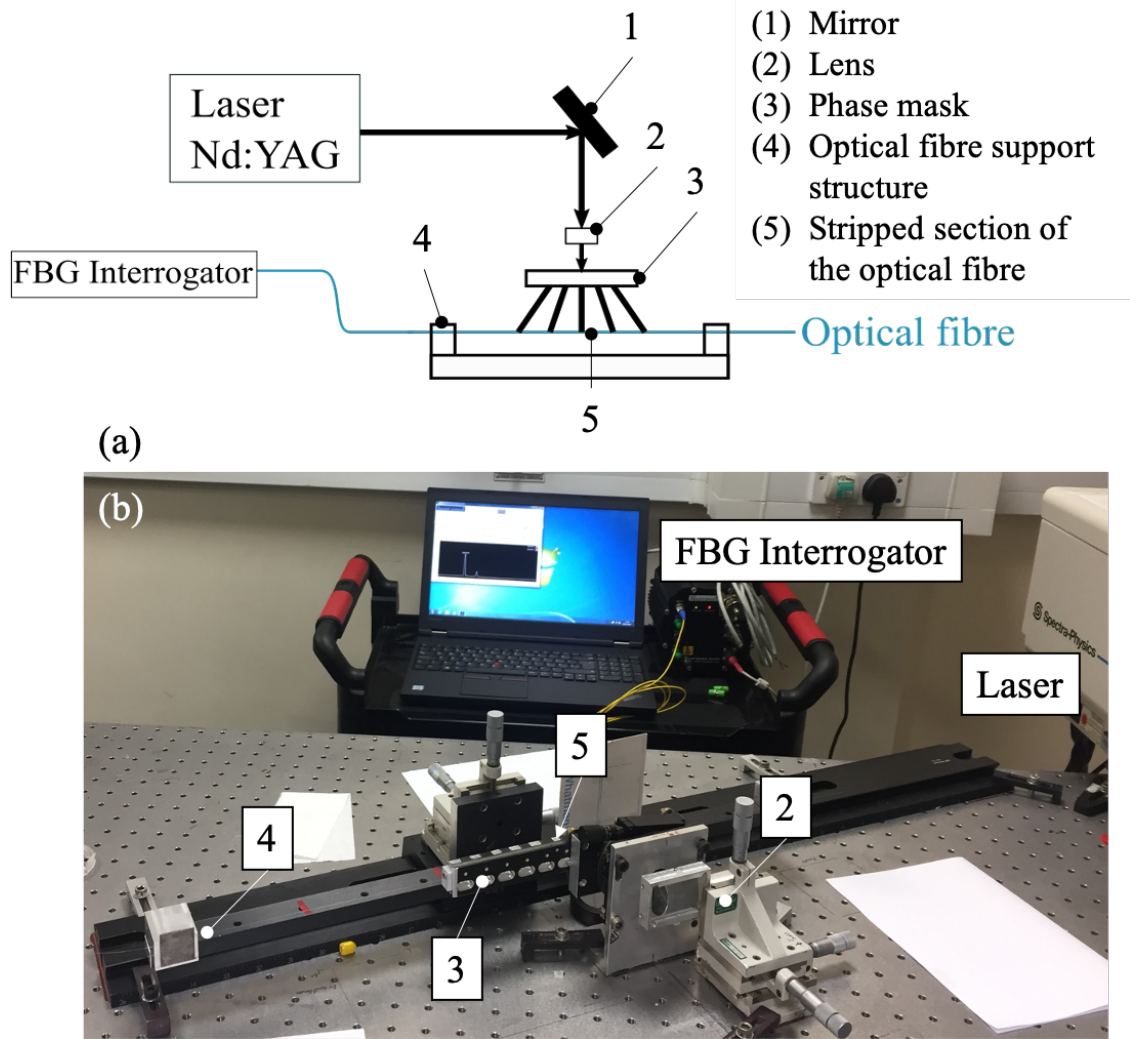


Figure 4.1: (a) FBG fabrication configuration comprising of a laser beam, lens, phase mask, optical fibre, support and FBG interrogator, (b) an image of the setup.

The fibre was then placed in a jig that kept it straight and taut, with the centre of the stripped region positioned to coincide with the beam exiting the phase mask, parallel to and 1 mm behind the phase mask. The optical fibre was irradiated through the phase mask by the output from a frequency-quadrupled flash lamp pumped Nd:YAG laser, operating at 266 nm, with a pulse length of 8 ns, a rep rate of 30 Hz and an average power of 40 mW. The laser output was apertured using a slit of width 4 mm. A cylindrical lens of focal length 100 mm was then used to create a line focus parallel to the optical fibre. The optical fibre was connected to an FBG interrogator from SmartFibres to monitor the

reflection spectrum in order to allow the irradiation to be stopped once the reflected signal reached a desired level. To produce a wavelength multiplexed array, the optical fibre was translated to the adjacent stripped section, and the phase mask swapped to produce an FBG of different centre wavelength.

SMF-28 optical fibres with acrylate coating were used for all sensors used in this thesis, with the exception of the 25 mm diameter device presented in the improved manufacturing method in Section 5.3 involving a process that required the use of a SMF-28 fibre with a polyimide coating suited to higher temperatures. While the FBGs fabricated in the acrylate coated optical fibres were inscribed by the author, those fabricated in the polyimide coated optical fibres were supplied by commercial suppliers, detailed in Chapter 7.

4.2 Sensor Design and Material Selection

The working principle of the pressure sensor was presented in Chapter 3. There, it was shown that the longitudinal strains experienced by an FBG bonded to the centre of a circular diaphragm are directly proportional to the deflection of the diaphragm, when the deflection is less than $1/5$ the diaphragm thickness, and depend mainly on the diaphragm's thickness and material properties. The restrictions placed on the overall dimensions of the diaphragm were set by the application defined by the project sponsors, with a maximum diameter of 30 mm for a minimum resolution of 20 Pa. Using the analytical solution in Equation (3.7) and the effect of the position of the optical fibre relative to the neutral axis described in Chapter 3, it was found that, to achieve the measurement specification, the Young's modulus of the membrane had to be lower than 700 MPa. Figure 4.2 shows the categories of materials sorted by their Young's Modulus. In order to compare materials, a 30 mm diameter diaphragm with a 1 mm thickness was considered. It appeared that only polymer and rubber materials were possible candidates, based on the requirement for a 1

mm thick diaphragm. Three material categories were however investigated: elastomers, metals and composite materials, with the option of reducing the thickness.

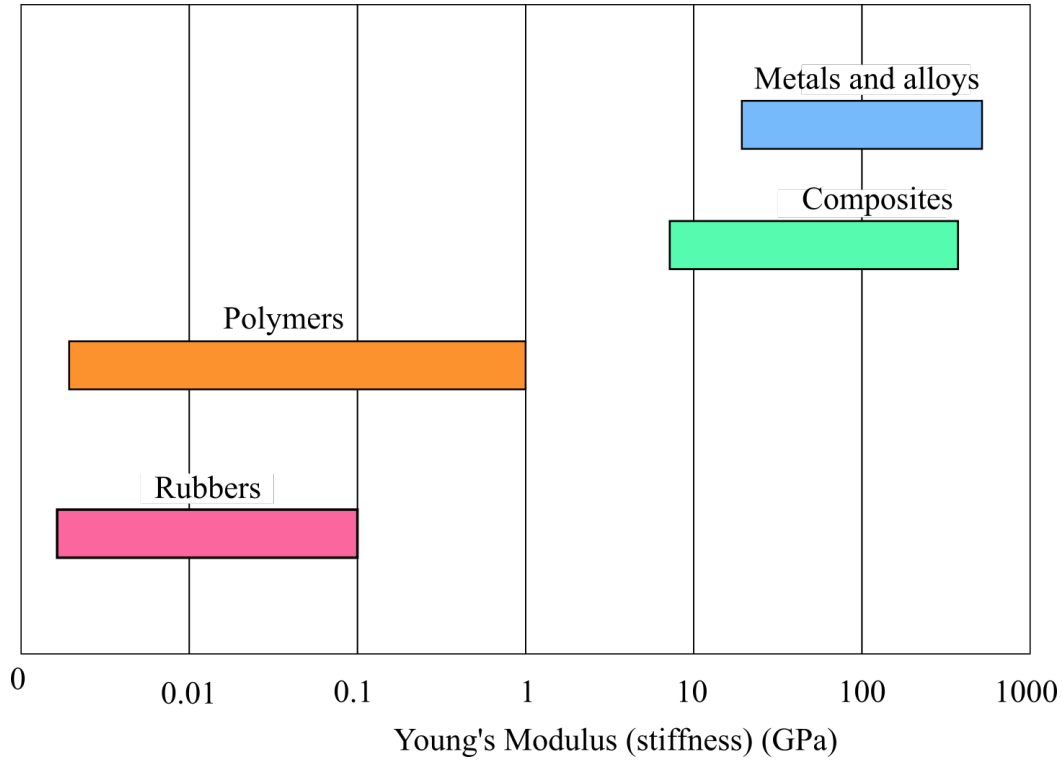


Figure 4.2: Several material categories with their stiffness [112].

Metals are good candidates for pressure sensors as they do not display hysteresis and are robust if used in harsh environments. However, with the required resolution and the calculated Young's modulus, their utilisation in this design would either require the use of a thin sheet of metal, of order 50 microns, which could make the sensor fragile, or, alternatively, the use of a larger diameter which would go beyond the maximum 30 mm diameter specification requirements. Literature showed that metal-based diaphragms have low sensitivity [86, 87] even with large diameter so for feasibility and requirement reasons, metals were not investigated further. The study focused firstly on rubber materials in this chapter, due to their low Young's modulus and then composite materials in Chapter 5, for their potentially bespoke material properties and for the potential for embedding the optical fibre within the composite.

4.3 Pressure Sensor Using a Rubber Material as the Diaphragm

The first pressure sensor design was based on the use of a circular rubber plate, as it offered the greatest potential for providing the resolution and sensitivity due to its low Young Modulus. Hydrogenated Nitrile Rubber (HNBR) was selected for its numerous advantages for use in a motor sport vehicle application, such as its resistance to oils, fuel, heat and tearing as well as its high strength and high sealing properties [113]. The HNBR chosen had a hardness of 100 Shore A, equivalent to 5.6 MPa [113].

4.3.1 Rubber Diaphragm Manufacturing

The HNBR was provided by Mercedes in 0.5 mm wet plies. Two plies were cut to A4 size, laminated together and cured for 30 min at 160 °C, followed by a post cure at 150 °C for four hours. The 1 mm thick sheet was then cut into 9 discs, each of 32 mm diameter, to perform characterisation of the dependence of the sensitivity of the working diameter of the sensor defined by the pressure chamber apertures presented in Section 4.3.2.

4.3.2 Pressure Chamber: Design and Manufacturing

A bespoke pressure chamber was designed and manufactured to test simultaneously up to nine sensor designs. Figure 4.3 illustrates the 3D model of the jig with (a) the whole design and (b) a section view of one of the pressure chambers. The jig comprised three pressure chambers, with each chamber allowing the assessment of the performance of three sensors.

Due to the low Young's modulus of HNBR, theoretically a 3 mm diameter circular diaphragm could provide a measurement resolution of 20 Pa with a typical commercially available FBG interrogator of resolution 1 pm. As the strain along the diameter is non uniform, to avoid the strain gradient over the FBG 4 mm length the smallest diameter

aperture on the jig was 6 mm, with a theoretical sensitivity of $434 \mu\epsilon/\text{kPa}$ for an uncoated fibre of diameter 0.125 mm, bonded to a rubber plate of Young's Modulus of 5.6 MPa. The pressure sensing performance of FBGs bonded to HNBR diaphragms of several diameters were assessed experimentally. Figure 4.4 illustrates the jig with apertures of diameter varying from 6 mm up to 30 mm and the sealed pressure intake tubes.

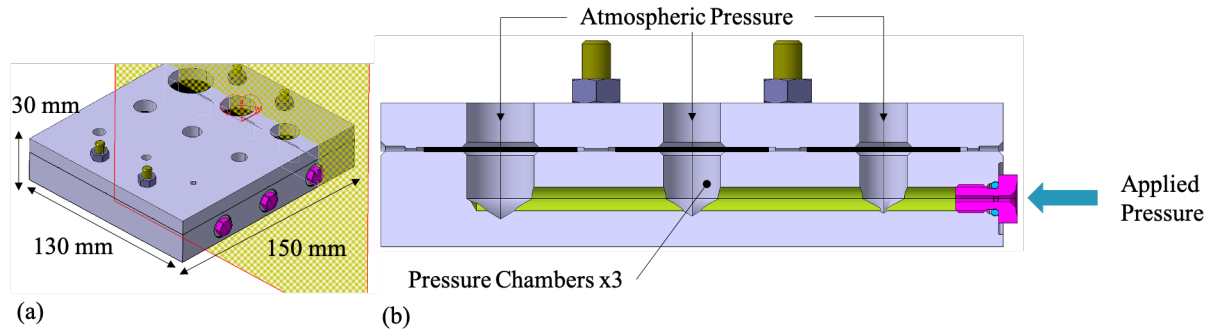


Figure 4.3: 3D model of the pressure chamber jig with (a) the whole model showing the 9 apertures and (b) a section showing one pressure chamber. The pressure was applied to the lower side of the diaphragm with atmospheric pressure acting on the upper side where the fibre was bonded.

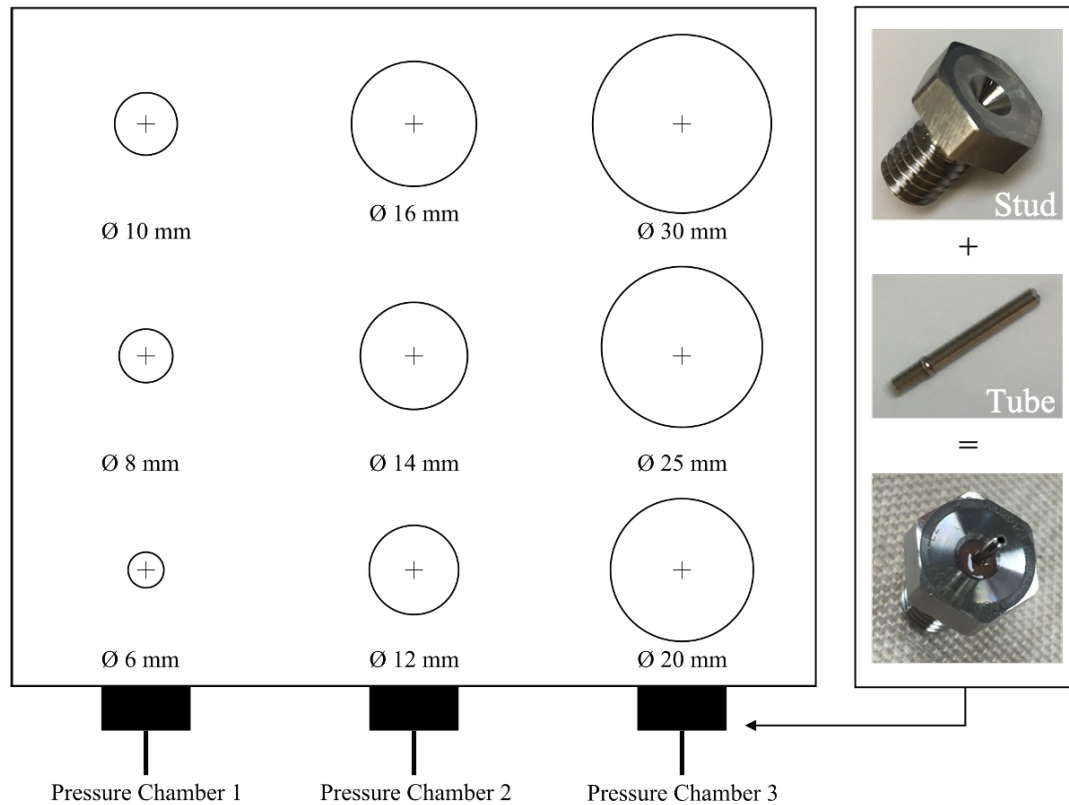


Figure 4.4: Schematic of the jig including the diameters of the apertures connected to the three pressure chambers. The pressure is delivered through the tubes that are bonded to the sealed studs and are shown on the right.

Figure 4.5 shows the whole jig. The areas around each aperture to which the rubber diaphragms were bonded were vapour blasted. Vapour blast, also called liquid honing, uses water to create a dust free surface with a fine finish in preparation for bonding [114]. Each rubber disc was then placed in the appropriate circular notch and bonded to the metal using a Cyanoacrylate adhesive (Loctite 401). The apertures and surfaces were protected with Polytetrafluoroethylene (PTFE) tape to avoid having the glue flowing into undesired places. The top of the jig illustrated in Figure 4.3 acted to clamp the plates together to ensure that the diaphragms were deflecting over the whole of the aperture diameter using the top jig and not only relying on the glue bond on the lower side.

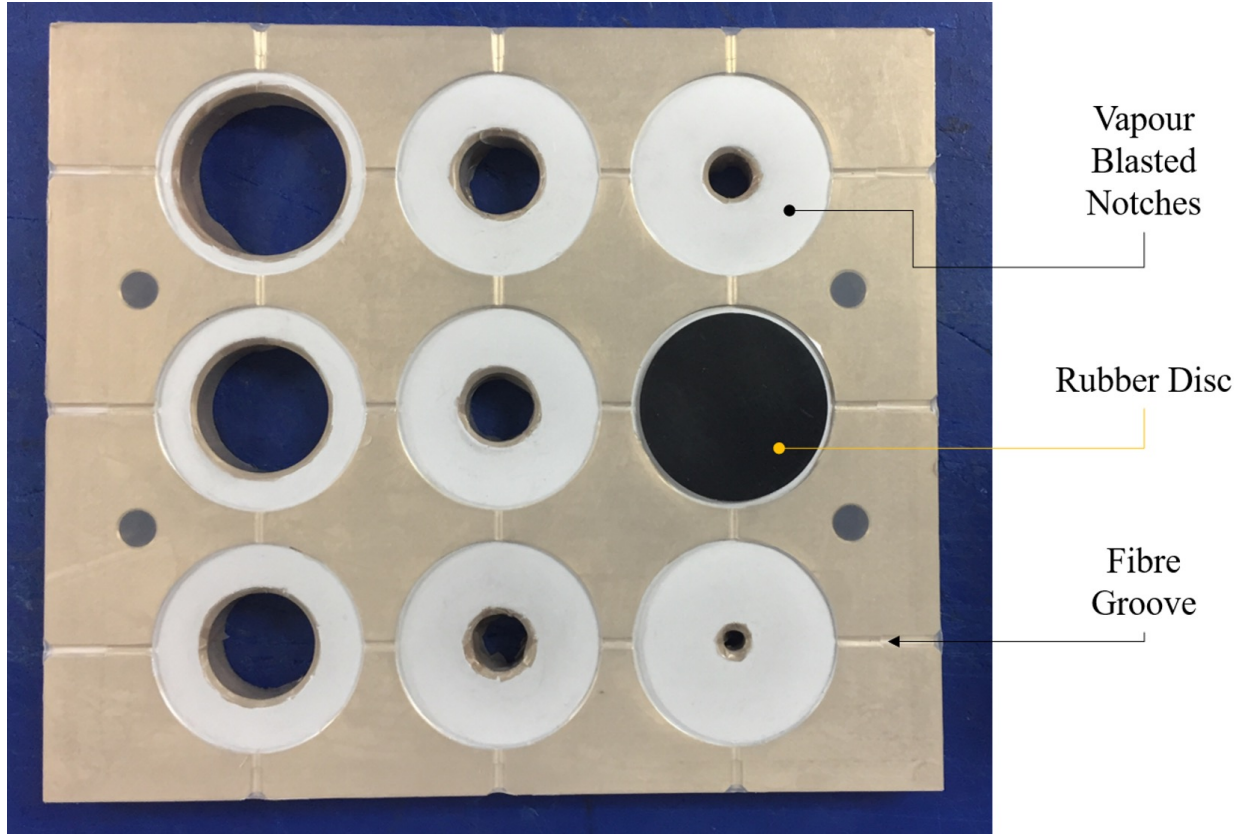


Figure 4.5: Photograph of the pressure chamber jig showing the vapour blasted surfaces and PTFE tape for protection. The image also shows one rubber disc already bonded using Cyanoacrylate. The fibre groove is designed to protect the fibre when clamped between the top and lower part of the jig.

4.3.3 Fibre and Membrane Assembly

The initial set of FBGs were manufactured as described in Section 4.1. The FBG arrays each contained three gratings written at different wavelengths to allow the simultaneous interrogation of the three sensors in each of the pressure chambers. The grating wavelengths were 1534 nm, 1542 nm and 1548 nm and they were physically separated by 36 mm. The optical fibre was coated with acrylate coating with the stripped section marked either side. The gratings were positioned so that the three stripped sections were placed in the centre of the three diaphragms and the vertical position was controlled by fitting the

optical fibres in the horizontal grooves as shown in Figure 4.6. The optical fibres were then bonded to the rubber along the length of the FBG, and 3 mm either side using Cyanoacrylate. The bonded area and optical fibres in the grooves are shown in Figure 4.6. The extra glue on either side of the uncoated section of optical fibre, as shown in Figure 4.7, served as protection due to the fragility of the fibre at this particular abrupt change of diameter. Lightly bonding adhesive tape was used to keep the fibres in place during the bonding process. The characterisation of these sensors is discussed in Chapter 5.

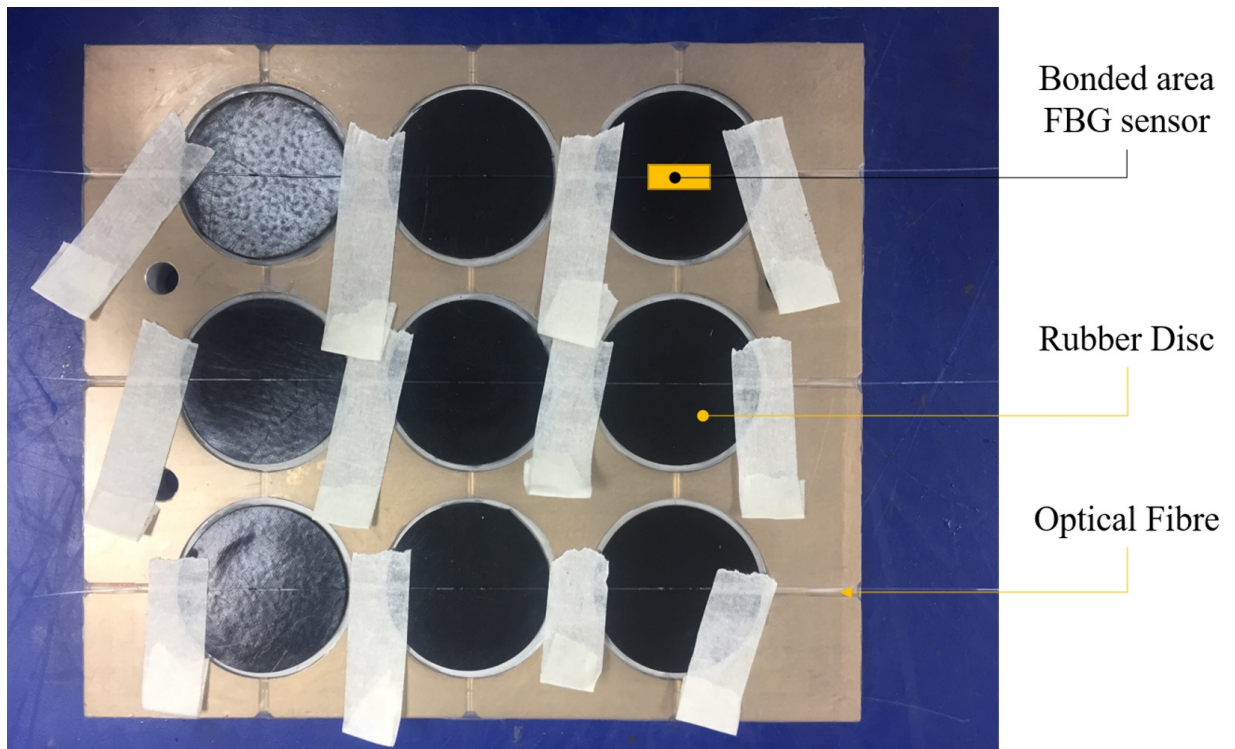


Figure 4.6: Pressure chamber jig with the nine discs showing the bonded area of FBG sensors.

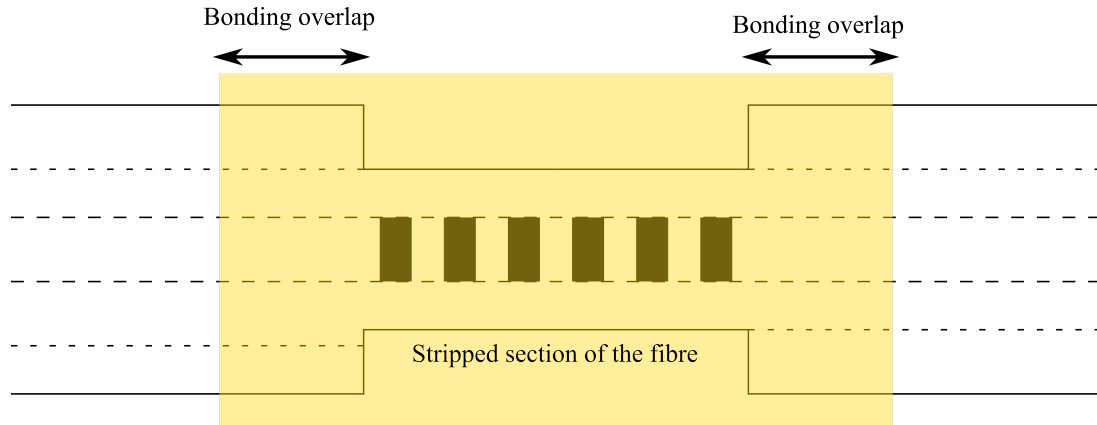


Figure 4.7: Yellow rectangle representing the glue around the FBG, overlapping the optical fibre between the uncoated section and the coated section to reduce breakage. Not to scale.

4.3.4 Limitations of the Rubber Material

The rubber diaphragm manufacturing process, thickness control and surface quality are relatively simple. The main manufacturing challenge concerned the control of the glue line along the optical fibre. The glue line thickness between the fibre and the membrane can vary due to the amount of glue that is applied, which in turn can affect the sensitivity of the sensor by moving the FBG sensor relative to the neutral axis of the diaphragm. This impacts on the repeatability of the sensor manufacture and performance.

The second main limitation concerns the rubber material itself. Internal frictions can occur during testing, also known as hysteresis. The hysteresis exhibited by the sensor using a diaphragm made from rubber is presented in Section 4.5.1. Several studies report an increase in the resilience of rubbers by the addition of fillers [115]. Despite this, the study presented in this thesis has not investigated rubber materials further due to the more advantageous properties of composite made from glass fibres, such as similarities with the optical fibre, the bespoke properties that the use of composite materials allow, and the small ply thickness that the particular composite selected offers.

4.4 Experimental Configuration

Figure 4.8 shows a schematic of the jig used to characterise the HNBR pressure sensors. It was designed to allow the simultaneous assessment of the performance of sensors based on diaphragms of nine different diameters, ranging from 6 mm to 30 mm. As described in Section 4.2, the diameters were selected based on the FE results to ensure that the bonded FBG did not experience a significant strain gradient. The jig comprised three pressure chambers, each containing 3 apertures onto which the diaphragms were bonded. The routing of the fibre within the jig was such that it was possible to mount a single optical fibre containing three wavelength division multiplexed FBG sensors bonded to the three diaphragms in a single pressure chamber, or three separate fibres, each containing a single FBG bonded to one of the diaphragms.

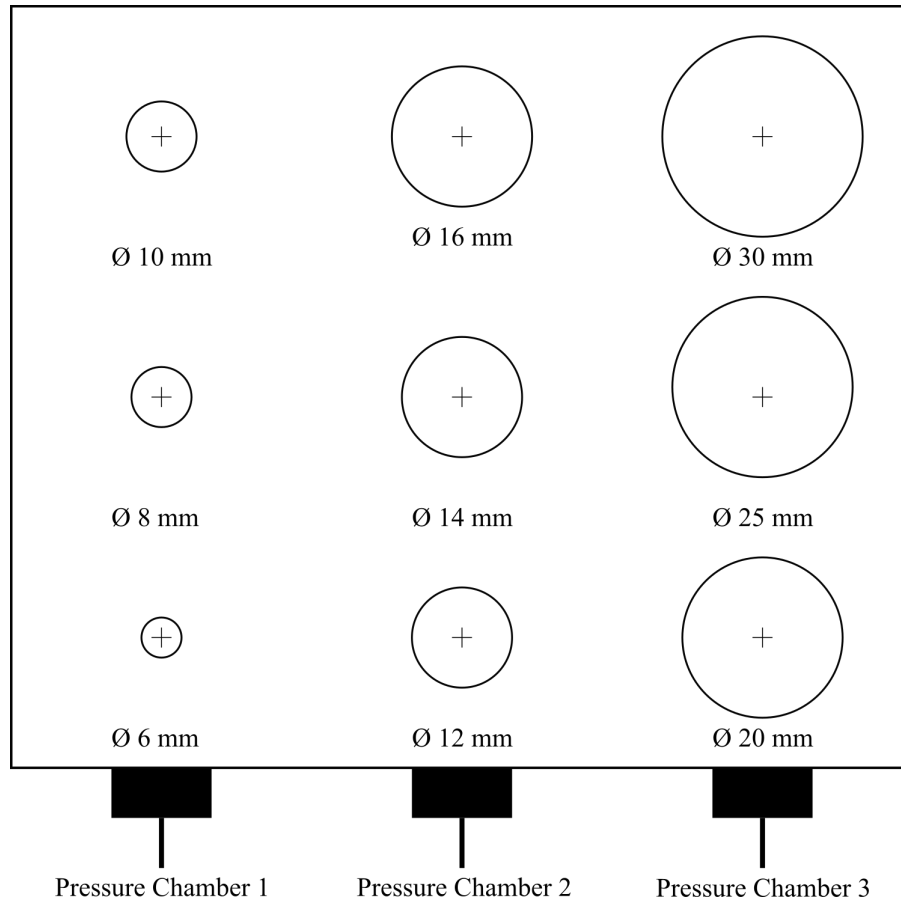


Figure 4.8: Schematic of the pressure jig with the nine diameters.

The pressure was applied using a Pace 6000 pressure controller over a range of ± 35 kPa with an accuracy of $\pm 0.02\%$ of full scale, while the responses of the diaphragm-bonded FBG sensors were monitored at a logging rate of 250 Hz using a SmartScan FBG interrogator, as shown in Figure 4.9. The pressure was changed in a series of steps, as illustrated in Figure 4.10 and 4.11, and the calibration curves determined from the time series of the measured Bragg wavelength shifts.

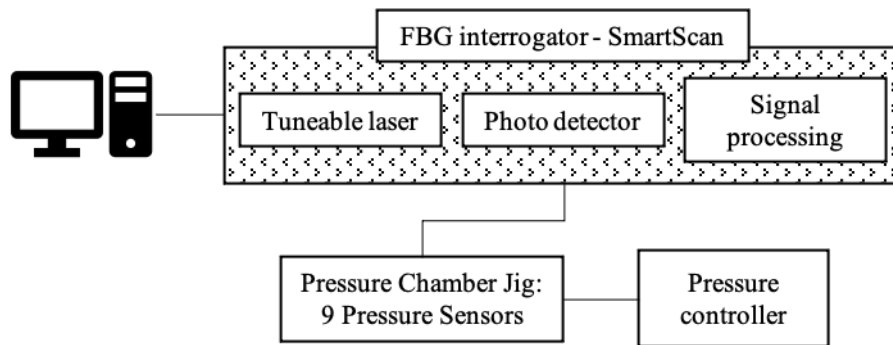


Figure 4.9: Schematic of the experimental configuration with pressure chambers connected to the pressure controller and the optical fibre connected to the SmartScan interrogator.

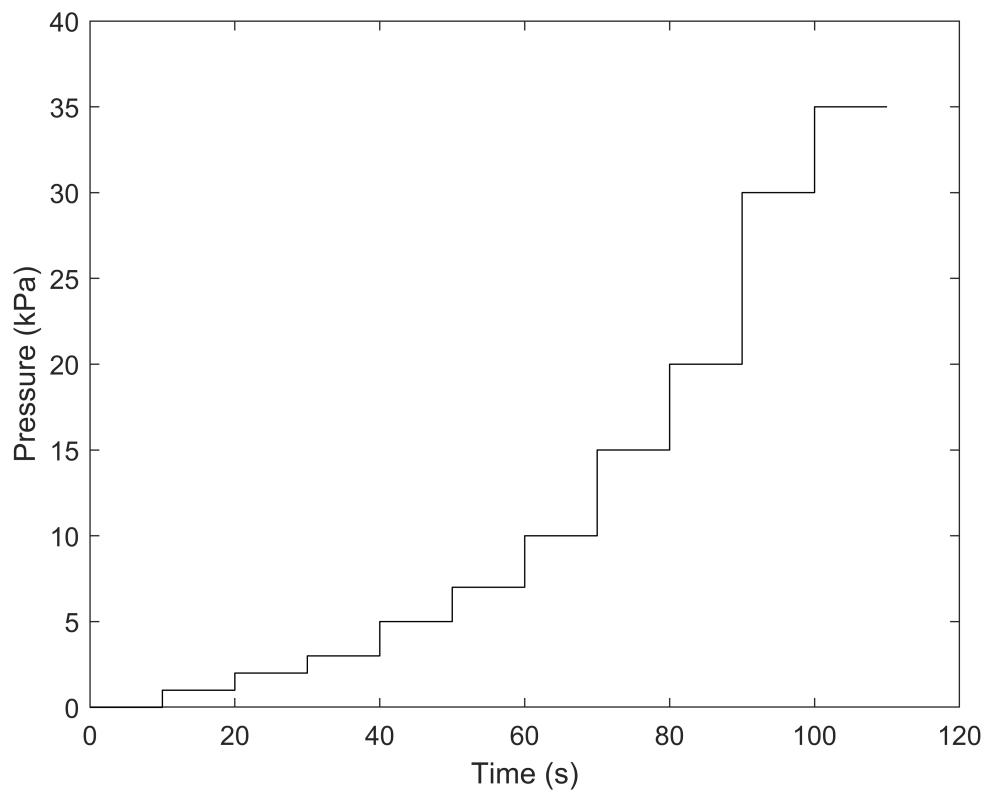


Figure 4.10: Typical pressure profile used for the characterisation of the pressure sensors; the high pressure regime, up to 35 kPa, for pressure chambers 1 and 2.

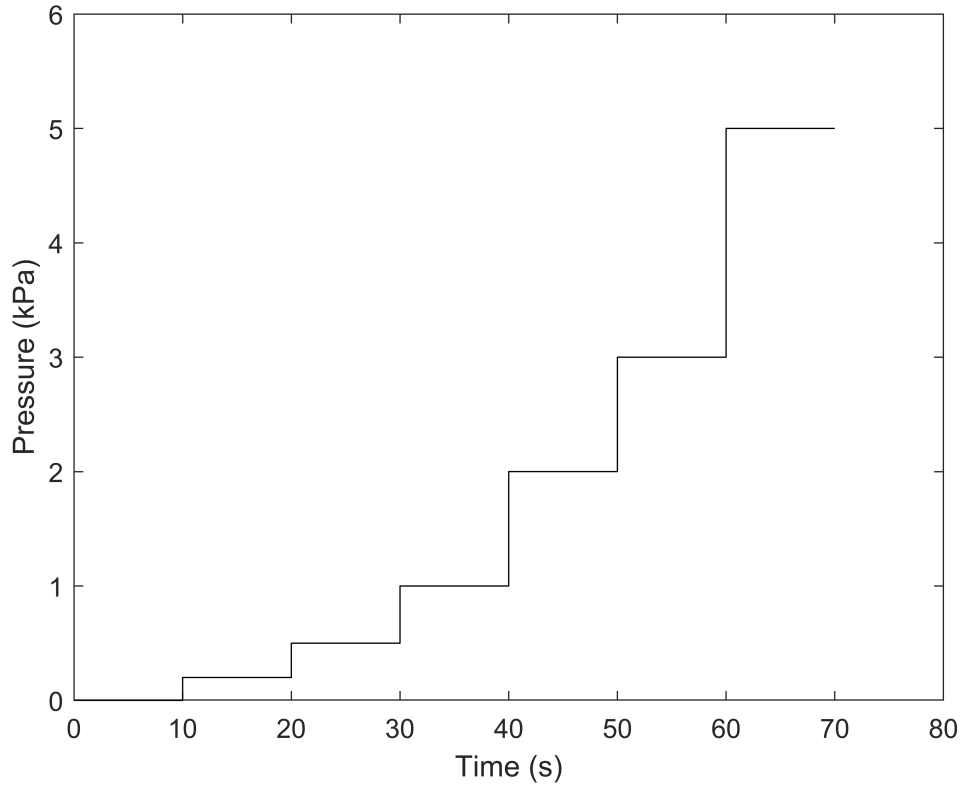


Figure 4.11: Typical pressure profile used for the characterisation of the pressure sensors; the low pressure regime, up to 5 kPa, for pressure chamber 3.

4.5 Experimental Analysis

HNBR was initially selected as a candidate material for the formation of the diaphragm as a result of its wide availability, physical strength and the retention of its properties following long-term exposure to heat, oil and chemicals [116]. HNBR diaphragms of varying diameters were cut from a sheet of thickness 1 mm, as described in Section 4.3. According to the elastic plate theory, diaphragms of diameters lower than 10 mm were expected to follow a linear behaviour over the full pressure range. Sensors of diameter above 10 mm were expected to exhibit nonlinear behaviour, starting at different pressures depending on their dimensions.

The initial testing was performed with each diaphragm based sensor being interrogated individually. The sensors in pressure chambers 1 and 2 were assessed over a range of 35 kPa. Those in chamber 3, corresponding to the large diameter sensors with a correspondingly larger deflection for a given pressure, were assessed over a range of 5 kPa to avoid permanent deformation of the diaphragm and changes to the adhesion between the fibre and the diaphragm. Figure 4.10 shows the pressure profile applied to the sensors in chamber 1 and 2 and Figure 4.11 the pressure profile applied in chamber 3.

4.5.1 Results and Discussions

Figure 4.12 shows the temporal responses of the HNBR sensors with diameters of 10 mm (1), 8 mm (2) and 6 mm (3) in pressure chamber 1, while Figure 4.13 shows the calibration curve determined from the time series. The single point at each pressure was obtained by averaging the stable portion of each pressure change. As would be anticipated, the sensor with the smaller diameter diaphragm exhibits the lowest sensitivity and a linear response due to the deflection being less than $1/5$ the diaphragm thickness. The wavelength shift is also stable during each step.

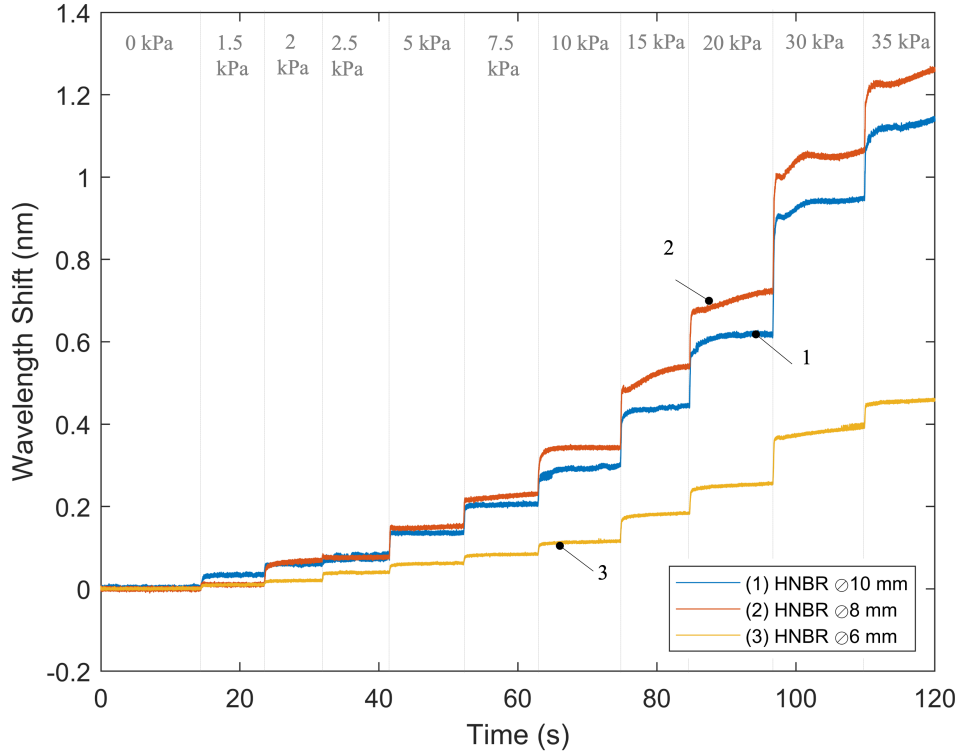


Figure 4.12: Temporal pressure responses of optical fibre based pressure sensors with HNBR circular diaphragms of diameter 10 mm (1), 8 mm (2) and 6 mm (3).

The 8mm diameter diaphragm responds linearly to increasing strain, with a sensitivity that is approximately three times that of the 6mm diameter diaphragm, as predicted by Equation (3.7). However, it is noted that for pressures > 20 kPa the wavelength shift drifts during the pressure steps, which is likely to be caused by the visco-elastic characteristics of the HNBR. The 10 mm diameter diaphragm exhibits a response that is lower than that of the 8 mm diameter diaphragm, which is attributed to the predicted onset of nonlinear response at pressures > 12 kPa, due to the increasing influence of membrane effects, which reduces strain per applied pressure. Initially, the membrane resists the pressure load only with its bending stiffness. Once deformed due to the applied pressure, the deformed geometry exhibits stiffness that is added to the original bending stiffness. The diaphragm deflection in response to increased pressure is then not only due to bending but is now a mix of bending and tensile force, acting inside the diaphragm, horizontally when

looking at a section cut along the diameter. Thus the deformation changes the membrane stiffness such that the deformed membrane is stiffer than the flat, undeformed membrane. This analysis is the physical interpretation of the output from the FE model.

Other possible contributions to the responses shown in Figure 4.12 include differences in the thickness of the glue line, which change the position of the FBG with respect to the neutral axis of the diaphragm, and an offset of the location of the FBG from the centre of the diaphragm (where the largest strain would be expected). This could explain the gap in the observed sensitivities between the sensors. Although it was expected that a constant sensitivity increase occurs between the sensors with increase in diameters (in the linear regime), the difference between the sensitivities of the 6 mm and 8mm diameter sensors is larger than that of those of diameter 8 mm and 10 mm. The FBG sensor bonded on the 10 mm diameter can be offset from the centre of the disc as a sensitivity factor of two is expected between the sensors 6 and 8 mm and between the sensors 8 and 10 mm, according to Equation (3.7). Finally, the drifts observed in the 8 and 10 mm diameter sensors, from 80 seconds onwards, can be explained by potential leakage from the sensor's bonded areas.

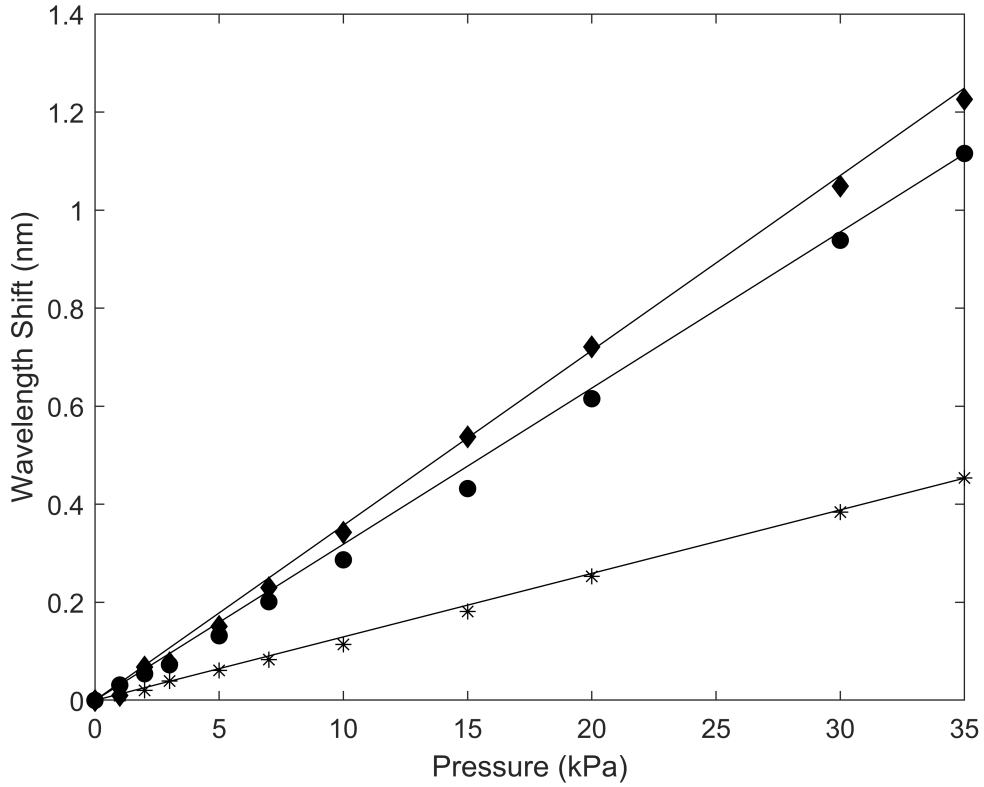


Figure 4.13: Calibration of the pressure responses of HNBR optical fibre sensors of diameter 10 mm (●), 8 mm (◆) and 6 mm (*).

Figure 4.14 shows the temporal responses of the sensors connected to pressure chamber 2, with diameters 12, 14 and 16 mm, and tested in accordance with the pressure profile shown in Figure 4.10. The wavelength shifts are plotted against the applied pressure in Figure 4.15. The responses show the expected increase in sensitivity with increasing diaphragm diameter. Additionally, an unexpected vibration is observed at higher pressures. This was not experienced by the sensors with smaller diameters. With the effect arising only with larger diameter and with an increase in amplitude with increased diameter and increased pressures, this phenomenon could be associated with resonance. This effect is also observed for the sensors of largest diameters mounted in the third pressure chamber.

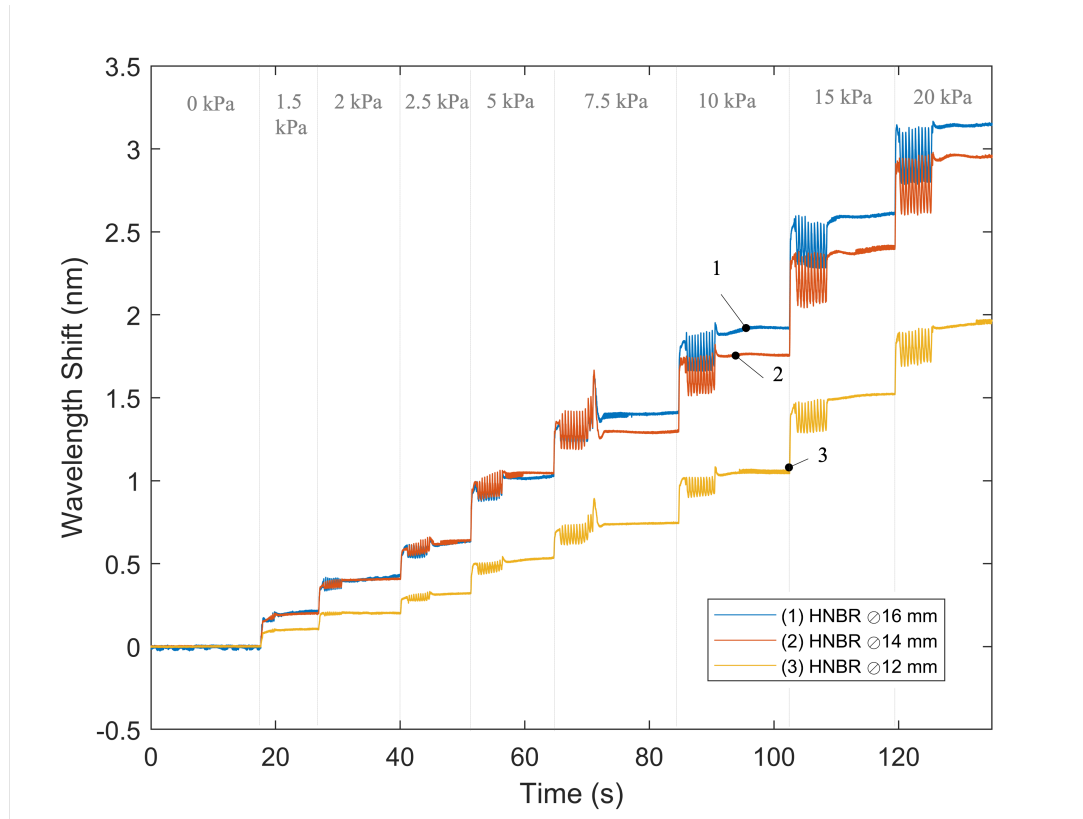


Figure 4.14: Temporal pressure responses of optical fibre based pressure sensors with HNBR circular disc of diameter 16 mm (1), 14 mm (2) and 12 mm (3).

Figure 4.15 shows the calibrations curves of the 12, 14 and 16 mm diameter sensors, determined using the temporal responses from Figure 4.14 and the applied pressure of Figure 4.10, where the nonlinear behaviour of all three sensors is clear. A linear response is observed for pressures up to 5-10 kPa, where the response is dominated by the bending response of the plate, with increasing nonlinear behaviour resulting from the mixture of bending and tensile forces evident for larger pressures. The sensor of diameter 12 mm has a larger bending response due to its higher stiffness arising from its smaller diameter. Both the 14 mm and 16 mm diameter sensors have similar bending responses at pressures up to 7 kPa, with the sensitivity of the 16 mm diameter sensor increasing with respect to that exhibited by the 14 mm diameter sensor. As observed for the sensors mounted in pressure chamber 1, the gap between the sensitivities of the three sensors is not constant, with the two larger diameter sensors showing similar responses, which suggest that the

whole array of FBGs bonded on the diaphragms of diameters 10, 16 and 30 mm were offset from the centres of the diaphragms.

The temporal responses reveal the presence of a strong oscillatory signal at the beginning of many of the pressure steps. The source is not clear, however it might be a resonant response from the rubber's natural frequency, being increased with increased diameter and reduced stiffness.

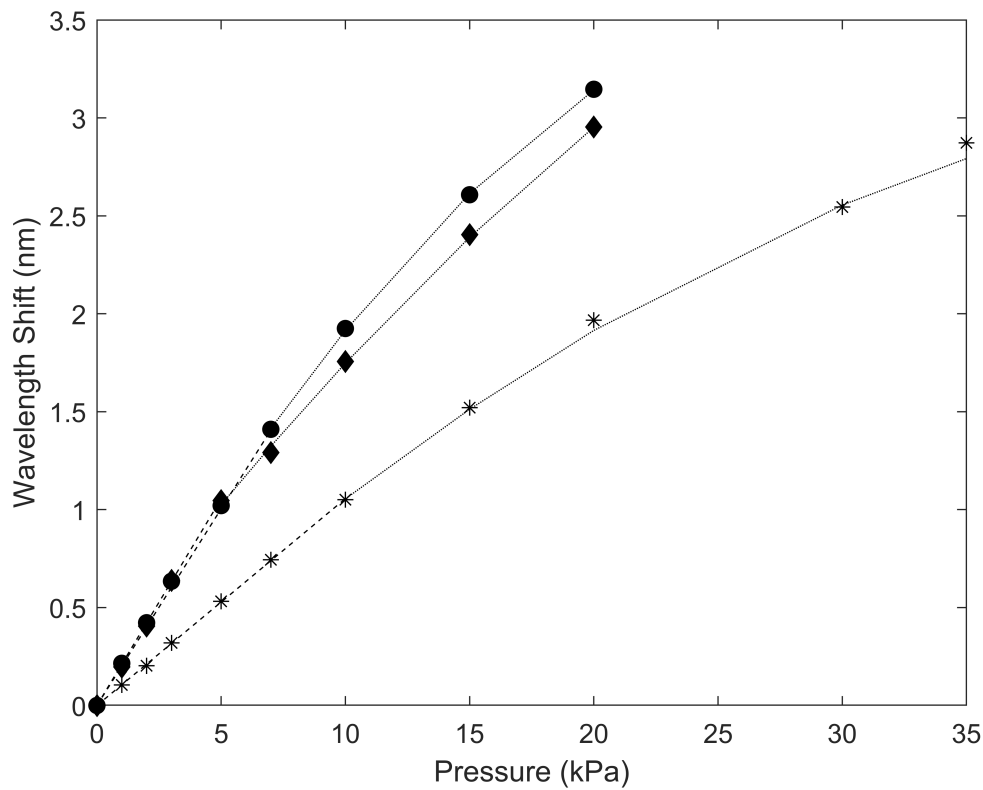


Figure 4.15: Calibration of the pressure responses of HNBR optical fibre sensor of diameter 16 mm (●), 14 mm (◆) and 12 mm (*).

The hysteresis of the sensors exploiting HNBR diaphragms was investigated using the 16 mm diameter diaphragm, where the pressure was increased to 35 kPa in increments of 5 kPa, and then stepped down in 5 kPa increments. The temporal response to the applied pressure cycle is illustrated in Figure 4.16 (a), and the wavelength shifts are plotted against pressure in Figure 4.16 (b). The plots show a significant hysteresis of 17% and a

significant drift of the reading at zero pressure. Such behaviour is an intrinsic property of rubber materials as they absorb more energy when load is applied than is given up when unloaded. Its effects can be mitigated by adding fillers [115].

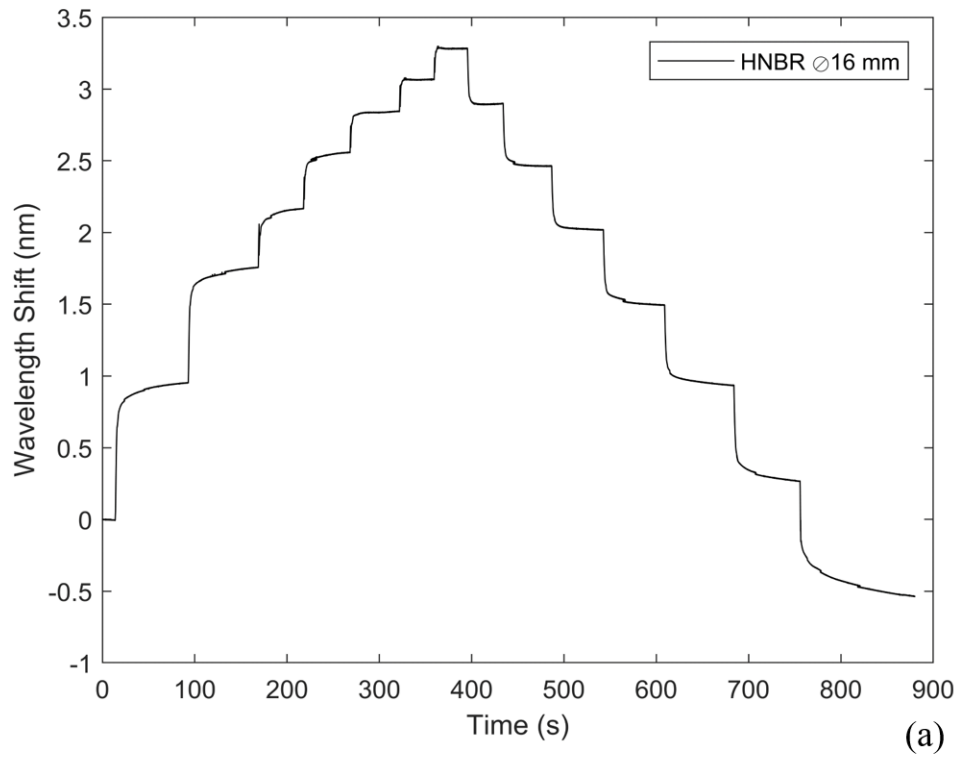
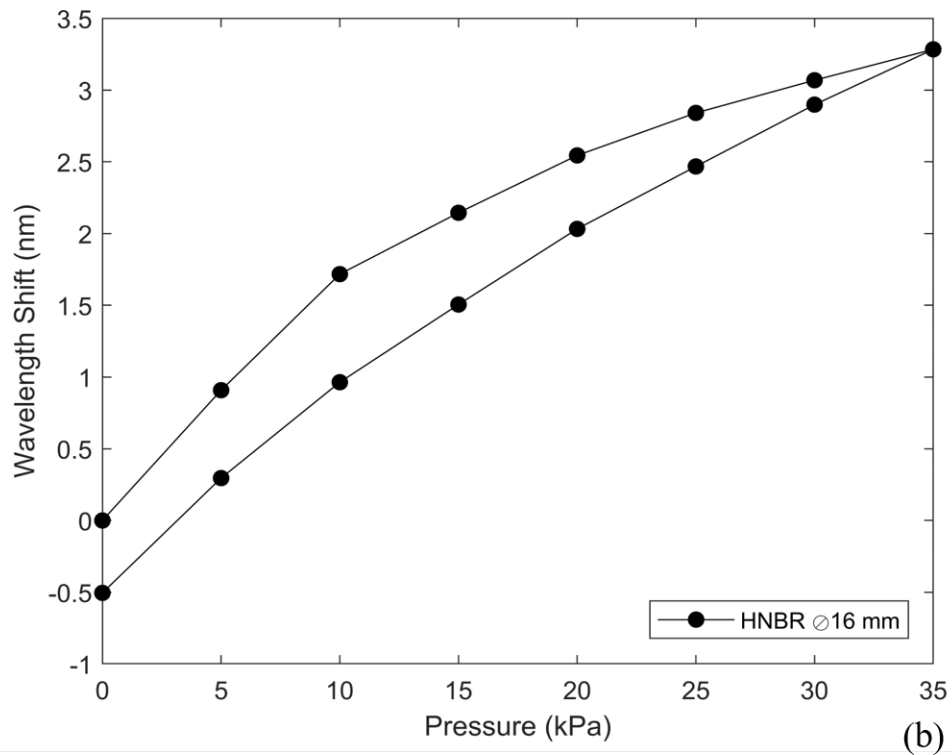


Figure 4.16: (a) temporal response of the 16 mm diameter HNBR disc according to pressure profile of Figure 5.6. (b) calibration of the same sensor using pressure data from Figure 5.6.

The pressure responses of the larger sensors with the 20, 25 and 30 mm diameter HNBR diaphragms over a range 0 - 5 kPa are shown in Figure 4.17. There are a number of anomalies, with the 25 mm diameter diaphragm exhibiting a larger sensitivity than that of the 30 mm diameter sensor, which itself shows a significantly nonlinear response. Again there may be issues with the positioning of the FBGs relative to the centre of the diaphragm, although these effects would be expected to be less significant for larger diameter diaphragms. There may also be issues relating to the initial state of the diaphragms at zero pressure as they were not pretensioned prior to bonding to the pressure rig, and as such the responses at low pressure might be expected to be compromised, which could explain the form of the response of the 20 mm diameter diaphragm.

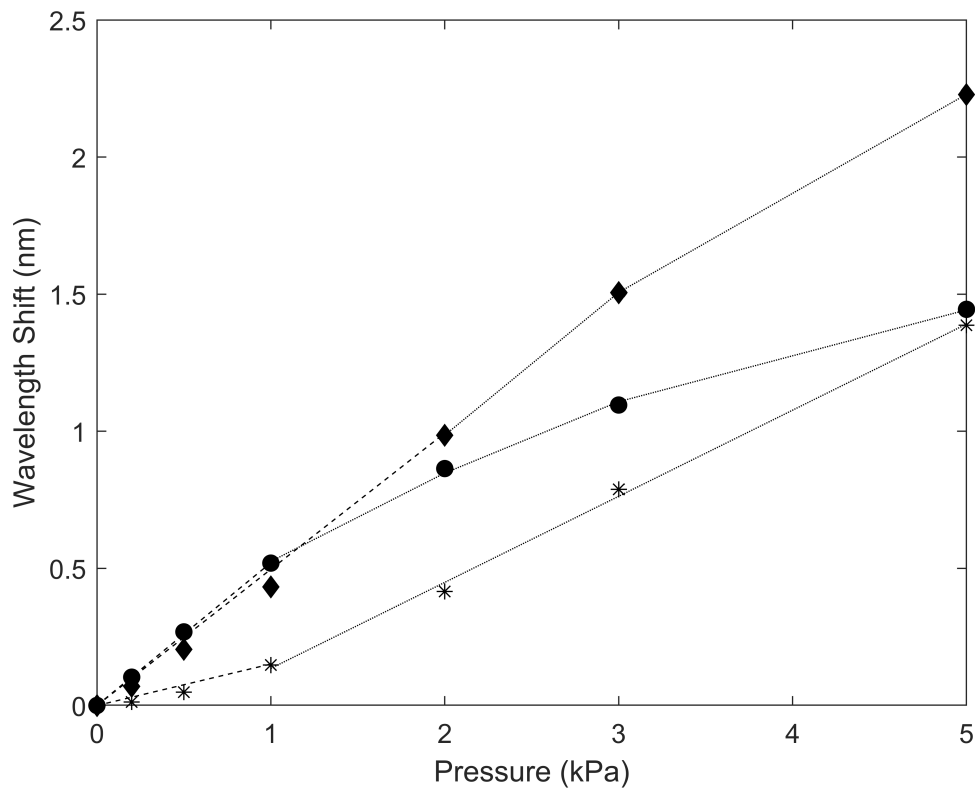


Figure 4.17: Calibration of the pressure sensitivity of HNBR optical fibre sensor of diameter 30 mm (●), 25 mm (◆) and 20 mm (*).

Although it is clear from the results of most HNBR diaphragm based sensors that their

responses were not linear, a linear fit was applied to determine and easily compare their sensitivities, which are summarised in Table 4.1. A single linear fit was applied to sensors of diameters 20 mm, 25 mm and 30 mm.

Although high sensitivities could be achieved with the rubber diaphragms, the reduction of the hysteresis of the rubber was not further investigated. Instead, GFRP, which provides better properties in terms of its compatibility with the optical fibre, has been used, which is described in the following section, Section 5.2.

Table 4.1: Pressure sensitivities of all sensors made from HNBR

ϕ 6	13 pm/kPa
ϕ 8	36 pm/kPa
ϕ 10	32 pm/kPa
ϕ 12	99 pm/kPa
ϕ 14	148 pm/kPa
ϕ 16	160 pm/kPa
ϕ 20	285 pm/kPa
ϕ 25	461 pm/kPa
ϕ 30	290 pm/kPa

4.6 Conclusion

This chapter described the process used to manufacturing the sensors using basic tools such as metal plates. The materials used for the membranes comprised of an elastomer, namely HNBR. The chapter follows by an experimental analysis of multiple rubber diaphragms using optical fibres containing FBG strain sensors bonded on the surface. The pressure chamber designed allowed the simultaneous testing of up to nine sensors of various diameters, ranging from 6 to 30 mm. The rubber based sensors presented a significant

disadvantage of being intrinsically subject to hysteresis, making the calibration of each sensor unreliable. Bigger diameter also showed high resonance and the position of the FBG sensor relative to the centre of the diaphragms were possibly misplaced, explaining the response of some sensors. Overall, HNBR-based pressure sensors with bonded FBG showed high sensitivity. Table 5.1 summarises all sensor performances.

Table 4.2: Summary of sensor performances describe in this chapter

	Sensitivity (pm/kPa)	Pressure range (kPa)	Hysteresis (%)	Comments
HNBR, ϕ 6	13	0 to 35	/	Linear
HNBR, ϕ 8	36	0 to 35	/	Low non-linearity
HNBR, ϕ 10	32	0 to 35	/	Low non-linearity; Possible FBG misplacement
HNBR, ϕ 12	99	0 to 35	/	Low resonance; Non-linearity
HNBR, ϕ 14	148	0 to 32	/	Medium resonance; Non-linearity; Possible FBG misplacement
HNBR, ϕ 16	160	0 to 32	17	Medium resonance; Non-linearity; High hysteresis
HNBR, ϕ 20	285	0 to 5	/	High resonance; Non-linearity; Possible FBG misplacement
HNBR, ϕ 25	461	0 to 5	/	High resonance; Non-linearity
HNBR, ϕ 30	290	0 to 3	/	High resonance; High non-linearity

Chapter 5

Design, Manufacturing and Analysis of Optical Fibre Pressure Sensors Using Composite Diaphragms

Introduction

This chapter describes the manufacturing methods, processes and experimental analysis of composite diaphragms of 25 mm in diameter, detailing two manufacturing methods and their limitations. The second section covers the characterisation of a sensor exploiting a 25 mm diameter GFRP diaphragm fabricated using an optimised process to achieve an improved result and the experimental analysis of this sensor is investigated.

5.1 Pressure Sensor Using a Composite Material as the Diaphragm

The material used to form the composite plate was a Glass Fibre Reinforced Polymer (GFRP) of ply thickness 0.044 mm [106] selected for its thin ply thickness and compatibility with optical fibre property. Although GFRP is stiffer than HNBR, its thin ply

thickness makes it a good candidate for the application. The GFRP used was provided by Mercedes as a prepeg material consisting of woven glass fibres, with fibres orientated at 90° from one another, and epoxy resin. Various laminates were manufactured consisting of 1 to 7 plies of GFRP, with all the glass fibres orientated in the same direction to produce an easy to manufacture, consistent and repeatable composite laminate. Each manufacturing method involving GFRP followed the same cure process, carried out at a temperature of 180°C under a pressure of two bars for a duration of two hours.

In this case, each sensor was interrogated separately, with the use of an optical fibre containing a single FBG written at 1542 nm bonded to each diaphragm. Several methods for manufacturing the diaphragms were investigated, as detailed in Sections 5.1.1 and 5.1.3. Section 5.3 presents a discussion regarding the limitations of those manufacturing methods, with a suggestion for appropriate tooling that answers the issues encountered.

5.1.1 Composite Plate Manufacturing: Method One - Bonded FBG

The first manufacturing method was inspired by the process used to create the rubber diaphragms presented in Section 4.3.1. Multiple A4 sheets were produced using different numbers of GFRP laminate plies, ranging from 1 to 7. The laminate was placed between two metal plates to produce an A4 sheet. Once cured and solid, 32 mm diameter discs were cut from the sheets. The laminate was non uniform in thickness due to the resin flow toward the edges and, as a result, the discs were selected based on consideration of their thickness, which was calculated from the number of plies and their nominal thickness.

Similar to the process presented in Section 4.3.3, the FBG was bonded to the central surface of the disc using a Cyanoacrylate adhesive. To reduce the stiffness of the sensor and increase its sensitivity, the optical fibre was orientated and bonded at $\pm 45^\circ$ with respect to the longitudinal glass fibres from the composite prepeg, as shown in Figure 5.1 to create an isotropic structure together with the optical fibre.

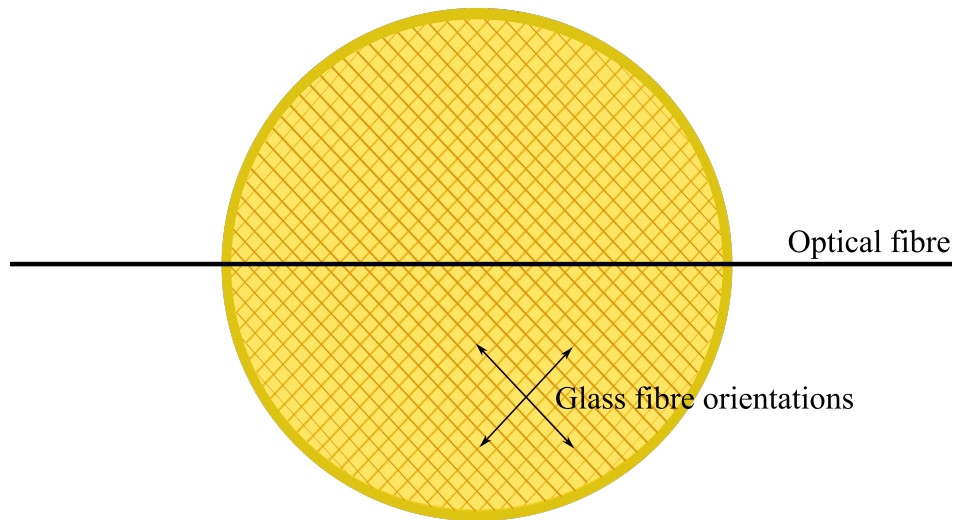


Figure 5.1: Schematic of the optical fibre oriented at 45° with respect to the longitudinal glass fibres.

5.1.2 Challenges Encountered During the GFRP Manufacturing of Method One - Bonded FBG

Several limitations and challenges were encountered with the manufacturing method used for one of the GFRP composite diaphragms. Firstly, the repeatably was found to be poor, with inconsistencies in the thicknesses in a single sheet when measured. It is thought that the pressure applied to the plates during cure pushes the resin towards the edges, leaving less resin in the centre of the A4 sheet. As the final ply thickness depends on both the resin content and the glass fibres, the thickness over the whole A4 sheet was non uniform.

The second manufacturing issue was the same as that observed for the HNBR membrane: the position of the optical fibre relative to the neutral axis of the diaphragm. Figure 5.2 (a) shows the inconsistency in the amount of glue around the optical fibre. The repeatability of this manufacturing process was also poor as a result. Figure 5.2 (a) also shows the non-uniformity of the glue above and on the sides of the optical fibre, which suggests non-uniformity along the optical fibre. This non-uniform bond line can distort

the FBG peak and result in a wider or a shape distortion of the single peak into several peaks [61]. As seen in Chapter 3, the position of the optical fibre relative to the neutral axis of the circular plate is important in defining the strain experienced by the FBG.

The application of the adhesive in small quantities was a challenge that could be avoided with the GFRP composite. The laminate of the GFRP contained resin in the prepreg plies that can be used to bond the optical fibre fully and uniformly, ensuring a uniform strain transfer and protection of the uncoated section of the optical fibre. To resolve this issue, a second manufacturing process, which involved curing the GFRP diaphragm with the fibre containing the FBG in-situ, was investigated, as described in Section 5.1.3.

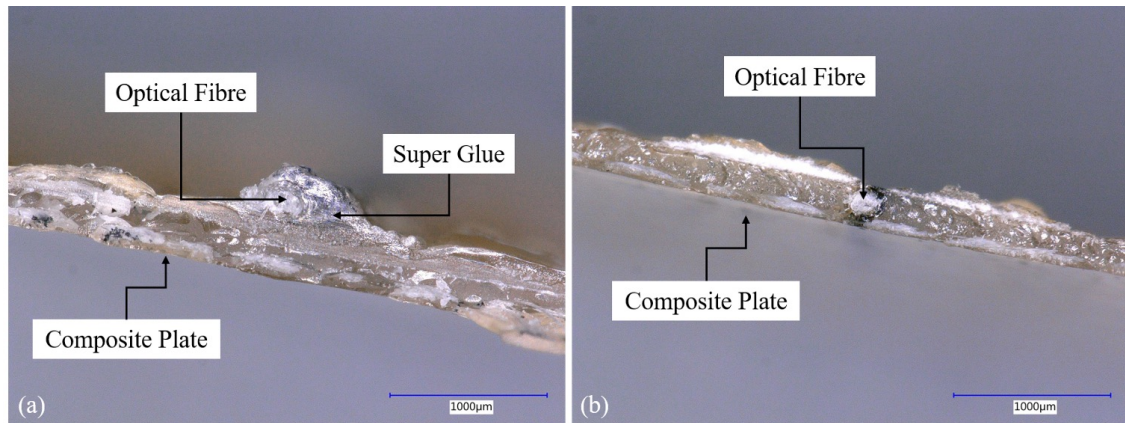


Figure 5.2: Microscopic image of a section cut from (a) an optical fibre bonded using Loctite 401 to the surface of discs cut from an A4 sheet of a cured prepreg using method one presented in Section 5.1.1 and (b) the optical fibre that sunk through the centre of the laminate using manufacturing method two as shown in Section 5.1.3.

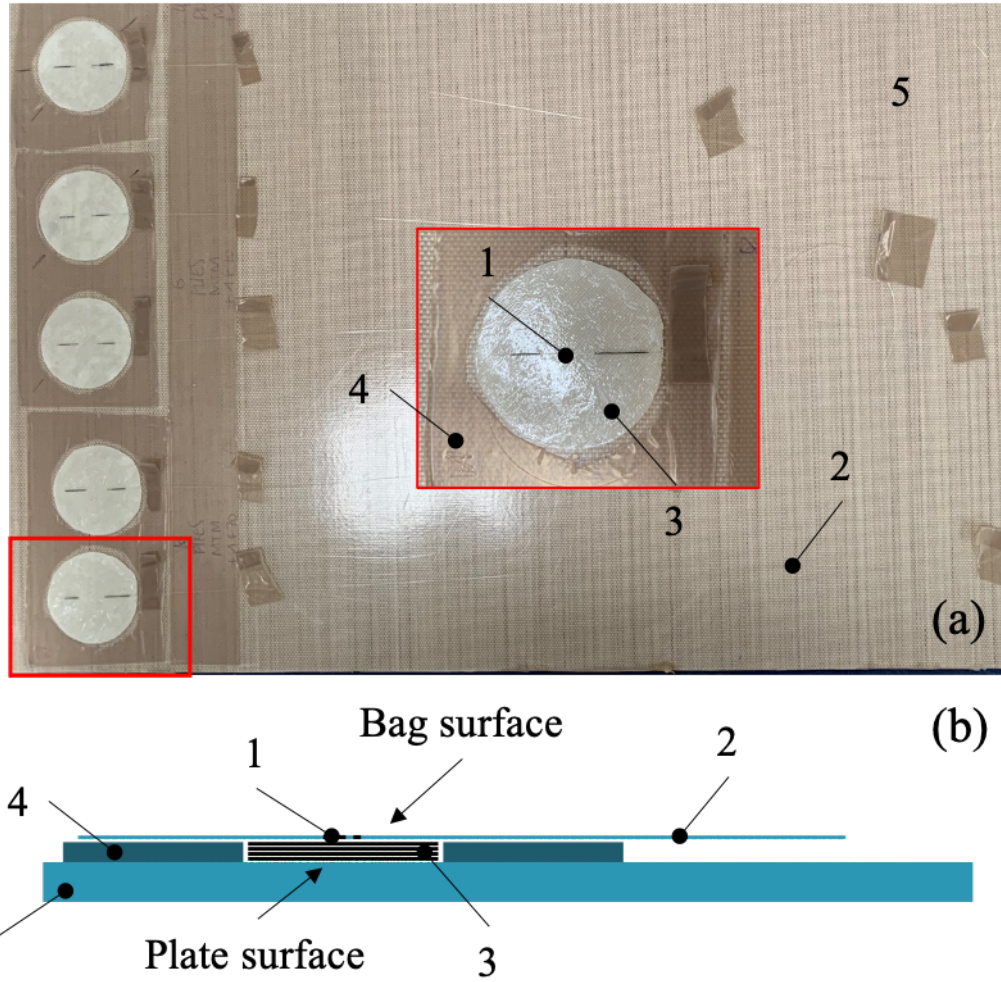
5.1.3 Composite Plate Manufacturing: Method two - Co-cured FBG

The second manufacturing method incorporated the optical fibre during the manufacturing and curing of the diaphragm laminate. The discs were cut into the laminate prior to adding the optical fibres, as shown in Figure 5.3 (a). Several attempts to cut out the diaphragm after bonding the fibre to the A4 sheet revealed the difficulty of cutting a circular

shape around the co-cured optical fibres. Figure 5.3 (a) shows the circular guides cut out from PTFE tape and bonded to the metal plate to contain the laminate and to position the optical fibre on the top surface, as shown in the schematic in Figure 5.3 (b). The circular guide helped to contain the laminate and locate the optical fibre on the stop surface.

Both the rubber and the first GFRP manufacturing processes used a second metal plate placed on top of the laminate to produce a flat A4 sheet. A second plate was not used in this process to avoid imposing lateral stress on the optical fibre during the cure, which was carried out under a pressure of two bars. Instead, this surface was enclosed only by the vacuum bag, which gives what is called a "bag surface". The surface is usually less smooth and uniform when compared to a surface made from a flat mould. This can have an implication for this application as the sensor is thin and any variation in thickness can affect the sensitivity.

Overall, several issues were encountered with this technique and a description is given in Section 5.1.4. An elaborate manufacturing process emerged from the issues encountered, which was able to produce sensor with repeatable characteristics, which is presented in Section 5.3.



(1) FBG; (2) Optical fibre; (3) Laminate; (4) PTFE tape; (5) Metal plate.

Figure 5.3: (a) Image of the manufacturing of the disc using PTFE guide to aid the positioning of the optical fibre on the top surface of the laminate and (b) the schematic of the section along the optical fibre showing the optical fibre on the surface of the GFRP laminate.

5.1.4 Challenges Encountered During the GFRP Manufacturing of Method Two - Co-cured FBG

Figure 5.4, shows six sensors after cure. Although PTFE guides were used to contain the laminate, a considerable amount of resin flowed along the optical fibres, which made

them brittle and difficult to remove from the plate without damage. As a result of the resin flow, the thickness of the membrane was different from that expected for the number of plies determined via nominal ply thickness calculations. Between the six sensors, the amount of resin flow was inconsistent, which makes the expected final thickness arbitrary and difficult to predict.

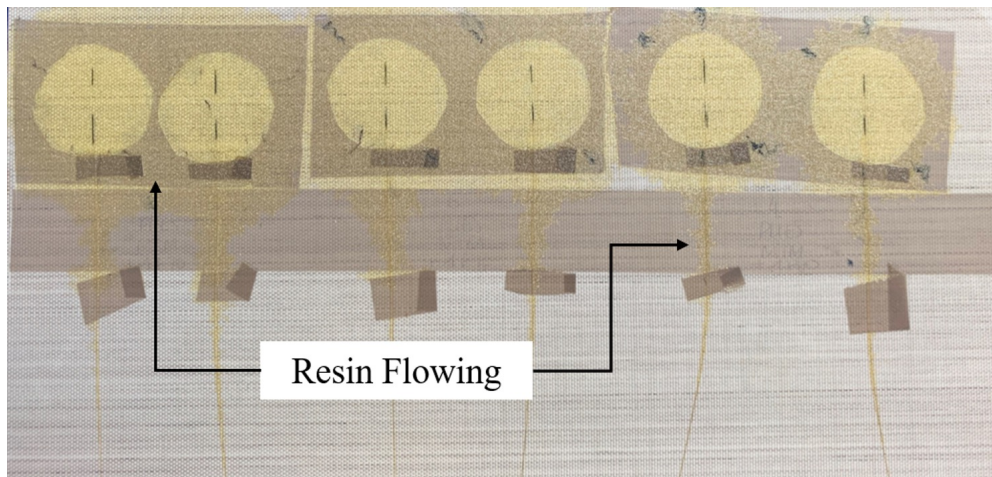


Figure 5.4: Image of the manufacturing method presented in Section 5.1.1 showing the resin flow of each discs.

The second use of the PTFE tape was to keep the optical fibre on the top surface of the membrane and to minimise the possibility of damaging the optical fibre by having abrupt change of thickness beyond the boundaries of the membrane due to the high cure pressure. However, as the PTFE is a soft tape, the cure pressure applied to the laminate pushed the optical fibre down, into the laminate, as shown in Figure 5.2 (b). This sensor, tested and described in Chapter 5, showed very low sensitivity to pressure due to the optical fibre being closer to the neutral axis of the membrane.

Although both techniques highlighted several issues, the advantage of using GFRP was its low hysteresis compared with rubber materials. Moreover, the glass fibres characteristics are similar to that of the optical fibre which is an advantage especially with

thermal environments. The resin flow was an issue in both techniques and was the first area of improvement to investigate, with the second being fixing the position of the optical fibre relative to the surface of the membrane and thus its neutral axis. The improved manufacturing process is presented in Section 5.3.

5.2 Experimental Analysis of GFRP Pressure Sensors Using Two Manufacturing Methods

This section compares the performances of GFRP diaphragm based sensors.

5.2.1 Material

The GFRP diaphragm-based sensors were fabricated using the two methods that are presented in Sections 5.1.1 and 5.1.3. One sensor was made by bonding the optical fibre to the surface of the diaphragm using cyanoacrylate (Loctite 401) after the laminate was cured, and is described in Section 5.1.1. The second sensor was made by placing the optical fibre on top of the laminate and co-curing the whole assembly together, and is described in Section 5.1.3. This second method produced a sensor where the optical fibre sank towards the centre of the thickness, such that the optical fibre was close to the neutral axis of the diaphragm. Both laminates were cut to 32 mm discs and used in the 25 mm diameter aperture on the jig used in the characterisation of the HNBR-based sensors, shown in Section 4.3.2. The 25 mm diameter was first selected for the ratio between expected sensitivity of 10 Pa/pm and the largest diameter within the requirements of a diameter of maximum 30 mm. While this sensor is made from seven plies, an eight-ply diaphragm for the given sensitivity would require a diameter outside the specification requirements. The diaphragm with the optical fibre bonded on the surface had a thickness of 0.31 mm, while the diaphragm with the optical fibre co-cured had a thickness of 0.27 mm. Both sensors were made using seven plies of GFRP and the difference in thickness is explained by the resin flow during the manufacturing, as described in Sections 5.1.2 and 5.1.4.

5.2.2 Instrumentation

The sensors presented in this section were characterised using the single 25 mm diameter aperture cell of the rig shown in Section 4.3.2. It should be noted that the experiments took place on different days, as the jig only has one 25 mm diameter aperture. Unlike the rubber sensors testing, an electrical pressure sensor was used as reference, a Texense PDif [4] connected to a pitot tube, typical of the sensors found on F1 cars, logging at a rate of 250 Hz.

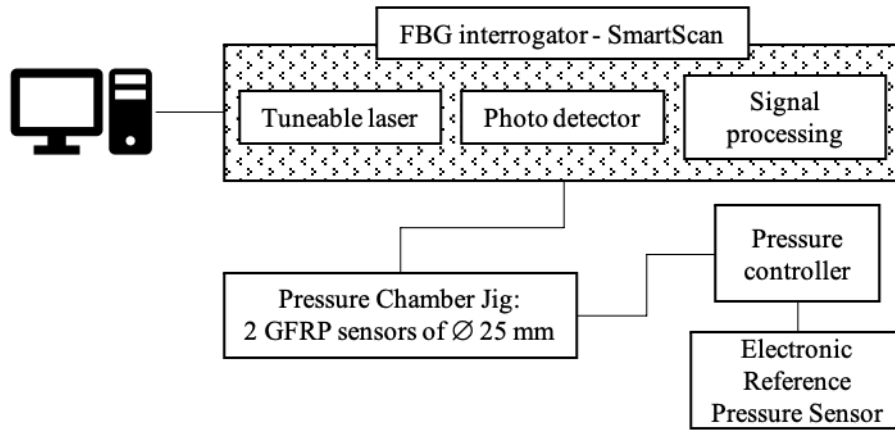
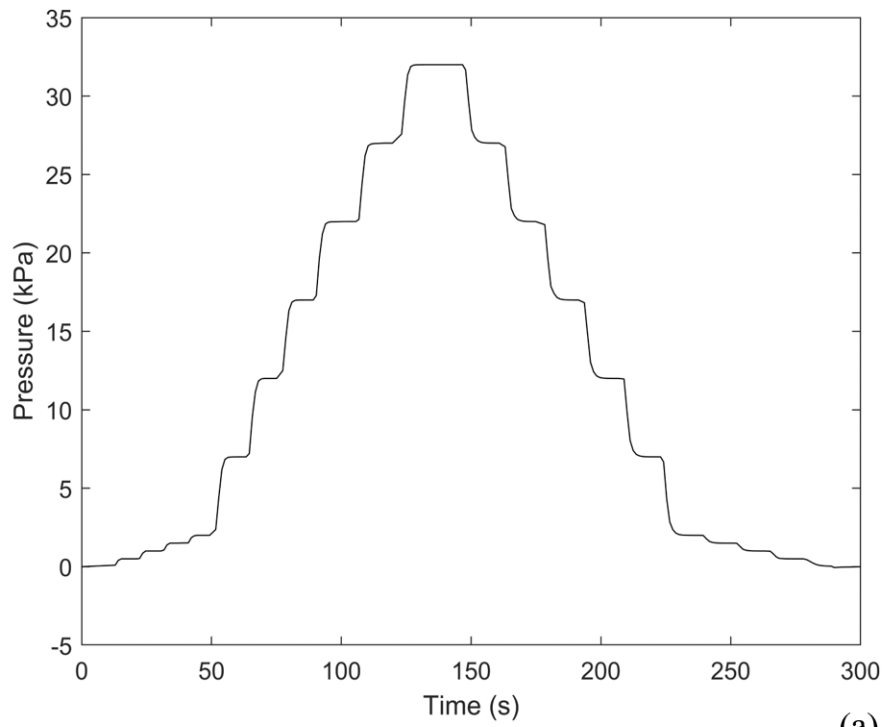


Figure 5.5: Schematic of the experimental configuration used to characterise the sensors based on GFRP diaphragms, with the pressure chamber connected to the pressure controller and the optical fibre connected to the SmartScan interrogator. 25 mm diameter aperture used by one sensor at the time due to availability of the pressure chamber.

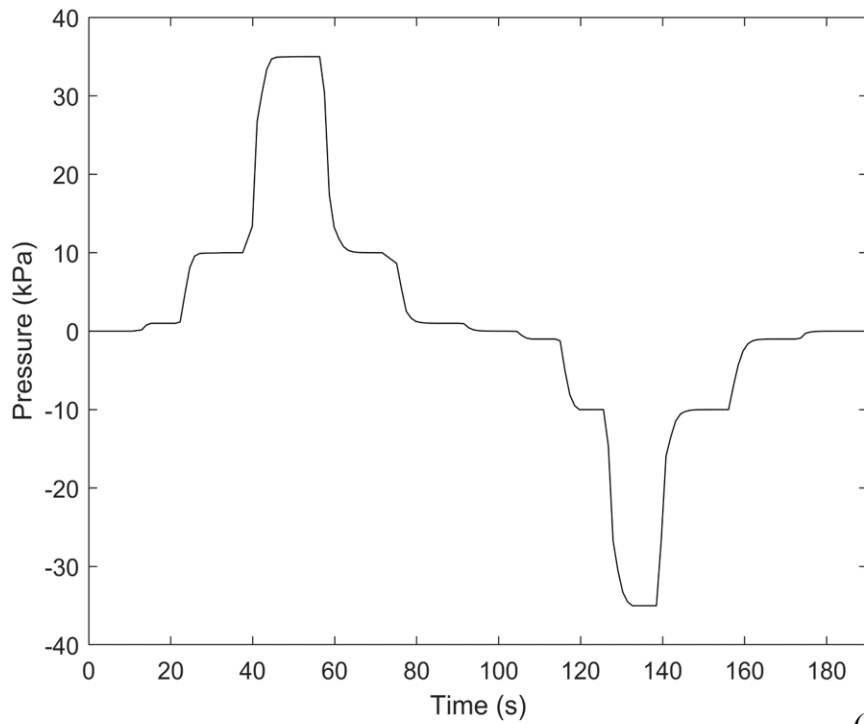
5.2.3 Results and Discussions

Figs. 5.7 and 5.8 show the temporal response of the sensor using manufacturing method one, with the optical fibre bonded to the surface of the membrane using cyanoacrylate. Overall, the form of the response of the FBG compares well with that of the electronic reference sensor of Figure 5.6. The increased frequency observed during the characterisation of the HNBR sensors is not observed here, which suggests that the natural frequency of the GFRP is dependent on the applied pressure and hence resonance is not observed. There is evidence of low hysteresis, 1.5%, giving a maximum Bragg wavelength differ-

ence of 50 pm for a given pressure between the increasing and decreasing pressure cycles. There is however no drift back to zero pressure due to the low viscoelasticity of GFRP and the low hysteresis.



(a)



(b)

Figure 5.6: Typical profile of the applied pressure measured by the electronic pressure sensor. (a) shows the positive static step test and (b) shows the positive pressure applied followed by negative pressure, over the full scale ± 35 kPa.

Figure 5.8 shows that when a negative pressure is applied, a blue shift of the Bragg wavelength is observed as the diaphragm takes on a convex shape and the upper surface experiences a compressive strain. However, the response of the optical fibre sensor is not symmetrical when positive and negative pressures are applied, with the response to positive pressure having a sensitivity that is approximately 1.7 times larger than that to negative pressure.

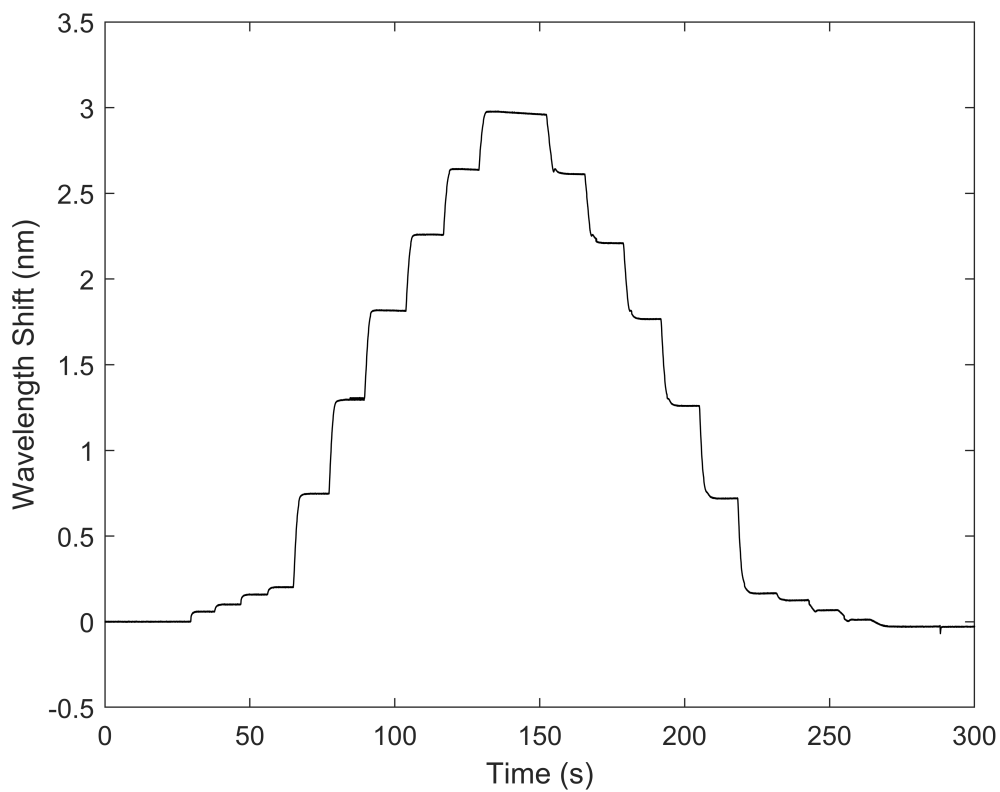


Figure 5.7: Temporal pressure responses of the sensor with the optical fibre bonded on the surface, comprising of positive steps.

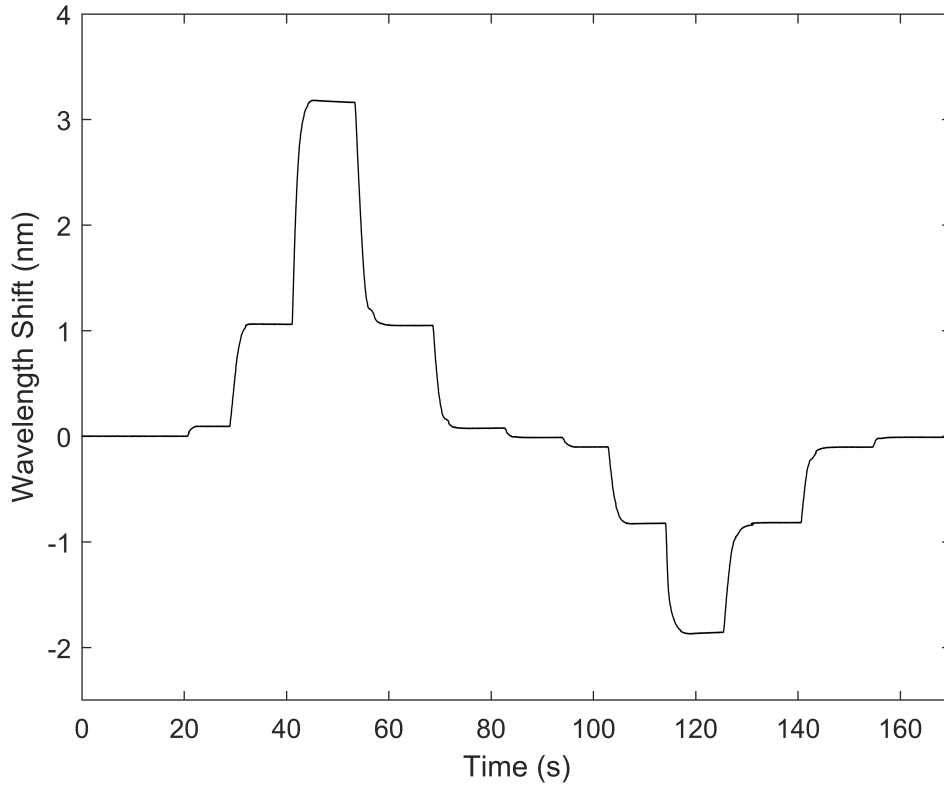


Figure 5.8: Temporal pressure responses of the sensor with the optical fibre bonded on the surface, comprising of negative and positive steps.

The sensor manufactured with the fibre co-cured within the GFRP composite has a different behaviour, as shown in Figure 5.9, which shows the response at positive pressures from 0 to 35 kPa. While the sensor with the bonded FBG had a positive response to pressure, at pressures below 5 kPa this sensor exhibits a negative response (from the start up to 50 seconds) followed by positive response for pressures higher than 5 kPa (between 50 and 200 seconds). At 32 kPa, it shows sensitivity that is three times less with than that of the bonded FBG sensor. The hysteresis however is less pronounced, with an average difference of the wavelength recorded on the upward and downward cycles being 1 pm. However when the 5 kPa is applied again during the step down and the optical fibre exhibits compression (from 200 seconds onward), there is a much higher offset of, on average, 20 pm.

Figures 5.9 and 5.10 show that when negative pressures are applied (from 90 seconds onward), the sensor with the co-cured FBG exhibits a red shift while the bonded FBG sensor exhibits a blue shift. While the latter had a lower sensitivity with negative applied pressure, the co-cured optical fibre sensor shows a higher sensitivity, with the wavelength shift at -32 kPa being 1.2 larger than that at 32 kPa pressure.

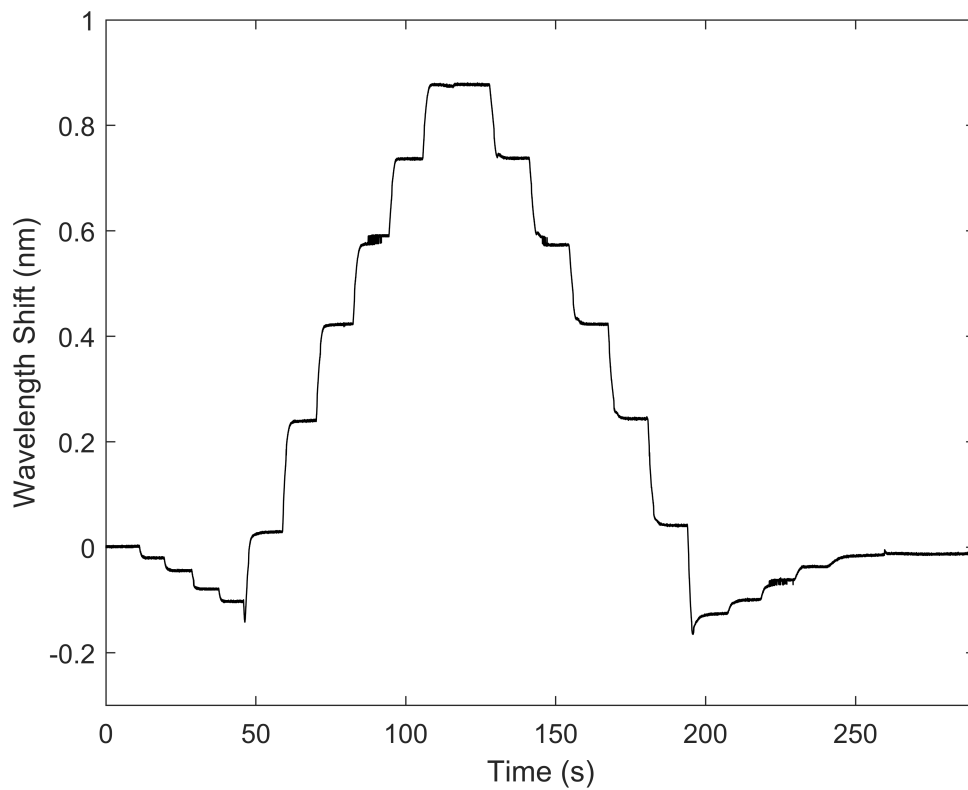


Figure 5.9: Temporal pressure responses of the sensor in which the optical fibre was co-cured within the composite and the FBG sensor in the centre of the thickness, comprising of positive steps.

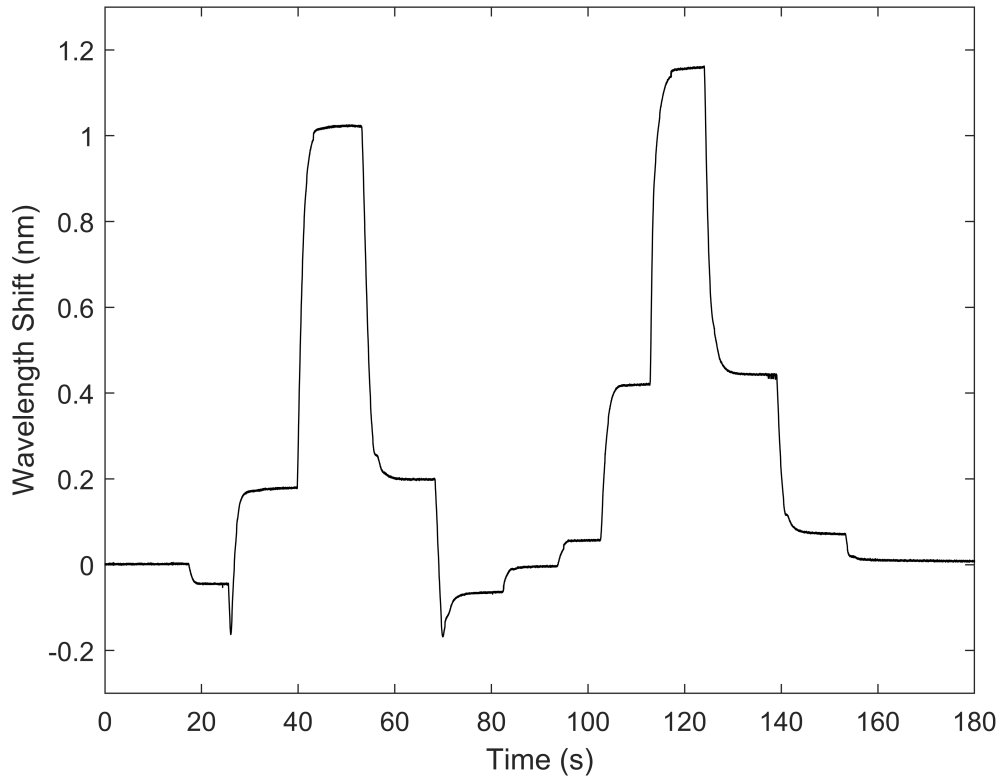


Figure 5.10: Temporal pressure responses of the sensor in which the optical fibre was cured within the composite and the FBG sensor in the centre of the thickness, comprising of negative and positive steps.

The different sensitivities observed for positive and negative applied pressure for the sensor with the optical fibre bonded to the surface of the diaphragm is in agreement with the FE model, which predicts a difference of a factor of 1.3. The difference between the experiment and FE model is likely to be due to the uncertainty in the location of the optical fibre with respect to the neutral axis of the diaphragm. The difference between the sensitivities to positive and negative applied pressures can be explained by the membrane stiffness. When experiencing positive pressure the optical fibre is located on the surface so it is experiencing tension, then the tensile forces appear while bending is reduced, resulting in strain decrease in the optical fibre and so the nonlinear behaviour of Figure 5.12 appears. However, when the negative pressure is applied, the optical fibre experiences

compression which should be, assuming a linear response, of the same magnitude, but opposite sign as observed when in tension, however that is not the case here. As explained above, although acting to reduce the strain caused by the pressure loading of the diaphragm, the tensile forces work in the same direction as the tension as they are acting against the edge load. In compression in this configuration, the same tensile forces are acting in the diaphragm, also acting against the compression load thus reducing the whole strain in the optical fibre and as a result, reducing the sensitivity at negative pressure. This configuration is illustrated in Figure 5.11 (1-b).

The behaviour of the sensor with the optical fibre co-cured within the composite suggests that, although the optical fibre is close to the neutral axis of the membrane, as seen in Figure 5.2, the optical fibre might even be on the opposite side of the neutral axis, meaning that it experiences compression, which could explain why the optical fibre initially exhibits a blue shift with positive applied pressure. Then, the nonlinear behaviour introduces tensile loads. Because the optical fibre is close to the neutral axis of the membrane, the influence of bending is small, while the tensile forces are present irrespective of the position of the optical fibre relative to the neutral axis. As described in the previous paragraph, the tensile forces act against the edge load from the fixed diaphragm over the annular section, inducing a red shift in the FBG reflection. This hypothesis can also be confirmed by Figure 5.10. With the second part of the test, where negative pressures are applied (from 90 seconds onward), the response of the FBG shows a higher positive sensitivity, suggesting that the optical fibre is closer to the opposite surface by exhibiting a red shift in response to negative pressures. While opposite surfaces exhibit the same strain but of opposite sign, the higher sensitivity can be explained by the tensile forces working with the bending when the sensor experiences negative pressures, while the tensile forces work against the bending when the sensor experiences positive pressures. This is true in this configuration because of the position of the optical fibre relative to the neutral axis and the curvature of the membrane depending on the applied pressure, as shown in Fig-

ure 5.11 (2).

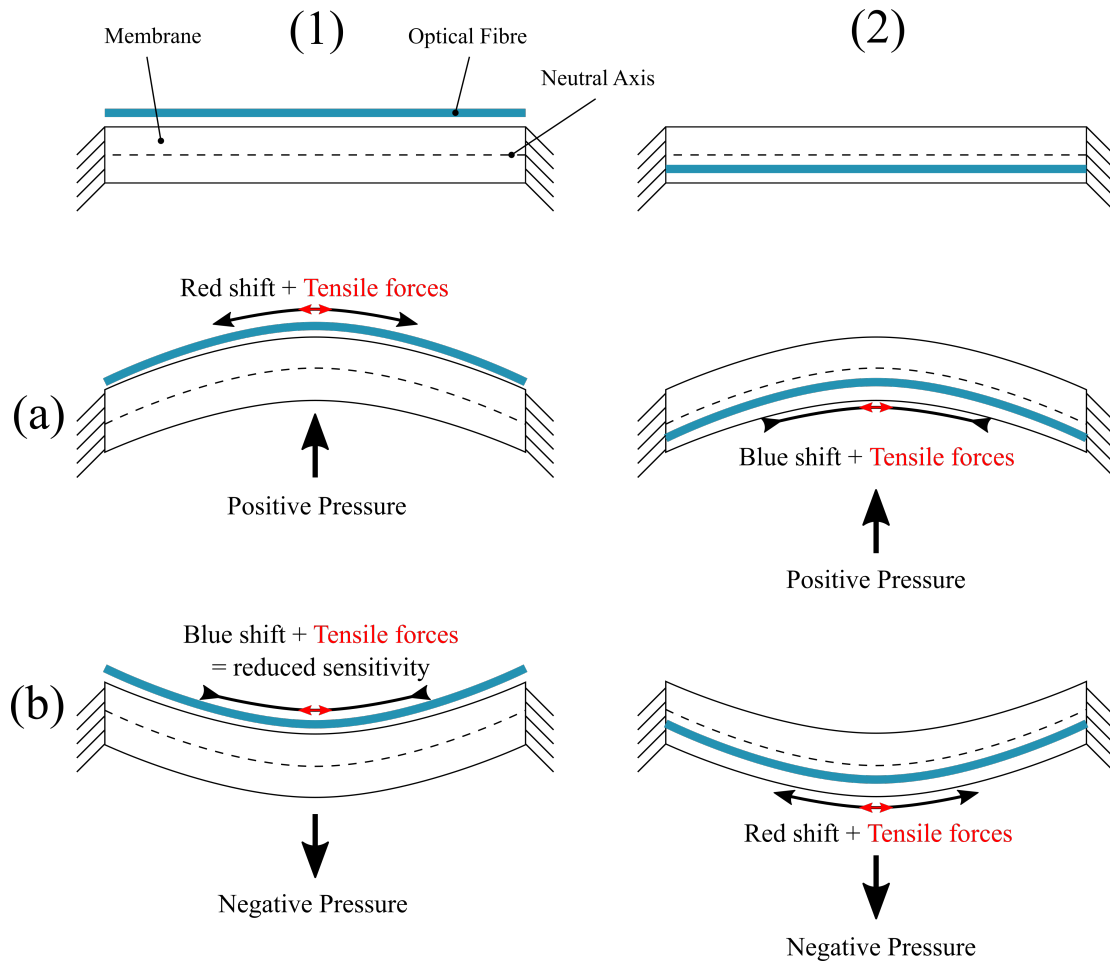


Figure 5.11: Schematic of the two GFRP sensors. The sensor with the optical fibre on the upper of the surface of the diaphragm (1) and the sensor with the optical fibre positioned closer to the neutral axis (2) in the two different configurations of positive (a) and negative (b) pressures. The two configurations show the nonlinear behaviour with the addition of tensile forces.

Figure 5.12 shows the calibration curves of both the bonded FBG and the co-cured FBG GFRP sensors for the positive step pressure test of Figure 5.6 (a). As seen in the temporal responses of Figure 5.7 and Figure 5.9, the sensitivity to pressure of the bonded optical fibre sensor, with the optical fibre glued on top of the surface of the diaphragm is almost three time larger than that of the co-cured FBG sensor. A small offset from

the increase and decrease of the pressure can also be observed, however it is significantly smaller compared to that exhibited by the HNBR sensor in Figure 4.16 (b). The co-cured FBG sensor exhibits an initial negative sensitivity for pressures up to 5 kPa, followed by a linear positive response, unlike the first sensor which has a slight nonlinear behaviour. The membrane effect in the thin diaphragm can explain the non-symmetrical response seen in Figure 5.8.

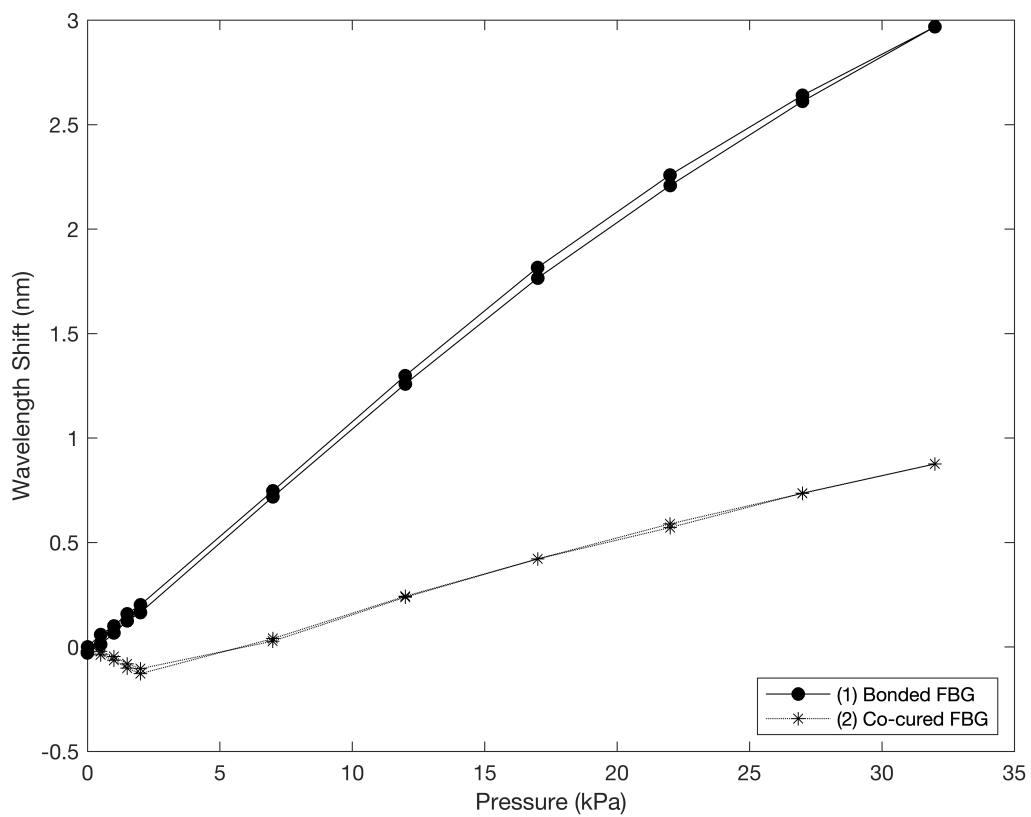


Figure 5.12: Pressure sensitivity of the GFRP-based sensors with bonded FBG sensor placed on the surface (●) and the co-cured FBG sensor close to the neutral axis (*). Positive pressures only, from 0 to 32 kPa.

Figure 5.13 shows the calibration of both sensors during the alternative positive and negative pressures shown in Figure 5.6 (b), where the subtle difference between their

sensitivities can be observed.

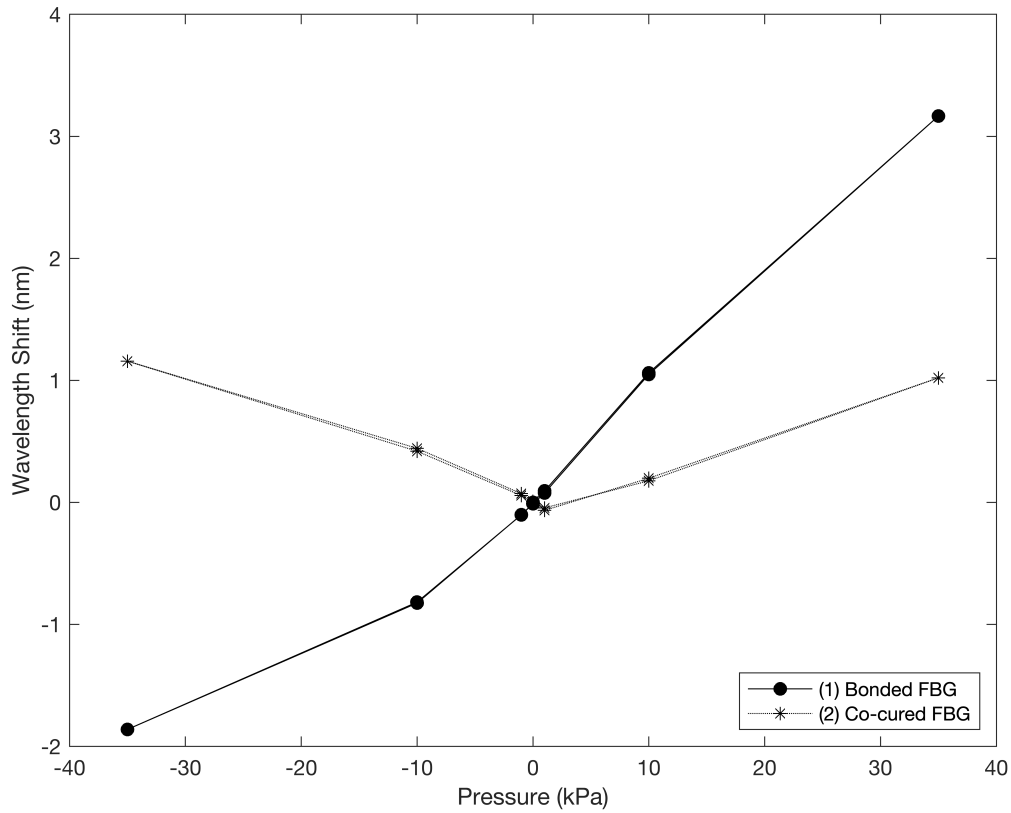


Figure 5.13: Pressure sensitivity of the GFRP-based sensors with bonded FBG sensor placed on the surface (●) and the co-cured FBG sensor close to the neutral axis (*). Pressure scale of ± 35 kPa.

5.2.4 Conclusion

GFRP has good properties for use as the diaphragm in optical fibre based pressure sensors as it has properties similar to that of the optical fibre and does not show viscoelastic characteristics and exhibits significantly less hysteresis than rubber materials. However, sensors fabricated using the manufacturing methods presented in Sections 5.1.1 and 5.1.3 exhibit limitations. The first method, which involved bonding the optical fibre containing the FBG to the top of the surface of the diaphragm using a cyanoacrylate adhesive, shows

good response to pressure but a lack of control over the thickness of the glue line, with a concomitant influence on the separation of the core of the fibre from the neutral axis of the diaphragm, influences the sensitivity and reproducibility of sensors made in this way.

Sensors fabricated using the co-cured FBG, where the optical fibre containing the FBG was cured within the composite, also exhibit issues with the control of the position of the fibre with respect to the neutral axis of the diaphragm. It was noted that the optical fibre could sink through the thickness of the GFRP plate during curing, which reduces the sensitivity to pressure and impacts on the repeatability of sensor manufacture. As a result of this, work was undertaken to develop an improved manufacturing method which consists of a custom-designed press mould that includes a groove for the positioning of the optical fibre relative to the diaphragm's neutral axis in a repeatable fashion. The improved manufacturing process is described in Section 5.3.

5.3 Improved GFRP Based Optical Pressure Sensor Manufacturing

5.3.1 Press Mould Design

Significant issues with previous GFRP manufacturing processes were encountered as described in Sections 5.1.2 and 5.1.4. The laminate had to be contained and the thickness controlled, and to do so, a press mould technique was investigated. A carefully designed mould would also contribute to consistency and repeatability between sensors and an opportunity to place the optical fibre on top of the membrane without the use of additional resin.

The mould, shown in Figure 5.14, was comprised of three main parts: the base, the top and the ring. The mould was designed to be used for all membrane thicknesses so that the

base and the ring could be re-used and the top part was the only component to be changed depending on the chosen thickness. All sensors were made with the same diameter, 32 mm, with the aperture on the testing pressure chamber jig defining the active diameter of the sensor. The top parts were designed with a different thicknesses to produce the required sensor thickness, depending on the number of plies. The void between the base mould and the top part defined the thickness of the laminate. With the cure pressure, the top mould presses the laminate to the desired thickness, with small grooves on either side of the ring designed to push excess resin out of the mould. The press-mould also contained a groove to accommodate the positioning of the optical fibre on the surface of the laminate.

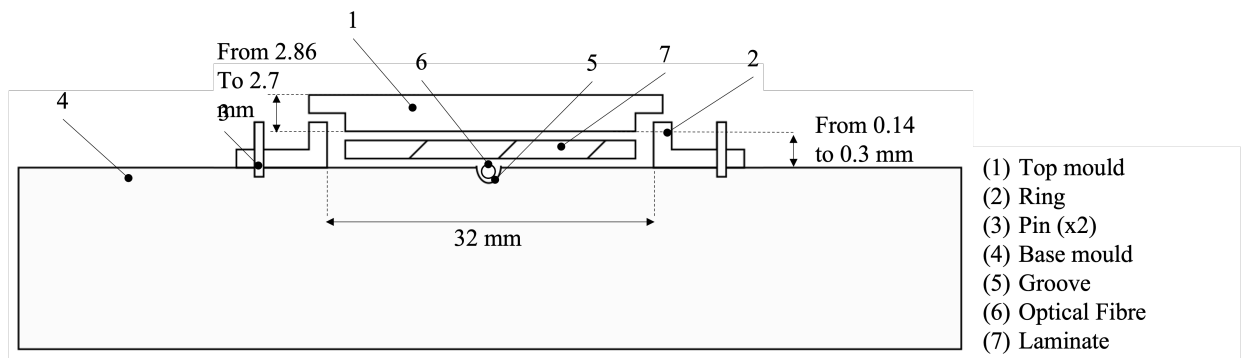


Figure 5.14: Schematic of the press mould representing a section cut along the diameter of the disc. Not to scale.

Each part of the mould was prepared prior to use using release agent [117] all over the surfaces to prevent the resin from sticking to the mould. After several attempts and after encountering difficulty with removing the sensor from the mould, the surfaces in contact with the laminate were also protected with PTFE tape for additional bond release.

The manufacturing method consisted of positioning the optical fibre (6) inside the groove (5) on the mould base, as shown in Figure 5.15 (a), and securing it in place with

PTFE. A roll of epoxy with the same properties as the prepeg resin [118] was available so a small amount was added along a 32 mm length (diameter of the disc) in the centre of the groove to bond the optical fibre to the laminate. The ring (2) was then fixed with two pins (3) as per Figure 5.15 (b) and the laminate layup (7) inserted inside the ring with the composite glass fibres oriented at $\pm 45^\circ$ from the optical fibre axis as shown in Figure 5.15 (c). The final step involved closing the mould by adding the top part (1), as depicted in Figure 5.15 (d).

After several design iterations regarding the grooves used for removal of the excess resin, the resulting part consisted of uniform discs with the optical fibre bonded all along the diameter as shown in Figure 5.16.

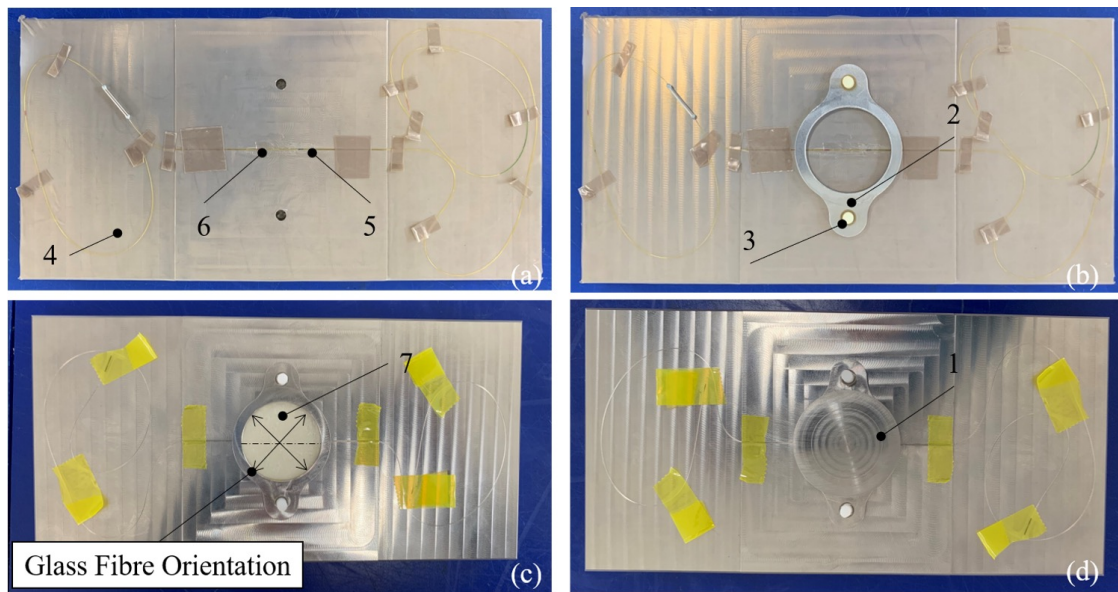


Figure 5.15: Images showing the steps in the fabrication of the sensor using the press mould: (a) the optical fibre (6) is placed inside the groove (5) on the base mould (4) and taped down. In (b) the ring (2) is secured with two pins (3). In (c) the laminate is inserted at $\pm 45^\circ$ relative to the optical fibre's longitudinal axis and (d) the top part of the mould is inserted (1). Images (c) and (d) are from another production, which is why the tape is of different colour.

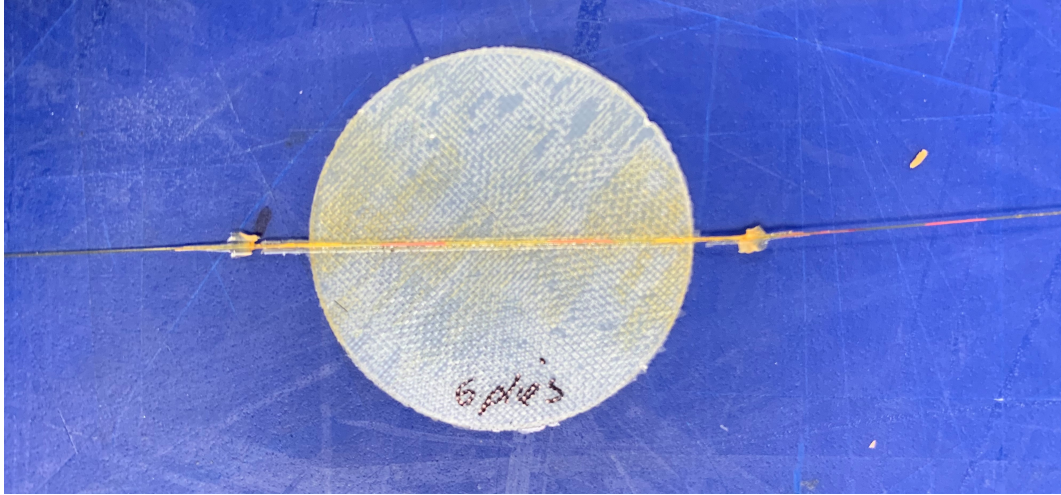


Figure 5.16: Image of the sensor extracted from the press mould with a diameter of 32 mm. Picture shows a sensor made out of 6 plies to be used with a pressure chamber of aperture 21.5 mm.

The performance of the sensors made using the press-mould were not tested on the first pressure chamber jig presented in Figure 4.4. Instead, a single pressure chamber was designed to improve the sealing by reducing the number of apertures.

5.3.2 Improved Pressure Chamber

The design of the pressure chamber used for the characterisation of the improved sensor was based on the nine aperture jig.

Similar to the pressure chamber with multiple apertures, a upper component clamped the sensor in order to increase the seal and avoid shear of the annular glued surface when pressure was applied. Figure 5.17 shows (a) a 3D model of the jig and (b) a section showing the pressure chamber, the membrane and the optical fibre. Figure 5.17 (c) and (d) shows photographs of the pressure chamber. Four screws and bolts secured the upper and lower parts together. The aperture was designed depending on the working diameter calculated from the theory and FE analysis, presented in Chapter 3. The jig works as a gauge pressure sensor, with atmospheric pressure acting on one side of the disc and the pressure of interest on the other.

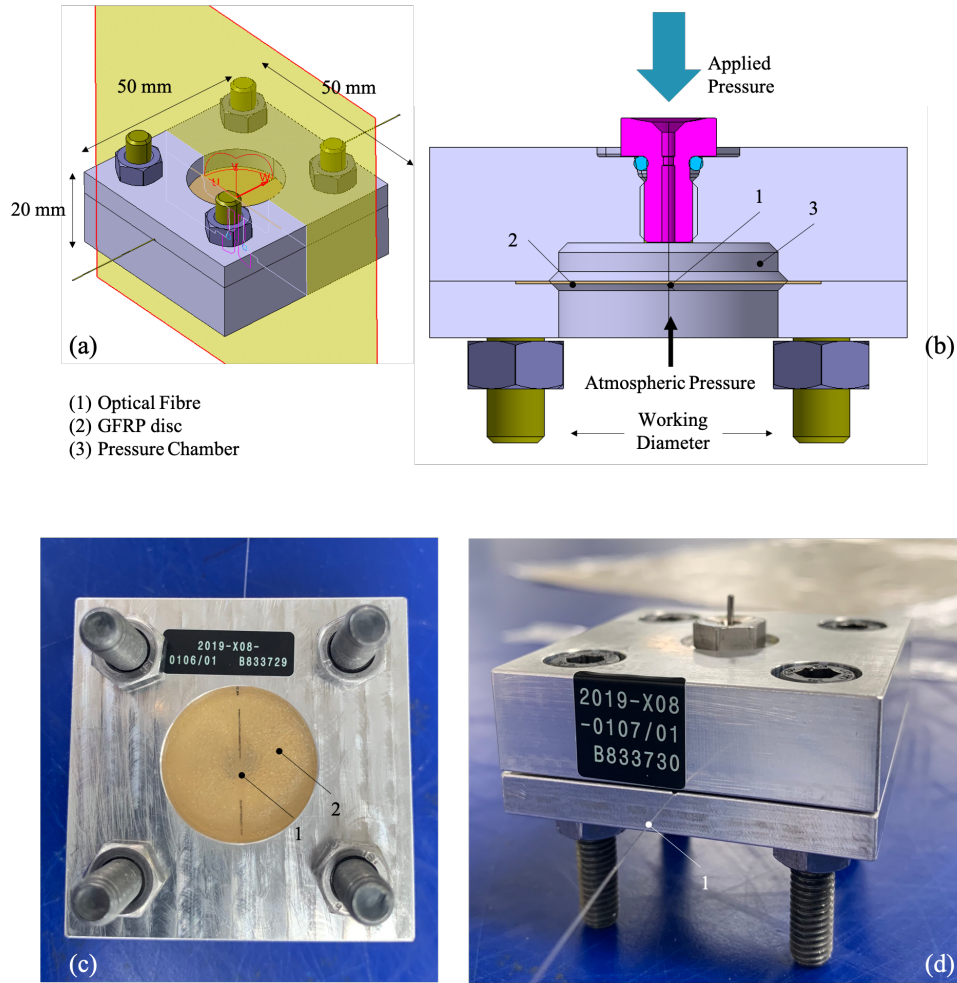


Figure 5.17: (a) 3D model of the improved pressure chamber jig design and (b) the section cut showing (1) the optical fibre, (2) the GFRP disc and (3) the pressure chamber. (c) and (d) photographs showing the pressure chamber jig and sensor.

5.3.3 Results and Improvements

Overall, the press-mould method improved the sensor surface quality and repeatability. The sensor manufacturing was more controlled, whether it is regarding the position of the optical fibre, the diaphragm surface quality or the thickness. Figure 5.18 shows a microscope picture of a sensor made from the press-mould.

The groove on the base mould consistently located the optical fibre on the surface of

the membrane, which is important to ensure consistency in the sensitivity of the fabricated sensors. By having the optical fibre placed on the surface, the sensitivity prediction of a given sensor dimension can be more accurate than with previous manufacturing processes adding glue afterwards. The optical fibre was also protected by the resin over the full membrane diameter, which secured the bond as the groove was filled with resin, unlike fabrication method 2, where one sensor exhibited disbonding of the optical fibre due to the resin flow. The resin also protected the optical fibre from breakage at locations where the acrylate coating was removed, although most sensors made with the press mould used polyimide coated optical fibres supplied by FemtoFiberTec, who fabricate their FBG through the polymer coating.

The thickness of the diaphragm is also an important factor to take into account concerning the sensitivity of the fabricated sensor. With the press-mould, the thickness was uniform over the full membrane with a tolerance of ± 0.02 mm and the dimensions were true to the gap between the top and base mould. However, an issue occurred with smaller laminate, which is described in Section 5.3.4.

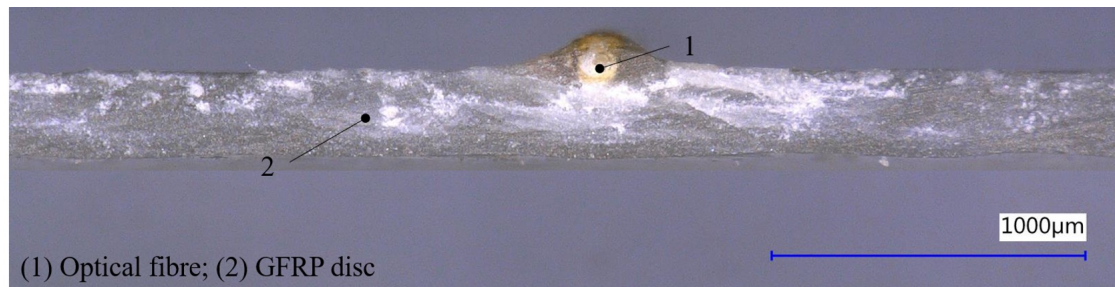


Figure 5.18: Microscopic picture of the sensor made with the improved manufacturing method.

5.3.4 Limitations

The main issue regarding this manufacturing process was encountered when fabricating diaphragms using smaller thicknesses, specifically of 3, 4 and 5 plies of GFRP. The top

part of the mould was designed to produce the thicknesses based on a single ply cured thickness of 0.044 mm, dimensions provided by the supplier. The ply thickness of 0.044 mm is the mean value with a tolerance of ± 0.003 mm. A layup comprising 3 plies of GFRP has a thickness of 0.132 mm, 4 plies has a thickness of 0.176 mm and 5 plies a thickness of 0.22 mm. The top part was designed to achieve thicknesses of 0.14 mm, 0.18 mm and 0.22 mm respectively. For a press mould to work efficiently, the volume of material inside has to be slightly higher than the expected final product, so the excess resin can be pushed out. If the volume is less, the top part is not in contact with the laminate and the press moulding does not compress the laminate enough, resulting in a diaphragm of lower thickness than expected as resin escaped.

While the top press is used to push the laminate down and push the resin through the grooves, the high cure pressure and the vacuum bag also pull the resin out of the grooves, which also reduces the final thickness. Discs made with this mould with three to five plies were unusable due to their porosity. Figure 5.19 (a) shows a successfully manufactured membrane, while (b) demonstrate the porosity of the thinner discs. The weaves of the smaller thickness plates contain voids, leaving microscopic holes distributed over the composite diaphragm.

The thicker discs, with 6 and 7 plies, were designed with a top press mould of 0.26 and 0.3 mm respectively. The mean value of 6 and 7 plies was thicker than the gap left inside the mould between the top press mould and the base mould, which covered the working principle of the press moulding, avoiding porosity. A suggestion for future work using a press mould with composites is to calculate the mould gap using the minimum thickness provided by the supplier instead of the mean value as was used here.

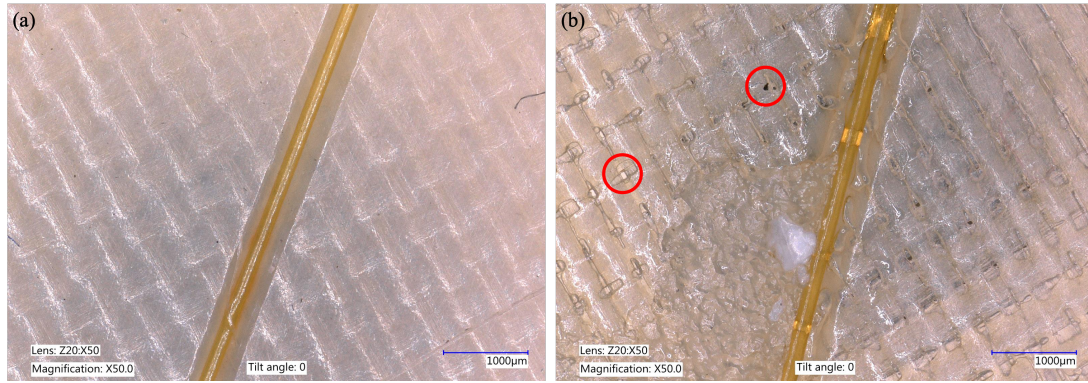


Figure 5.19: Microscope pictures of (a) a non-porous sensor (7 plies of GFRP) and (b) a porous sensor (3 plies of GFRP) showing multiple holes in the weave at the intersections between each glass fibres. Red circles highlighting holes.

5.4 Experimental Analysis of GFRP Pressure Sensor Using the Improved Design

A GFRP diaphragm of diameter 25 mm and thickness 0.27 mm was fabricated using the press mould, described in Section 5.3. The sensor was made from the 32 mm disc mounted in the single pressure chamber of 25 mm diameter aperture used with the two previous GFRP sensors and presented in Section 5.3.2. Its performance was assessed using the configuration shown in Figure 5.5 and according to the positive pressure profile shown in Figure 5.20

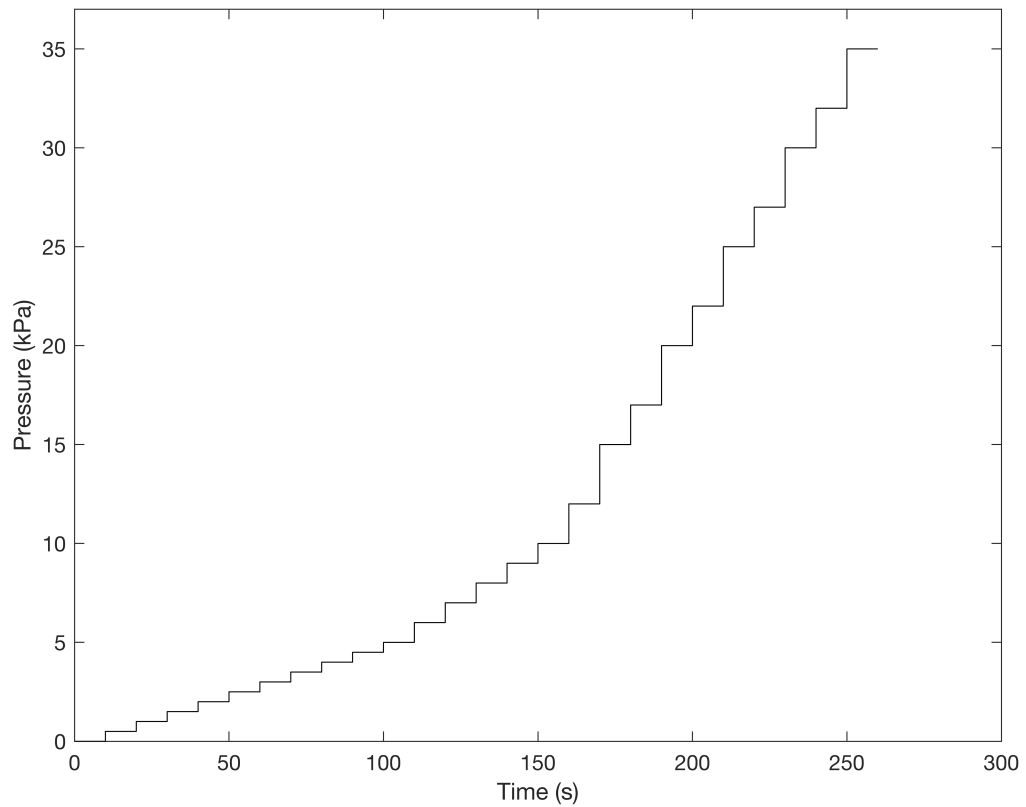


Figure 5.20: Typical pressure profile applied to the diameter 25 mm GFRP sensor made using the press moulding process.

Figure 5.21 shows recorded the temporal response of the sensor, showing a good agreement with the positive applied pressure profile by exhibiting a red shift from the start of the test. Similarly to previously assessed GFRP sensors, there is no evidence of vibration of the diaphragm, which confirms that the issue was associated only with the HNBR diaphragms.

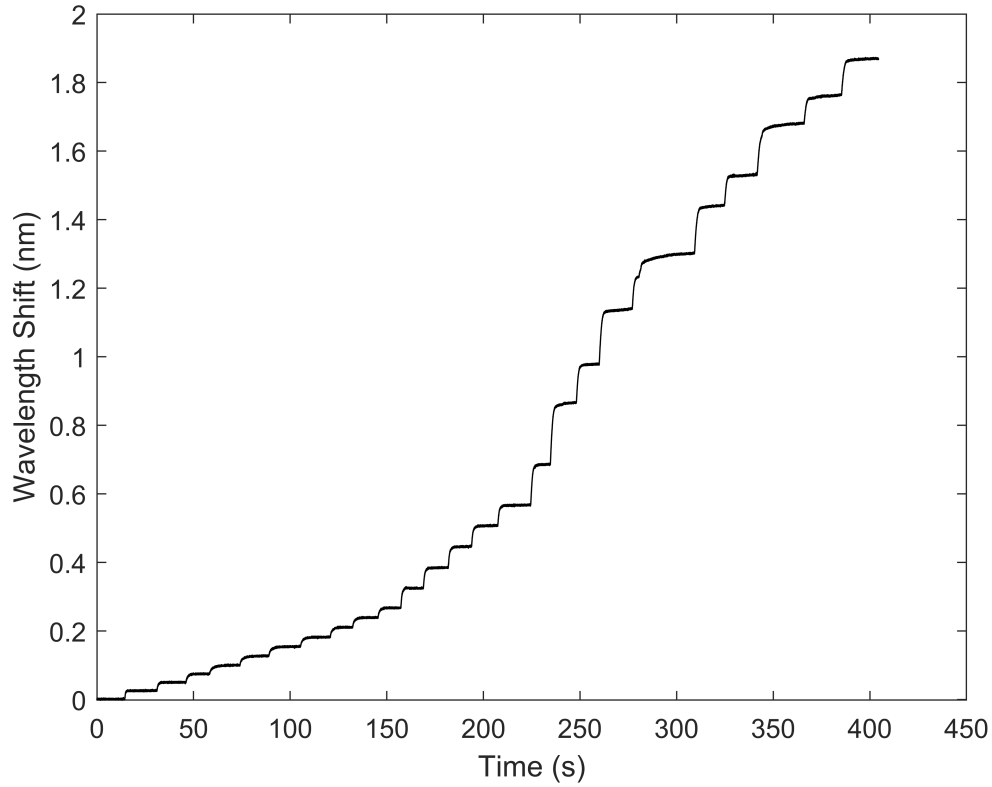


Figure 5.21: Temporal response of the 25 mm diameter GFRP sensor made using the press moulding process.

In Figure 5.22, the wavelength shift is plotted as a function of the applied pressure, indicating a nonlinear response from which it can be concluded that the response of the sensor at pressures up to 17 kPa is predominately a result of the bending of the diaphragm, while above this pressure the membrane effects start to dominate, reducing the pressure sensitivity. The nonlinearity is, however, subtle and could be considered as a bi-linear curve which has the advantage of a reduced resolution at higher pressures, where the resolution might not be required to be as high.

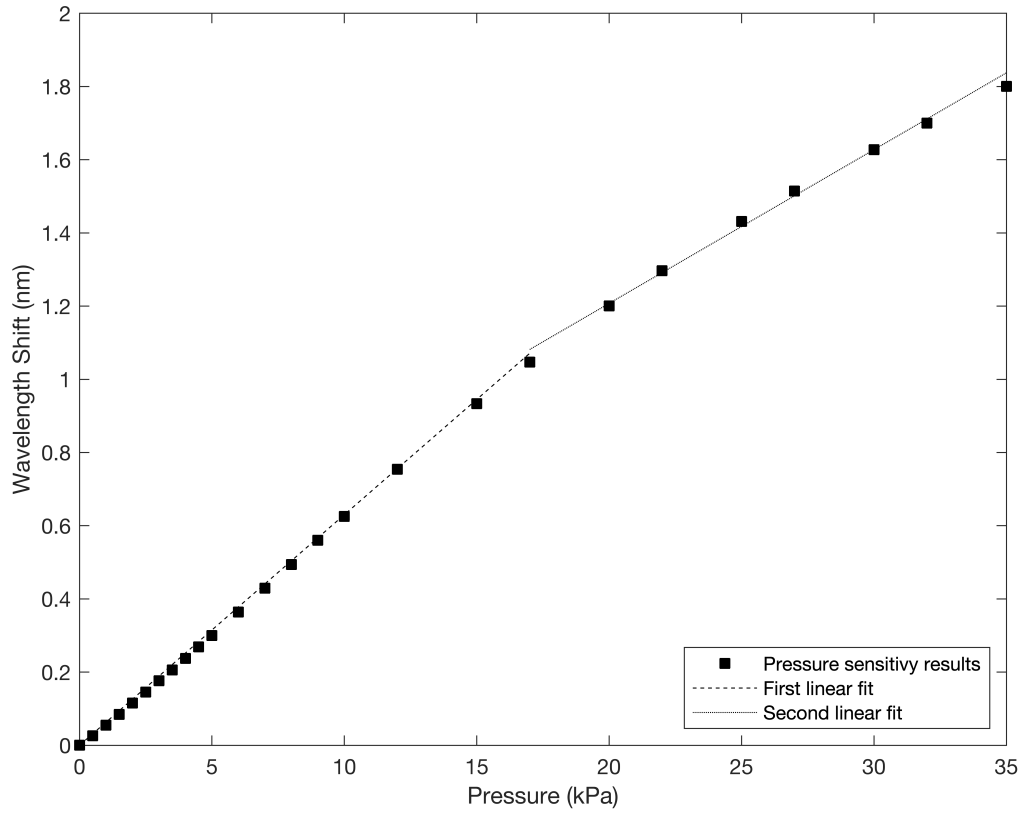


Figure 5.22: Calibration of the pressure response of the GFRP sensor made from the press moulding process with two linear fit showing a possible bi-linear behaviour. First fit: $R^2 = 0.9997$, second linear fit: $R^2 = 0.9943$.

The difference between the strain on the surface of the membrane and the strain in the optical fibre is approximately a factor of 1.5 and is investigated in Chapter 3. This is a point that is raised here as similar designs reported in the literature do not consider the influence of the position of the optical fibre core relative to the neutral axis of the diaphragm, rather using the simple elastic plate theory to predict the sensitivity of their sensor [89, 94].

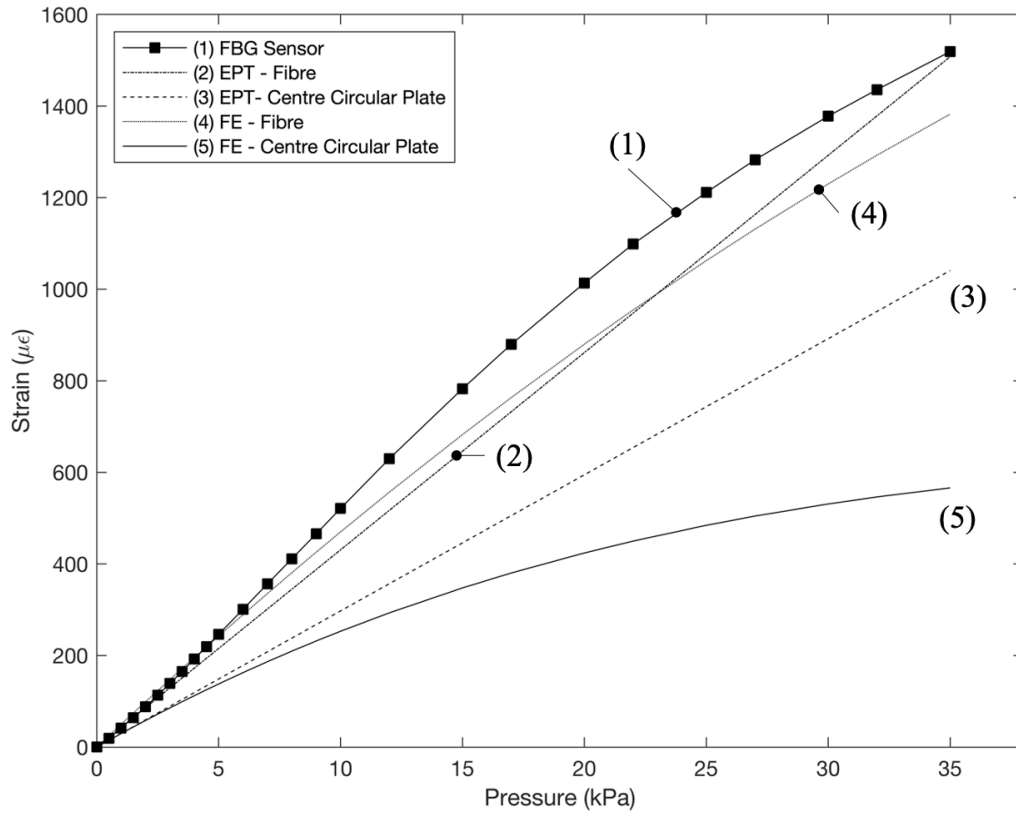


Figure 5.23: Comparison of the sensor response converted to strain (1) and the maximum strain from elastic plate theory (EPT) of the optical fibre (2), the maximum strain in centre of the circular plate from the elastic plate theory (3), the maximum strain representing the optical fibre from the FE results (4) and the maximum strain in the centre of the circular plate from the FE results (5).

Figure 5.23 compares the experimentally determined response of the sensor with the sensitivities predicted by the elastic plate theory and FE model. The response of the sensor was converted into strain, as per Equation(2.3), for ease of comparison.

The FE results on the diaphragm surface shows how different the strain in the optical fibre is. This is also true for the elastic plate theory on the diaphragm surface. The predictions of the strain experienced by the optical fibre give a better estimation of the

experimental observations. The FE results show the same trend, with a lower coefficient, suggesting that in the experiments the appreciable thickness of the glue line means that the cladding is not in direct contact with the upper surface of the diaphragm, increasing the separation between the core and the neutral axis. The same applies with the elastic plate theory, showing an overall lower sensitivity than the sensor itself. Due to the thickness of the membrane and the diameter of the optical fibre, the position of the latter makes great difference in the sensitivity. It also delays the tensile forces as the FE shows when comparing the membrane surface the predicted strain in the optical fibre and the actual strain in the FBG sensor.

With this behaviour in mind, the onset of the membrane effect can be delayed by designing a sensor where the gap between the surface of the plate and the optical fibre is greater, increasing the sensitivity of the whole sensor and creating a bending only response. By using this approach, the sensor can also be designed using a simple equation, removing the need for FE analysis. Using the mould described in Chapter 4, Section 5.3, the groove can simply be machined to a deeper depth. Overall, the sensitivity of this sensor, using a linear fit, was 56.7 ± 7.6 pm/kPa with an error of 7 % when compared to the linear fit. This is four times more than reported by Ambashta *et al.* [95] for a sensor made with a 25 mm diameter, 0.5 mm thick glass epoxy diaphragm.

5.5 Conclusion

This chapter described the evolution of the process used to manufacturing the sensors, from using basic tools such as metal plates to build the laminate, to the elaboration and design of a press-mould to improve consistency and repeatability between sensor manufacturing. The limitations of the HNBR material led to the investigation of different materials, and the choice turned to a composite GFRP for several performance reasons. The characterisation of the performance of sensors manufactured using each of the methods described is investigated. The two first manufacturing methods were used with two con-

figurations: the optical fibre bonded on the surface and the optical fibre co-cured within the composite. While the latter was manufactured with the aim of keeping the optical fibre on the top surface of the diaphragm, it instead sank to be closer to the neutral axis. The performances of both sensors were characterised in a pressure chamber of 25 mm diameter aperture. Positive and negative pressures were applied and the nonlinear behaviour with the tensile forces was highlighted, as well as the effect of having the FBG sensors close to the neutral axis of the diaphragm in the co-cured sensor. The limitations of each manufacturing process was described in term of performances and an improved method of sensor production was tested, which is compared with FE results and the elastic theory. The improved sensor showed lower sensitivity compared with the sensor with the bonded FBG sensor and higher sensitivity when compared with the co-cured FBG sensor, which was due to the position of the optical fibre relative to the neutral axis. Overall, the FE results and the experimental results are in good agreement and highlighted the limitations of the elastic plate theory, which is not applicable for thin diaphragm based sensors. Table 5.1 summarises all sensor performances.

Table 5.1: Summary of sensor performances describe in this chapter

	Sensitivity (pm/kPa)	Pressure range (kPa)	Hysteresis (%)	Comments
GFRP (FBG bonded), ϕ 25	98.2	± 35	1.5	High sensitivity; Inconsistent glue gap
GFRP (FBG co-cured), ϕ 25	30.4	± 35	0.2	Low sensitivity; FBG close to neutral axis of diaphragm
GFRP (Improved), ϕ 25	56.7	0 to 35	0.3	Consistency between sensor manufactured with press mould

Chapter 6

Enhanced Sensitivity Pressure Sensor Using Fibre Segment Interferometry

Introduction

This chapter describes a comparison of two optical fibre-based approaches to measure pressure-induced strain on a GFRP diaphragm: FBG and FSI. The first part of the chapter describes a sensor containing one FBG and three FSI and the optical fibre based sensor is characterised for its response to pressure, temperature and its temperature pressure cross sensitivity is examined. Based on these observations and the FE analysis presented in Chapter 3, a new approach to the discrimination of the influences of pressure and temperature is described. The second part of the chapter describe the analysis of a single FSI located over the diameter of the diaphragm, along with one FBG sensors for direct comparison.

6.0.1 Pressure Sensor Material

The simultaneous comparison of the two optical fibre sensing approaches was achieved by bonding FBGs and fibre segment interferometers to a composite diaphragm. The manufacturing of the GFRP diaphragm was based on the improved method described in Chap-

ter 4, Section 5.3. However, in this case, the optical fibres were not cured within the composite laminate as the groove in the base mould only accommodates one optical fibre. The groove was filled with PTFE tape in order to fabricate a flat disc. The optical fibres were bonded to the surface of the diaphragm afterwards, using the bonding process described in Chapter 4, Section 4.3.

Figure 6.1 (a) shows an image of the sensor mounted on the aluminium pressure chamber, with the SMF-28 fibre with acrylate coating removed at the gratings, bonded to the composite diaphragm. As for all sensors characterised in this thesis, the 21.5 mm active diameter of the diaphragm was defined by the pressure chamber aperture. The diaphragm had a thickness of 0.23 mm. The optical fibre containing the FBG sensor contained a single grating of length 4 mm, central wavelength 1542 nm and reflectivity 50%, located in the centre of the diaphragm where it would experience the highest and most uniform strains. The FSI segments, of low reflectivity (of order 35 ppm), central wavelength 1521 nm and full-width-half-maximum reflection bandwidth of approximately 5 nm, were positioned such that FS 1, of length 10 mm, covered the region of the diaphragm experiencing positive strains (in the centre of the diaphragm), while FS 2, of length 10 mm, experienced negative strains at the edge. This choice allowed for pressure temperature discrimination by having opposite response to pressure but same response to temperature. The third segment, FS 3, of length 35 mm, did not react to the pressure as it was not mounted to the working diameter of the sensor and was only sensitive to temperature. FS 2 was bonded such that one half of its length was on the working section of the diaphragm and the other half attached to the annular bonded section of the diaphragm to the pressure chamber. The cleave, at the end of the optical fibre containing the low reflectivity gratings, acts as a reference reflection for the three interferometers which appear at different frequency with their different path lengths. The tip of the optical fibre is protected to avoid dirt affecting the back reflection of the cleaved end. The Fresnel reflection at the air-core interface at the cleaved end has a reflectivity of 3.5 % [119]. The sensor elements and their positions on

the surface of the diaphragm are shown in Figure 6.1 (b). Figure 6.2 shows the FE results with the indication of the sensor gauge lengths, showing their expected strain responses at 35 kPa.

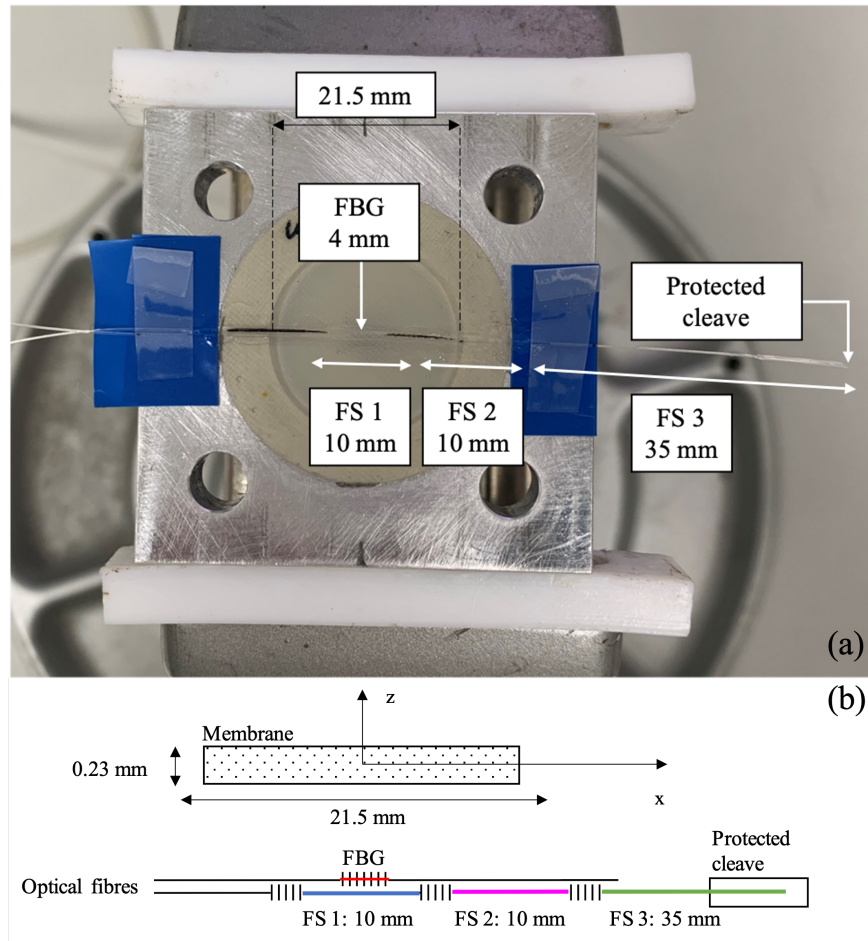


Figure 6.1: (a) Image showing the optical fibre pressure sensor, comprising a GFRP diaphragm instrumented with two optical fibres, one containing an FBG and the other containing 3 fibre segment interferometers (FS 1, FS 2 and, FS 3) mounted within an aluminium support structure. (b) Schematic of the two optical fibres, one containing an FBG and the other containing 3 fibre segment interferometers (FS 1, FS 2 and, FS 3), and their positions on the diaphragm. Not to scale.

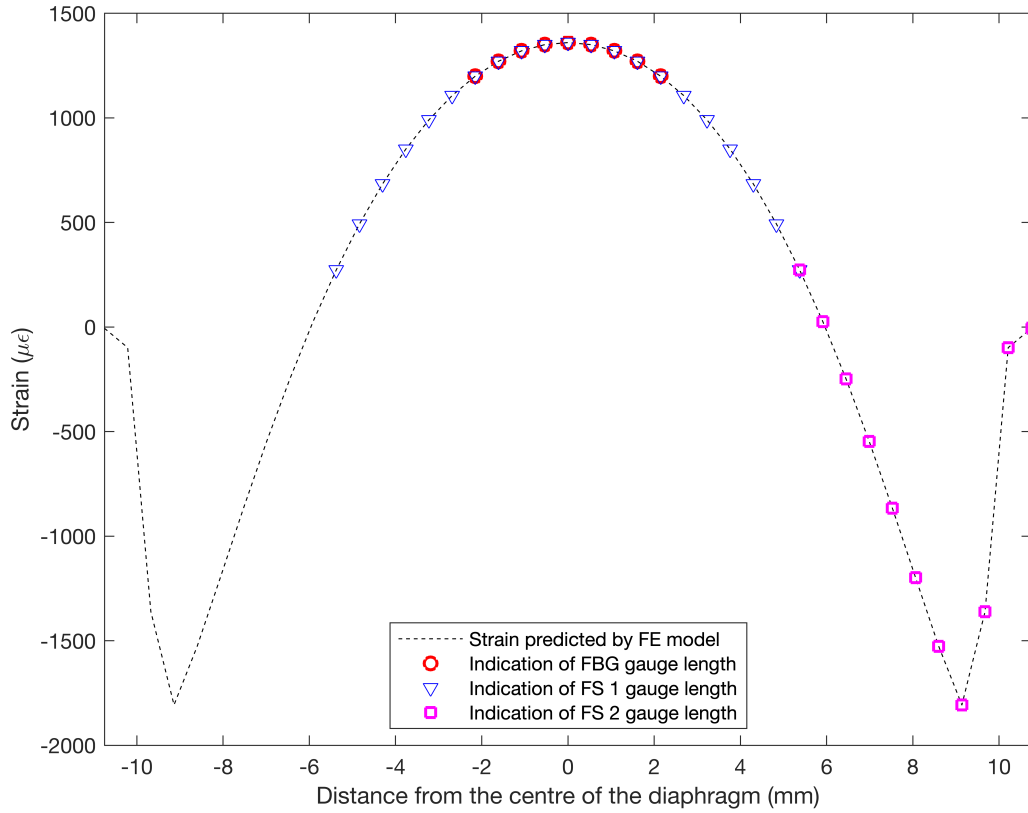


Figure 6.2: Output from a Finite Element Analysis of the diaphragm under deflection, with the simulation of an optical fibre mounted on its surface. Strain plotted at an applied pressure of 35 kPa over the diameter of the diaphragm and calculated over the gauge lengths of the three optical fibre sensors such as: red circles (○) for the indication of the 4 mm long FBG, blue triangles (▽) for the indication of the 10 mm long FS 1 and magenta squares (◻) for the indication of the 5.75 mm long section of FS 2 bonded to the pressure responsive region of the diaphragm.

6.0.2 Pressure Characterisation

6.0.2.1 Experimental Setup

Figure 6.3 illustrates the experimental configuration used to characterise the pressure sensor. The FBG was interrogated using the Smart Fibres FBG interrogator and the FSI sensors were interrogated using an in-house designed and built RRI interrogator [120] from Cranfield University, operating at a bandwidth of 1 kHz. The pressure reference and pressure controller were the same as used in Chapter 5. The experiment was performed in a stable thermal environment, maintained at $22^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$.

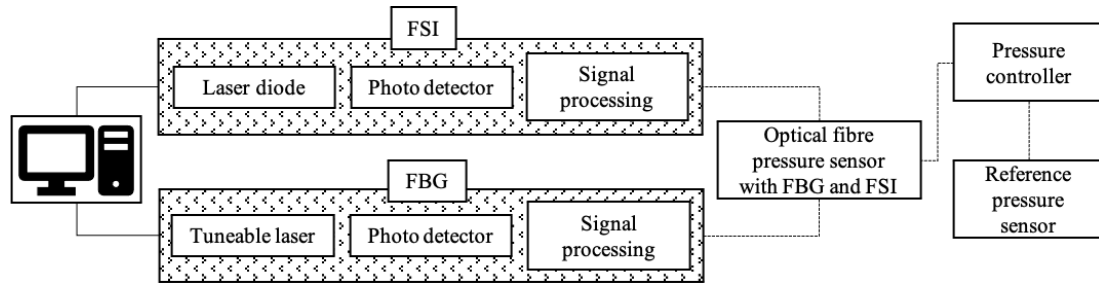


Figure 6.3: Schematic diagram of experimental configuration used to characterise the pressure sensor.

Figure 6.4 shows a typical pressure run that was applied to the sensor, with a step wise fashion up to 35 kPa, followed by a dynamic profile to characterise hysteresis.

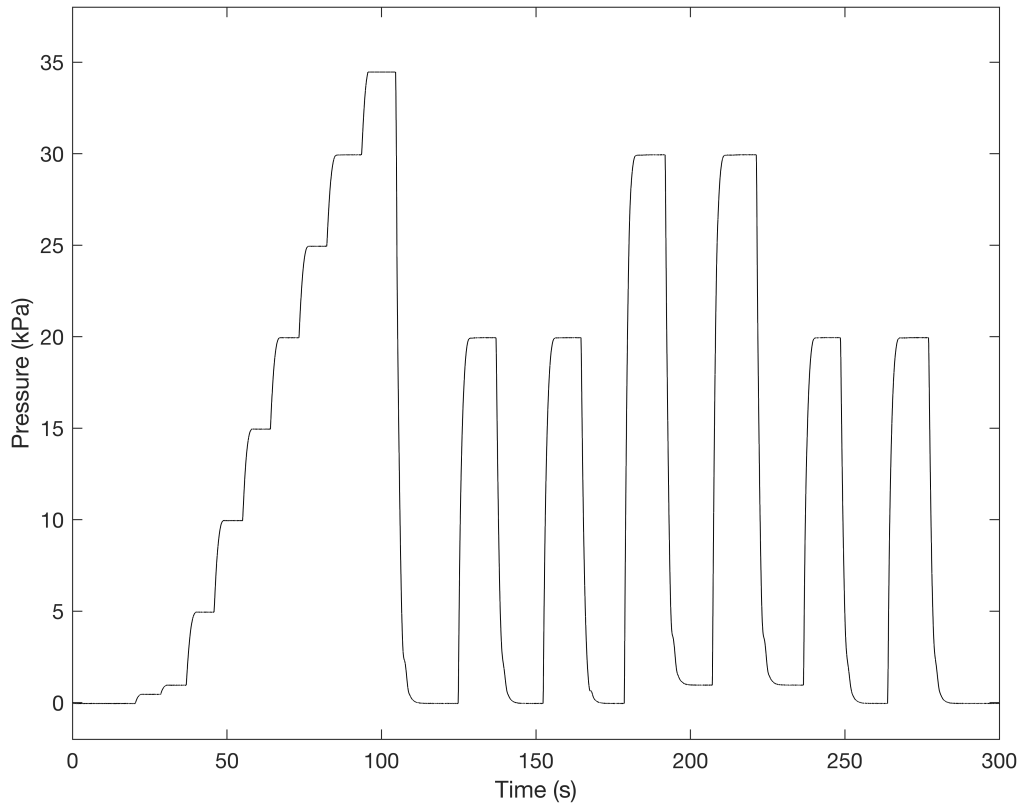


Figure 6.4: Typical pressure profile applied to the pressure sensors containing FBG and FSI sensors.

6.0.2.2 Predicted Pressure Sensitivity

In order to establish the theoretical pressure sensitivities achievable using each of the optical fibre-based approaches for the proposed sensor, the output from the FE analysis was combined with the strain sensitivities provided in Figure 6.2 and Chapter 2, Sections 2.3 and 2.4.3. The FE results over the sections of the diaphragm corresponding to the locations of the FBG and FS 1 were averaged over 4 mm and 10 mm lengths to reflect the measurements that would be made by the sensors. Likewise, the FE predictions for the strains at the section at the edge of the diaphragm, corresponding to the location of FS 2, were averaged over a length of 5.75 mm, as illustrated in Figure 6.2. The predicted strain

sensitivities along with the corresponding pressure sensitivities are detailed in Table 6.1.

Table 6.1: Strain and predicted pressure sensitivities of the GFRP-mounted FBG and FSI sensor elements

	Strain Sensitivity	Predicted Pressure Sensitivity
FBG (4 mm)	1.2 pm/ $\mu\epsilon$	45.6 pm/kPa
FS 1 (10 mm)	0.096 rad/ $\mu\epsilon$	2.77 rad/kPa
FS 2 (over 10 mm)	(0.096 rad/ $\mu\epsilon$)	/
FS 2 (over 5.75 mm)	0.055 rad/ $\mu\epsilon$	-1.21 rad/kPa
FS 3 (35 mm)	0.335 rad/ $\mu\epsilon$	/

6.0.2.3 Results and Discussions

To facilitate the comparison of the performances of the FBG and the FSI sensors, and to correlate their responses with the output from the FE model, their responses have been converted to strain using Equations (2.3) and (2.6), detailed in Chapter 2. The data obtained from a series of pressure cycles and averaged from three separate experiments, are shown in Figure 6.5. The pressure measurement provided by the Texense PDif pressure sensor is shown on the right-hand y-axis, while the strains measured by each of the fibre sensor elements are shown on the left-hand y-axis. As described previously, FS 3 does not experience any strain, as this segment is not bonded to the diaphragm. FS 2 exhibits negative strain and FS 1 positive strain, matching the output from the FE model shown in Figure 6.2 and [87], with the FBG sensor exhibiting more strain than FS 1.

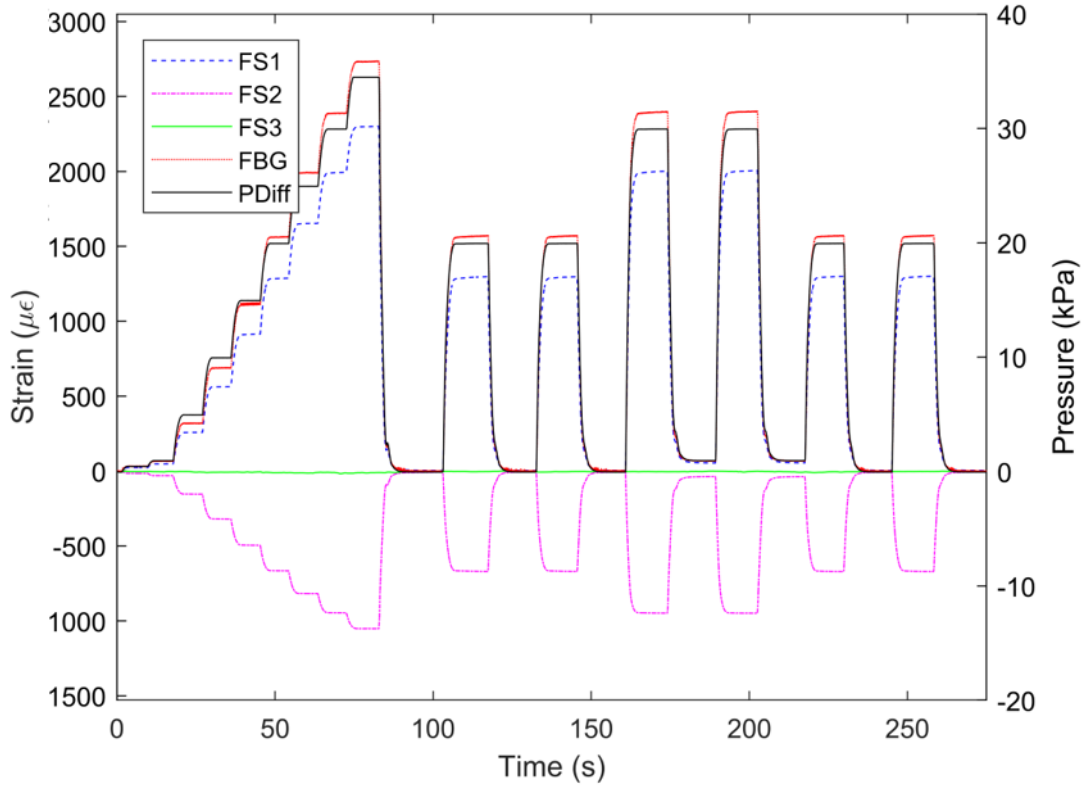


Figure 6.5: Measurements obtained from the optical fibre sensors and the electrical pressure sensor (Texense, PDiff) during a series of pressure cycles. Results averaged over three runs. The optical fibre sensor responses are plotted in terms of the strain, facilitating comparison of the sensor responses. Left-hand axis: strain measured by optical fibre sensors. Right-hand axis: output from the electrical pressure sensor.

The calibration curves presented in Figure 6.6 show the pressure sensitivities of the optical fibre sensors. The wavelength shift exhibited by the FBG sensor at each pressure step is plotted against applied pressure on the right-hand y-axis, while the phase changes of FS 1 and FS 2 are plotted on the left-hand y-axis. The optical fibre sensors all show linear responses. The FBG based sensor exhibits a sensitivity of 95 ± 4.4 pm/kPa, while FS 1 and FS 2 exhibit sensitivities of 6.3 ± 0.2 rad/kPa and -2.6 ± 0.3 rad/kPa, respectively. The pressure sensitivities of the sensors are summarised in Table 6.2. The FSI resolutions are based on Equation and experimental sensitivities. The FBG resolutions are based on

the 1 pm interrogator resolution.

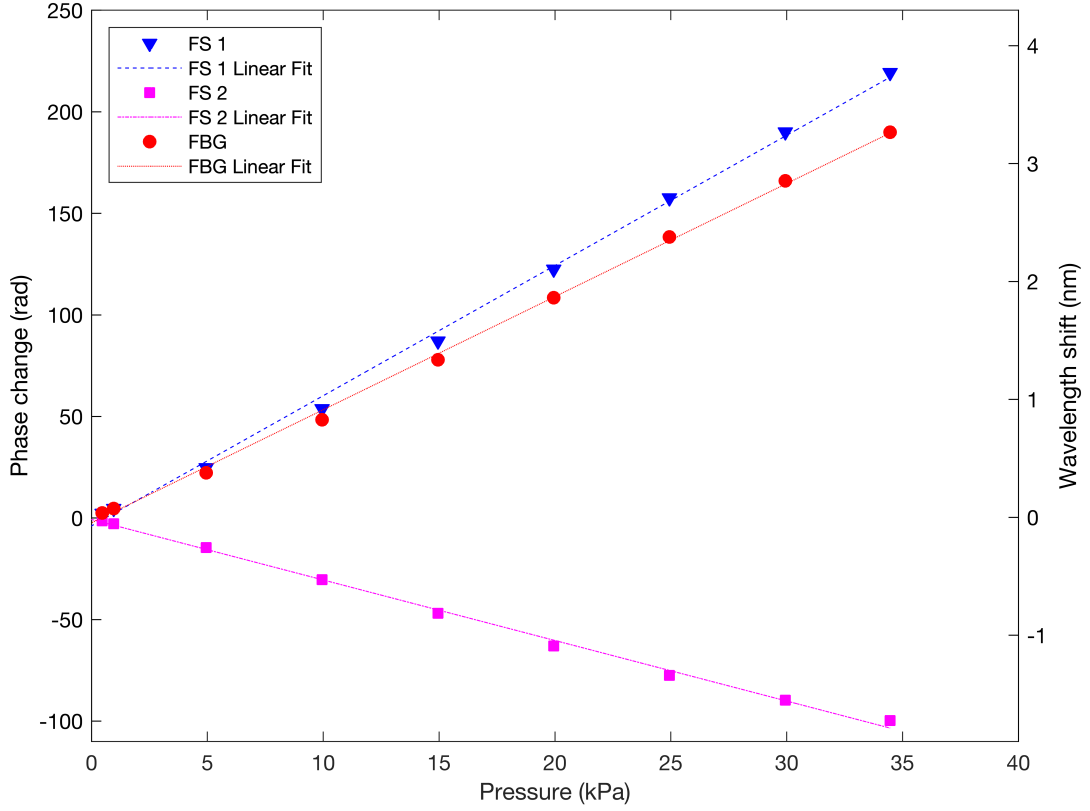


Figure 6.6: Pressure induced phase change and wavelength shift of FSI segments and FBG sensor with linear fits. Left-hand axis: Blue triangle ($\blacktriangledown$) represents FS 1 with a linear fit $R^2 = 0.9972$ and pink square ($\blacksquare$) represents FS 2 with a linear fit $R^2 = 0.9973$. Right-hand axis: Red circle ($\bullet$) represents the FBG with a linear fit $R^2 = 0.9981$. The linear coefficients are reported in the Table 6.2.

Qualitatively, the form of the data obtained from each of the optical fibre sensors are in agreement with the FE output. The converted strain-pressure responses indicate that FS 1 experienced a lower strain than that experienced by the FBG, due to the integration of the strain over a gauge length that has a large strain gradient. The response of FS 2 is of opposite sign, as expected from the compressive strain at the edge of the diaphragm predicted by the FE results shown in Figure 6.2. By combining Equation (3.7) with the

measured sensitivities with the addition of the z formula from Section 3.3.4.2, it can be shown that the centre cores of the FBG and FSI optical fibres are located approximately $380\text{ }\mu\text{m}$ and $310\text{ }\mu\text{m}$ above the surface of the diaphragm, respectively. This suggests that the glue line has a thickness of about $250\text{ }\mu\text{m}$, taking into account the $250\text{ }\mu\text{m}$ coating diameter of the fibre containing the FBG and the $125\text{ }\mu\text{m}$ cladding diameter of the fibre containing the FSI sensors, as the coating was removed over the whole section from first to last reflector. This is consistent with the measurements made from cross sections of similar fibre-bonded diaphragms shown in Chapter 4.

Table 6.2: Optical fibre sensor pressure and temperature linear coefficients and resolutions determined from the experimental data

	Pressure Coefficient K_P	Pressure Resolution (Pa)	Temperature Coefficient K_T	Temperature Resolution ($^{\circ}\text{C}$)
FBG	$95 \pm 4.4 \text{ pm/kPa}$	$10 \text{ } 43 \pm 0.1 \text{ pm}/^{\circ}\text{C}$	0.23	
FS 1	$6.3 \pm 0.2 \text{ rad/kPa}$	3.1×10^{-3}	$3.6 \pm 0.1 \text{ rad}/^{\circ}\text{C}$	5.3×10^{-3}
FS 2	$-2.6 \pm 0.3 \text{ rad/kPa}$	-7.3×10^{-3}	$2.5 \pm 0.1 \text{ rad}/^{\circ}\text{C}$	7.6×10^{-3}
FS 3	/	/	$3.7 \pm 0.1 \text{ rad}/^{\circ}\text{C}$	1.8×10^{-2}

6.0.3 Thermal Characterisation

6.0.3.1 Experimental Setup

Figure 6.7 illustrates the experimental configuration used to characterise the thermal response of the sensor. The two optical fibre sensor interrogators detailed in Section 6.0.2 were used. The pressure sensor was placed in a Vötsch VTM 7004 oven and two PT100 thermocouples recorded the temperature on the surface of the aluminium support using a PicoLog [121] of accuracy $\pm 0.03^\circ\text{C}$. The thermocouples were terminated with polyimide thin film and were secured to the support structure using polyimide tape. The temperature of the oven was varied from $37 \pm 0.01^\circ\text{C}$ to $82 \pm 0.01^\circ\text{C}$.

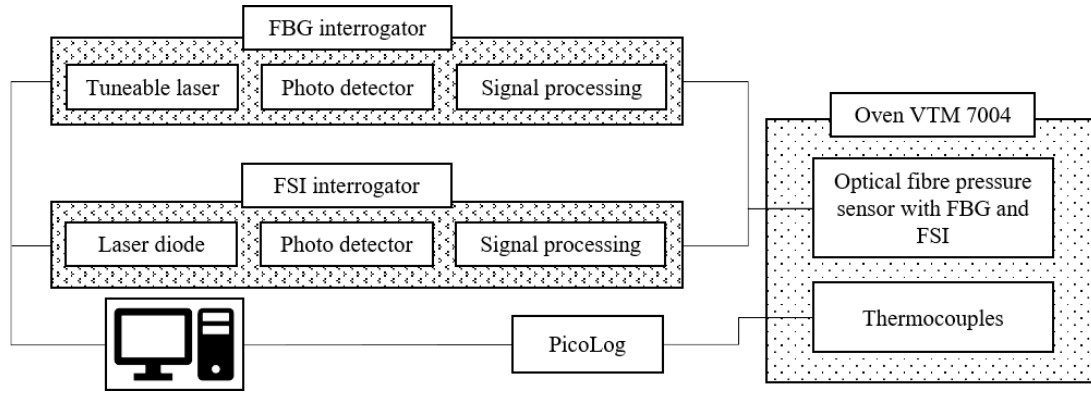


Figure 6.7: Schematic diagram of the experiment set up used to characterise the thermal responses of the sensor.

6.0.3.2 Results and Discussions

Figure 6.8 (a) shows the thermal responses of the thermocouple and FBG sensor while the responses of the three FSI sensors are shown in Figure 6.8 (b) as the temperature was increased in steps. Three similar experiments were ran during three separate days and Figure 6.8 shows an average of the three responses. The data shown in Figure 6.8 (a) was used to produce a temperature calibration for the FBG based pressure sensor, shown in Figure 6.9 and reported in Table 6.2. The data shown in Figure 6.8 (b) was used for FS 1, FS 2 and FS 3. Figure 6.8 (b) highlights the lower response of FS 2 at the edge of the diaphragm, as well as the close relationship of the thermal responses of FS 1 and

FS 3, even though FS 1 is fully bonded to the diaphragm and 3.5 times shorter than the unbonded FS 3. FS 1 appears to have a slight thermal lag in comparison with the free segment, which can be explained by the thermal inertia of the bonded GFRP diaphragm and aluminium support.

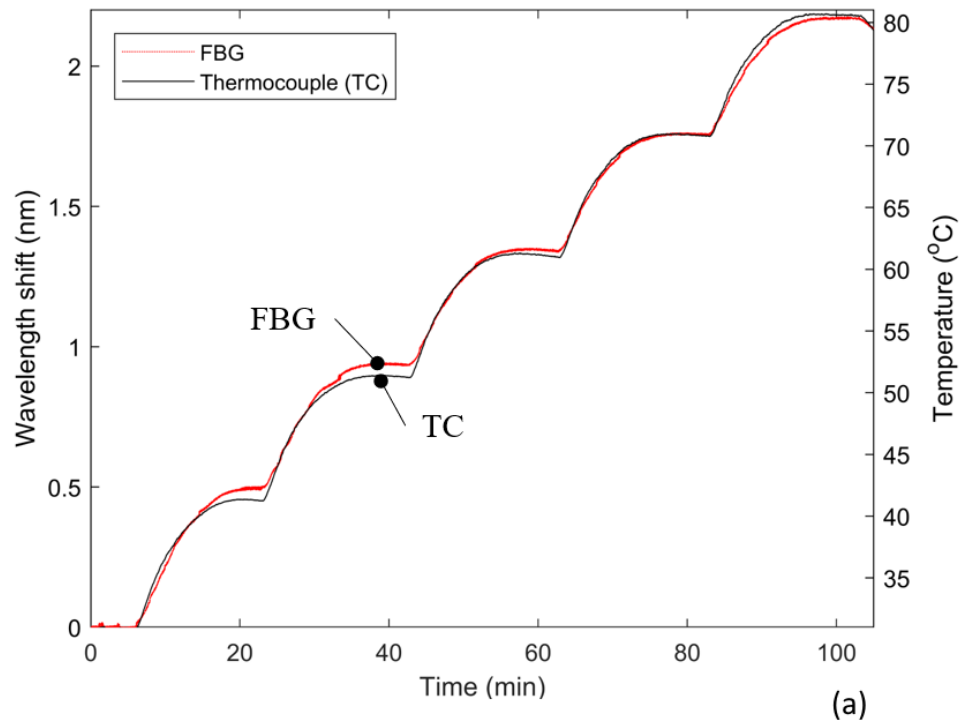
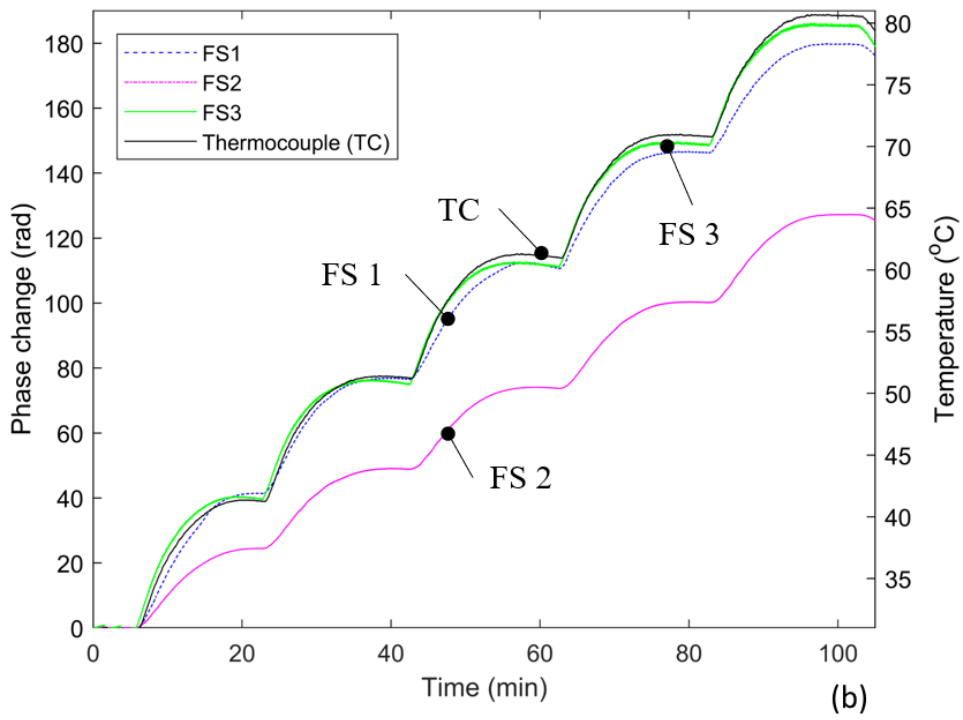


Figure 6.8: Optical fibre sensors and thermocouple raw responses plotted as a function of time, averaged from three runs. (a) FBG and thermocouple and (b) FS 1, FS 2, FS 3 and thermocouple (TC).

The calibration curves in Figure 6.9 show the temperature sensitivities of each optical sensor, determined by correlating the optical measurements with those from the thermocouples, using the data presented in Figure 6.8. The FBG wavelength shift (●) is shown on the right-hand y-axis and the FS phase changes are shown on the left-hand y-axis. It is clear that the sensitivities of both FS 1 (▼) and FS 3 (◆) are similar and that FS 2 (■) is lower. All sensors exhibit linear responses. The FBG exhibits a sensitivity of 43 ± 0.1 pm/°C, while the sensitivities of the other gauges were recorded as; FS 1 3.6 ± 0.15 rad/°C, FS 2 2.5 ± 0.15 rad/°C and FS 3 3.7 ± 0.15 rad/°C. Each of these sensitivity values is reported in Table 6.2.

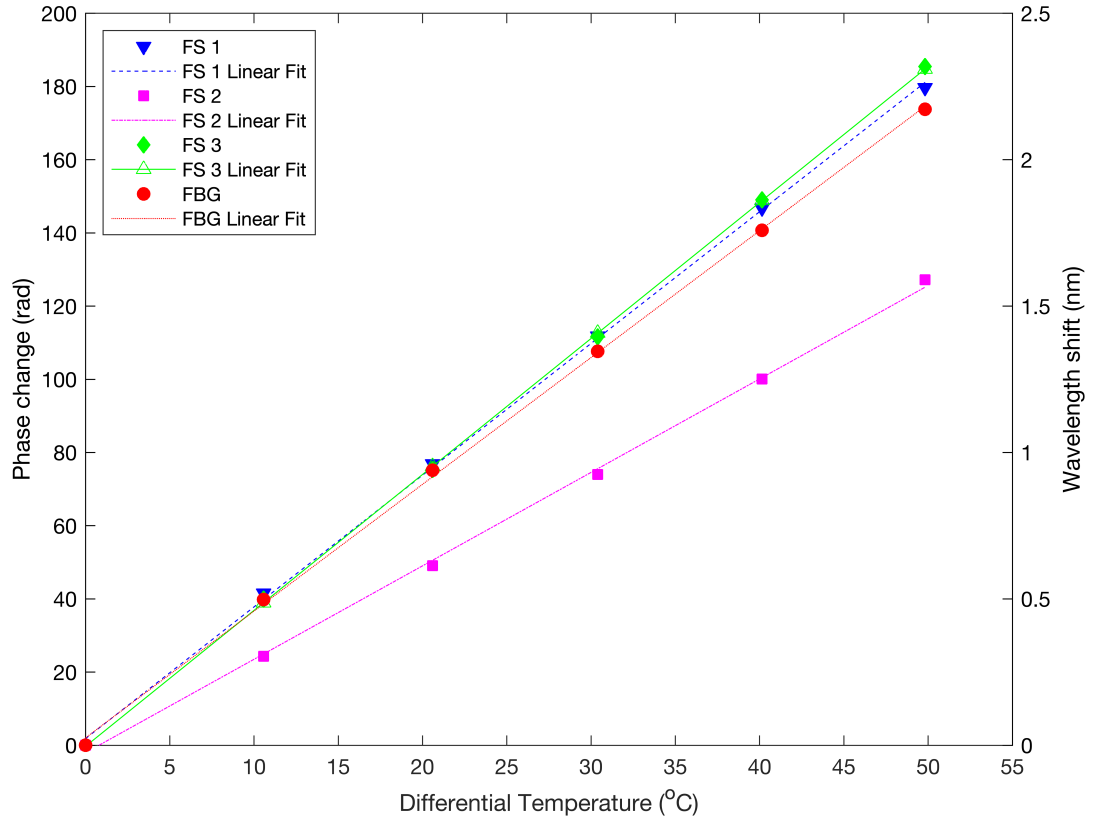


Figure 6.9: Thermal phase change and wavelength shift of FSI segments and FBG sensor with linear fits. Left-hand axis: Blue triangle ($\blacktriangledown$) represents FS 1 with a linear fit $R^2 = 0.9992$, pink square ($\blacksquare$) represents FS 2 with a linear fit $R^2 = 0.9969$ and green lozenge ($\blacklozenge$) represents the FS 3 with a linear fit $R^2 = 0.9999$. Right-hand axis: Red circle ($\bullet$) represents the FBG with a linear fit $R^2 = 0.9992$. The linear coefficients are reported in the Table 6.2.

The temperature sensitivities of FS 1, FS 2 and of the FBG are influenced by the thermal expansion of the sensor structure, as they are bonded to the GFRP diaphragm, which, in turn, is also mounted on the aluminium support. Equation 2.7 shows that the thermal sensitivity of a free, unmounted, optical fibre is dominated by the thermo-optically-induced refractive index change, with the thermal expansion component being a factor of 10 smaller. However, in the sensor configuration described here, the thermal expansion is

also influenced by the diaphragm and the support structure assembly. The challenge here is that, while the coefficient of thermal expansion (CTE) of aluminium is well known to be $23 \times 10^{-6}/^{\circ}\text{C}$ [122], the CTE of GFRP depends on many factors, such as fibre resin ratio, fibre orientation, void volume, and can vary from 1 to $20 \times 10^{-6}/^{\circ}\text{C}$ [123, 124, 125].

In order to understand issues concerning the design of the sensor, additional experiments were performed to investigate the influence of material selection on the thermal response. The investigation involved the comparison of the thermal responses of an unmounted, free, FBG with those of FBGs bonded to an unsupported diaphragm and to a diaphragm that was mounted in the aluminium support. The investigation is described in Chapter 7, Section 7.3. The unmounted FBG and the encapsulated FBG exhibit similar sensitivities of $11 \pm 0.05 \text{ pm}/^{\circ}\text{C}$, which is the thermal sensitivity of FBG sensors. The GFRP-bonded FBG shows a sensitivity of $16 \pm 0.07 \text{ pm}/^{\circ}\text{C}$, which increased to $43 \pm 0.1 \text{ pm}/^{\circ}\text{C}$ when the diaphragm is bonded to the aluminium support, corresponding to the composite CTE in the order of $5 \times 10^{-6}/^{\circ}\text{C}$, and aluminium of $23 \times 10^{-6}/^{\circ}\text{C}$. This correlates with the sensitivity determined in Section 6.0.3.2.

By replacing the optical fibre's CTE with that of aluminium in Equation (2.4), the theoretical values are seen to be in alignment with the experimental results and are presented in Table 6.3. The experimentally determined thermal sensitivity of the optical fibre bonded to the GFRP diaphragm suggests that the CTE of the diaphragm is in the order of $5 \times 10^{-6}/^{\circ}\text{C}$. In this configuration, the thermal properties of the aluminium appear to dominate over those associated with the diaphragm or adhesive.

Table 6.3: FBG thermal sensitivities for bare and specimen-mounted fibre

	α ($\mu\epsilon/^\circ\text{C}$)	Theoretical (pm/ $^\circ\text{C}$)	Experimental (pm/ $^\circ\text{C}$)
SMF-28	0.55	11	11 ± 0.05
GFRP	1 to 20	10 to 40	16 ± 0.07
Aluminium	23	46	43 ± 0.1

The thermal sensitivities of FS 1 and FS 2 can be calculated using the parameters shown in Table 6.3. By using the value of α for aluminium in Equation 2.7, we obtain a sensitivity of $3.6 \text{ rad}/^\circ\text{C}$, which correlates well with the experimental measurement of FS 1, described in Section 6.0.3.2. The predicted and measured values for all FSI are summarised in Table 6.4. FS 2 exhibits a lower temperature dependence, which can be explained by considering the mounting of the fibre segment, which is partly bonded to the free-standing part of the diaphragm and partly to the section of diaphragm that is bonded to the aluminium support. Thus, a 5.8 mm long portion on the right hand side of FS 2 in Figure 6.1 is in similar condition to that of FS 1, so that it can be assumed that this portion experiences the thermal expansion of the aluminium support, giving a thermal sensitivity of $2.1 \text{ rad}/^\circ\text{C}$. The 4.2 mm long section on the right hand side of FS 2 is influenced by both the GFRP and aluminium, which counteract each other's thermal expansion. The thermal sensitivity of the part of this segment is thus calculated to be $0.77 \text{ rad}/^\circ\text{C}$. A total sensitivity of $2.8 \text{ rad}/^\circ\text{C}$ is then predicted for FS 2, assuming that the reflectors forming FS 1 are equally spaced about the centre of the diaphragm. This differs from the experimentally determined value by 12%, which can be explained by the uncertainty of the exact position of the segment on the diaphragm. The experimentally measured sensitivity of FS 2 suggests that the segment is bounded to a 4 mm long free centre section of the diaphragm rather than the expected 5.8 mm, which may reflect the accuracy with which the absolute locations of the FSI reflectors within the fibre were known.

Table 6.4: Predicted and measured FSI thermal sensitivities

	FS 1	FS 2	FS 3
Predicted (rad/°C)	3.6	2.8	3.2
Measured (rad/°C)	3.6±0.1	2.5±0.1	3.7±0.1

6.0.4 Pressure - Temperature Cross-Sensitivity

The existence of regions on the diaphragm that show similar thermal sensitivities but pressure sensitivities of opposite sign suggests the potential for the discrimination of the temperature and pressure responses of the sensor [87, 100, 91, 87] by solving a pair of linear equations using a matrix operation. In general, when considering the performance of sensors capable of discriminating between the influences of two measurands, an analysis of the conditioning of the matrix of coefficients is undertaken, with the condition number providing an indicator of the sensitivity of the solutions to errors in the data [126]. This may be followed by an analysis of the error propagation and an estimate of the uncertainties in the calculated values of the measurands [126]. The temperature and pressure discrimination can also be achieved by decoupling their frequencies [127].

6.0.4.1 Experimental Setup

The sensor shown in Figure 6.1 was placed in the oven and pressure applied using the experimental set up shown in Figure 6.10, which combines both the pressure and temperature set up described in Sections 6.0.2.1 and 6.0.3.1. While the temperature was varied from ambient to up to 82 °C, the pressure was applied according to the cycles shown in Figure 6.5. The temperature of the oven was stabilised at 37±0.01 °C, 62±0.01 °C and 82±0.01 °C.

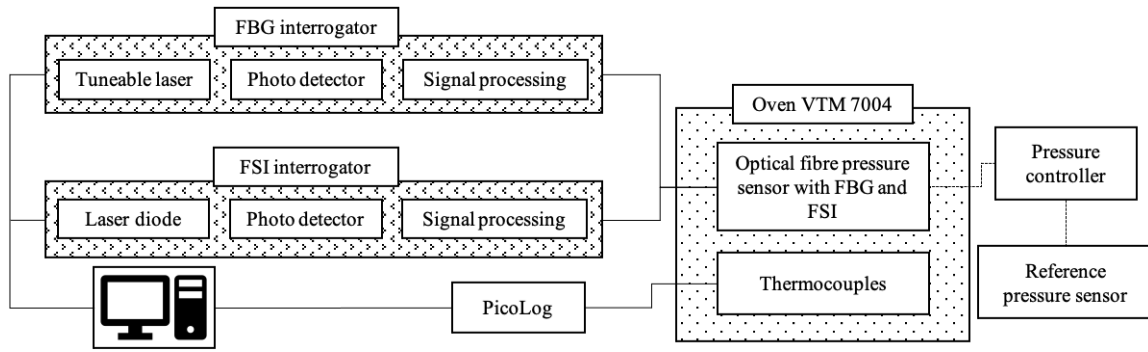
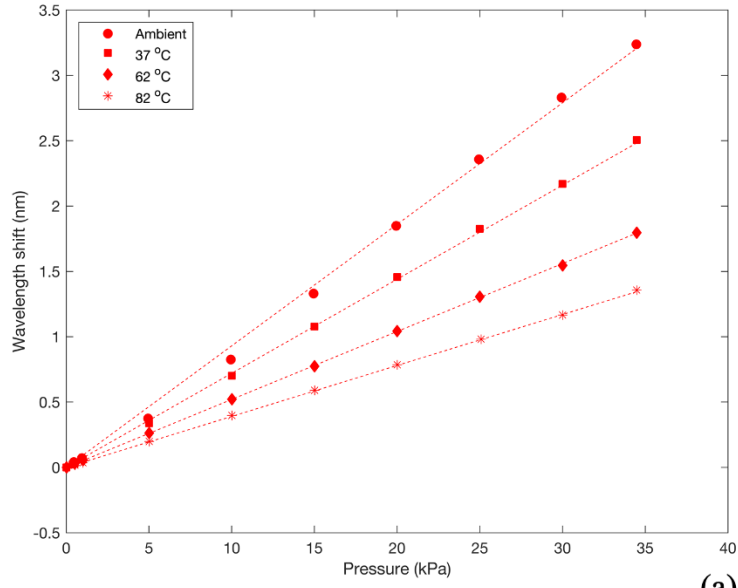


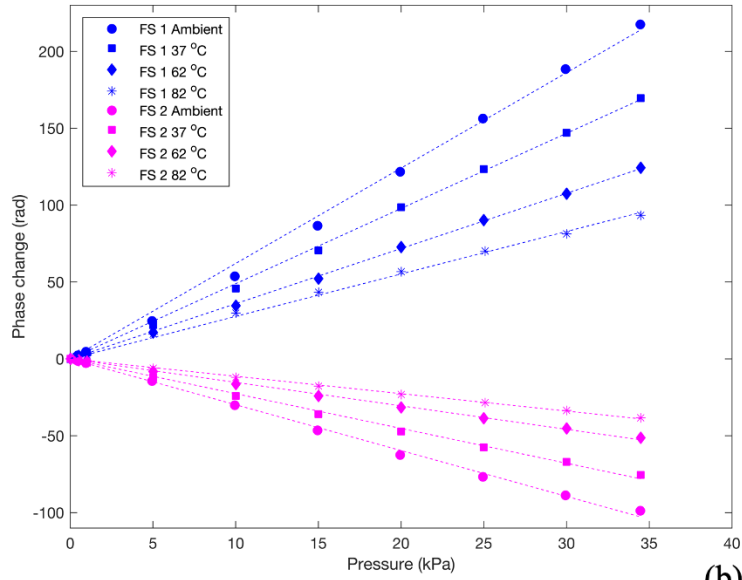
Figure 6.10: Schematic diagram of the experiment set up used to characterise the pressure temperature cross sensitivity response of the system.

6.0.4.2 Results and Discussions

The results of changing the pressure in the chamber in step-wise fashion are shown in Figure 6.11.



(a)



(b)

Figure 6.11: Pressure responses at ambient (●) 37°C (■), 62°C (◆) and 82°C (*) for (a) the FBG sensor and (b) the FS 1 sensor in blue (positive phase change) and FS 2 sensor in pink (negative phase change) with associated linear fit. FBG: ambient, $R^2 = 0.9991$; 37°C, $R^2 = 0.9999$; 62°C, $R^2 = 1$; 82°C, $R^2 = 1$. FS 1: ambient, $R^2 = 0.9987$; 37°C, $R^2 = 0.9997$; 62°C, $R^2 = 0.9998$; 82°C, $R^2 = 0.9992$. FS 2: ambient, $R^2 = 0.9989$; 37°C, $R^2 = 0.9989$; 62°C, $R^2 = 0.9992$; 82°C, $R^2 = 0.9995$.

The temperature greatly influences the pressure response of the sensor, showing a decrease in sensitivity when the temperature increases. The opposite was observed in [91], where the increased temperature increased the pressure sensitivity. The pressure sensitivity at each temperature is detailed in Table 6.5. As seen in Figure 6.11 and Table 6.3, the thermal expansion of the aluminium support acts to mechanically load the diaphragm, which stiffens the sensor and reduces the deformation of the diaphragm in response to pressure changes. Figure 6.12 shows the FBG wavelength change over the various temperature and the overall pressure trend showing the reduction of pressure sensitivity with increasing temperature.

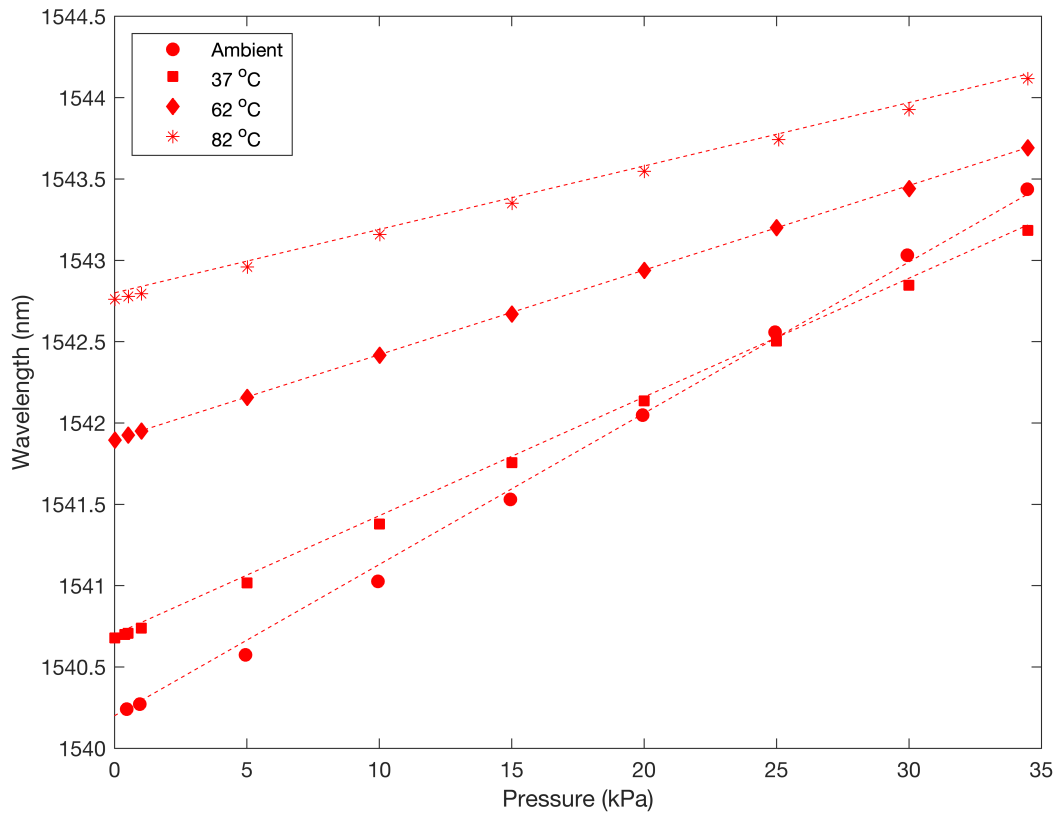


Figure 6.12: Pressure responses at ambient (●) 37°C (■), 62°C (◆) and 82°C (*) for the FBG sensor with initial wavelengths.

Table 6.5: Pressure sensitivities measured at different temperatures, averaged over three experimental runs

	Ambient	37±0.01 °C	62±0.01 °C	82±0.01 °C
FBG (pm/kPa)	95±4.4	73±3.3	52±1.6	39 ±2.3
FS 1 (rad/kPa)	6.3±0.2	4.9±0.2	3.6±0.2	2.7±0.2
FS 2 (rad/kPa)	-2.6±0.3	-2.3±0.3	-1.5±0.3	-1.1±0.3

The influence of temperature on the pressure response is illustrated clearly by comparing the strains experienced by the optical fibre sensors during step-wise changes in pressure, carried out at two constant temperatures, ambient and 80°, as shown in Figure 6.13.

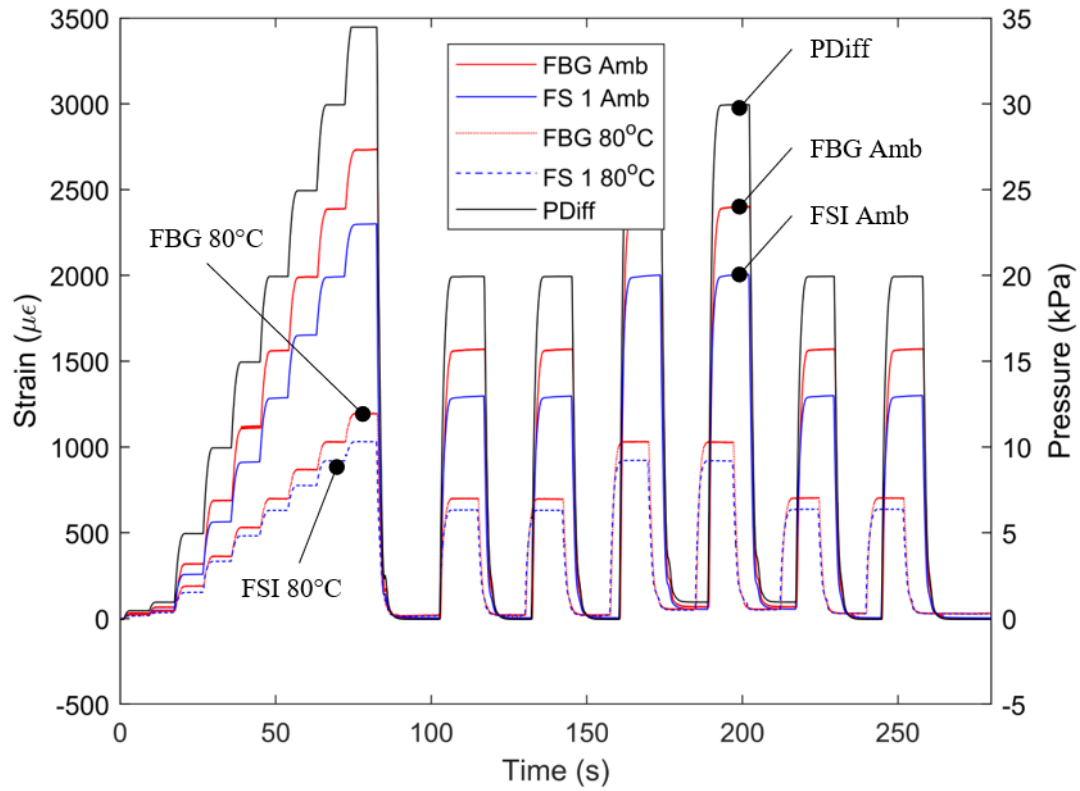


Figure 6.13: Left axis: Comparison of FS 1 and FBG sensors at ambient and 80°C with applied pressure showing the reduced pressure sensitivity at elevated temperature. Right axis: PDiff reference electronic pressure sensor. Note that the timing of the pressure steps in the two experiments differed slightly, which is the cause of the apparent offset between the time series.

Furthermore, it has been observed that changes in temperature during a measurement will change the baseline in a nonlinear fashion, compromising significantly the measurement even when an independent measurement of temperature is provided by a thermocouple. Further, the cross sensitivity means that it would not be possible to ignore the influence of temperature even in dynamic measurements, where the temperature varies on a different timescale to the pressure. The use of higher order compensation techniques to take into account the cross sensitivity to measurands was reported in [128], where a Taylor expansion was used to generate simultaneous equations taking into account the cross sensitivity. This approach is inappropriate for use here due to the large pressure and

temperature excursions and the nonlinearity of the cross sensitivity.

The results highlight the importance of the selection of the material used to package the sensor, especially when the sensor is to operate in an environment subject to temperature variations. While this is not a new observation, the analysis shown here identifies the origin of the effects and highlights the importance of undertaking a full experimental study of cross sensitivity issues when designing optical fibre based sensors. In the design of electrical pressure sensors where the pressure induced deformation of diaphragm is monitored using piezo-resistive sensors, matching the thermal expansion of the support structure and the diaphragm is noted to be a means for minimising thermo-mechanical influences on the pressure response [129, 5]. It is informative to consider a sensor of the type shown in Figure 6.1, in which the support structure should be thermally balanced with the diaphragm, thus removing the thermal cross-sensitivity.

6.0.4.3 Estimation of a Pressure-Temperature Discrimination of an All-GFRP Sensor

The analysis presented in Chapter 7, Section 7.3, shows that the thermal expansion of the aluminium support structure, as well as enhancing the thermal sensitivity, caused the pressure sensitivity to become temperature dependent. It is informative to consider a sensor in which the support structure is also formed from GFRP. In this case, the thermal characteristics would be the same as those of the diaphragm. A housing with a CTE value of $5 \times 10^{-6}/^{\circ}\text{C}$ would greatly alleviate the influence of temperature changes, although other factors such as specific heat capacity will also influence the performance in dynamic thermal environments. For this hypothetical sensor, the thermal responses of fibre segments FS 1 and FS 2 can be recalculated using the CTE of the GFRP reported in Section 6.0.3.2 at $5 \times 10^{-6}/^{\circ}\text{C}$. The sensor's response can then be expressed in a matrix that has the coefficients indicated in Table 6.6, with matrix inversion used to discriminate the two parameters.

Table 6.6: FS 1 and FS 2 pressure and temperature coefficients determined for a hypothetical sensor, where the support structure is made from the same material as the diaphragm to reduce thermal dependence of the pressure sensitivity

	Pressure Coefficient K_P	Temperature Coefficient K_T
FS 1	6.3 rad/kPa	1.8 rad/°C
FS 2	-2.6 rad/kPa	1.8 rad/°C

$$(\phi)_{FS1} \phi_{FS2} = K_{P,FS1} K_{T,FS1} K_{P,FS2} K_{T,FS2} (P) T \quad (6.1)$$

The condition number of the matrix gives a measure of the performance of the discrimination between the two measurands, with the uncertainties in the separation of the parameters being derived from the precision in the measurement of the phase change in the interferometers and the determination of the matrix components [126]. The condition number of the matrix for this sensor is 2.97, suggesting that the matrix is well-conditioned, with the error in the measurements not impacting significantly the discrimination of the two parameters. Jin *et al.* [126] reported that the maximum errors caused by temperature and strain errors can be expressed by Equation (6.2) and Equation (6.3) respectively, while the matrix errors are expressed by Equation (6.4) and Equation (6.5). Following this approach for the pressure sensor reported here, the errors in the pressure and temperature measurements are given by:

$$|\delta T| \leq \frac{|K_{P,FS2}| |\delta \phi_{FS1}| + |K_{P,FS1}| |\delta \phi_{FS2}|}{|\Delta|} \quad (6.2)$$

$$|\delta P| \leq \frac{|K_{T,FS2}| |\delta \phi_{FS1}| + |K_{T,FS1}| |\delta \phi_{FS2}|}{|\Delta|} \quad (6.3)$$

$$\left| \frac{\delta T}{T} \right| \approx \frac{|K_{T,FS1} K_{P,FS2}| + |K_{P,FS1} K_{T,FS2}| + 2 |P/T| |K_{P,FS1} K_{P,FS2}|}{|\Delta|} |\gamma| \quad (6.4)$$

$$\left| \frac{\delta P}{P} \right| \approx \frac{\left| K_{P,FS1} K_{T,FS2} \right| + \left| K_{T,FS1} K_{P,FS2} \right| + 2 \left| T/P \right| \left| K_{T,FS1} K_{T,FS2} \right|}{\left| \Delta \right|} \left| \gamma \right| \quad (6.5)$$

With $\Delta = \left| K_{P,FS1} K_{T,FS2} - K_{T,FS1} K_{P,FS2} \right|$ and γ being the maximum relative errors in all elements of the characteristic matrix [126]. The errors in pressure due to measurements and matrix inversion are 138 Pa and 0.9 Pa, respectively, and 0.23 (°C) and 2×10^{-3} (°C), respectively, for temperature. The calculated errors are summarised in Table (6.7).

Table 6.7: Pressure and Temperature performances with errors due to measurements and matrix inverse

	Matrix Errors	Measurement Errors
δP (Pa)	138	0.9
δT (°C)	0.23	2×10^{-3}

6.0.5 Performance Comparison

The general noise behaviours of the FBG, FS 1 and the electrical pressure sensor are compared in Figure 6.14. At a bandwidth of 250 Hz, the FBG sensor exhibits noise with a standard deviation of $0.75 \mu\epsilon$, while FSI segment FS 1 achieves a noise standard deviation of $0.04 \mu\epsilon$ over a much higher bandwidth of 1 kHz. When converted to pressure using the respective calibration curves from Figure 6.6, the standard deviations correspond to 9.5 Pa for the FBG and 0.61 Pa for FS 1, where the FS 1 sensor exceeds the pressure resolution of the electrical pressure sensor, which has a noise standard deviation of 1.3 Pa at 250 Hz bandwidth. These values are summarised in Table 6.8.

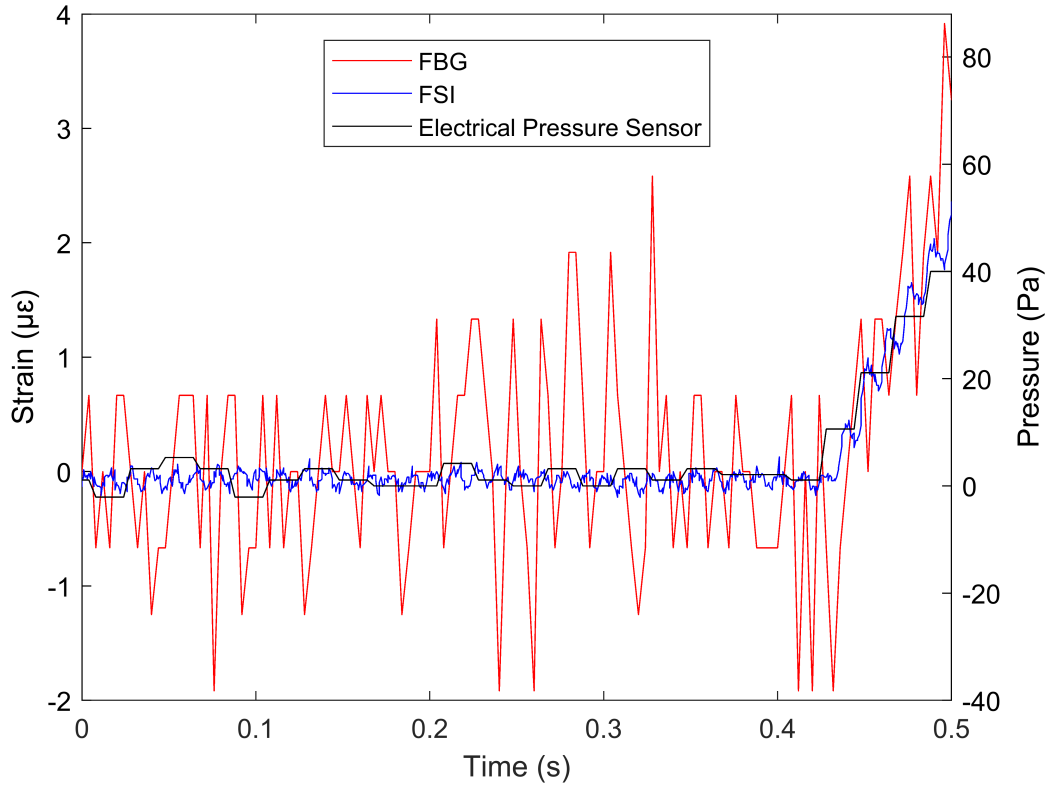


Figure 6.14: Change in pressure showing the fast response of each sensor. The wave behaviour appearing in in the FS 1 sensor data can be directly traced back to the pressure pump use. Here, the same dataset as used in Figure 6.5 was used.

Table 6.8: Comparison of the noise performance of the investigated sensing technologies

	FBG	FSI	Electrical
Bandwidth (Hz)	250	1000	250
Noise ($\mu\epsilon$)	0.75	0.04	-
Noise (Pa)	10.5	0.61	1.3

During the recording time of Figure 6.14, the pressure was maintained at 0 Pa, followed by the a ramp to 500 Pa. The response to the start of the increase in pressure can be located on the later part of the time series, at approximately 0.42 s. It can be seen that only FS 1 is able to resolve the pressure wave at 80 Hz that is a result of the pumping

action of the pressurisation system. Even though the FSI sensor has the higher inherent strain response due to the longer gauge length used, these results confirm that the much higher resolution of the FSI interrogation approach results in an overall increase in the pressure sensitivity of the system by more than 15 times.

The fundamental measurement principles of both FSI and FBG sensors are based on the same physical glass properties of optical fibres [43] in response to strain and temperature. Therefore, for similar physical placement of the sensing element on the diaphragm, the repeatability of the measurement will depend solely on the performance of the interrogators, which for FBG interrogators is documented by the interrogation system manufacturers and for FSI was discussed in [120, 41]. Furthermore, as can be seen in Figure 6.2, the existence of strong strain gradients [130] across the diaphragm makes the exact placement of the sensing element on the diaphragm important, potentially affecting reproducibility. Here, for FBGs, the effect of strain gradients can potentially lead to distorted readings between different sensors, depending on the exact location of the FBG and on the peak finding algorithm used within the interrogator. However, for FSI, where the interferometric measurement principle guarantees an exact integration of the strain within the sensing region, strain gradients are not expected to significantly influence on the fidelity of the measurement, therefore making the exact placement of the sensing region less critical.

6.1 Conclusion

The performance of a pressure sensor that relies upon the optical fibre based measurement of the strain induced by the deflection of a GFRP diaphragm has been investigated. Two approaches to the measurement of strain have been compared; the well-established FBG approach and the new interferometric technique. At ambient temperature, the reported pressure sensitivity achieved using an FBG bonded to the centre of the diaphragm was 95 ± 4.4 pm/kPa with the corresponding sensitivity of an FSI segment, with the reflectors

spaced approximately equally about the centre of the diaphragm, being 6.3 ± 0.3 rad/kPa. Taking into consideration the noise behaviour of the two interrogation approaches, their pressure resolutions exceed the design specification target of 20 Pa, with values of 10.5 Pa and 0.61 Pa, respectively. Exploiting the characteristics of the diaphragm revealed in an FE study, where an annulus of compressive strain is revealed near the outer circumference of the free area of the diaphragm, a fibre segment interferometer was arranged to measure the positive strain over the central region of the diaphragm, and another to measure the compression at the edge. The position of the two FSI sensors and their experimental results show the agreement with FE model from the nonlinear analysis, which predicted the edge condition. With increasing temperature, the measured pressure sensitivities were observed to decrease due to the high CTE of the aluminium support, which acted to tension the diaphragm, increasing its stiffness. This shows the importance of the material selection for all parts of the assembly. It is suggested that the response of these FSI segments can be used for the separation of the temperature and pressure responses of the diaphragm with very low errors when used with the same material throughout.

6.2 Strain Measurement Over the Diaphragm Diameter Using FSI

A similar pressure characterisation as presented in Section 6.0.2 was conducted in order to understand the effect of a single FSI sensor over the diaphragm diameter, knowing the edge condition from the FE model and the effects such strain gradient can have on FBG sensors.

6.2.1 Pressure Sensor Material

In this experiment, the aperture was 11.5 mm in diameter with the disc consisting of 3 GFRP plies, of thickness 0.12 mm, as shown in Figure 6.15 (a). As per previous sensor described in Section 6.0.1, the disc was made using the improved manufacturing method

with the groove filled and optical fibres containing FBG and FSI bonded afterwards. Additional resin was also added in the mould gap to avoid porosity in the diaphragm.

A single FSI segment of 30 mm was bonded to the whole diameter of the sensor as shown in Figure 6.15 (b) and the FBG was bonded in the centre of the diaphragm over the 4 mm.

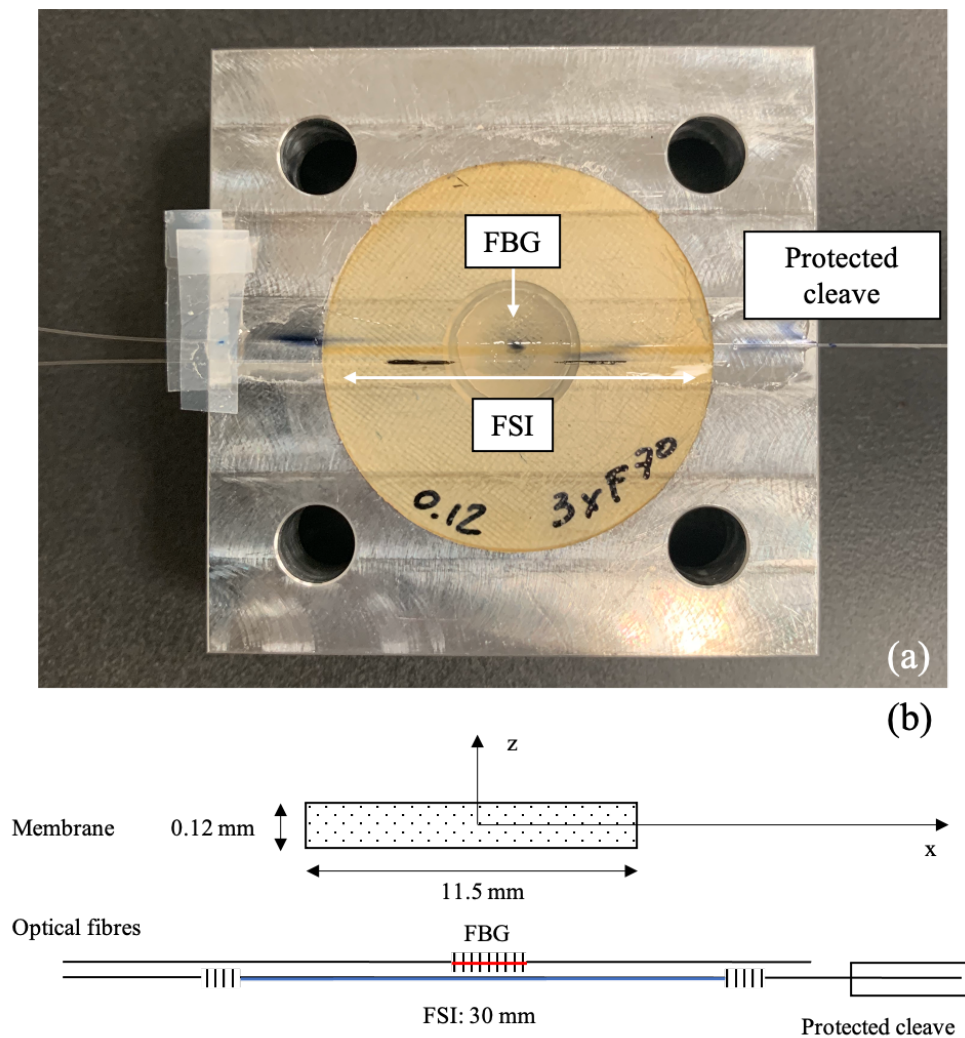


Figure 6.15: (a) shows the optical fibre pressure sensor, comprising a GFRP diaphragm instrumented with two optical fibres, one containing an FBG and the other one containing one fibre segment interferometer mounted within an aluminium support structure. (b) schematic of the two optical fibres, one containing an FBG and the other one containing one fibre segment interferometer and their positions on the diaphragm. Not to scale.

6.2.2 Experimental Setup

The sensor was characterised for its response to pressure only, following procedure described in Section 6.0.2.1. The expected behaviour of both the FBG and FSI at 35 kPa was determined by analysis of the FE output shown in Figure 6.16. Both the FBG and the FSI sensors were expected to experience a strain gradient, with the FBG experiencing only positive strain while the FSI sensor extended over the entire diameter, experiencing regions of both positive and the negative strains.

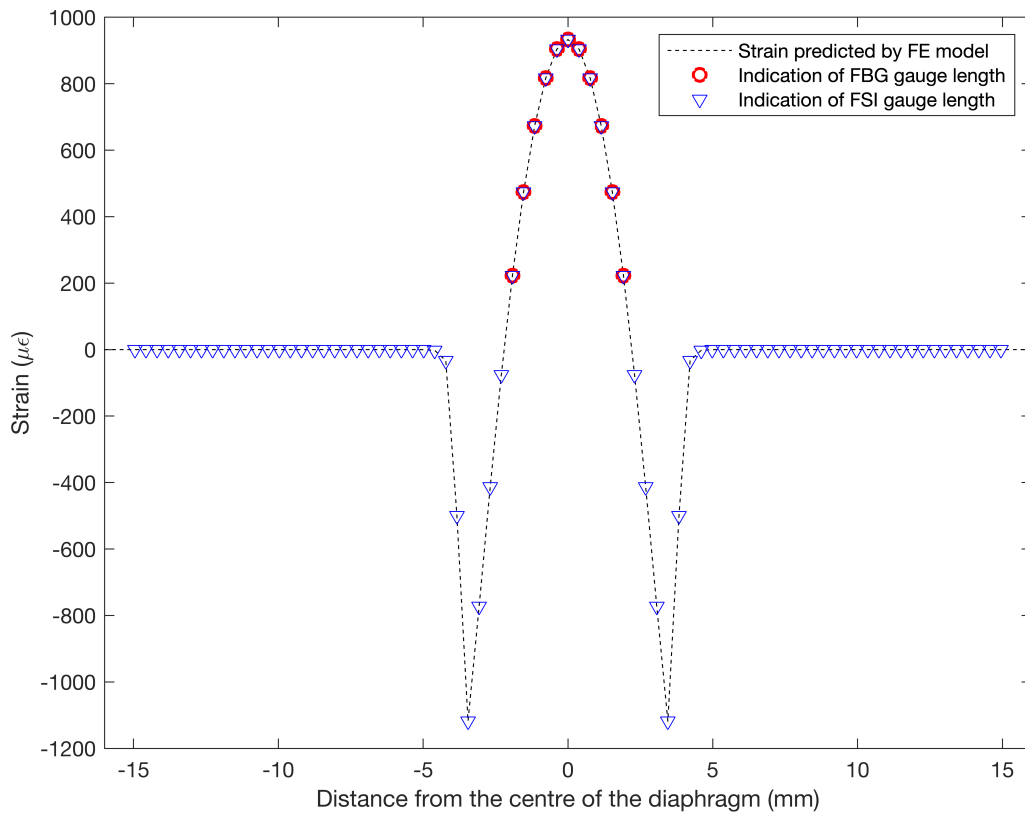


Figure 6.16: Output from a Finite Element Analysis of the diaphragm under deflection with optical fibre mounted on the surface. Strain plotted at 35 kPa over the diameter of the diaphragm with the gauge lengths of the two optical fibre sensors indicated by: red circles (○) for the 4 mm long FBG, blue triangles (▽) for the 30 mm long FSI bonded to the pressure responsive region of the diaphragm.

6.2.3 Results and Discussions

Figure 6.17 shows the FBG and FSI sensor responses to a series of pressure cycles, with the responses converted to strain for ease of comparison. The FE results shown in Figure 6.16 indicate that the maximum strain, at the centre of the diaphragm, for an applied pressure of 35 kPa is approximately $1000 \mu\epsilon$. The strain averaged over the central 4 mm of the diaphragm is $645 \mu\epsilon$ and over 30 mm, $16 \mu\epsilon$. During the experiment shown in Figure 6.17, the strain exhibited by the FBG at an applied pressure of 35 kPa, at the highest step of the first part of the test, was $636 \mu\epsilon$. The FSI sensor exhibits a strain of $12 \mu\epsilon$. Both show good agreement with the FE results, with small discrepancies which can have origin in the location of the sensors along the diameter or relative to the neutral axis of the diaphragm due to the glue gap. Additionally, the composite material can have discrepancies in the alignment of the glass fibres, which is possible due to the laminate being made by hands.

It is clear that the FSI sensor, which integrates the strain over the entire diameter of the diaphragm, balancing the positive and negative strains as expected from the FE, exhibits lower response than that of the FBG.

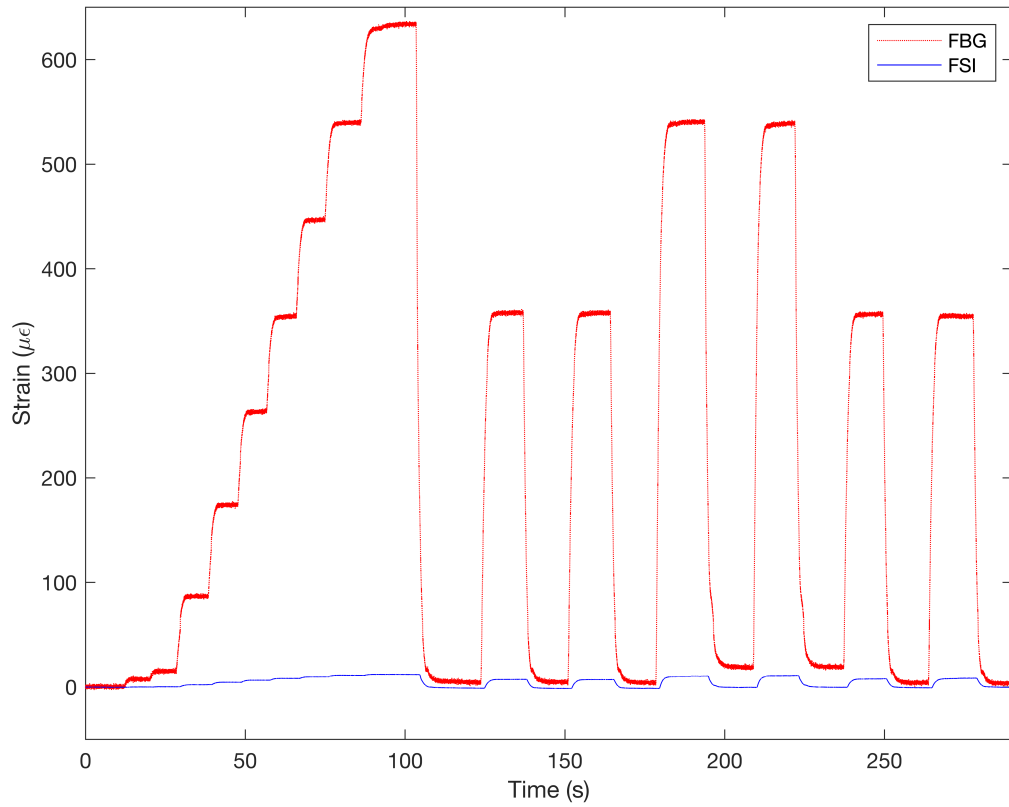


Figure 6.17: Measurements obtained from the optical fibre sensors during a series of pressure cycles. The optical fibre sensor responses are plotted in terms of the strain, facilitating comparison of the sensor responses.

Although the FBG is placed over a strain gradient, it is sufficiently short that the influence on the bandwidth of the Bragg reflection was smaller than could be resolved by the interrogator, however based on experience and on review of the literature, strain gradients are known to result in broadening or splitting of the Bragg peak [61]. This issue does not influence the FSI measurements, which can provide the advantage of having a clean signal independent of variation of strain over the segment length, but can also have the disadvantage of missing important localised information in the event of using a large segment length.

6.3 Conclusion

This chapter described the direct comparison of an FBG and the novel approach of deploying interferometric sensors on a diaphragm in a pressure sensor. Three optical fibres were bonded to the surface of a GFRP diaphragm, one containing an FBG, one containing three FSI segments and a third containing a single FSI segment extending over the whole sensor diameter. An attempt to correct the pressure measurement for the influence of temperature was presented with the three FSI segments, by exploiting the positive and negative regions of the diaphragm highlighted by the FE results, with positive strain in the centre and negative strains around the fixed edge. The temperature discrimination introduced errors due to the thermal expansion of the aluminium pressure chamber, described in Chapter 7, which introduced an increase in stiffness with increase temperature. A theoretical error analysis of the temperature discrimination is presented for an all glass pressure chamber. The condition at the edge was investigated using the longitudinal strain in [87] in an attempt to discriminate temperature and pressure. The integral approach of both optical fibre sensing technologies is demonstrated, highlighting the advantage of the fidelity of measurement and disadvantage with large FSI sensor segment lengths, which can miss important information for more localised strains that would be balanced by the rest of the strains along the segment length and the position not identified along the segment.

Chapter 7

Thermal Characteristics of Fibre Bragg Gratings Encapsulated in Capillary and Bonded to Different Materials

Introduction

In this chapter, two aspects of the thermal sensitivity of FBG sensors are analysed, encapsulated FBG and bonded to specimen FBG. Capillary encapsulation of FBGs is a commonly used approach for the temperature compensation of FBG strain sensors, where the capillary is assumed to isolate the encapsulated FBG from strain, while allowing it to be positioned close to the strain sensor so that they can experience the same thermal environment. The first study presented in this chapter considers the influence of the dimensions of the capillary and the material from which it is made from on the performance of the temperature sensor. The second investigation considers the influence of the thermal characteristics of the materials used in the construction of the pressure sensor upon its temperature response.

7.1 Experimental Analysis of Strain-Free FBGs Encapsulated in Capillary Tubes

The responses of FBGs to strain and temperature are discussed in Chapter 2. The main challenge in optical fibre sensing is to compensate for the thermal response of the sensor to measure only the value of interest. The most common method used to compensate for temperature changes is the use of an additional, strain-free FBG [131, 132, 133]. The reference temperature sensor experiences a Bragg wavelength shift due to temperature variation only. When using a nearby strain measuring FBG that experiences both strain and temperature changes, the reference temperature sensor wavelength shift can be subtracted to extract the strain response. This method is particularly useful when the optical fibre is incorporated within a composite laminate during manufacturing. A split in peak is also a method [61, 39] as well as wavelength differential using 2 FBG of opposite strain [97, 98, 99, 100]

Once the composite is cured and under environmental variations, the FBG inside the capillary responds only to the temperature changes with its own thermal sensitivity, regardless of the physical deformation of the structure, while the other FBG experiences both temperature and longitudinal/transverse strain. The later FBG, used as a strain sensor, measures strain from the physical tension or compression of the specimen they are mounted on or embedded with due to the thermal expansion of the specimen as well as the optical fibre intrinsic thermal sensitivity due to the thermo-optic effect and its thermal expansion. Depending on the host material's thermal properties, its CTE can dominate the thermo-optic coefficient of the fibre, increasing the thermal sensitivity of the FBG sensor. This should be taken into consideration when compensating for temperature effects and this phenomenon is investigated in the latter part of this chapter. Methods using the peak splitting are not appropriate for this type of application due to the length of FBG and overall embedding of the optical fibre.

The properties of the capillary can influence the performance of the encapsulated FBG and this is explored in the first part of this chapter. Bespoke FBG sensor arrays were ordered from FemtoFiberTec. Each array contained either two or three FBGs of reflectivity $> 50\%$ and wavelengths 1533 nm and 1537 nm for arrays of two FBGs and 1543 nm, 1548 nm and 1553 nm for arrays of three FBGs. The last FBG was positioned 5 mm from the cleaved end of the SMF-28 polyimide coated fibre. The polyimide coating was selected for its capacity to withstand temperature above $70\text{ }^{\circ}\text{C}$. The last FBG on each fibre was encapsulated in a capillary as illustrated in Figure 7.1. The various capillary properties are summarised in Table 7.1.

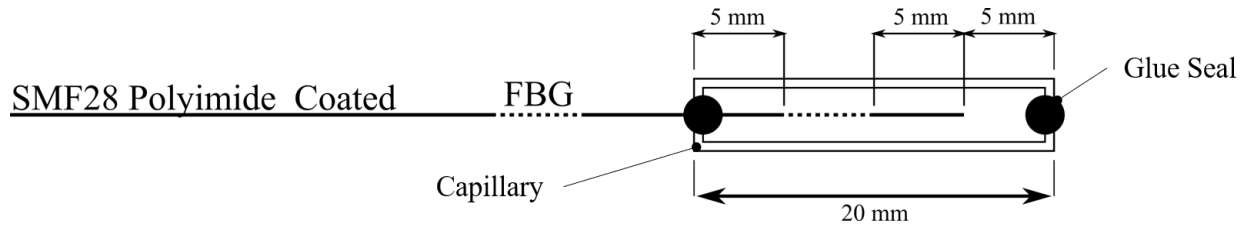


Figure 7.1: Schematic of an array with the final FBG encapsulated within a capillary. Not to scale.

Table 7.1: Optical fibre array capillary properties

Capillary Material	Stainless Steel	Fused Silica	Fused Silica	Borosilicate
Length (mm)	20	20	20	20
ID (mm)	1.5	0.32	0.20	0.15
OD (mm)	2	0.44	0.36	0.25
Wall Thickness (mm)	0.5	0.12	0.16	0.10

7.1.1 Commercially Available FBG Temperature Sensor: X8CrNiS18-9 Stainless Steel Capillary

7.1.1.1 Material

The FBG sensor array ordered for the suspension load measurement detailed in Chapter 8 of the thesis contained two FBGs with the final FBG encapsulated in a stainless steel capillary of length 20 mm, inner diameter of 1.5 mm and outer diameter of 2 mm. The capillary was sealed at one end, with the cleaved end of the fibre positioned 5 mm away, enclosing the FBG as shown in Figure 7.1. This design was supplied to the commercial supplier as an off the shelf option. The performance of the capillary encapsulated FBG was analysed prior to using the fibre arrays in the suspension measurements.

7.1.1.2 Instrumentation

The section of the fibre containing the stainless steel capillary and the strain sensor was placed in an oven as depicted in Figure 7.2. The other end of the fibre was connected to the SmartScan FBG interrogator as illustrated in Figure 7.3. Figure 7.4 shows the configuration of the test.

The Instron tensile testing system was enclosed in an oven to allow the component to be tested under load while simultaneously varying the temperature. However, there can be difficulties with the stabilisation of the temperature within this oven due to its size, the presence of multiple unsealed areas and temperature gradients. The use of thermocouples located as close as possible to the optical fibre sensors was essential. The temperature was increased in a step-wise fashion from ambient temperature to 36 °C. Although higher temperature aimed to be reached, the test was terminated at 36 °C when the equipment did not meet the testing requirements.

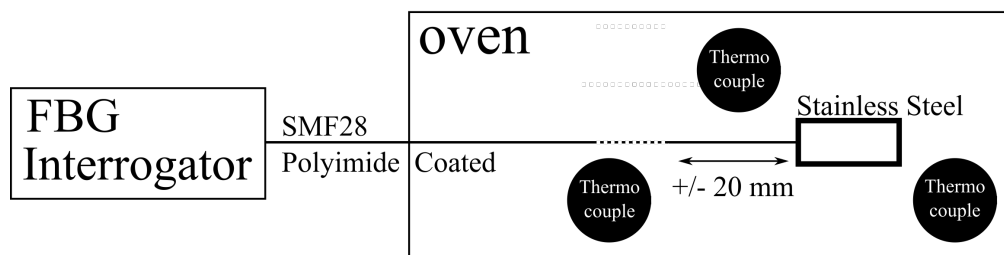


Figure 7.2: Schematic of the sensor array containing the stainless steel capillary inside the oven with the position of the thermocouples.

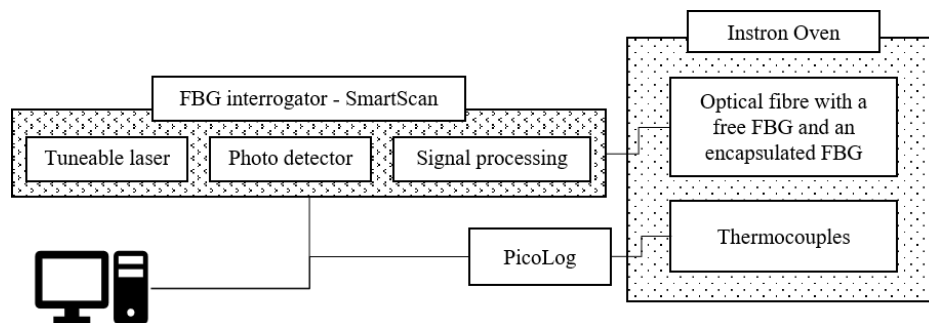


Figure 7.3: Schematic of the experimental configuration with the optical fibre placed in the oven and connected to the SmartScan interrogator.

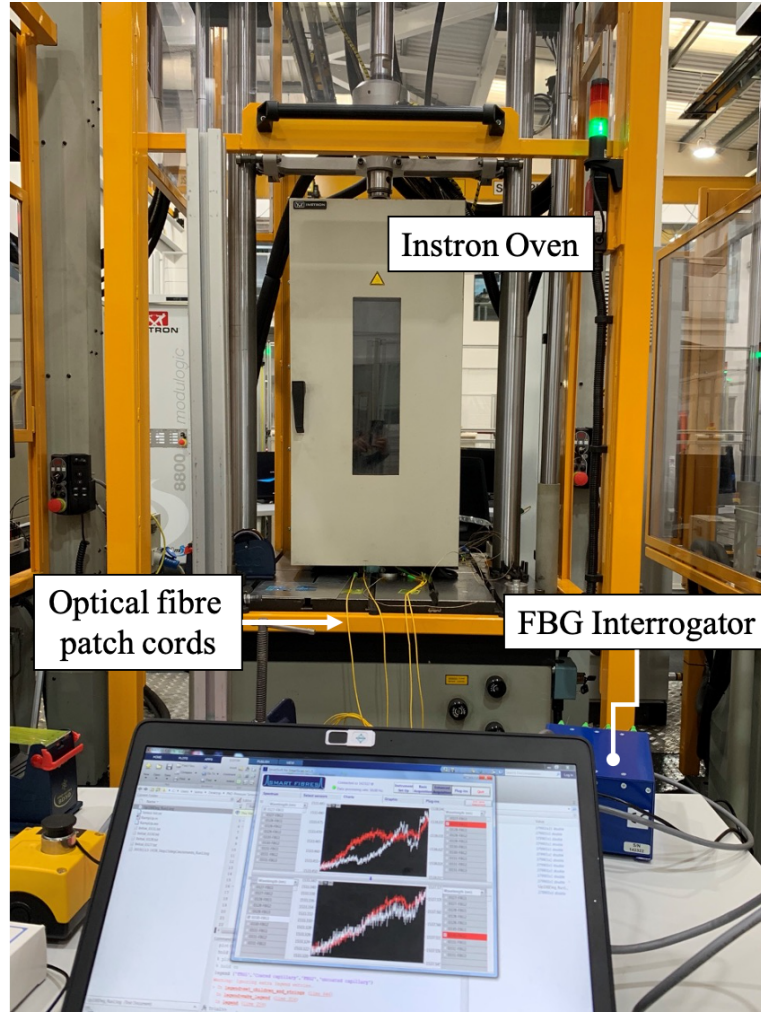


Figure 7.4: Instron oven used for thermal response characterisation of the free FBG and the FBG encapsulated in the stainless steel capillary.

7.1.1.3 Results and Discussions

Figure 7.5 shows the temperature variation recorded by the thermocouples over the duration of the experiment. The plotted curve is the average of the data from the three thermocouples. Figure 7.5 shows the wavelength shifts of both the bare and encapsulated FBGs with temperature variation. The bare FBG exhibits a response that appears faster than the thermocouples, while the FBG encapsulated in the stainless-steel capillary has a slower response time. Figure 7.6 shows the portion of the time series corresponding to the first temperature step, demonstrating a lag of more than 2 minutes between the data

from the encapsulated FBG and the bare FBG.

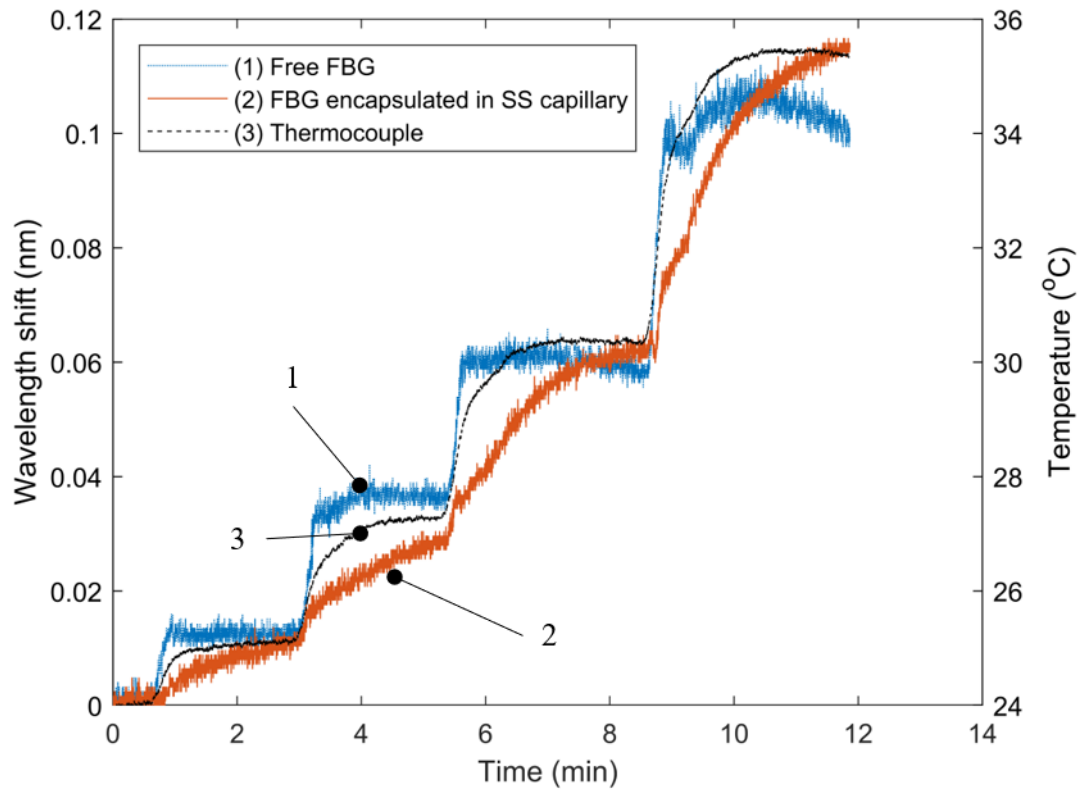


Figure 7.5: Temporal responses of the average thermocouples, the FBG encapsulated in the stainless steel capillary and the free FBG.

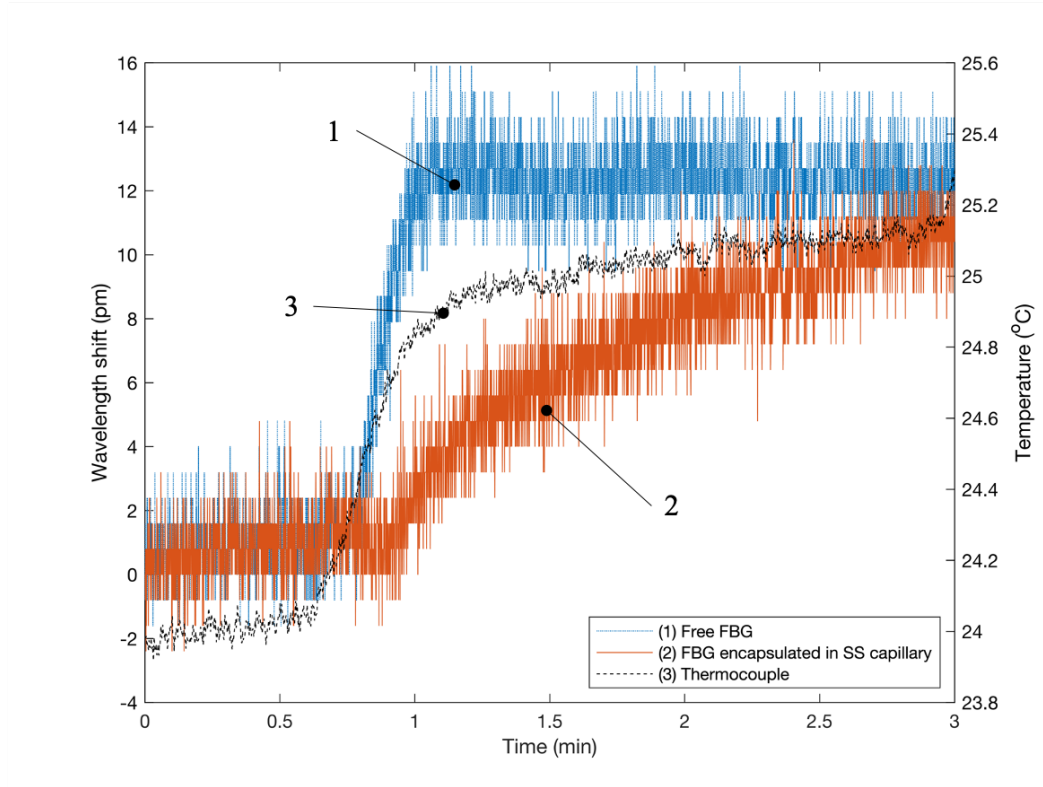


Figure 7.6: Times series of the data recorded during the first temperature step showing a 2-minute delay between the response of the encapsulated FBG and the free FBG.

This behaviour can be explained by the geometry and material used to form the capillary. The air inside the capillary occupies a large portion of the capillary volume which slows the heat transfer as air is a poor conductor. The stainless steel is sealed at both ends which reduces the air flow resulting in weak convection. Finally, shiny surfaces such as metal are poor emitters and absorbers of infrared radiation. There is also the possibility of temperature gradient between the two FBGs due to the oven size and poor sealing.

This experiment demonstrated the importance of the use of testing facilities that are appropriate for the test specimen and thus the experiments described in the following sections were performed in an oven that was more compact and better sealed. Despite the limitations of the initial experiment, the data shows clearly that the performance of the stainless steel capillary design suffered from a significant thermal lag. To overcome

this problem, research focused on the use of capillary made from materials with thermal properties similar to those of the optical fibre and that had much smaller inner and outer diameters. Two candidates appeared to have the right properties and sample were sourced from suppliers: fused silica with polyimide coating and borosilicate, with design specifications reported in Table (7.1).

7.1.2 Experimental Comparison of Stainless Steel, Borosilicate and Fused Silica Capillaries

7.1.2.1 Material

Several samples of various materials and dimensions were sourced from PostNova [134] (fused silica capillaries - Z-FSS-200365, Z-FSS-320440) and CM Scientific [135] (borosilicate capillary - CV1525). Three SMF-28 polyimide coated optical fibre arrays containing two or three FBG sensors were provided to Diamond SA from FemtoFiberTec to be terminated. Diamond SA terminated the optical fibres with high temperature FC/APC connectors [136] and bonded 20 mm long capillaries over the FBG positioned at the extremity of the fibre as illustrated in Figure 7.1. A total of four optical fibres were compared with the final FBG encapsulated stainless steel capillary of inner diameter (ID) 1.5 mm and outer diameter (OD) 2 mm, presented in Section 7.1.1, two fused silica capillaries of ID: 0.32 mm, OD: 0.44 mm and ID: 0.20 mm and OD: 0.36 mm respectively and the borosilicate capillary of ID: 0.15 mm and OD: 0.25 mm. The capillary specifications of each fibre are reported in Table 7.1. The thermal responses of the four FBG arrays were characterised using a compact Votsch oven.

Figure 7.7 allows the comparison of the two types of capillary investigated: glass and metal capillaries. The dimensions and weights are considerable for such a small component. The handling of the smaller and lighter capillaries is much easier and the intrusion in the host component, with the resulted influence on mechanical properties, is

reduced.

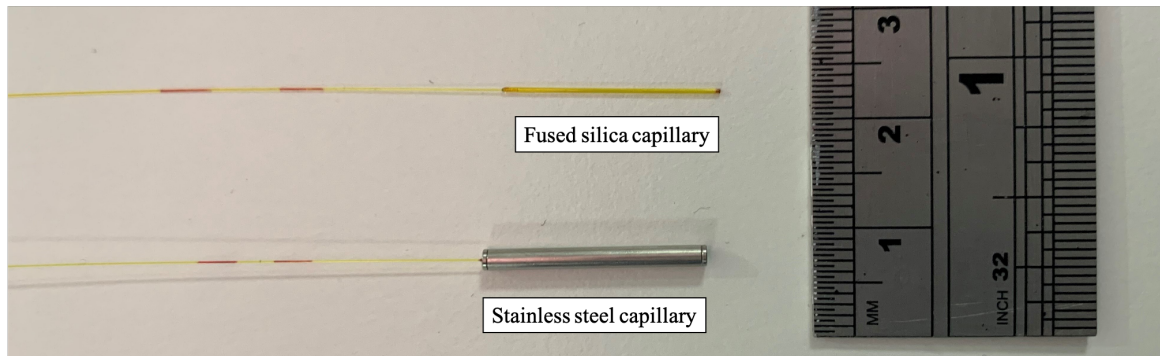


Figure 7.7: Image comparing a glass capillary encapsulated fibre with a metal capillary encapsulated fibre.

7.1.2.2 Instrumentation

The experimental configuration is illustrated in Figure 7.8. The sections of the fibres containing the free and encapsulated FBGs were positioned within the oven as illustrated in Figure 7.9, while the proximal end of the fibres, which were terminated with FC/APC optical fibre connectors, were connected to the FBG interrogator. In the first experiment, the glass capillary encapsulated FBGs were assessed, with thermocouples measuring the temperature near the capillaries and on either side of the free FBGs. In the second experiment, the steel capillary encapsulated FBG was characterised separately with thermocouples placed near the free FBG and the encapsulated FBG. Figure 7.10 shows an image of the glass capillary encapsulated fibres and thermocouples positioned inside the oven.

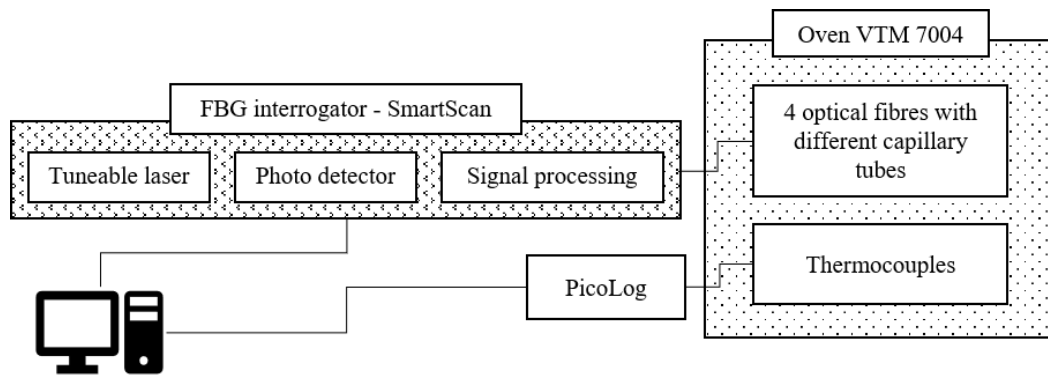


Figure 7.8: Schematic of the experimental set up.

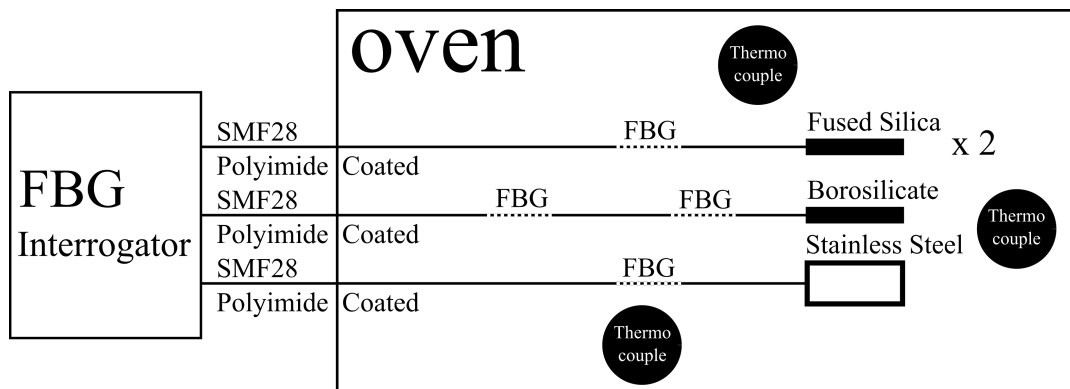


Figure 7.9: Schematic of the location of the sensor arrays inside the oven.

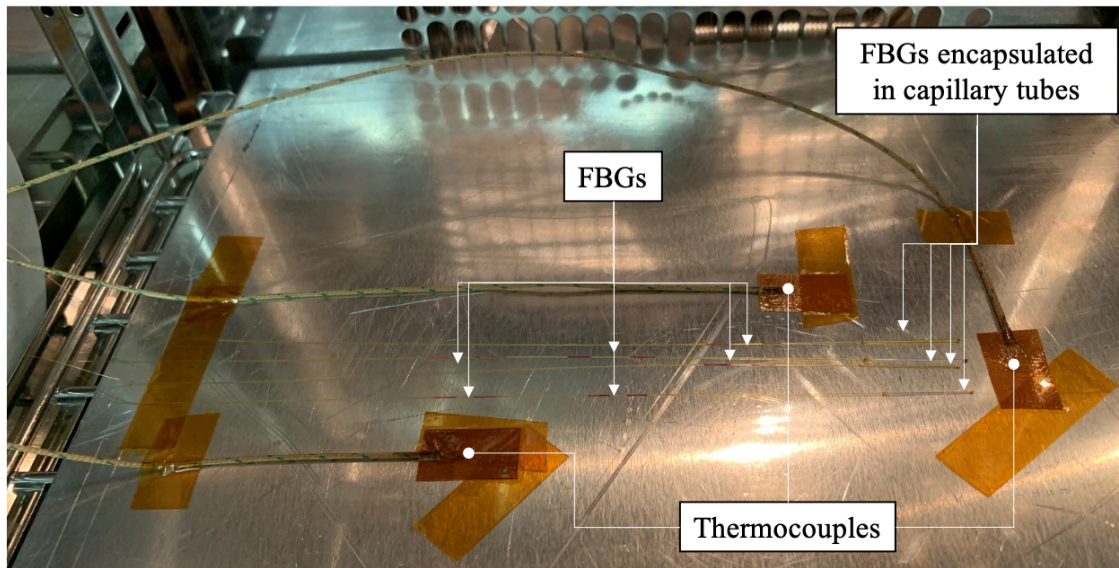


Figure 7.10: Glass capillary fibres inside the oven with three thermocouples. An additional fibre is visible but not in use due to breakage.

The thermal response of each FBG array was characterised over a temperature ranging from $30 \pm 0.03^\circ\text{C}$ to $100 \pm 0.03^\circ\text{C}$, logged by the thermocouples and PicoLog (accuracy of $\pm 0.03^\circ\text{C}$) to cover the temperature range of an F1 car on track. The first section of the test consisted of five 15°C step increments from 30°C to 90°C . After dwelling at 90°C for 10 min, the temperature was reduced to 60°C and then to 30°C . Once the temperature stabilized at 30°C , the second part of the test consisted of a ramp up to 100°C and back down to 30°C . Figure 7.11 illustrates a typical temperature profile recorded using a thermocouple. Each experiment was performed on separate day, leaving the oven, fibres and thermocouples enough time to cool down fully.

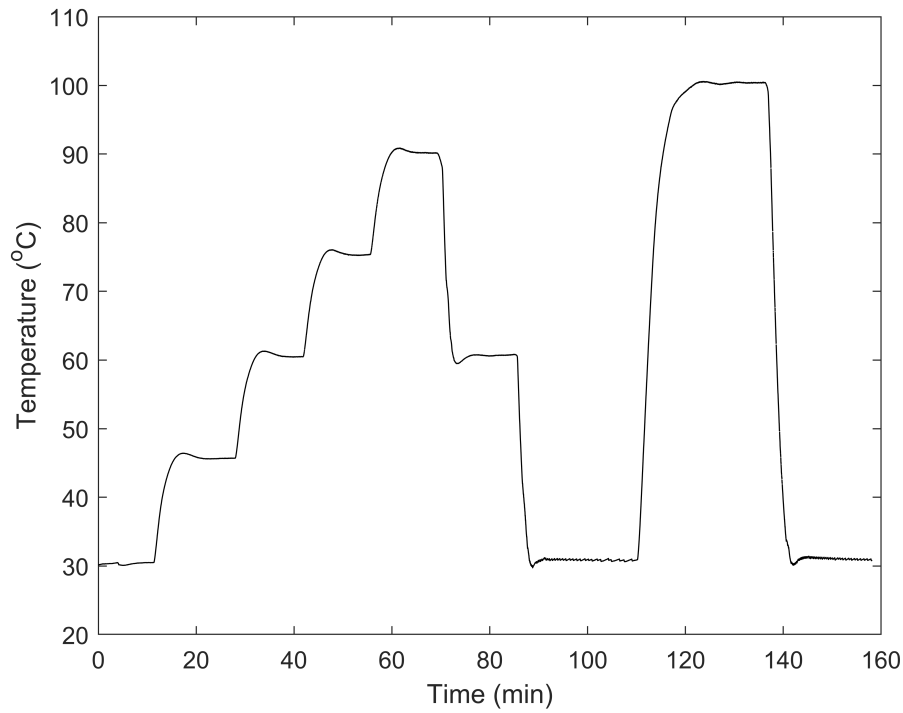


Figure 7.11: Typical thermal profile used to assess the performances of the encapsulated FBGs. The temperature was stepped from 30°C to 90°C in 15°C increments and then ramped up to 100°C and back down to 30°C.

7.2 Results and Discussions

7.2.1 Temperature Responses and Characteristics

Figures 7.12 and 7.13 show the temperature responses of the sensor arrays, averaged from three experimental runs taken over three separate days. Figure 7.12 (a) shows the response of the array containing an FBG encapsulated within the stainless steel capillary and Figure 7.12 (b) shows the response of the array containing an FBG encapsulated within the larger outer diameter fused silica capillary. The oscillations observed in the first 10 min of the time series shows the challenge with the stabilisation of the temperature inside the oven when it was close to the ambient temperature of the laboratory. This oscillation disappears when the temperature increased. Both the free and the encapsulated FBGs exhibit

the same wavelength shift until they reach the final step to 100 °C, where a difference in wavelength shift of 31.4 pm is observed. The oven initially cools down to a temperature lower than that set on the controller and then gradually increases to stabilise at the set temperature. Unlike the free FBG, the response time of the encapsulated FBG is not quick to represent it, with on average a delay of 2 minutes. This effect is common to all of the capillary encapsulated FBGs.

The other array containing the fused silica capillary shown in Figure 7.12 (b) exhibiting a similar response when compared to (a). The ramp to 100 °C also shows a discrepancy, this time with the encapsulated FBG showing a wavelength shift that is 5.8 pm larger than the free FBG. Overall, the encapsulated FBG exhibits a little more sensitivity than the free FBG, starting at 80 °C.

Figure 7.13 (a) represents the temporal responses of two free FBGs and the encapsulated FBG in the borosilicate capillary. First of all, it appears that the encapsulated FBG exhibits higher sensitivity than the bare FBGs, from 35.5 pm at lower temperature up to 109.5 pm at 100 °C. Both the free FBGs are also showing different wavelength shifts with 17 pm on average. This dissimilitude can be explained by the distance separating them as 17 pm is equivalent to about 1.5 ° according to their calibration given in Table 7.2.

Figure 7.13 (b) shows the thermal responses of the sensor array with the stainless steel capillary, the response is different from the three other fibres and is visible at the start of each step, when the temperature starts reaching the next step. There is a lag with the encapsulated FBG that is visible in Figure 7.14 (a). While the free FBG reach the next temperature, the encapsulated takes an additional 2 min to reach it. This does not happen with any other capillary as shown in the zoomed portion in Figures 7.14 (b) and 7.15. Even the borosilicate capillary in Figure 7.15 (b) that exhibits higher sensitivity does not show any delay. The free FBG gradually appears to increase its sensitivity in Figure 7.13

(b) compared to the encapsulated FBG until the cool down steps before and after the 100 °C ramp which could be in fact be explained by the encapsulated FBG gradual thermal lag over the increasing temperature.

Finally, Figures 7.14 and 7.15 show the tendency of all FBG sensors to oscillate when the temperature is changing only and not when the temperature stabilises. This effect was also noticed when applying a load to the suspension in Chapter 8, with the oscillation only occurring when the load was varying and not when constant. This effect could be due to oven/load variations but was not found to occur with fibres made in the Photonics lab at Cranfield University. The second hypothesis can be the etalon effect. This appears when the fibre and interrogator lose physical contact resulting in a micro cavity of order 1 to 5 μm . It can be due to dirty connectors however this happened with all the fibre supplied, even after cleaning them. Light Machinery.com [137] offers an "etalon designer" tool, allowing an understanding of the possible cause. A small reflectivity of 0.001 % at the connector would be sufficient for a modulation in the transmitted power which corresponds to the oscillation that occurs.

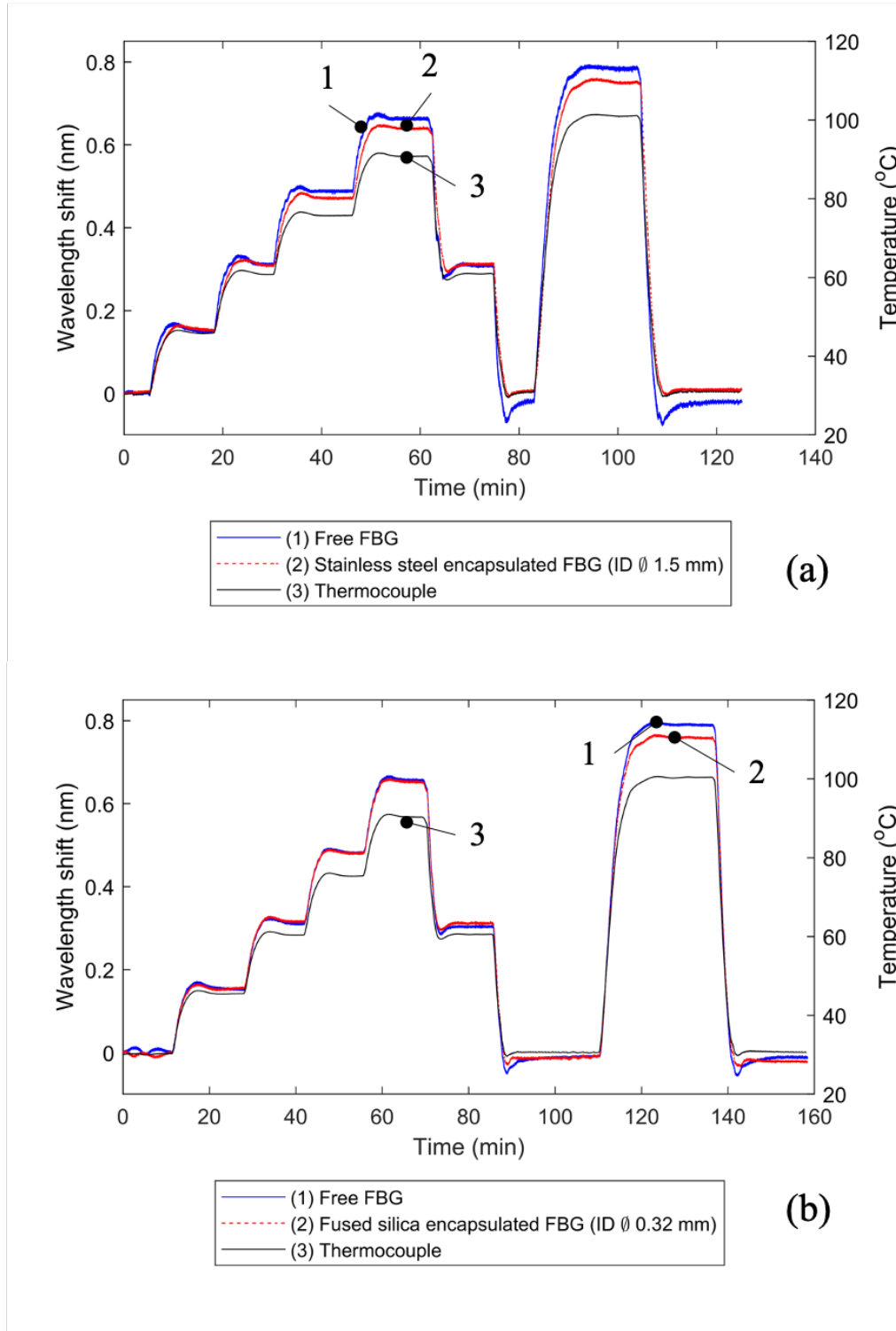


Figure 7.12: Temporal thermal responses of (a) fibre with (1) free FBG, (2) stainless steel encapsulated FBG. (b) fibre with (1) free FBG, (2) fused silica encapsulated FBG. Average of three experimental runs taken over three separate days.

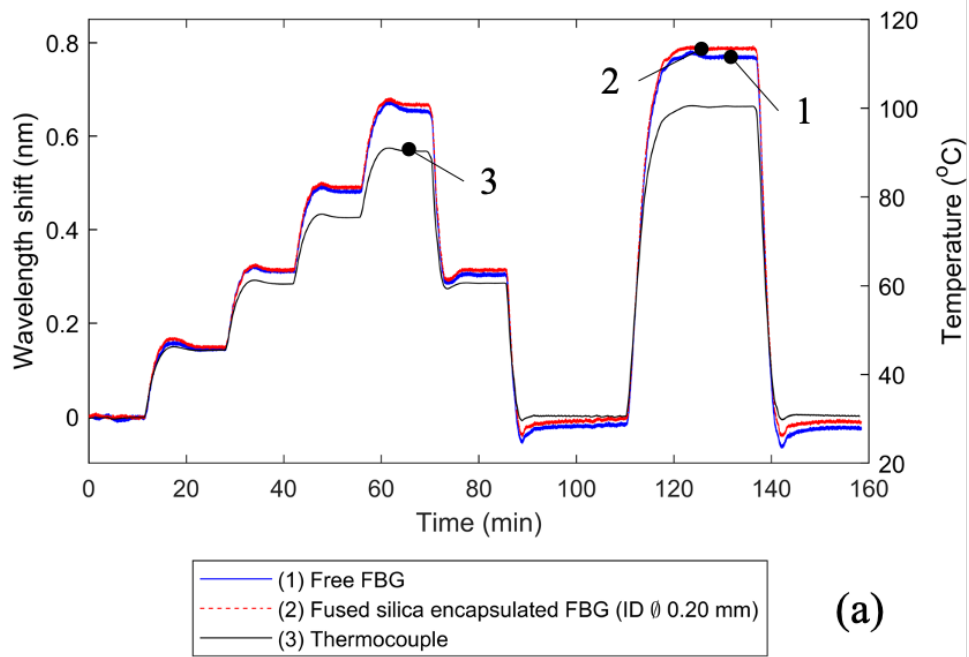
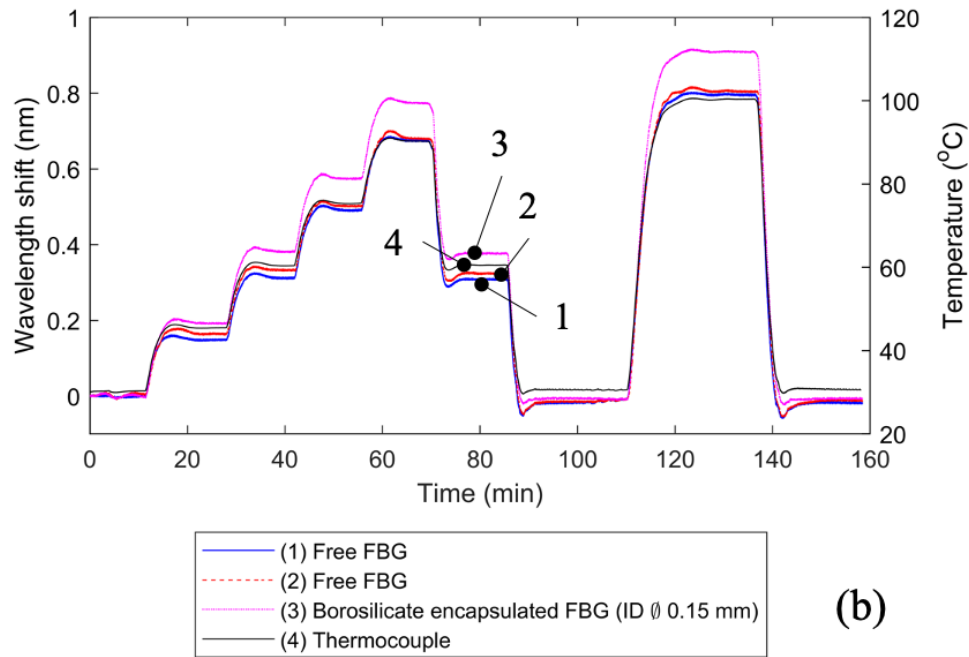


Figure 7.13: Temporal thermal responses of (a) fibre with (1) free FBG, (2) fused silica encapsulated FBG. (b) free FBG 1, (2) free FBG 2, (3) borosilicate encapsulated FBG. Average of three experimental runs taken over three separate days.

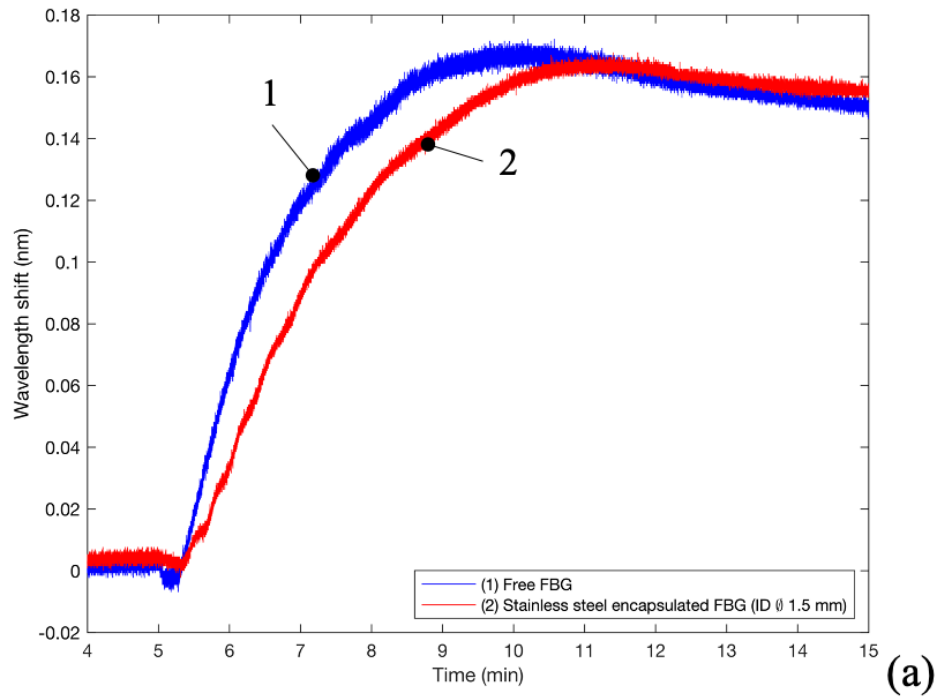
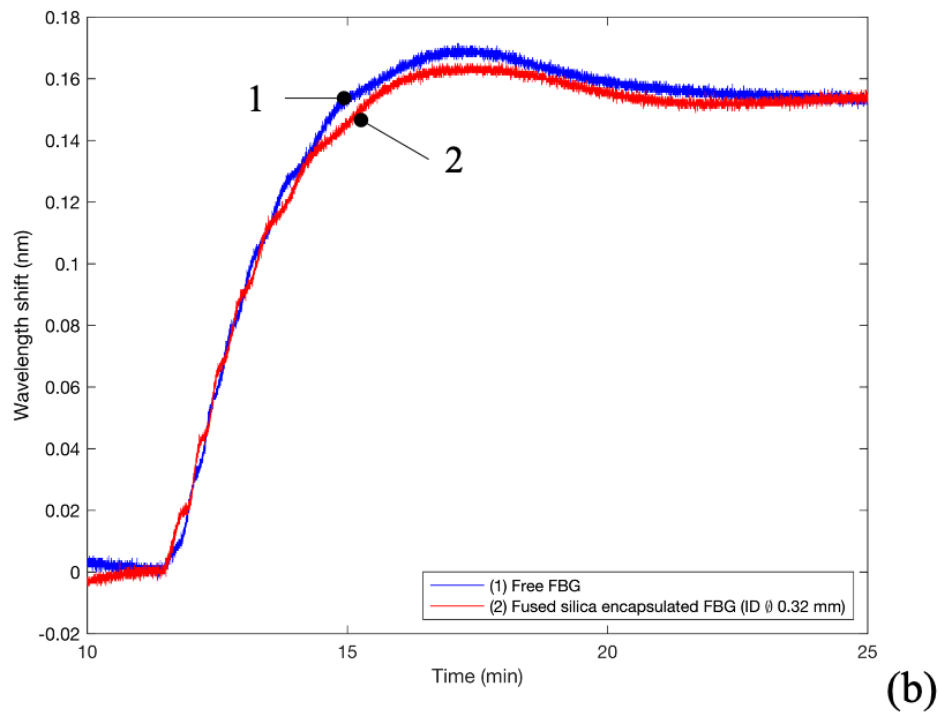


Figure 7.14: Temporal thermal responses of the first step over several minutes (a) fibre with (1) free FBG, (2) stainless steel encapsulated FBG. (b) fibre with (1) free FBG, (2) fused silica encapsulated FBG.

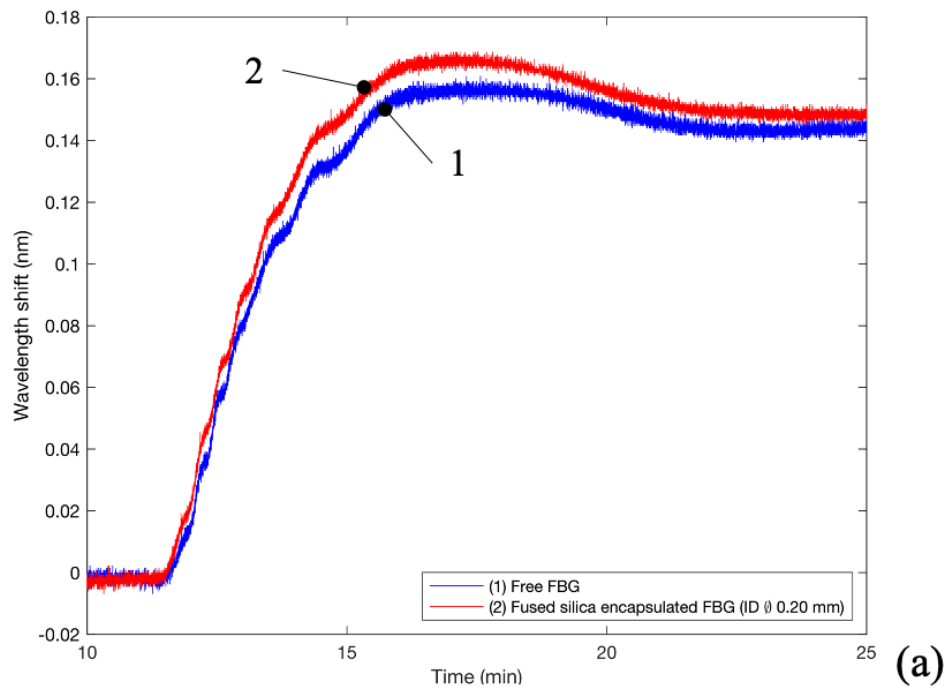
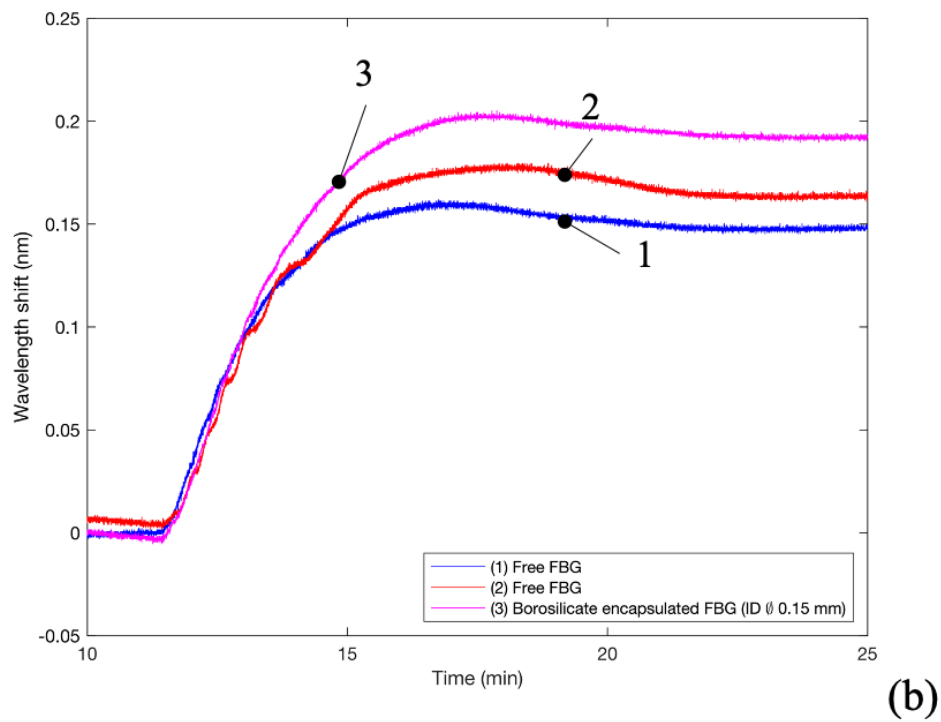


Figure 7.15: Temporal thermal responses of the first step over several minutes (a) fibre with (1) (1) free FBG, (2) fused silica encapsulated FBG. (b) free FBG 1, (2) free FBG 2, (3) borosilicate encapsulated FBG.

Figures 7.16 and 7.17 show the calibration of each FBG sensor. Each curve shows the oscillation discussed earlier that confirms the etalon effect. Both fused silica capillary fibres (a) and (b) exhibit linear and similar response whether the FBG is encapsulated or free. Their thermal sensitivities are about $11 \pm 0.05 \text{ pm/}^\circ\text{C}$, which correspond to the reported FBG thermal sensitivity given by [25]. FBGs thermal sensitivities are reported in Table 7.2.

The temperature sensitivity of the borosilicate encapsulated FBG is higher than the bare FBGs of the same fibre array as expected from Figure 7.13 (b) with $13 \pm 0.06 \text{ pm/}^\circ\text{C}$ and $11.6 \pm 0.05 \text{ pm/}^\circ\text{C}$ respectively. The potential reason why the borosilicate encapsulated FBG exhibits higher sensitivity is investigated in Section 7.2.2. Their responses are also linear with $R^2 = 0.9998$, suggesting no thermal lag with this capillary. However, this is not the case with the stainless steel capillary where (d) clearly indicate the hysteresis behaviour of the encapsulated FBG, The response of the free FBG of this fibre does not appear to be as clean and linear as the other free FBG which suggest the capillary have an effect also on the rest of the fibre. Their sensitivities however are in the expected range and are similar with $11.5 \pm 0.05 \text{ pm/}^\circ\text{C}$ and $10.6 \pm 0.1 \text{ pm/}^\circ\text{C}$ for the free and encapsulated FBGs respectively.

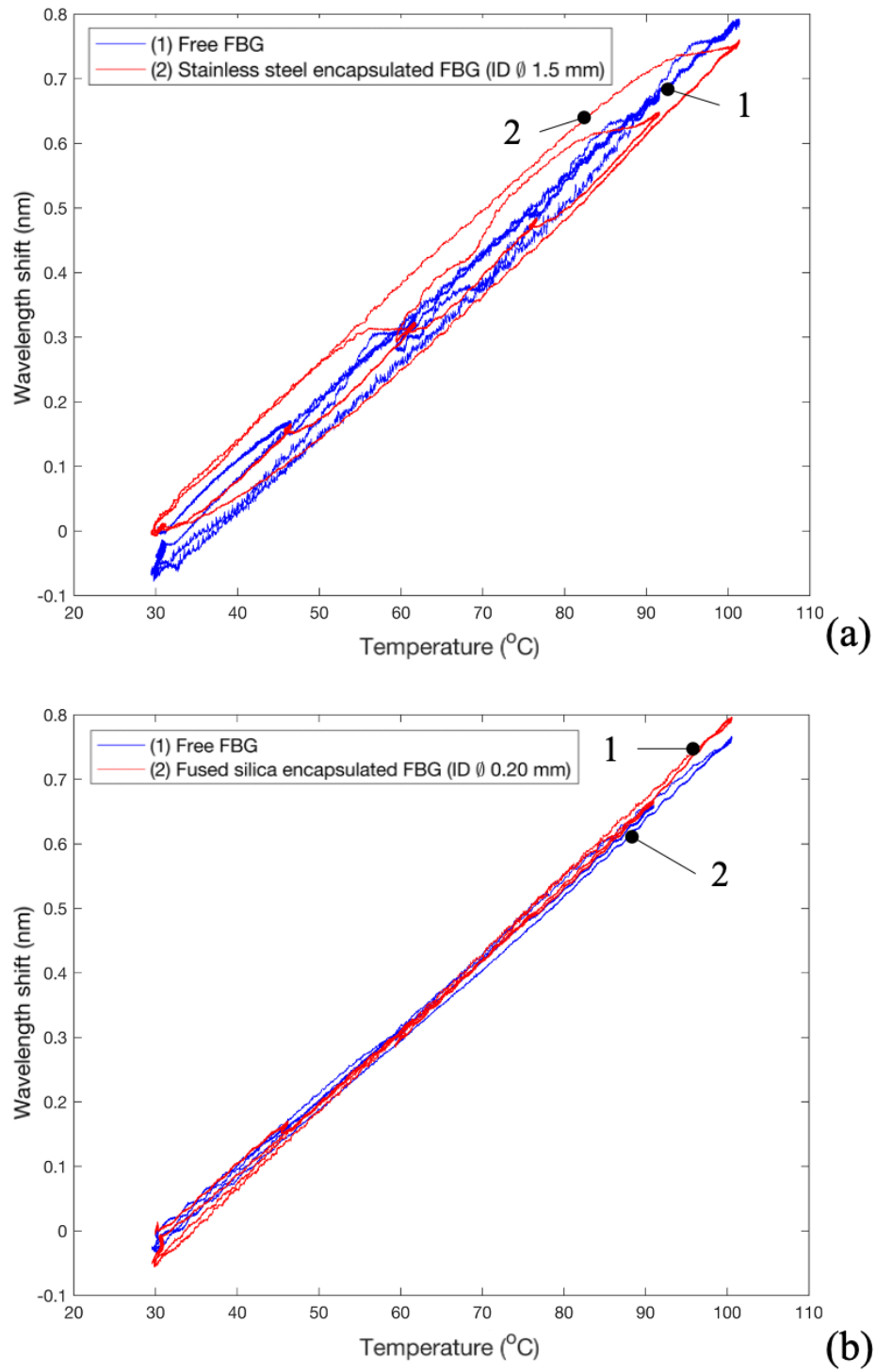


Figure 7.16: Thermal calibration curves taken from the data in Figure 7.12. (a) fibre with (1) free FBG, (2) stainless steel encapsulated FBG. (b) fibre with (1) free FBG, (2) fused silica encapsulated FBG.

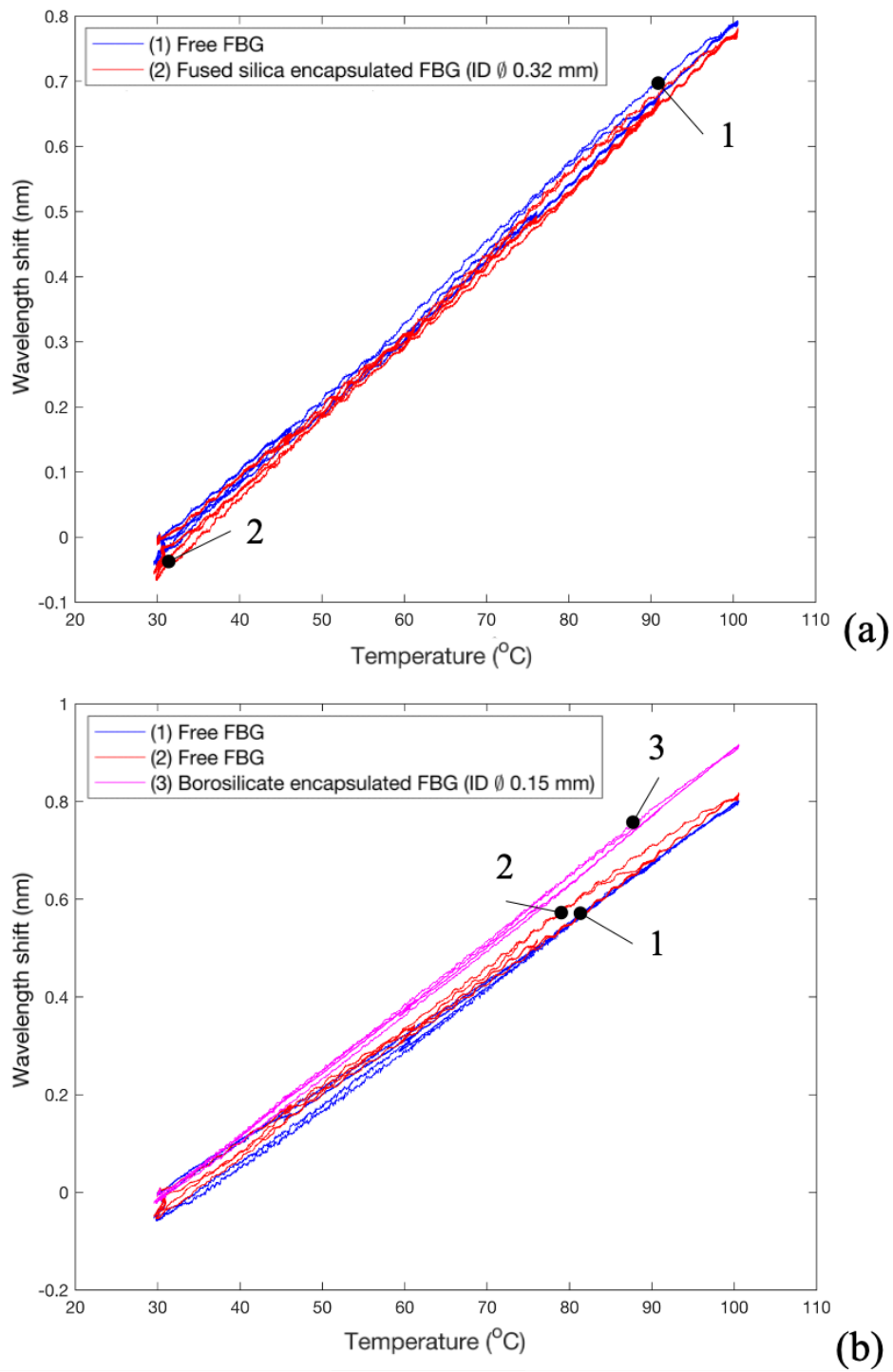


Figure 7.17: Thermal calibration curves taken from the data in Figure 7.12. (a) fibre with (1) free FBG, (2) fused silica encapsulated FBG. (b) free FBG 1, (2) free FBG 2, (3) borosilicate encapsulated FBG.

Table 7.2: Thermal sensitivities of all FBGs

Bare FBG	Encapsulated FBG	Capillary material
$11.4 \pm 0.05 \text{ pm/}^\circ\text{C}$	$11.1 \pm 0.05 \text{ pm/}^\circ\text{C}$	Fused silica
$11.3 \pm 0.05 \text{ pm/}^\circ\text{C}$	$11.5 \pm 0.05 \text{ pm/}^\circ\text{C}$	Fused silica
$11.6 \pm 0.05 \text{ pm/}^\circ\text{C}$ (both)	$13 \pm 0.06 \text{ pm/}^\circ\text{C}$	Borosilicate
$11.5 \pm 0.05 \text{ pm/}^\circ\text{C}$	$10.6 \pm 0.1 \text{ pm/}^\circ\text{C}$	Stainless steel

7.2.2 Discussion

The thermal sensitivities of each FBGs seen in Section 7.2.1 and reported in Table 7.2 show that they are all in the expected range and exhibit similar sensitivities whether they are encapsulated or not, which is what was expected from the strain free FBG sensors. However, as seen in Figure 7.13 (a), the borosilicate encapsulated FBG exhibits higher sensitivity. As the FBGs in the same fibre are showing the presumably right sensitivity with what is reported in the literature, the issue is assumed to come from the capillary itself and not the fibre or the FBG sensor. Two possible effects can be responsible for the sensitivity increase and concern the manufacturing of the array. The first hypothesis is the fibre is bonded to the capillary by the glue seal at the extremity of the fibre. The second is the FBG sensor inside the capillary is bonded by the other glue seal. Both glue seals are illustrated in Figure 7.1. Those two hypotheses concern the fibre being bonded to the borosilicate capillary. In each case, the fibre is not strain free anymore as its thermal response also depends on the material properties and its thermal expansion. This can be an advantage when the desire is to increase the temperature sensitivity [138].

The thermal sensitivity of FBG sensor in Equation (7.1) arises from a combination of the thermal expansion of the fibre and the thermally induced refractive index change, with a value of $10 \text{ pm/}^\circ\text{C}$ [25] for an FBG written with a Bragg wavelength of around 1550 nm.

$$\frac{\Delta\lambda_{bragg}}{\lambda_{bragg}} = (\alpha + \xi)\Delta T \quad (7.1)$$

with α the thermal expansion coefficient of the optical fibre ($0.55 \times 10^{-6}/^{\circ}\text{C}$) and ξ the thermo-optic coefficient approximately equal to $10 \times 10^{-6}/^{\circ}\text{C}$ for silica core fibres doped with germanium [32].

Equation (7.1) shows the dominance of the thermo-optic coefficient with more than two orders of magnitude above the CTE of the fibre. However, the CTE can have more effect to the sensitivity if the fibre is attached to a specimen with a higher CTE. This is what is observed here by comparing the fused silica and borosilicate capillaries. While the former has similar CTE compared to the optical fibre, the latter has a higher CTE of $3 \times 10^{-6}/^{\circ}\text{C}$. When replaced in Equation (7.1), the theoretical thermal sensitivity of the FBG is $13.5 \text{ pm}/^{\circ}\text{C}$, meaning the FBG is also sensing the thermal expansion of the capillary.

In order for this capillary design to work, the fibre has to be strain free from the specimen it is mounted to but also from the capillary as it can have higher CTE and so higher sensitivity to temperature change. To do so, the design has to reflect what is shown in Figure 7.1, with the end of the fibre free inside the tube. However, after investigation and feedback from the supplier of the assembly, it appeared that the glue used to seal the end of the fibre was running down the inner diameter when polymerising, bonding the fibre to the capillary. Figure 7.18 shows the image of the glue moving down the capillary. The other side was also running down, with resin flow over 3 mm as shown in Figure 7.19. Although the FBG is 5 mm away as depicted in Figure 7.1, the tolerances, especially the exact position of the FBG, can be off and result in the FBG being partly bonded to the capillary. However, the wavelength peak was not altered during testing, suggesting the glue was not bonding part of the grating as it would have induced a strain gradient on the FBG sensors, resulting in a broaden or distorted peak. The hypothesis of the end of the fibre being bonded to the capillary is more likely. It is also likely that it happened to the other glass capillaries due to their small inner diameters, however the phenomenon is not

as significant since the fused silica capillaries have the same CTE as the optical fibre.

After exchanges with the supplier of these sensor arrays, they brought the solution of sealing the end of the capillary with plasma as shown in Figure 7.20. The disadvantage of this method is that it removes the protective polyimide coating on the capillary.

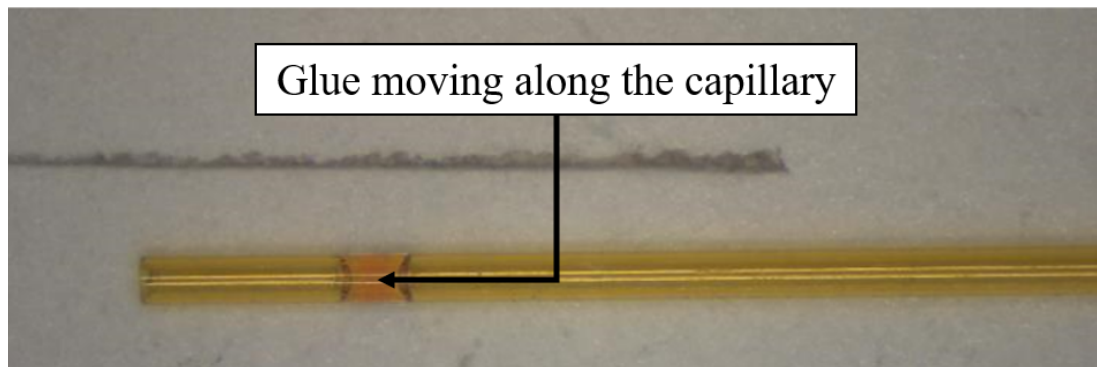


Figure 7.18: Image of a fused silica capillary showing the resin content moving down the tube during polymerisation.

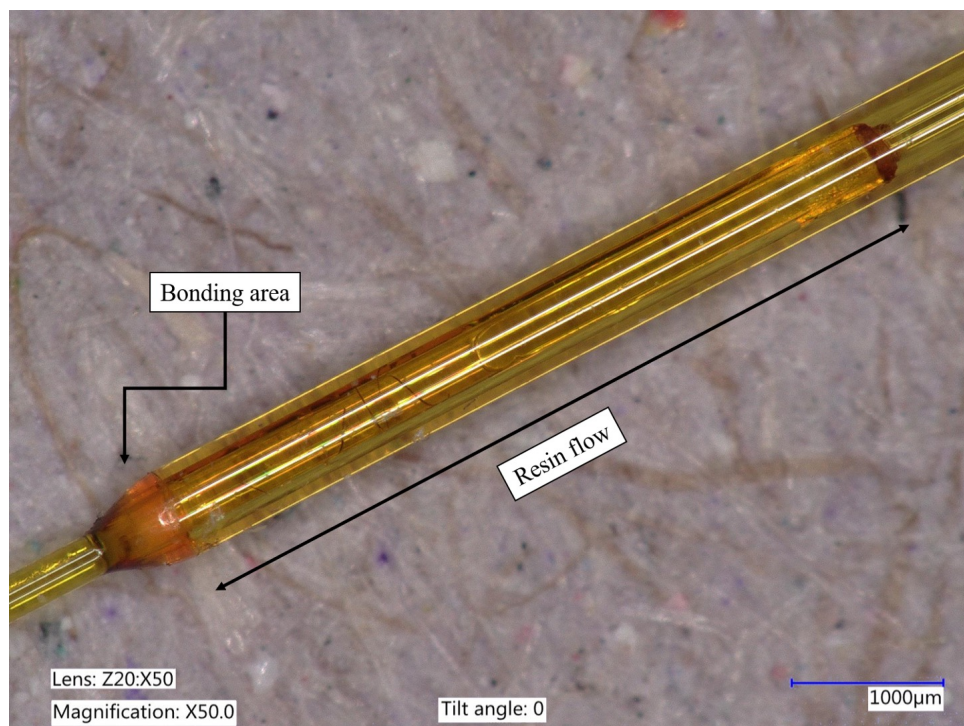


Figure 7.19: Fused silica capillary on the "connector" side showing the resin flow over 3 mm.

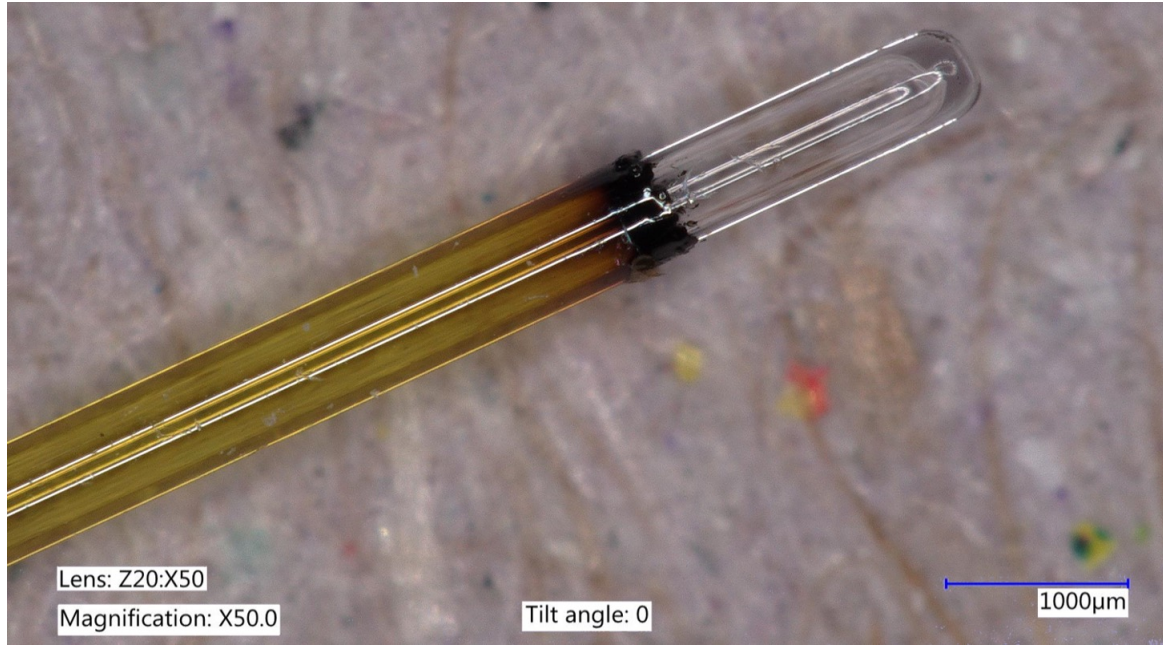


Figure 7.20: Fused silica capillary on the "end" side showing the plasma sealing method.

7.3 Experimental Thermal Characterisation of Fibre Bragg Grating Bonded to Specimens

This study arose from the concern over the decrease of pressure sensitivity with increasing temperature as seen in the experimental Chapter 6. The effect of the specimen material to which an FBG is attached is investigated in this section. The three sensor arrays with glass capillaries used in Section 7.1.2 were co-cured to a GFRP diaphragm and aluminium pressure chamber from the manufacturing method described in Chapter 4, Section 5.3. Figure 7.21 illustrates the set-up in the oven. The first investigation contained the three fibre + disc assemblies and the second test contained the addition of the aluminium pressure chamber support. Figure 7.22 illustrates a typical temperature profile recorded using a thermocouple. Each experiment was performed on separate day, leaving the oven, fibres and thermocouples enough time to cool down fully.

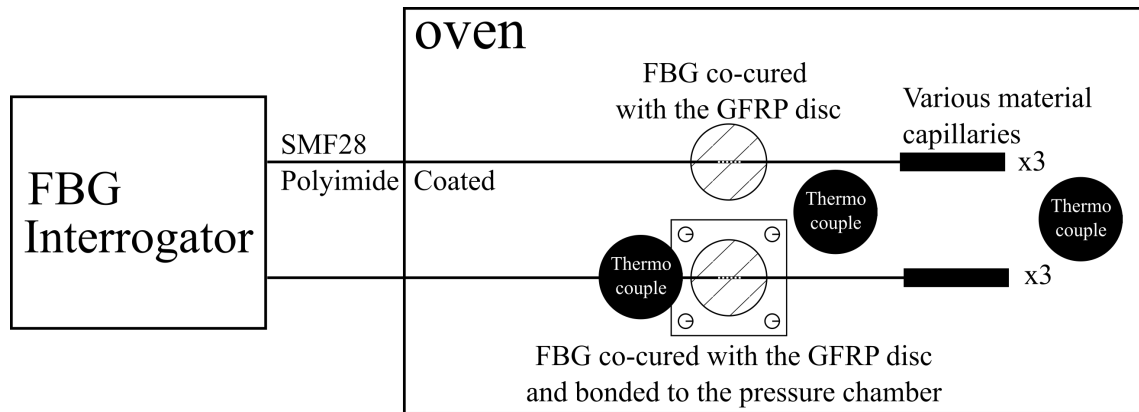


Figure 7.21: Schematic of the sensor arrays bonded to the GFRP discs and bonded to the aluminium pressure chamber. The first test comprising of the three fibre + disc assemblies. The second test comprising of the same assemblies bonded to the single pressure chambers.

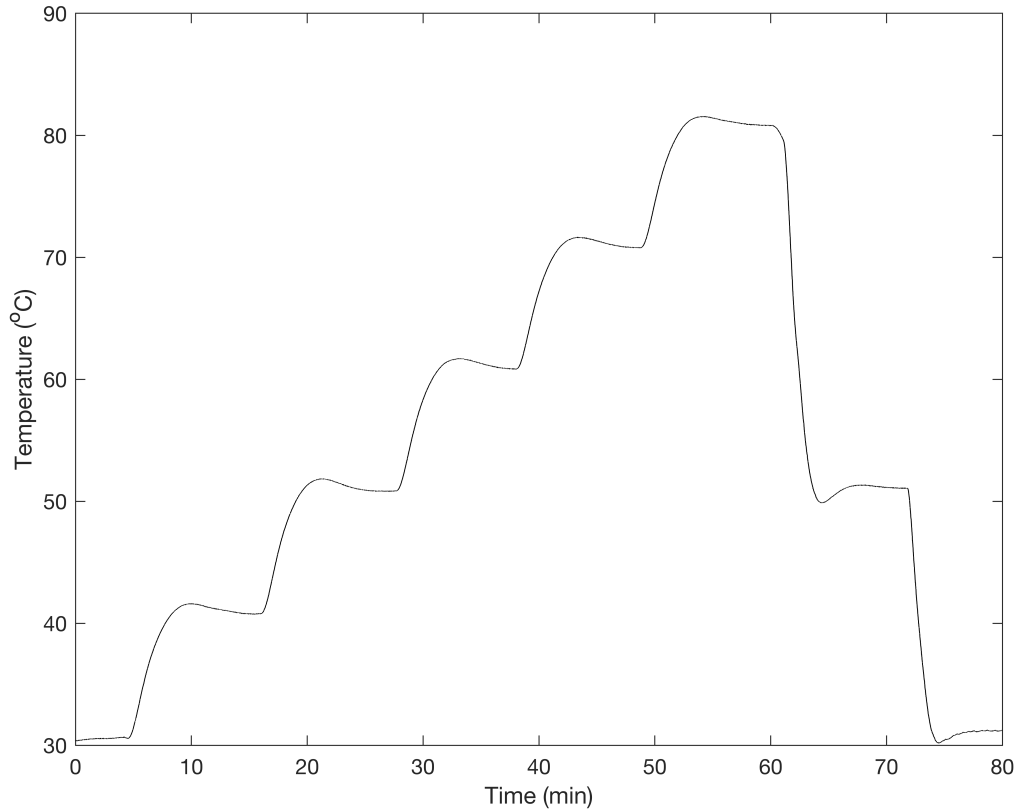


Figure 7.22: Typical thermal profile used to assess the performances of FBGs encapsulated and bonded to various materials. The temperature was stepped from 30°C to 80°C in 10°C.

7.3.1 FBG Bonded to Glass Fibre Reinforced Polymer

The free FBGs of each array were positioned in the centre of the disc as seen in Figure 7.21 and were then expected to increase their thermal sensitivities as seen in Section 7.2.2. The three array + disc assemblies were tested as per Figure 7.11. Figure 7.23 illustrated the set up inside the oven.

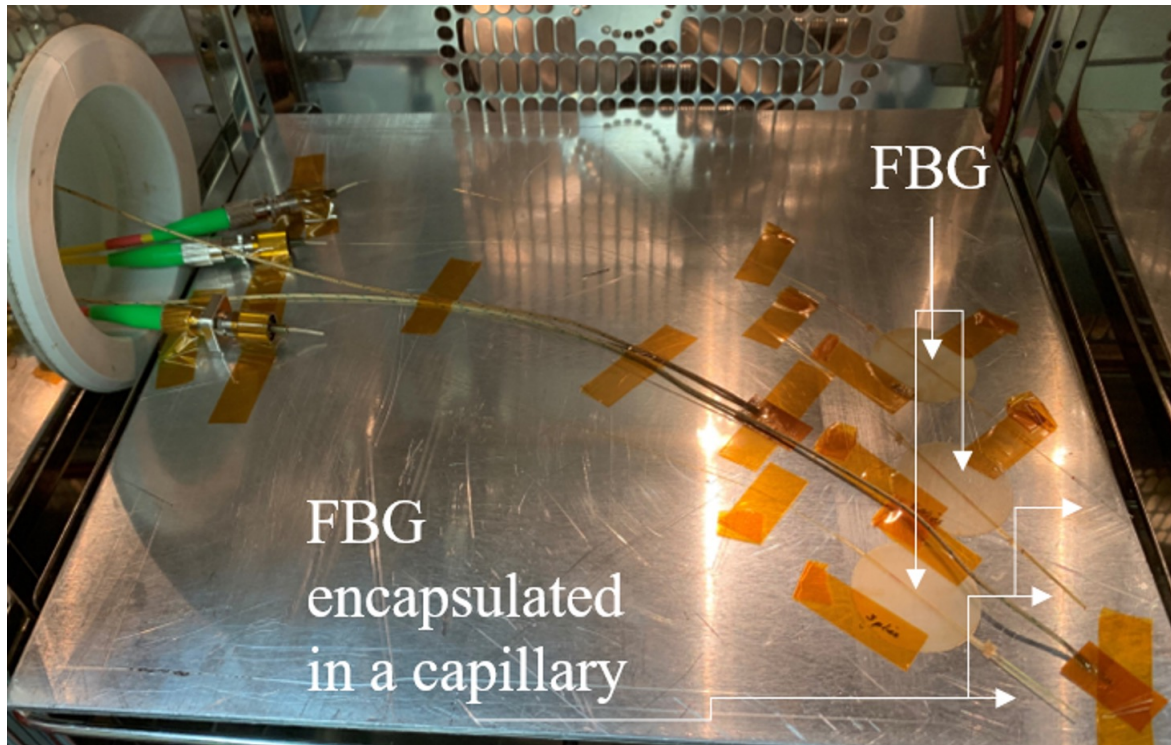


Figure 7.23: Image of the three sensor arrays with the glass capillaries bonded to the GFRP disc inside the oven.

The temporal thermal responses of each FBGs is shown in Figure 7.24 with the FBG bonded to the GFRP disc and the encapsulated FBGs in various material. One free FBG was also recorded in the borosilicate capillary fibre.

The thermal responses of the free and encapsulated FBGs are similar to the test presented in Section 7.2.1. The free and fused silica encapsulated FBGs show similar response with divergences at higher temperature while the borosilicate encapsulated FBG exhibits higher sensitivity, with larger wavelength shift per $^{\circ}\text{C}$. Those four FBGs appear to have return to their original state/wavelength when the temperature decrease to 60°C and 30°C , however there is a great discrepancy with the bonded FBGs.

Compared with the initial 30°C where the base wavelength was taken, the bonded

FBGs shifted by 265 pm on average at the last 30 °C step. With the free and encapsulated FBGs return to the original wavelength, the issue here cannot be a difference in temperature but instead, it appears that the bonded FBGs are in compression, with the hypothesis of the composite discs contracting with abrupt temperature change. It is possible that the FBGs would eventually be back to their original state if the test continued for an additional hour as suggested by the trend of the curve increasing from 75 min. However time constraints did not allow to run the experiments any longer. The hysteresis observed here could be explained by the resin softening initially, allowing a more flexible material that increased the sensitivity followed by the resin consolidating when decreasing the temperature, making the composite stiffer and so appears on the FBG as the compressing longitudinal strain.

The behaviour of the GFRP bonded FBGs at each step with the increase and decrease of sensitivity and additional time for stabilisation could be explained by the optical fibre's lower CTE working against the GFRP, forcing it to buckle. The resulting effect could be the representing the data provided by the FBGs with initially an increase in sensitivity that then decrease during buckling.

Overall, the FBGs that are bonded to the GFRP discs are all exhibiting higher sensitivities compared to the free and encapsulated FBGs, with on average a sensitivity of 16 pm/°C. While the two fibres containing the fused silica capillaries show similar sensitivity from the FBG bonded to the GFRP discs, the fibre containing the borosilicate capillary shows higher sensitivity from the FBG bonded to the GFRP discs.

The CTE of GFRP can vary from 1 to $20 \times 10^{-6}/^{\circ}\text{C}$ due to laminate properties such as resin content or void volume [124, 125, 123]. By using Equation (7.1), the CTE of the GFRP can be calculated to be in the order of $5 \times 10^{-6}/^{\circ}\text{C}$.

With the aluminium CTE one order above the calculated GFRP CTE, the thermal sensitivity of the discs bonded to the pressure chamber support should be enhanced.

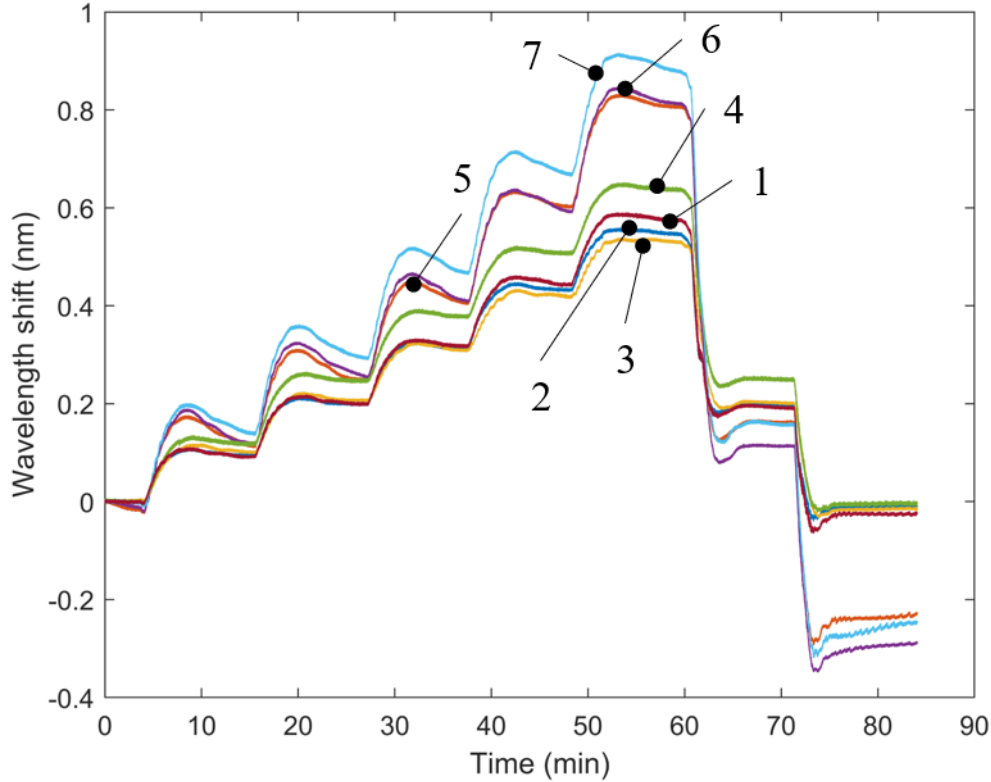


Figure 7.24: Temporal thermal responses of (1) free FBG. (2) fused silica encapsulated FBG (ID ϕ 0.32 mm). (3) fused silica encapsulated FBG (ID ϕ 0.20 mm). (4) Borosilicate encapsulated FBG (ID ϕ 0.15 mm). (5) FBG bonded to the GFRP disc, from the fibre with fused silica encapsulated FBG (ID ϕ 0.15 mm). (6) FBG bonded to the GFRP disc, from the fibre with fused silica encapsulated FBG (ID ϕ 0.32 mm). (7) FBG bonded to the GFRP disc, from the fibre with borosilicate encapsulated FBG (ID ϕ 0.15 mm). The temperature profile is given in Figure 7.22.

7.3.2 FBG Bonded to GFRP and Aluminium Pressure Chamber

Once the membranes were bonded onto the aluminium supports, they were also placed into the oven shown in Figure 7.8 and tested according to Figure 7.11 and Figure 7.25. Figure 7.26 shows the temporal thermal responses of the free and encapsulated FBGs and

the FBGs previously bonded to the GRRP discs that were also bonded to the aluminium support as presented in Chapter 3, Section 5.3. The fused silica encapsulated FBG of ID ϕ 0.32 mm broke during the handling of the components. As expected, the free and fused silica encapsulated FBGs exhibit similar thermal responses as Figure 7.24 and the borosilicate encapsulated FBG shows higher sensitivity to temperature change. They kept the same sensitivity throughout the experiments, making them reliable.

The thermal responses of the FBGs bonded to the discs and aluminium pressure chamber supports are exhibiting an enhanced sensitivity that shows quicker temperature stabilisation than when bonded to the GFRP discs only. At each step, the response of the FBGs mounted to the aluminium support appear to stabilise at a similar rate than the free and encapsulated FBGs. This time, the CTE of the aluminium is far greater than this of the optical fibre and GFRP, which overpower the effect seen in Section 7.3.1. With a CTE of $23 \times 10^{-6}/^{\circ}\text{C}$, the aluminium pressure chamber supports overtook the two other materials and the FBGs are measuring the thermal expansion of the aluminium. The enhanced sensitivity achieved $43 \text{ pm}/^{\circ}\text{C}$, corresponding to the aluminium CTE when replaced in Equation (7.1).

Finally, while the free and encapsulated FBGs return to their original wavelength when the temperature decreases back to 30°C , the aluminium support requires more time to cool down and be completely at equilibrium due to its mass. The FBGs responses appear to start decreasing around 100 min.

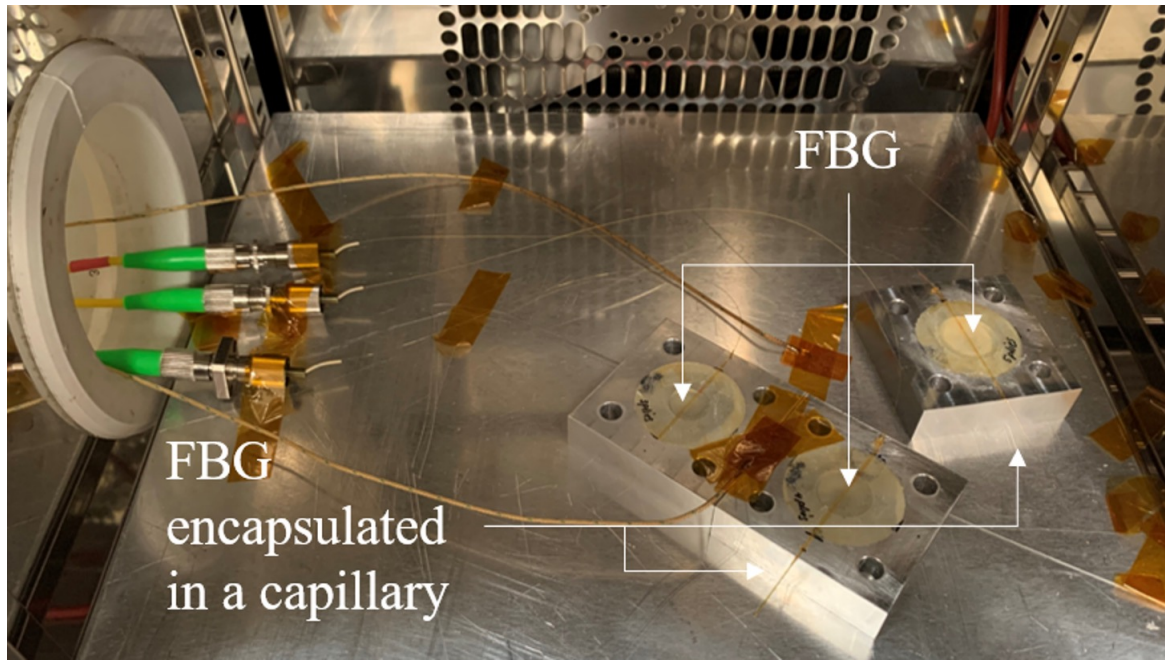


Figure 7.25: Image of the three sensor array + disc assemblies bonded to the single pressure chamber supports. One fused silica encapsulated FBG broken and does not appear on the picture.

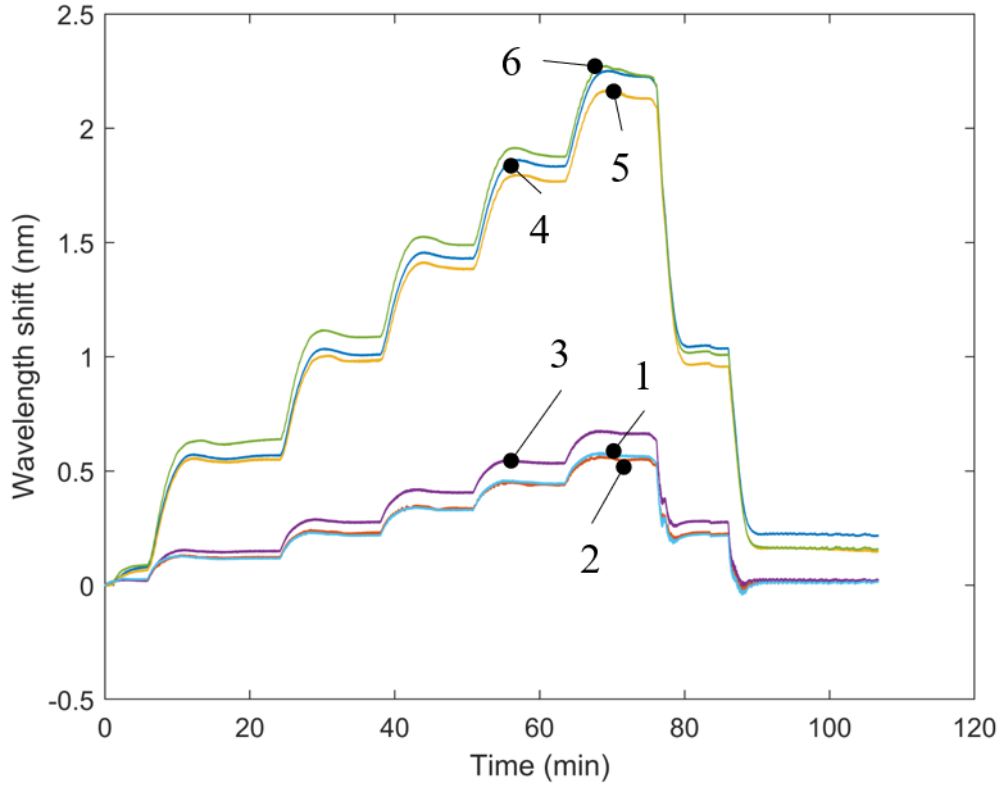


Figure 7.26: Temporal thermal responses of (1) free FBG. (2) fused silica encapsulated FBG (ID ϕ 0.20 mm). (3) Borosilicate encapsulated FBG (ID ϕ 0.15 mm). (4) FBG bonded to the GFRP disc and pressure chamber, from the fibre with the broken fused silica encapsulated FBG (ID ϕ 0.32 mm). (5) FBG bonded to the GFRP disc and pressure chamber, from the fibre with fused silica encapsulated FBG (ID ϕ 0.20 mm). (6) FBG bonded to the GFRP disc and pressure chamber, from the fibre with borosilicate encapsulated FBG (ID ϕ 0.15 mm). The temperature profile is given in Figure 7.22.

7.3.3 Discussion

Figure 7.27 shows the four stages of the manufacturing and the characterisation of the fibre sensing arrays: a free FBG, a fused silica encapsulated FBG, a bonded to GFRP material FBG and finally a bonded to GFRP and aluminium FBG. This graph was produced using the average values from Figures 7.12, 7.13 7.24, and 7.26, at each increasing step. While most were stabilized, the GFRP data were taken at the end of the step where it was

assumed to be the most stabilised. However, it appeared that more time was required for the GFRP bonded FBGs to stabilise due to the influence of the optical fibre as described in Section 7.3.1, meaning that the sensitivity and the calculated CTE could have errors. Figure 7.27 shows however that the thermal sensitivity of an FBG is greatly influenced by the material it is mounted to. With the increase thermal dependence of the aluminium support, the whole structure stiffens which explains why the pressure response decreased with increased temperature as seen in Chapter 6. The sensor itself is only composed of the GFRP disc + optical fibre, with the aluminium pressure chamber used for lab testing. Although the GFRP appears to only increase the thermal dependence by 1.5 times, its buckling behaviour might bring additional issues in a temperature variable environment. The sensitivities of each configuration is reported in Table 7.3, with free and encapsulated FBG, bonded to GFRP and bonded to aluminium at $11 \pm 0.05 \text{ pm}/^\circ\text{C}$, $16 \pm 0.07 \text{ pm}/^\circ\text{C}$ and $43 \pm 0.1 \text{ pm}/^\circ\text{C}$ respectively. The aluminium response with the linear and quick stabilisation is a great example of how the FBG sensors can be used to measure the CTE of a material.

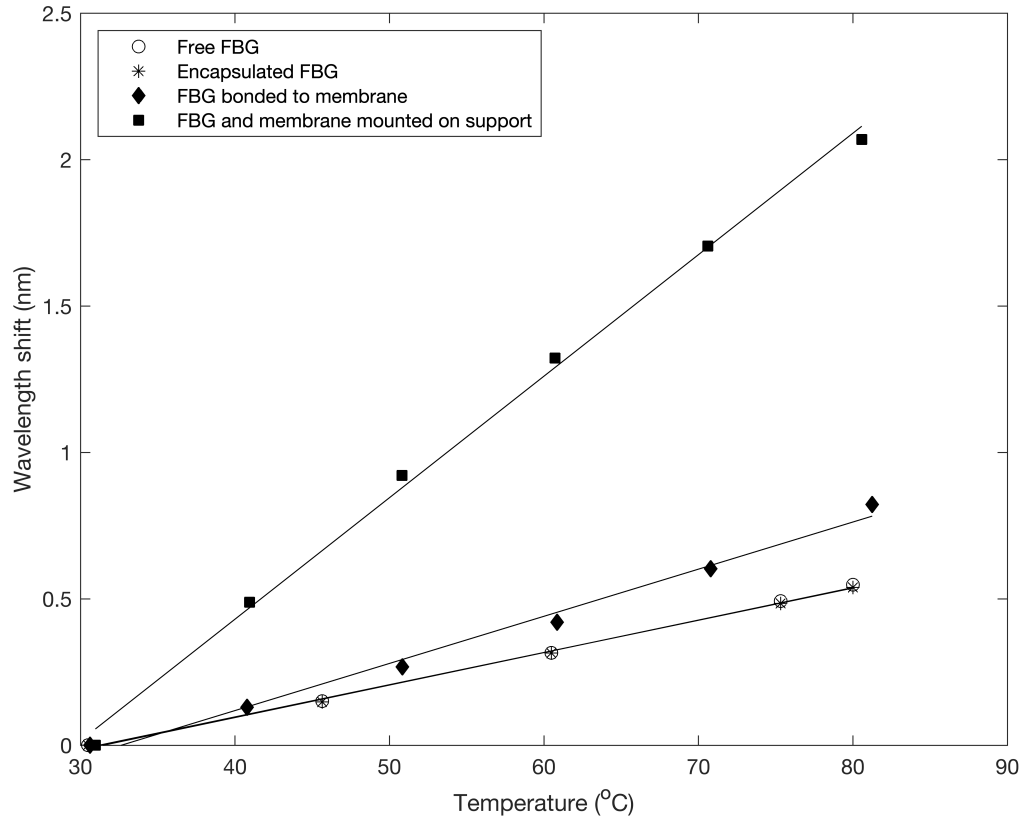


Figure 7.27: Thermal calibration curves of the free, fused silica encapsulated, bonded to GFRP and bonded to both GFRP and aluminium FBGs with respective linear fits ($R^2 = 0.9986$, $R^2 = 0.9989$, $R^2 = 0.9972$ and $R^2 = 0.9902$).

Table 7.3: Thermal sensitivities of the FBG at different stages

	Thermal sensitivity (pm/°C)
Free FBG (fused silica)	11 ± 0.05
Encapsulated FBG (fused silica)	11 ± 0.05
FBG bonded to GFRP	16 ± 0.07
FBG bonded to GFRP and aluminium	43 ± 0.1

7.4 Conclusion

This chapter presented thermal studies investigated for enhanced performances of temperature compensation, as well as addressing the decrease in pressure sensitivity discussed in Chapter 6. The choice of material and dimensions for an encapsulated FBG is important to consider when using capillaries for temperature compensation. The study revealed how smaller inner diameters and change of material have better responses and how the manufacturing of such arrays should be made with extra care on the bonding and sealing of the capillary. This new design using fused silica encapsulated FBG has been agreed by the engineering team at Mercedes AMG F1 as their new standard. In Chapter 8, the study on the F1 suspension is using the metal capillary as the components were produced before this study. The decrease in pressure sensitivity encountered during simultaneous temperature and pressure experiments was developed in this chapter and understood through the dependence of the material to which an FBG is mounted to. With small pressure applied to the sensor, the temperature sensitivity plays an important role in the stiffness of the structure and so the pressure (or strain) response with variable temperature environment. Further work should involve a different material for lab testing that is similar to those used in the final sensor design to avoid bias calibrations. The enhanced thermal sensitivity with aluminium and its linearity deserve more investigation where application require a higher temperature resolution than the minimum fibre resolution of $0.1\text{ }^{\circ}\text{C}$ for a typical interrogation system of resolution 1 pm.

Chapter 8

FBG Case Study: Strain Measurement of F1 Suspension Members

Introduction

This chapter covers a collaboration with the sponsor of this thesis, Mercedes AMG F1, on the instrumenting of the suspension of an F1 car with FBG strain sensors to determine the wheel loads. The challenges of this project laid within the manufacturing, where the incorporation of the FBG sensors into the wishbone highlighted several areas for consideration: the uniform bonding of the optical fibre so that the FBG sensor is not affected by a strain gradient, signal quality and the ingress/egress of the optical fibre from the component. This chapter firstly describes the processes and specifications required for embedding optical fibres in the composite components, considering the manufacturing constraints and the issues encountered with the signals obtained from the optical fibre sensors. The characterisation of the sensors embedded in the suspension during a F1 free practice session is reported, presenting a calibrated and temperature compensated data set which is compared with data obtained from strain gauges. By implementing optical fibre sensor technology in these components, it is possible to resolve the matrix of loads coming from the wheels in all suspension members and also opens up the possibility for the

development of additional measurements such as pressure and temperature, which is not possible in some areas using currently available sensors due to the tight racing structure design constraints.

8.1 Project Description

The aim of the project was to improve wheel-load measurements by instrumenting all suspension members using the same interrogating instrument as the pressure sensors. Electrical strain gauges are currently installed on some components, with the constraint of being bonded to a metal section in order to have a linear response. In these experiments, only one strain gauge was mounted on the surface of a wishbone, usually on the forward (FWD) leg, while FBG were embedded in both forward and rearward (RWD) legs, allowing the complete suspension load acquisition.

Previous work was undertaken by the composite R&D department at Mercedes AMG F1. Optical fibres FBG sensors were embedded in a suspension member and the work of this chapter builds on the learning from their manufacturing and testing experience. The development program contained several phases, with firstly the instrumentation of a wishbone member, followed by an improved procedure for bonding the optical fibre to the structure using carbon fibre blocks, representing a simplified version of a suspension with the same laminate. The analysis of the influence of the incorporation of the optical fibre sensors on the manufacturing process, the design of the means for robust ingress/egress of the optical fibre from the component and the selection of high temperature optical fibre connectors were investigated. The final piece of work involved the instrumentation of a whole suspension corner, which was calibrated and tested on the car during a practice session at the Portuguese track.

8.2 Manufacturing Process

The first part to be instrumented was a front wishbone. The suspensions are made from CFRP and are laminated and cured as two separate halves that are subsequently hot bonded together using a film adhesive. The load applied from the wheels oriented along the component longitudinal axis was of interest, rather than the strain due to flexion of the part. As a result, the optical fibre sensors were placed in the neutral axis of the part, in between the two bonded halves. The first stage of the manufacturing process used hot bonding to embed the optical fibres, rather than laminating them within the composite.

Four grooves were machined in each half of the wishbone and four optical fibres were placed above the film adhesive, as shown in Figure 8.1. Each optical fibre contained four FBG sensors, where the two FBGs at the distal end of each fibre were encapsulated in a metal capillary tube to make them strain free and facilitate their use as temperature sensors for compensation of the influence of temperature on the two strain sensors. Figure 8.2 illustrates a typical optical fibre, showing FBGs 3 and 4 encapsulated in the metal capillaries and placed very close to FBGs 1 and 2 for temperature compensation. This process was based on work undertaken prior to this research project, which consisted of predominantly the same process, with the difference being that the optical fibres were placed on top of the film adhesive without the help of the grooves. This was the simplest and most straight forward process. However, without grooves, it was difficult to maintain the appropriate orientation of the optical fibres, parallel to the edges of the part and following the minimum 10 mm bend radius. In this process, the paths of the optical fibres followed the guides and were locked in position using pieces of film adhesive, as shown in Figure 8.1. Once the optical fibres were secured with the film adhesive, the upper half was bolted to the lower half and the whole assembly was cured in an autoclave at 180°C, under 3 bars pressure.

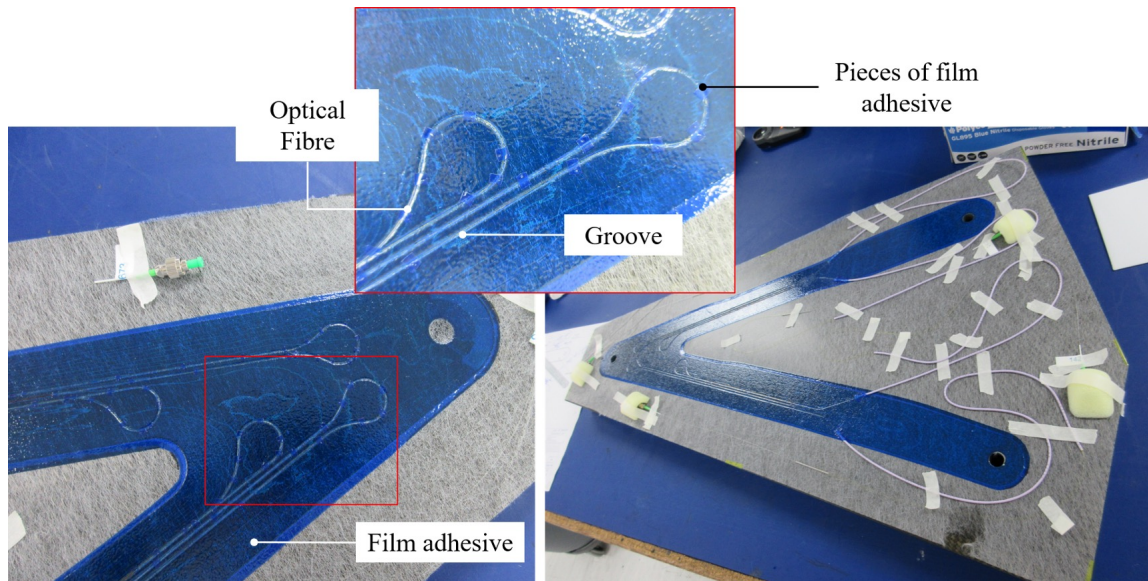


Figure 8.1: Images showing the lower part of the wishbone where the blue film adhesive has been applied over the surface and the grooves. The optical fibres were secured in place over the bends with strips of film adhesive as shown in the enlarge picture.

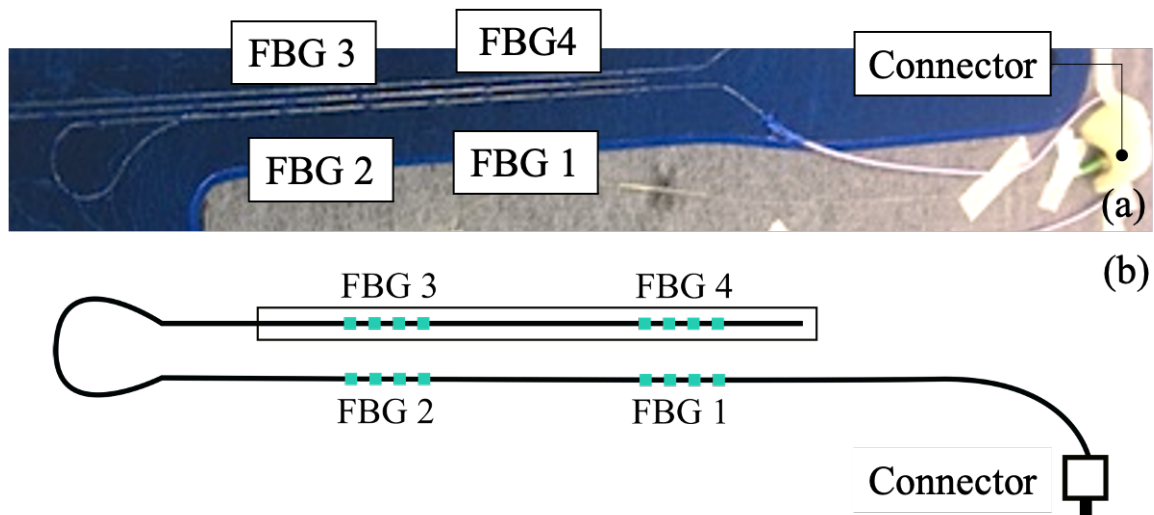


Figure 8.2: (a) photo and (b) schematic of a typical optical fibre showing the four FBG sensor with FBG 1 and 2 used as strain sensor and FBG 3 and 4 used as temperature sensor by being encapsulated in a capillary tube and used to temperature compensate the FBG 1 and 2 sensors.

8.2.1 Limitations

Although this method for the incorporation of the optical fibres into the component was simple and required only the additional steps of machining the grooves and placing the optical fibres into the grooves, analysis of the signals returned from the FBG sensors, indicated that the process required further refinement.

Figure 8.3 and Figure 8.4 show the spectra of the four fibres, before and after the hot bond process, with FBG 1 and 2 used as strain sensors and FBG 3 and 4 as temperature sensors as shown in Figure 8.2.

The interface used with the FBG interrogator from SmartFibres gives the option to setup wavelength windows per gratings, assigning its own properties and spectral limits [139]. This is useful when an FBG unexpectedly exhibits high strain and risks overlapping spectrally with another grating. By setting a window, the signal will be lost once outside its own slot. Assignable properties include gain control up to 8 times to avoid loss of signal. The instrument can automatically increase the gain when the return signal is weak, unless specified on a particular manual gain.

Overall, this automatic gain increase happened with all four fibres after the cure. Figure 8.3 and Figure 8.4 show the increase in the background spectrum reflectivity after the two strain FBG 1 and FBG 2 sensors, suggesting the automatic gain was activated because of the weak return signal. Only the fibre 4 in Figure 8.4 (b) shows the temperature sensors FBG 3 and 4, with low intensity peaks, even with the automatic gain increase. The reduced signal in the fibre and the loss of most temperature sensors can have multiple sources: the fibre was broken after FBG 1 and FBG 2 or the fibre was crushed in a way that introduced losses. As a result, the signals from FBG 3 and FBG 4 were not visible. The latter is more likely especially with fibre 4, where the two temperature sensors are still detected by the instrument.

The strain sensor FBG 2 in Figure 8.3 (a) also suggest the fibre is crushed by the introduction of side bands. This sensor single peak before cure resulted in three peaks after. A split in the peak can suggest non uniform residual strains and transverse loading that occurred during the manufacturing, introducing birefringence [140, 141].

Another sign of residual strain in all fibres is the post manufacture wavelength shift of all detectable sensors. In fibre 1, Figure 8.3 (a), FBG 1 was shifted by 1.276 nm and FBG 2 by 2.079 nm. In fibre 2, Figure 8.3 (b), FBG 1 was shifted by 0.981 nm and FBG 2 by 1.782 nm. In fibre 3, Figure 8.4 (a), FBG 1 was shifted by 0.981 nm and FBG 2 by 1.782 nm. In fibre 3, Figure 8.4 (b), FBG 1 was shifted by 0.494 nm and FBG 2 by 0.687 nm and both FBG 3 and FBG 4 were shifted by 0.3 nm. The shift in wavelength and the high loss in all fibres suggest residual strains all along the fibre, starting before FBG 1.

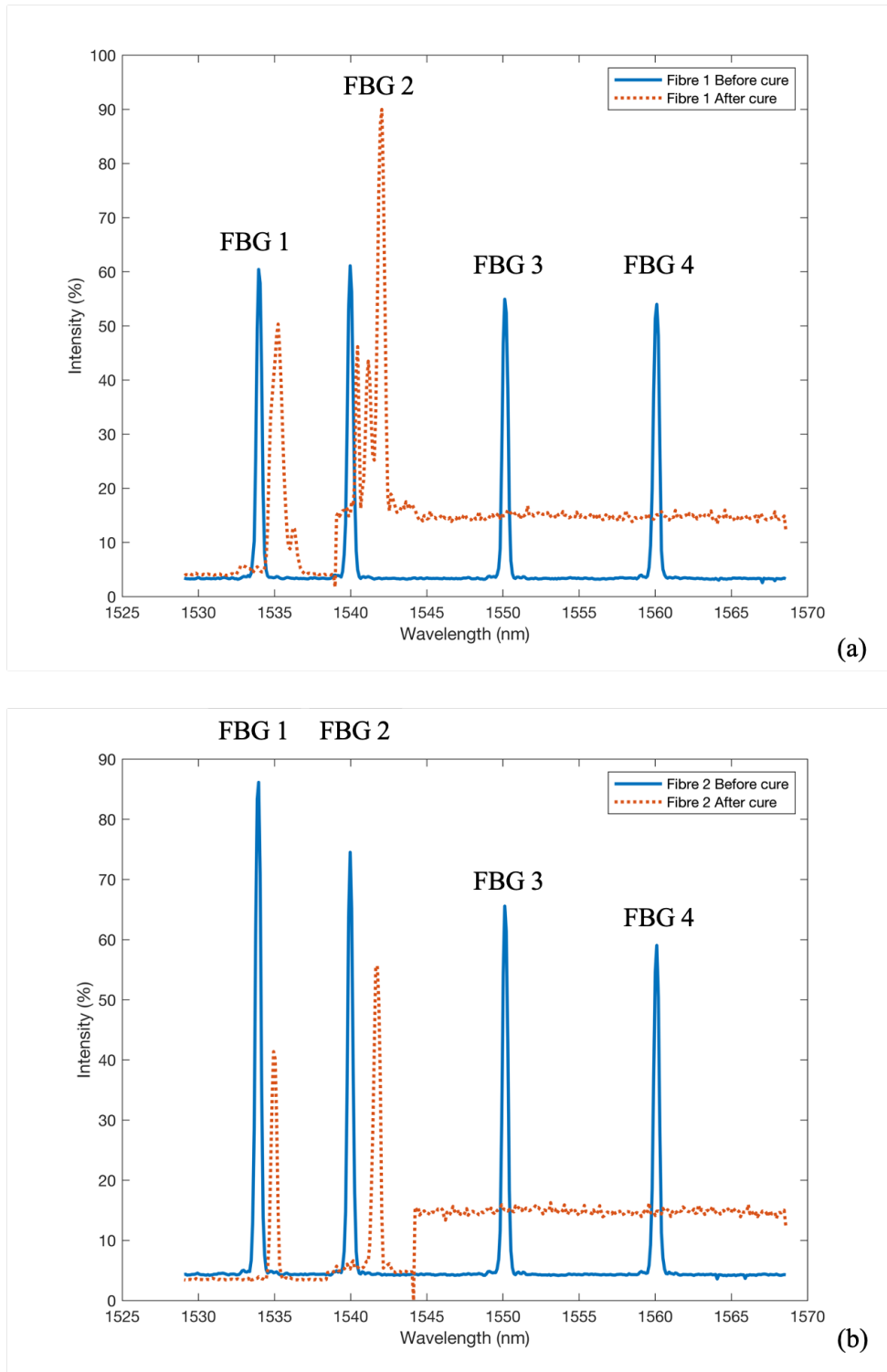


Figure 8.3: (a) Spectrum of the optical fibre number 1 (a) and 2 (b), showing the four wavelength peaks before and after the cure.

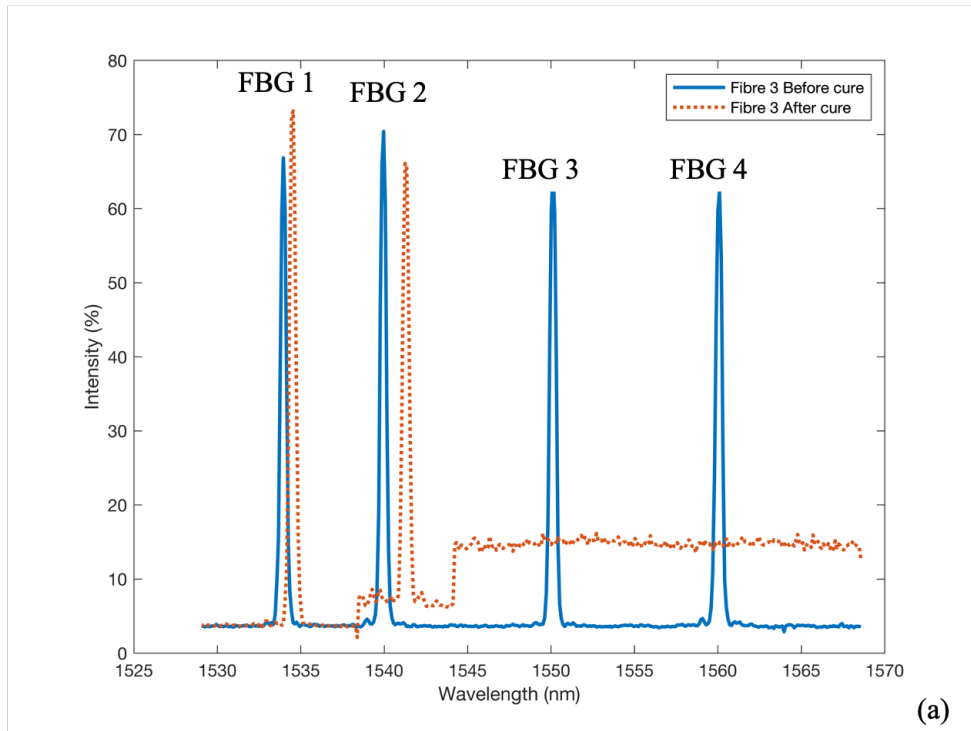
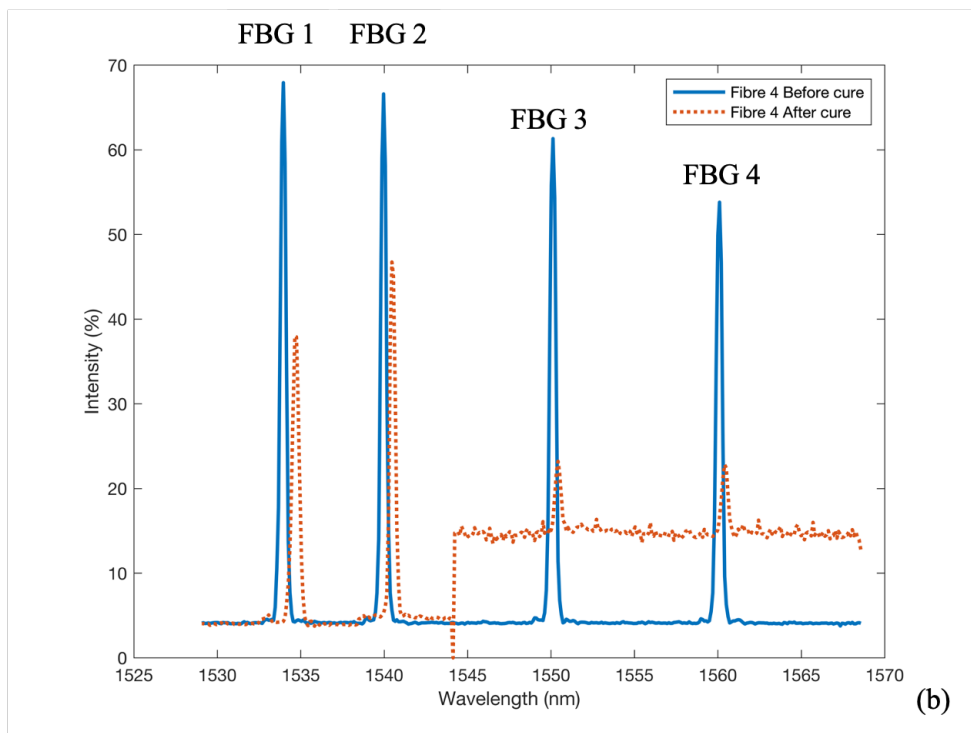


Figure 8.4: (a) Spectrum of the optical fibre number 3 (a) and 4 (b), showing the four wavelength peaks before and after the cure.

The previous spectra indicate that the process of manufacturing the wishbone induced

residual strain, non uniform strain and losses in the optical fibres, with the losses compromising the interrogation of the FBGs packaged as temperature sensors.

The wishbone was X-rayed with the intention of visualising the optical fibres and understanding if and where breakage had occurred, or if indeed the fibres could be simply crushed.

Figure 8.5 shows two X-ray images of the wishbone, focused at the neutral axis plane. Figure 8.5 (a) shows the top of the wishbone, where the optical fibres bend and Figure 8.5 (b) shows the ingress and egress of the optical fibre at the edge of the component. In the latter picture, we can identify the Kevlar fibres from the inside of the protective sleeve and assume this is the only bond between the sleeve and the part. As a result, the bond was weak at the ingress of the component and the pink sleeve slid off easily as shown in Figure 8.6. This happened during handling of the component.

Figure 8.5 allows the identification of the main issues that influenced the reflection spectra from the FBG arrays. As the part was cured in an autoclave under high pressure, the film adhesive flowed out to the edges. The process of manufacturing a suspension component involves trimming the excess adhesive all around the edges, which is an indication that the resin flow towards the edges of the parts due to the pressure in the autoclave. As a results, although the pieces of film adhesive helped to keep the optical fibre in position during their placement in the grooves, once heated during cure, they did not help with the resin flow and the optical fibres moved out of their grooves.

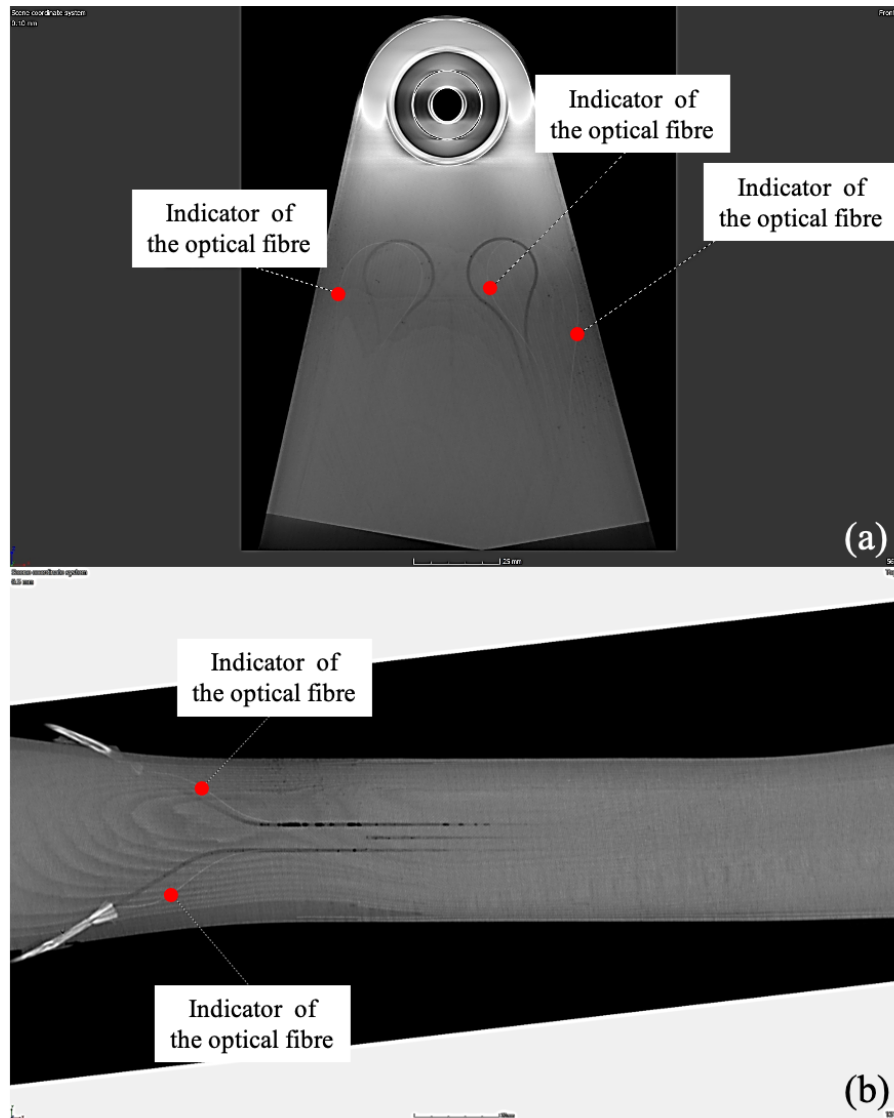


Figure 8.5: X-ray images of the wishbone on the neutral plane. (a) the top of the component showing the optical fibres offset from their grooves at the bends. (b) the exit of the optical fibres showing the offset from the slight bends and the Kevlar fibres from the protective sleeves.

The wishbone was loaded in an Instron tensile machine and handed from department to department during the process. As a result, several of the optical fibre sleeves pulled out from the part, leaving short section of fibres which were unable to be spliced again with a connector as shown in Figure 8.6.

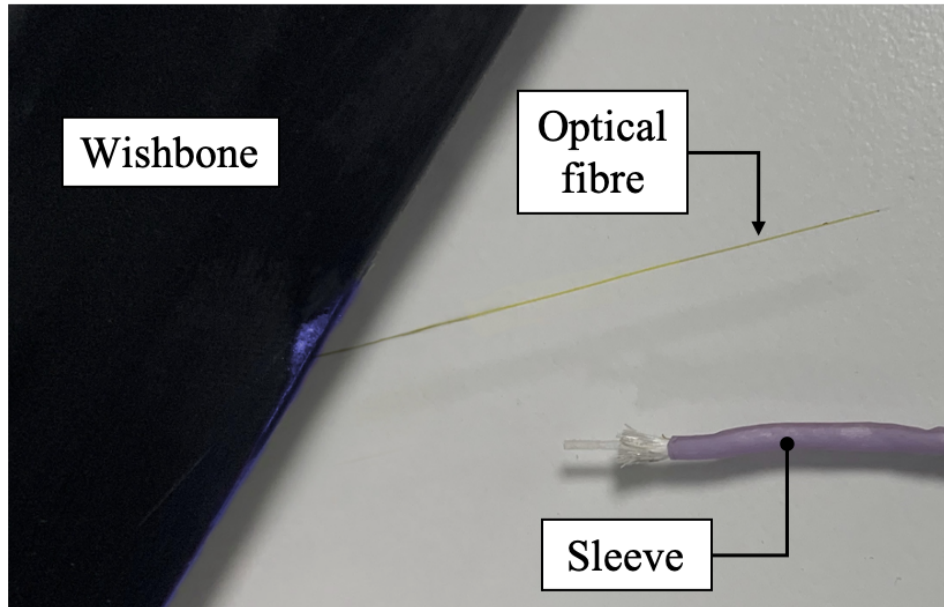


Figure 8.6: Image of the optical fibre sleeve pulled out of the part at the egress.

The three issues that had to be addressed were:

- The optical fibres were not secured in their grooves, so that they could move with the flow of resin. As a result of the displacement of the optical fibres, the FBG spectra were affected due to residual stresses from the part imposing a non-uniform load transverse to the optical fibres.
- The bond at the egress of optical fibre from the part was weak, especially where the sleeve started. As a result, the optical fibres broke when being handled, with the sleeves sliding out.
- Parts of the assembly of the connectors, designed for operation at temperatures up to 70 °C, were observed to have melted.

An investigation to improve the manufacturing process was performed, involving several iterations to ensure that a better bond with no porosity was obtained. An interface for

the ingress of the optical fibre into the part was designed and finally a high temperature connector was identified, tested and purchased from the commercial supplier.

8.2.2 Manufacturing and Design Investigations

As the main issue encountered with the manufacturing concerned the movement of the optical fibres within the component during the cure, it was decided to bond them in their grooves prior to hot bonding the two halves of the suspension component together.

Firstly, the Carlisle IT sleeve [142] was bonded to an in-house designed stainless steel part that allowed the change of diameter in the transition between the sleeve and the bare optical fibre to be smooth, reducing the potential for breakage at this weak point. The sleeve was bonded using epoxy paste adhesive to the larger diameter of the metal part as shown in Figure 8.7 (a). Once bonded to the metal part, the bare fibre was fed to the required position. This additional metal part also allowed a better bond by placing it in the groove inside the component, as shown in Figure 8.7 (b). The epoxy resin [143] was cured to set in an oven at 90 °C for one hour.

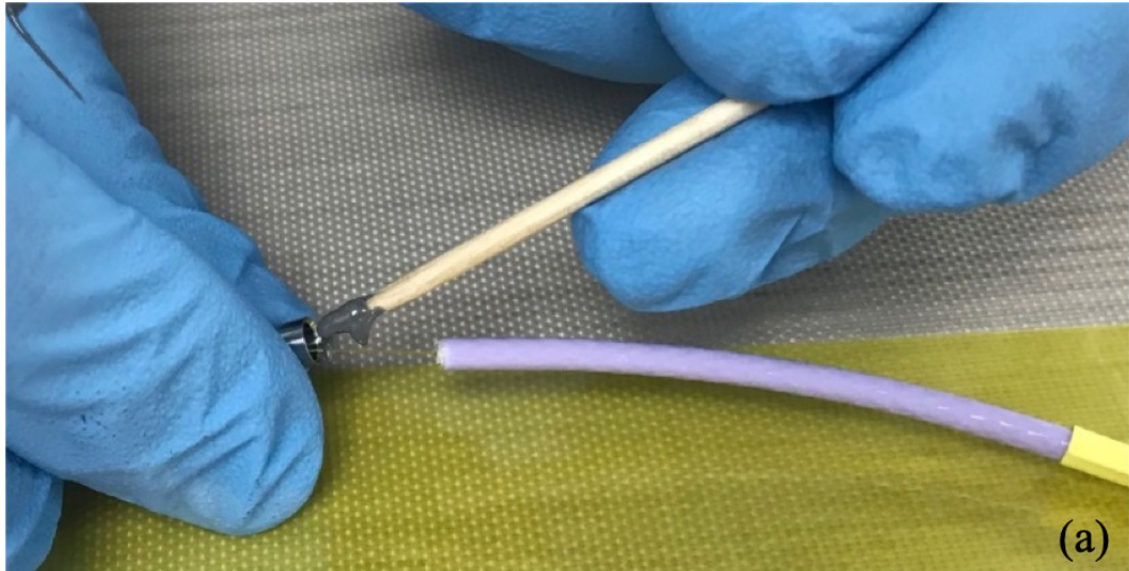
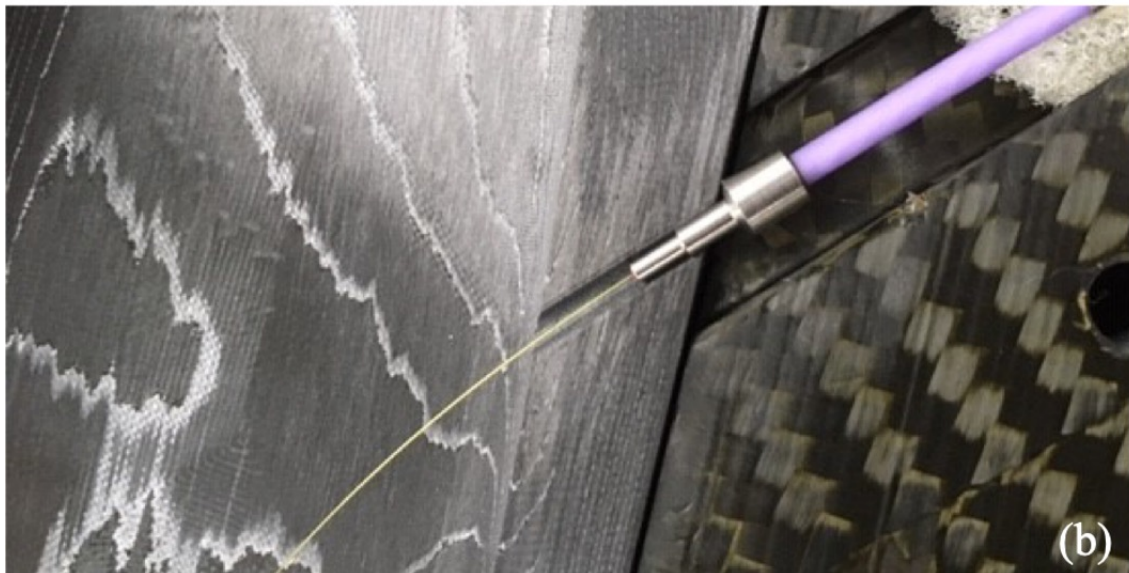


Figure 8.7: (a) pictures showing the bonding of the metal part to the protective groove (b) and the final result.

The lower half of the suspension component was then cleaned and degreased using a release agent [117] and the same epoxy resin was applied in the groove, as shown in Figure 8.8 (a). The resin was also applied around the optical fibre after degreasing it, as shown in Figure 8.8 (b). Once the optical fibre was placed in the groove, the latter was filled with resin and compacted to ensure that no air was trapped as shown in Figure 8.8 (c).

The component was placed in an oven at 40 °C for 30 min and checked for air bubbles before leaving it for 12 hours at room temperature. Once the whole resin had hardened, it was cured at 90 °C for one hour. With the optical fibres secured in their own grooves, both halves of the component were hot bond cured together at 180 °C under 3 bar pressure.



Figure 8.8: Pictures showing the manufacturing process to embed the optical fibres. (a) process involves the resin applied in the groove (b), the resin applied to the optical fibre (c) and the optical fibre placed in the groove with the resin filled flush.

Finally, the high temperature connector was purchased from Diamond SA from their high temperature range [136], designed to operate at temperatures of up to 150 °C. A sample comprising of a connector pigtail was tested under the hot bond conditions (180 °C, 3 bar pressure). The pigtail was analysed using an Optical Backscatter Reflectometer (OBR) from Luna Innovations [144] before and after the cure and the signals are shown in Figure 8.9. The connector did not exhibit an increase in its return loss nor any alteration to the signal, suggesting a high quality connector capable of withstanding the conditions of the suspension component manufacturing.

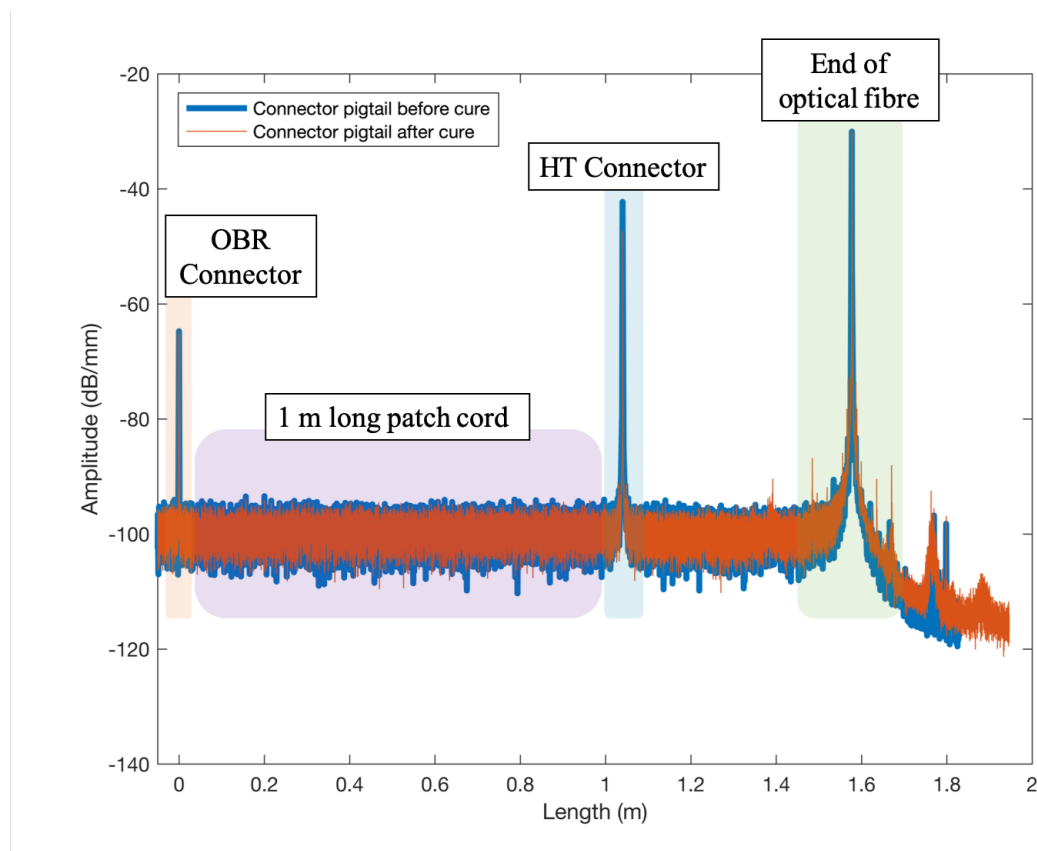


Figure 8.9: High temperature connector pigtail signals before and after high pressure and high temperature cure.

Although the wishbone described in Section 8.2 had unusable temperature sensors, it was however tested in an Instron tensile machine and under temperature variation. Positive and negative loads were applied to the part, which induced a wavelength shift due to

the strain. This test allowed the calibration of the component to deduce the loads experienced by the component when on the car. The calibration showed linear response and one of the sensor result is arbitrarily shown in Figure 8.10 (although restricted thesis, no additional information will be given on the figure for confidential reasons). Testing the part under load and temperature variations showed that the temperature compensation could be done by simply subtracting the change in wavelength of a working temperature sensor from the changes in wavelengths of the strain measuring sensors.

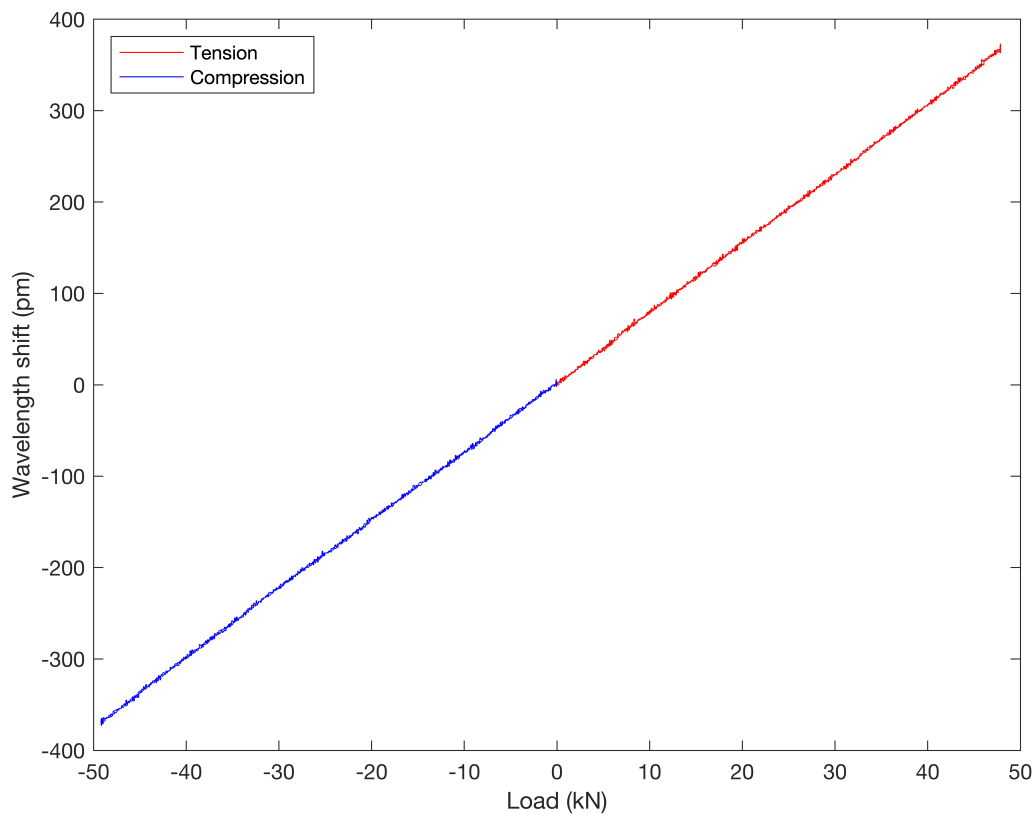


Figure 8.10: Calibration results in tension and compression of an FBG sensor embedded in the wishbone.

The calibration consisted of the force coefficient given by the linear gradient, in N/pm. When the instrumented wishbone is installed on the car and subject to loads, the delta

wavelength change can be multiplied by this coefficient. As a result, the loads are known and can be compared with the loads predicted by the surface mounted strain gauges. Although restricted thesis, the calibration coefficients will not be shared in this thesis for confidential reasons.

Section 8.2.3 presents an example of an on-car instrumented wishbone trialled on the track for a lap. The coefficients used to convert the wavelength shift into load were determined previously from the calibration of the sensors and use to compare the data with a strain gauge mounted on the same leg.

8.2.3 On Car Testing

Once the manufacturing process was deemed satisfactory and the calibration reliable and linear, a full corner of the car was instrumented to be tested during the 2019 free practice at the Barcelona track.

An inspection of the optical fibres was undertaken before the bonding of the two halves of the wishbone, where the dimensions, wavelength, intensity and position were verified against the drawings provided by the optical fibre FBG array manufacturer.

Four optical fibre FBG arrays were sourced from FemtoFiberTec for the four front suspension components: pushrod (FPRD), trackrod (FTRD), top wishbone (FTWB) and lower wishbone (FLWB). The FLWB FBG array was connected to the SmartScan FBG interrogator for inspection and the reflections from the FBGs could not be observed, as shown in Figure 8.11. The optical fibre arrays for the FTWB and FLWB were similar so their signals were compared to investigate the issue.

In an effort to improve the signal, the connector was firstly cleaned using a Cletop connector cleaner from Fujikura, without improvement. Then, the possibility of back reflection from the end of the fibre was considered. Unfortunately, it meant the temperature

sensor had to be cut as the end of the fibre and the FBG were encapsulated in the capillary tube, After cutting the fibre at an angle to avoid back reflection, the signal did not improve either.

The arrays were further investigated using the OBR as per the schematic shown in Figure 8.12. The OBR scans the entire length of the optical fibre and the backscatter light levels are measured by an Optical Time Domain Reflectometer (OTDR) to determine optical power, losses, reflections. Each interface of the optical fibre such as connector, splice, end of fibre reflect and contribute to the interference pattern. A peak in time domain can be located at the corresponding length of the optical fibre.

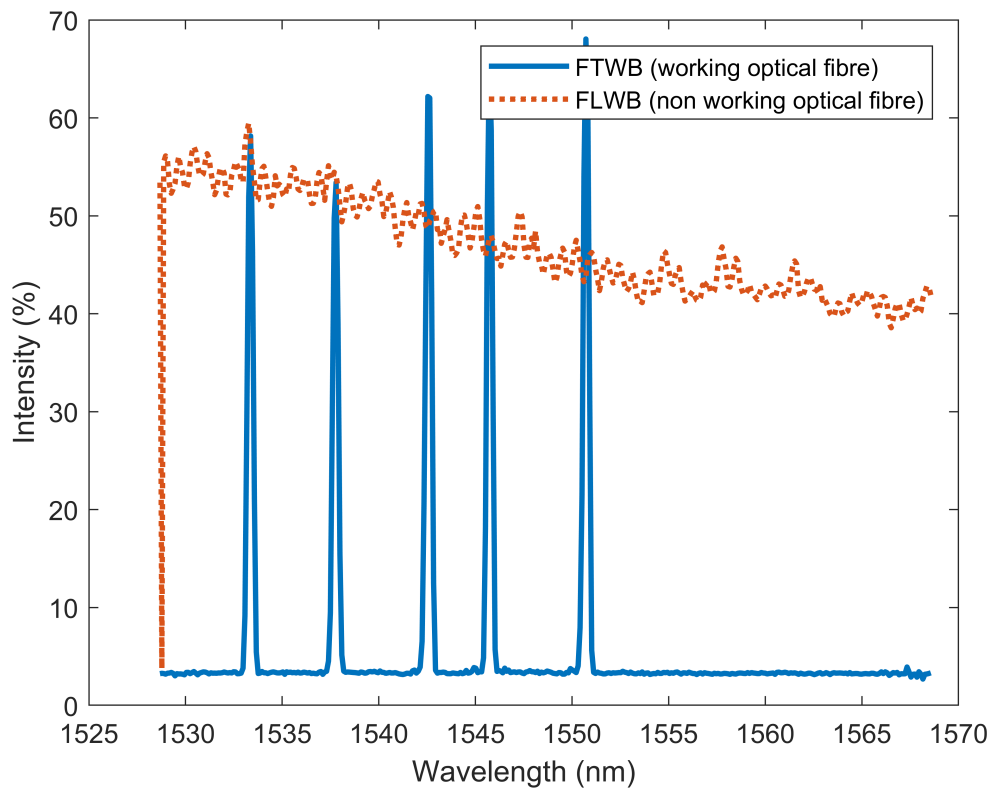


Figure 8.11: Optical spectrum of the optical fibres used for the FTWB and FLWB members.

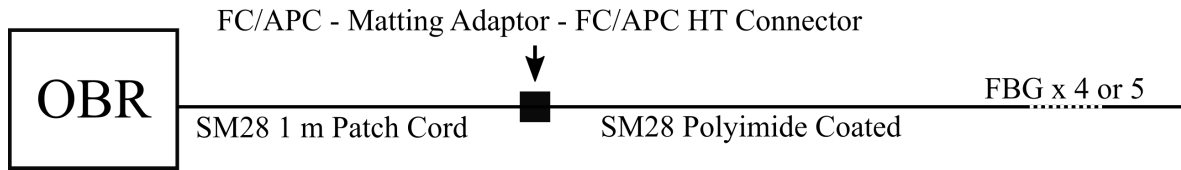


Figure 8.12: Schematic representing the testing of an optical fibre using an OBR.

Figure 8.13 shows the FTWB and FLWB optical fibres scanned with the OBR and shows the multiple interfaces in both optical fibres as the time domain linear amplitude converted to a log scale along the length of the fibre. The bulkhead connector in the OBR instrument, which is located at the egress of the instrument, is shown at 0 m by the first peak. An FC/APC patch cord of SM28 optical fibre is connected to the instrument with a matting adaptor to connect another FC/APC connector. At the 1 m length of the patch-cord, another peak can be seen which corresponds to the interface between the patchcord FC/APC connector, and the HT connector from commercial supplier. The subsequent peaks correspond to the reflections from the 4th and 5th FBGs and the end of the fibre located around 1.5 m from the connector. The FLWB only has the 4 FBG sensors as the temperature sensor was cut, as explained previously.

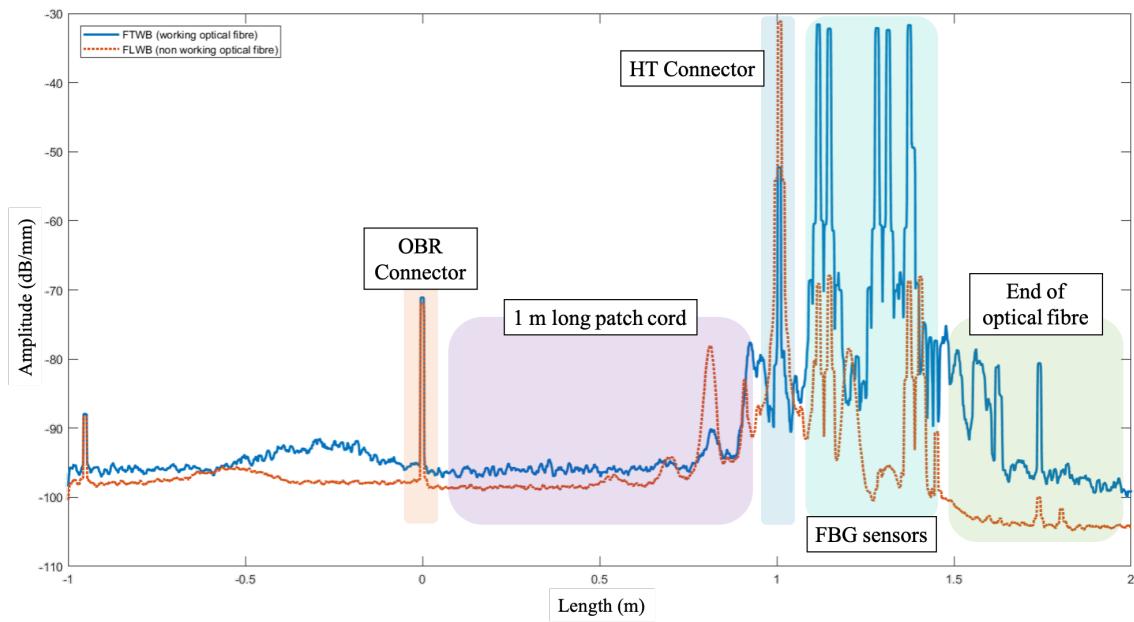


Figure 8.13: FTWB (blue line) and FLWB (red dash) optical fibres scanned with an OBR.

Figure 8.14 shows an enlarged version of Figure 8.13, focused on the length of the FTWB and FLWB optical fibres only, starting just before the connector. The FBG reflections are clearly distinguishable in both fibres, which shows that the FBGs are present in the FLWB optical fibre even if they were not visible in the spectrum from the SmartScan FBG interrogator in Figure 8.11. The reflectivity of the connector in the FLWB array is so high, indicating significant loss in the optical power reaching the FBGs and subsequently in the reflected signal arriving at the detector. As a result, the FBG interrogator was not able to resolve the signal and appear that no gratings are written in this optical fibre array. Unfortunately there was no possible solution apart from replacing the connector on this optical fibre.

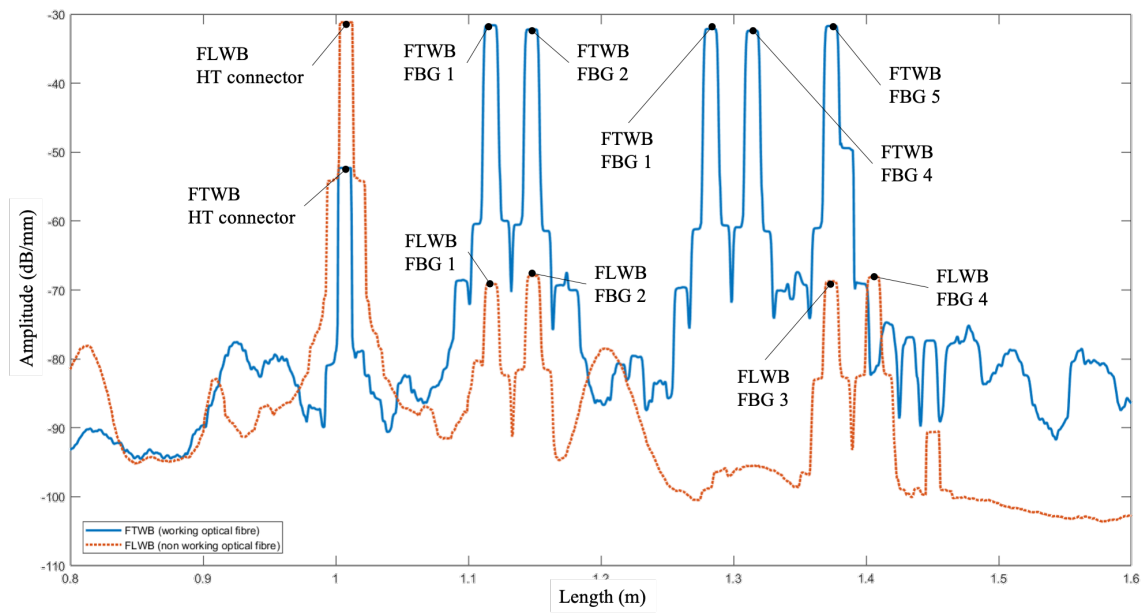


Figure 8.14: FTWB (blue line) and FLWB (red dash) optical fibres scanned with an OBR, focused on the multiple interferences.

The FLWB optical fibre array was replaced by the supplier and the full front left corner of the car was instrumented. A re-packaged SmartScan interrogator was installed in the cockpit of the racing car and patchcords connected to the instrumented suspension components were routed back to the interrogator. Figure 8.15 shows the components of the front left corner that were instrumented, with the FLWB in grey, the FTWB in cyan, the FPRD in yellow and the FTRD in magenta.

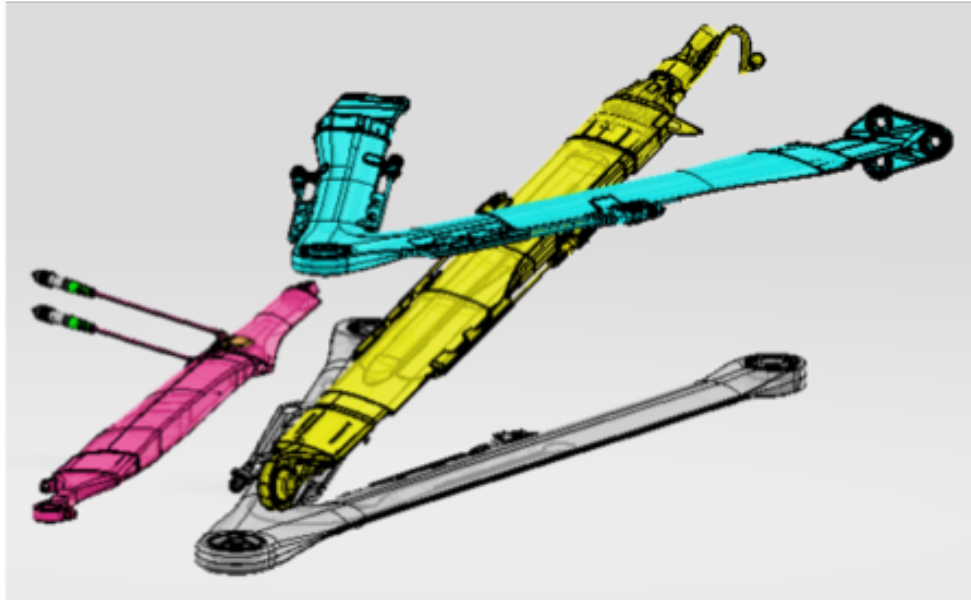


Figure 8.15: Picture showing the 3D of the front left corner with the instrumented suspension: FTWB (cyan), FLWB (grey), FPRD (yellow) and FTRD (magenta).

The data were logged over the duration of the free practice session, starting a few second before the lap, when the car was static in the garage. The following graphs plot the data extracted from the FTWB FWD leg, which is the leg closer to the front of the car, where the strain gauge is also located (no strain gauges were located at the rearward leg, while FBG sensors are embedded in both wishbone legs). The data recorded at the start of the log when the car was static were used as the datum for the subsequent measurements.

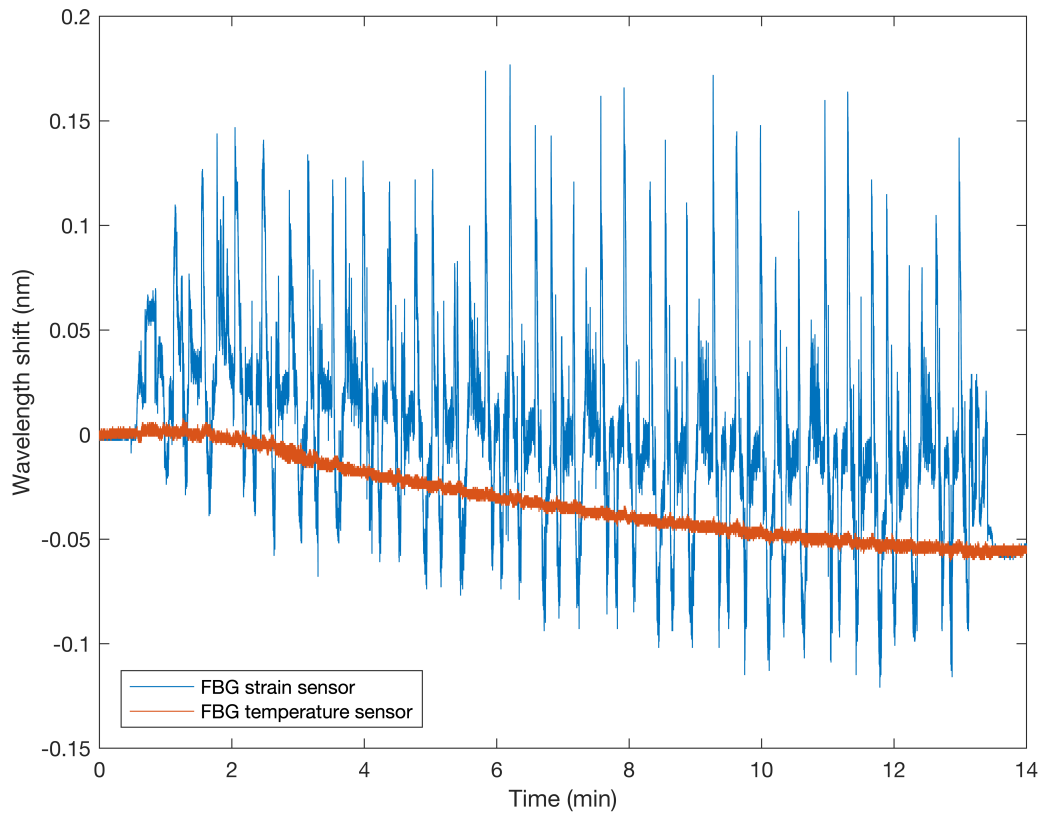


Figure 8.16: Optical fibre FBG sensor raw wavelength shifts plotted as a function of time. Strain and temperature FBG sensors during laps in a FTWB, forward leg.

Figure 8.16 shows the raw wavelength shifts of the two FBG sensors of the FTWB FWD leg, with one sensor used for load measurement (FBG strain) and the other used for temperature compensation (FBG temperature).

Figure 8.16 shows the temperature gradient from the start of the free practice to the end when the car returned to the garage, equivalent to about a 5.5 °C drop. The decrease of temperature can be explained by the air flow cooling the brakes when the car is in motion, with the temperature thus increasing when it is static in the garage after the laps. It can be observed that both sensors meet at the same wavelength shift when back in the garage at the end of the 14 min, suggesting they are both subject to the same temperature variations.

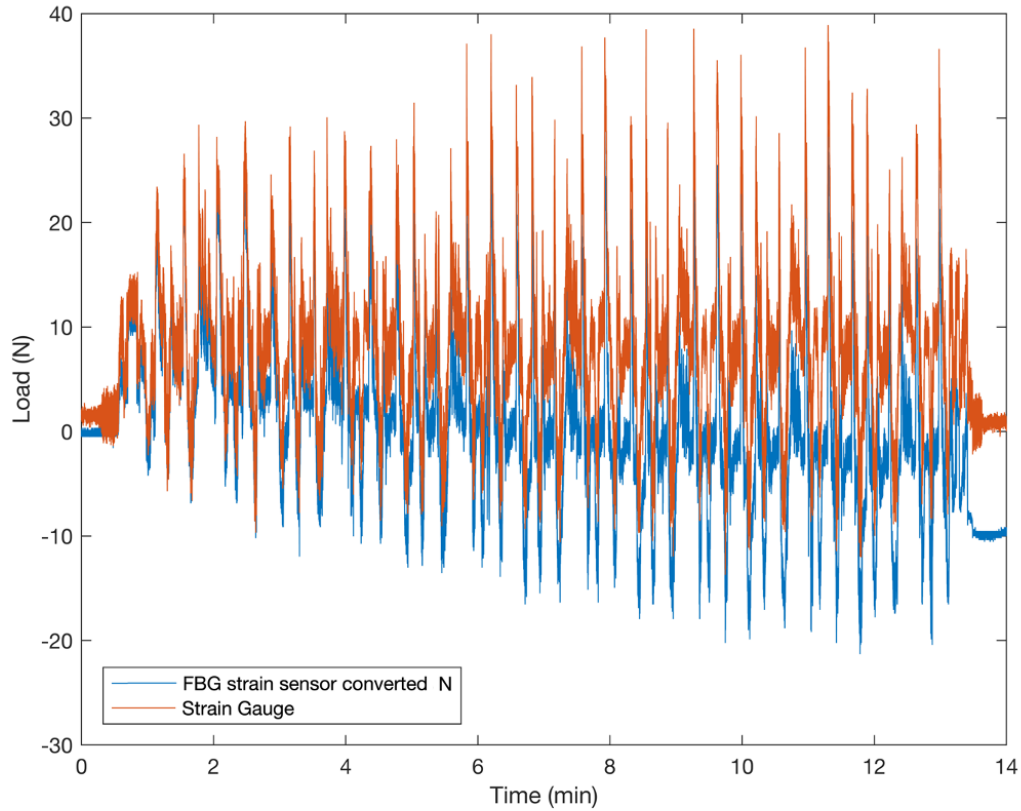


Figure 8.17: Temporal series showing the converted FBG strain sensor and the strain gauge sensor placed both on the forward leg of the FTWB.

Figure 8.17 illustrates the temperature variation of the strain sensor by comparing the temperature compensated strain gauge and the converted data FBG strain sensor. Both were calibrated in the test facilities at Mercedes F1 before being deployed on the car and their outputs (voltage and wavelength respectively) were given a coefficient to convert into Newton, in order to measure loads. The coefficients arose from the calibration curves. Figure 8.17 shows impressive correlation between the strain gauge and the FBG strain sensor. Although the FBG strain sensor is not temperature compensated, it shows the same trend as the strain gauge. The latter is already temperature compensated from the supplier and the temperature trend from the FBG temperature sensor from Figure 8.16 can be observed in Figure 8.17. Figure 8.18 shows the temperature compensated FBG

strain sensor, using the data from the FBG temperature sensor. The wavelength shift from the FBG temperature sensor was subtracted from the FBG strain sensor wavelength shift, before the latter was multiplied by the calibration coefficient.

Once compensated, the FBG output returns to original value once back in the garage at the end of the session, which suggests that the FBG strain sensor was well temperature compensated and measured load only. The overall trend, when compared to Figure 8.17, shows a flatter signal. The FBG strain sensor shows good correlation with the strain gauge data, with an error of 1.5% on average from data in Figure 8.18, providing confidence in the plans to replace the strain gauges by FBGs, as they respond linearly and are readily embeddable in composite materials, able to measure other physical properties and, most importantly, can be placed in all suspension legs, allowing to solve the whole wheel loads.

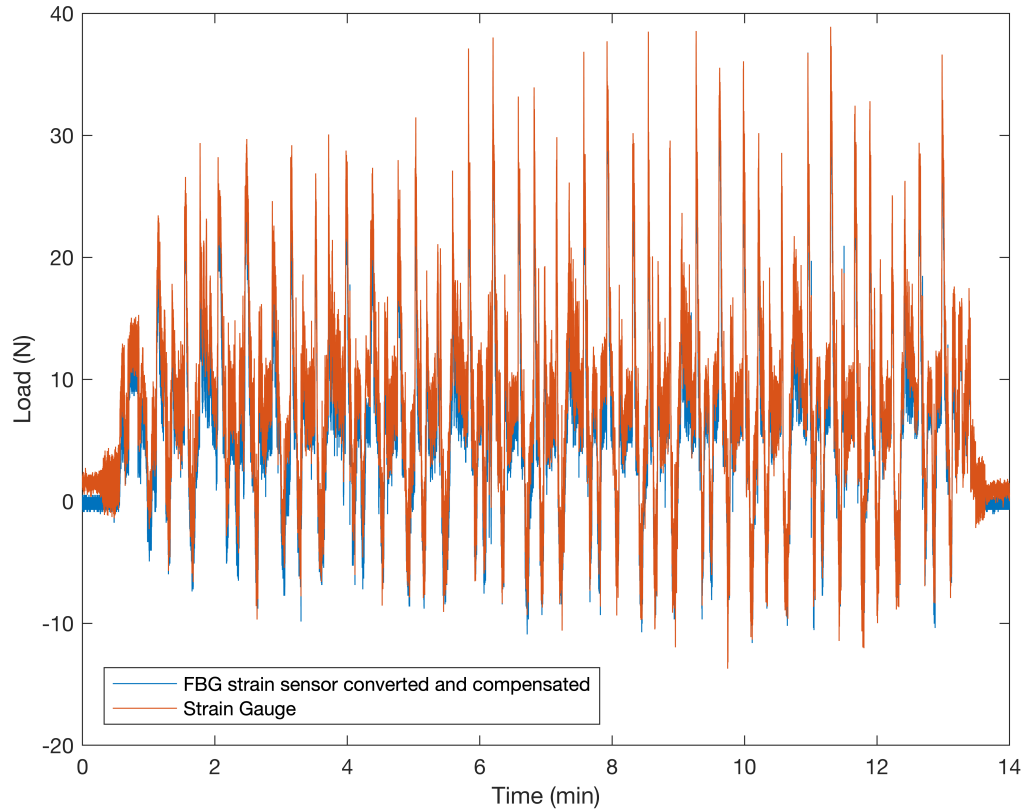


Figure 8.18: Temporal series showing the converted and temperature compensated FBG strain sensor and the electrical strain gauge sensor both placed on the forward leg of the FTWB.

During the 14 min session, it can be noted from the data the seven laps of less than 2 min each, with the first two up to 6 min showing the adjustment by the driver, who then drove in a similar style for the remaining 5 laps. The interpretation of the data set is not described in this thesis, and is for illustration only.

8.3 Conclusion

This chapter described a case study of an instrumented suspension of a racing car using FBG strain sensors. The manufacturing challenges of embedding optical fibres in

composite materials were investigated and satisfactory processes were put in place. The optical fibre sensor array was also analysed during manufacturing and inspection, and issues were raised regarding the quality. The process now includes the gain control to be set to manual, at a zero gain, to ensure consistencies between the manufacturing checks. The calibration process is not presented in this thesis in details, however a case study of use under track conditions was presented. The FBG strain sensor was validated with encouraging results compared to the strain gauges, where both used the calibration coefficients calculated by the testing the part in the test and development facilities.

The FBG strain sensor also shows good temperature compensation using an FBG temperature sensor in the same suspension component where the strain FBG correlate with the electrical strain gauge. The new temperature sensor encapsulated in silica capillary presented in Chapter 7 is now part of the default design, which is less intrusive and easier to handle due to its size and lightweight.

Chapter 9

Conclusion and Outlook

9.1 Conclusion

This research project aimed to develop an optical fibre based pressure sensor for use on an F1 car to enable in-situ pressure measurement during testing and ultimately racing. An F1 car is subject to strict regulations and the competition is high so the performance of the sensor is as important as the requirement for it to be compact and lightweight. The specifications provided by the team, 20 Pa resolution over a range 0-35kPa, with its overall dimension not exceeding 30 mm in diameter, prompted the investigation of several approaches, each with their own challenges.

The sponsor specified that optical fibre sensing technology should be used, so the first step involved selecting the appropriate specific sensing technology and the associated means for transducing pressure into strain. A diaphragm based sensor approach with an in-plane optical fibre sensor measuring the deformation induced strain was preferred for its minimal intrusion to the host structure. For this design, commercially available FBG sensors were highlighted as candidates as well as fibre segment interferometry, a novel technology developed at Cranfield University.

An analytical model was investigated for the strain developed in the diaphragm by the pressure-induced deflection. An FEA model was also developed to undertake a nonlinear analysis of a thin diaphragm with a surface bonded optical fibre. The model indicated that the strain inside the optical fibre is larger than that on the surface of the diaphragm, which are usually assumed to be the same in the literature. The analytical solution for the strain in the diaphragm-mounted optical fibre was re-written to include this finding and care was taken to ensure that the output from the FEA reflected the strain experienced by the optical fibre [86, 87, 72, 96].

With the requirements for a resolution of order 20 Pa and for the use of a commercially available FBG interrogation system of resolution $0.83 \mu\epsilon$ (1 pm), several diaphragm dimensions were fabricated using different materials and processes. The limitations of each manufacturing method and material were highlighted and an improved process presented.

The improved manufacturing process allowed the repeatable fabrication of sensors, where the position of the optical fibre relative to the neutral axis of the diaphragm was consistent. All of the different materials and processes used to fabricate HNBR and GFRP based sensors were experimentally analysed and the hysteresis in the sensor formed using the HNBR diaphragms were highlighted. The importance of the position of the optical fibre relative to the neutral axis of the diaphragm was experimentally validated and showed good agreement with the FEA output, demonstrating nonlinear behaviour. A 25 mm diameter, 0.27 mm thick diaphragm made from GFRP with an FBG mounted on its surface exhibited a sensitivity of $56.7 \pm 7.6 \text{ pm/kPa}$, equivalent to a resolution of 17.6 Pa, which achieved the requirements of the project.

The use of FSI to measure the strain on the diaphragm was also explored under the same experimental conditions, simultaneously with the FBG, on the same diaphragm. Over the pressure range of 0 to 35 kPa, the FBG sensor exhibited a sensitivity of 95 ± 4.4

pm/kPa, equivalent to a resolution of 10.5 Pa. The FSI sensor exhibited a sensitivity of 6.3 ± 0.3 rad/kPa, equivalent to a resolution of 0.61 Pa, exceeding the requirements for both sensor. A summary of their performances is given in Table 9.1.

Table 9.1: Summary of sensor requirements and performances achieved

	Resolution (Pa)	Sensitivity	Pressure range (kPa)	Diameter (mm)	Thickness (mm)
Requirements	20	50 (pm/kPa)	0 to 35	30 (max)	/
FBG sensor	17.6	56.7 ± 7.6 (pm/kPa)	0 to 35	25	0.27
FBG sensor	10.5	95 ± 4.4 (pm/kPa)	0 to 35	21.5	0.23
FSI sensor	0.61	6.3 ± 0.2 (rad/kPa)	0 to 35	21.5	0.23

The FEA had highlighted the presence of an annulus around the edge of the diaphragm that was exhibiting compressive strain in response to the pressure induced deflection. This behaviour only appears in nonlinear FE analysis, which is more complex than a linear analysis and analytical solution. While this is not an advantage for the available FBG interrogator due to the high strain gradient, it was used for pressure/temperature discrimination using FSI, with one segment over the positive strains in the centre of the diaphragm and a segment at the edge where negative strains occur. The design had some limitations, where the aluminium pressure chamber induced high strains due to the thermal expansion, stiffening the whole sensor and reducing pressure sensitivity for increased temperature. This effect was further investigated with FBG sensors, allowing the CTE of materials to be accurately measured. The FBG bonded to the aluminium support showed sensitivity of $43 \pm 0.1 \text{ pm}/^\circ\text{C}$, corresponding to an aluminium CTE of $23 \times 10^{-6}/^\circ\text{C}$ [122] when replaced in Equation (7.1). A pressure chamber made from a material of similar thermal characteristics as GFRP was considered and temperature discrimination of FSI sensors bonded to a GFRP diaphragm theoretically investigated. A well-conditioned matrix, of condition number 2.97 was performed, achieving low pressure and temperature errors.

The research thesis concluded with the report of strain measurements using FBG sensors embedded in multiple suspension members of an F1 car. The challenge of this part of the project laid within the incorporation of the optical fibre within the composite and its influence on the signal characteristics. After a number of iterations, instrumented components were calibrated before using the sensors and a car-mounted interrogator to monitor loads on the car during a race practice lap, which validated their performance compared to strain gauges. With the temperature compensation using strain-free FBGs encapsulated in capillary tubes, the FBGs achieved a correlation with an error of 1.5% compared to electrical strain gauges. Strain free, encapsulated FBG sensors allowed satisfactory temperature compensation but care should be taken in choosing the capillary material and dimension as well as fabrication methods to avoid bonding the FBG to both extremities

of the tube.

As a summary, the key findings of this research project are:

1. An optical fibre pressure sensor with characteristics that satisfy the requirements for use for aerodynamic measurements on an F1 racing has been developed. The required performance was achieved using an FBG sensor mounted on 25 mm and 21.5 mm diameter GFRP diaphragms of thickness 0.27 and 0.23 mm, respectively. Resolutions of 17.6 Pa and 10.5 Pa were achieved for the two diaphragm diameters, respectively.
2. The FBG-based sensor was outperformed when replaced by FSI sensing technology mounted on the GFRP diaphragm of diameter 21.5 mm, thickness 0.23 mm, with a resolutions 0.61 Pa being achieved.
3. This is the first reported pressure sensor using FSI and the technology offers higher performances with higher sensitivities, less noise and higher bandwidth than FBGs interrogated using a typical commercially available interrogator.
4. The position of the optical fibre sensing technology relative to the neutral axis of the diaphragm is one of the most influential parameters on the sensitivity of the sensor.
5. The elastic plate theory and the FE linear analysis of the clamped deflecting diaphragm under uniformly distributed pressure do not identify the presence of the annulus around the edge of the diaphragm that experiences compressive strain. This region is predicted by the nonlinear FEA and by experimental investigation using FSI sensors bonded to the diaphragm.
6. This effect can be used for temperature compensation by bonding two FSI segments to the diaphragm, one covering the central section that experiences tensile strain in response to the pressure induced deformation, the other over the annulus experiencing compression.

7. Rubber materials have intrinsic hysteresis and as a result are inappropriate for reliable pressure measurements.

This project opens up new potential applications using this novel pressure sensor such as pressure mapping of aerodynamic surfaces, especially with the use of FSI technology and temperature discrimination. With the sensitivity of FSI being 15 times more than that of an FBG, there are a number of possibilities, whether the interest is in reducing the diameter of the diaphragm or increasing robustness by increasing the diaphragm's thickness or the material from which it is made.

9.2 Outlook

The suggestion of further work includes several main areas. The sensor fabrication process to reduce porosity and design to increase robustness can be improved, especially with the use of FSI sensing technology. The pressure chamber material used for sensor pressure and temperature characterisations should be experimentally investigated to reduce temperature cross sensitivity, which can then lead into the incorporation of the sensor in composite structures. Further testing in a multiplexed installation for wind tunnel applications is proposed. A final area of further work concerns the temperature sensitivity enhancement of FBG, for high temperature resolution applications.

9.2.1 Fabrication of the Sensor

The main challenge of the improved manufacturing process was the porosity that arose for sensors of smaller thicknesses. The mean ply thickness value provided by the supplier was used to design the press mould top part, based on the desired thickness of the diaphragm after cure. This resulted in insufficient material to ensure that the diaphragm was fully compacted. The resin flow then left gaps between the ply weaves, as is shown in Figure 5.19, in Chapter 4. This limited the yield of usable sensors. It is recommended to add extra plies and/or epoxy for thin diaphragms, ensuring to fill the press mould and

allow any excess resin to flow out. As shown in Chapter 6, the use of FSI to measure the strain on the diaphragm, resulting in a significant improvement in the sensitivity, allows the design of a sensor with a thicker diaphragm to achieve the target specifications. While GFRP has the advantages of similar thermal and mechanical properties when compared to optical fibres, metals with low CTE can have benefits such as ease of manufacture, lower cost, robustness and easier to predict due to the homogeneous isotropic materials. From the literature, sensors made from metals [86, 87, 97, 100] exhibit lower sensitivity than those made from composite materials [95, 94, 96], however the high resolution of FSI would alleviate this issue.

A final fabrication suggestion is the FBG position on the diaphragm. While calibrating each sensor in all areas of the car is custom in F1, it might not be appropriate for other industries. Therefore, the exact position of the FBG along the diameter of the diaphragm should be automated or other means for accurately positioning it should be investigated. A suggestion is to inscribe the gratings after incorporating the optical fibre into the diaphragm, with appropriate support during FBG fabrication.

9.2.2 Design of the Sensor

Another area of further work includes the design of the sensor itself. While FBG sensing technology provided the required sensitivity within the dimension tolerances, the investigation of the use of FSI strain sensing technology presented in this thesis has shown the potential for bringing major improvements. These include the removal of the requirement for the incorporation of an additional reference FBG encapsulated for temperature compensation when using the approach FSI, presented in Chapter 6. In addition, the diameter of the diaphragm can also be reduced while still satisfying the required pressure sensitivity, resulting in an even more compact sensor. While reducing the diameter, its thickness could also be increased to create a more robust sensor. As a result, the sensitivity would

be reduced however current design is outperforming the requirements by two orders of magnitude.

9.2.3 Design of the Pressure Chamber

The sensor design was based on a GFRP diaphragm with an integrated optical fibre sensor. The aluminium pressure chamber was designed to apply the pressure in a controlled fashion for the characterisation of the sensor, rather than being suitable support structure to allow it to function within the car. The use of aluminium was shown to have a significant influence on the temperature response of the sensor, and imposed a temperature dependence on the pressure response. A suggestion of further work related to the pressure sensor support structure would be to validate the theoretical analysis presented in Chapter 6, Section 6.0.4.3, by using a GFRP pressure chamber or using a material of similar CTE. This analysis was performed to reduce the effect of temperature on the pressure sensitivity. In addition to validating the theoretical predictions, this would also allow the sensor to be incorporated to the composite structure of the F1 car. The CRFP composing the aerodynamic structures of the car has a CTE that is more similar to that of GFRP than aluminium, and thus the host structure would not be expected to have a significant impact on sensor performance. Additionally, the sensor itself would not impact the host structure due to similar mechanical and thermal properties.

Alternatively, the pressure chamber or diaphragm could be made from a material with negative thermal expansion [145], which could counteract the thermal expansion of the diaphragm or the optical fibre sensor respectively, resulting in a temperature compensated sensor.

9.2.4 Embedding of the Sensor in Composite Structures

The embedding of optical fibres in composite structures and the manufacturing challenges encountered were described in Chapter 8. The means developed for improving the robustness of the ingress/egress of the optical fibres in composite structures could also be used when embedding the pressure sensor. It is possible to envisage several laminates and structures that could be manufactured, and two designs are offered in Figure 9.1. Figure 9.1 (a) shows the embedding of the sensor, comprising of the diaphragm and optical fibre (with either FBG or FSI technology), where the laminate allows the working diameter to freely deflect with applied pressure and the laminate also provides a means for the clamping of the diaphragm's edge. The design is similar to the single pressure chamber shown in Figure 5.17, Chapter 4. The host laminate is arbitrary and will depend on the sensing area, where aerodynamic bodywork might have a laminate including a honeycomb core and a wing might only be made from CFRP. In this design, a large area is open, disturbing the aerodynamic surface. Figure 9.1 (b) offers another design which reduces the disturbance by having a porous surface over the working diameter dimension. The expected deflection of the diaphragm due to the pressure should be calculated prior to embedding to ensure that the gap between the porous surface and the diaphragm surface is sufficient.

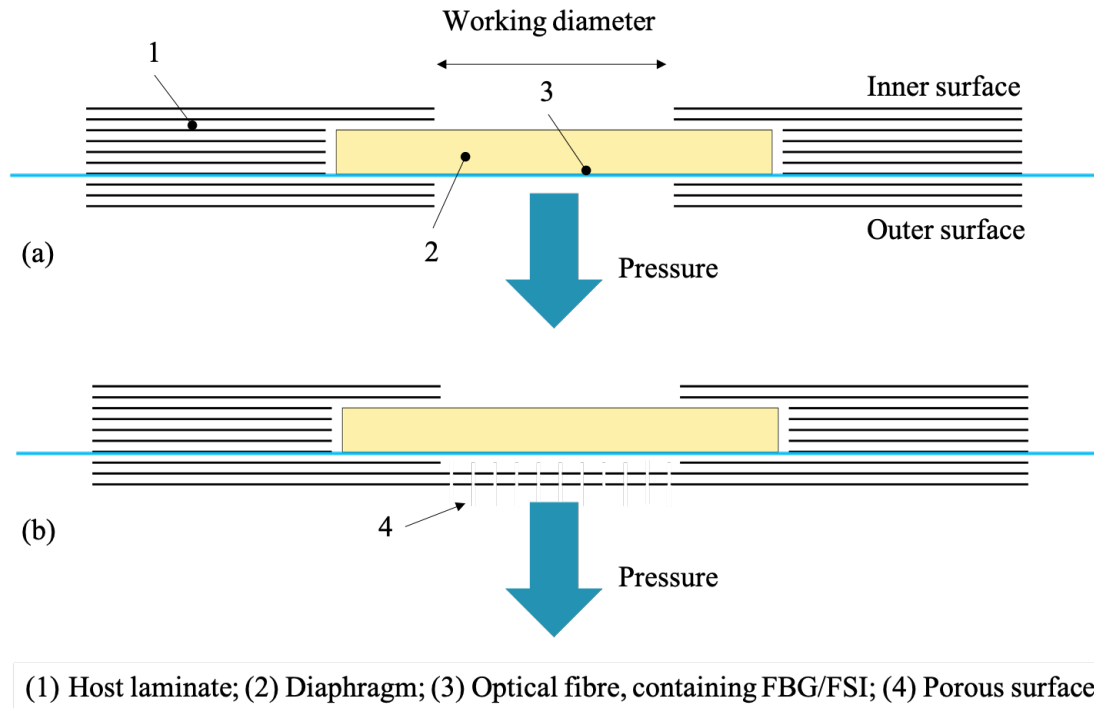


Figure 9.1: Schematic of two possible designs allowing the embedding of the pressure sensor. (a) open outer surface and (b) porous outer surface. Pressure acting as a vacuum for an aerodynamic structure such as the floor of the racing car. Not to scale.

9.2.5 Multiplexed Installation

Once a satisfactory process for the embedding of the sensor has been developed, the structure could be tested in a multiplexed installation. Although this was part of the aim of the thesis, only the HNBR-based pressure sensors were tested as a multiplexed array. A CFRP panel can be manufactured with the sensor incorporated following the embedding procedure shown in Figure 9.1 and with the fibre download ingress/egress following the process presented in Chapter 8. The grooves in the structure shown in Chapter 8 might not be possible to implement if the embedding of the sensor and fibres is performed prior to the cure, with the wet laminate. In this case, care should be taken to reduce lateral load on the fibre to reduce intensity loss and birefringence.

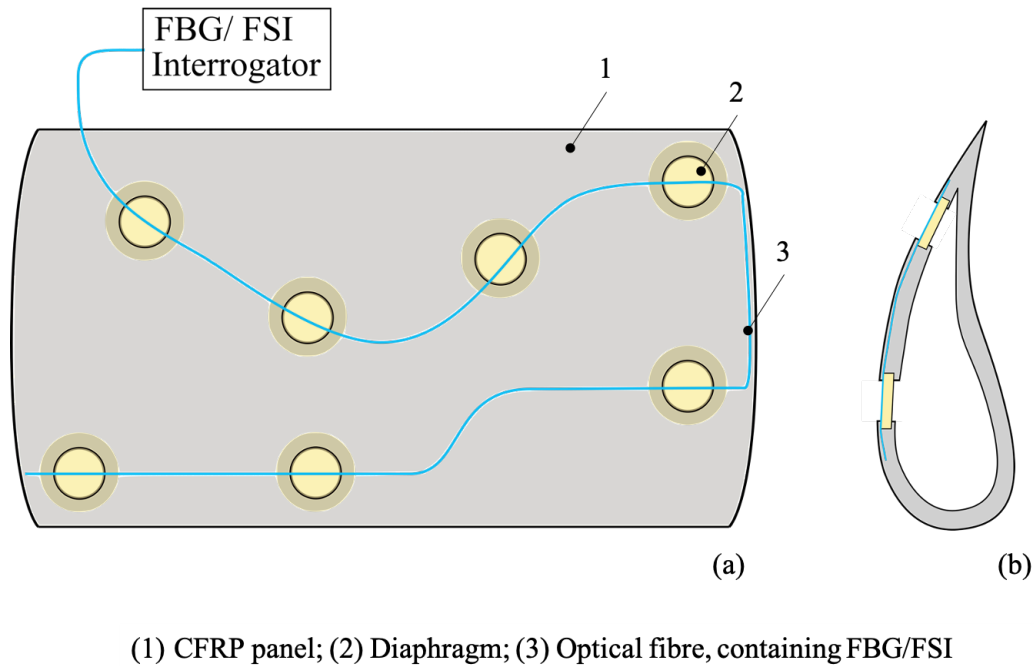


Figure 9.2: Schematic of an aerofoil panel with a multiplexed pressure sensor installation. (a) bottom view (sensor working in negative pressure) and (b) side view. Not to scale.

9.2.6 Wind Tunnel Testing

The flat panel could then be tested in a wind tunnel to assess performance of the embedded sensor in a representative aerodynamic flow. Unknowns that would otherwise arise from the on-car environment such as vibration or resonance could be identified and means to mitigate them found. It should be noted that the original plan for latter stage of the project was to trial an FBG based pressure sensor on a car during a preseason practice session. However, the impact of the Covid-19 pandemic on working practices at the factory meant that this was not possible.

9.2.7 Temperature Sensitivity Enhancement

Finally, another area of future work that arose from the thermal investigation in Chapter 7 is the enhancement of temperature sensitivity of an FBG for use as temperature sensors where high resolution is required. Work has been published where optical fibres coated in different materials with higher CTE increased the thermal sensitivity of FBGs [146, 147]. This is a great advantage where small size is required however availability and costs might be a drawback. However, using an FBG as thermocouple similar to what was used in Chapter 7, with the FBG bonded to a piece of material with high CTE could be an option where high resolution applications are required.

List of Publications Arising From This Research

Journal paper

L.F.J Aime, T. Kissinger, S.W. James, E. Chehura, A. Verzeletti and R. P. Tatam. "High sensitivity pressure measurement using optical fibre sensors mounted on a composite diaphragm". *Optics Express*, 29.3 (2021), pp.4105-4123.

Peer-Reviewed Conference Paper

L.F.J Aime, A. Verzeletti, S.W. James and R. P. Tatam. Optical Fiber Bragg Grating Based Pressure Sensor Using a Composite Diaphragm For Pressure Measurements. *2019 IEEE Sensors Conference*, (2019), 1-4.

Conference Paper

L.F.J Aime, T. Kissinger, S.W. James and R. P. Tatam. Comparison of FBG and Interferometric Surface Mounted Optical Fibre Pressure Sensor. *27th OFS conference*, TBC. OFS-27 has been cancelled twice due to COVID, however, the paper was accepted for presentation and will be published in due course.

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