

**NMW0403:
Optical sensor
characterisation and
calibration device for
integrated optical
systems**

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head, Materials Centre

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ABSTRACT

A novel calibration jig has been designed, built and used to initiate a new area of work at NPL concerned with the calibration of Fibre Bragg Grating sensors that are used as strain sensors in many applications. Individual fibres have been used in this work to develop a better understanding of the major metrology issues involved. The activity has led to the development of a potential new Studio project aimed at helping UK industry adopt this new technology by introducing standards and calibration services.

1 INTRODUCTION

Structural Health Monitoring is a key technology aimed at reducing whole of life costs for many structural applications across a wide range of sectors. The reduction in maintenance down-time afforded by a knowledge of critical stresses within structures leads to immediate cost savings. Applications where stresses and strains need to be routinely monitored include bridge spars, aerospace control surfaces, pipelines for oil/gas, oil/gas risers and well infrastructure, sporting goods, building structures and others. Often the stresses and strains need to be measured throughout a structure and so techniques have been developed to assess these quantities in a distributed fashion using fibre-optic technology taken from the mature telecommunications industry. One of the most promising methods used is the Bragg grating strain sensor. These tiny gratings are ‘etched’ into the core of a fibre optic and the wavelength of ‘reflected’ light is measured to determine the local strain, figure 1. In fact the grating is based on a modulation of the inner core’s refractive index. Multiple gratings may be ‘written’ on each fibre that, when embedded within structures, may serve as a fully distributed strain sensor. Advantages over conventional techniques include mechanical robustness when embedded, electromagnetic radiation immunity, large scale embeddability to sense relevant stresses, large scale distributed sensing capability, inherent safety (no electrical connections), very large and mature telecommunications market that supports this application, and a large academic and industrial backing.

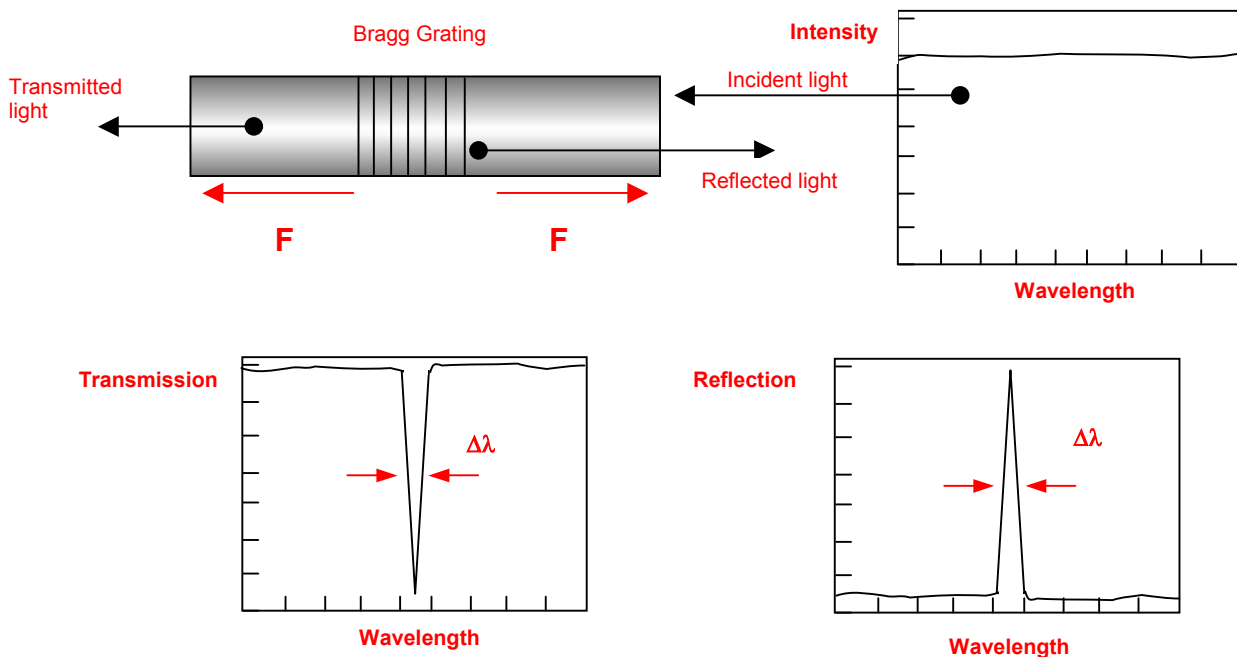


Figure 1: Schematic illustration of a Fibre Bragg Grating and its effect on incident light. Reflection efficiencies, caused by phase matching the incident wave with the periodicity of the grating, can approach 100% making these devices excellent low loss telecomms filters for example. (Adapted from **Orthonos 1999**).

Presently, there are no standards applicable for the *use* of Fibre Bragg Sensors (FBS) in strain sensing. In the UK, academic involvement is high especially in the development of interrogation technology. The FOS's are protected by international patents, which have the effect of adding significant cost to the price of individual FBS. However, one company (Fibre

Optic Tools Oxford – now Indigo) manufacturers gratings under license and supplies much of the UK's need that is still typically academic or R&D in origin. A Southampton based company (Smart Fibres Ltd) achieved recognition with their *smart mast* project (DTI LINK MAST programme 1998), using FBS's to assist the skipper in maximising sea and wind conditions in racing type sailing. Since these early days many more applications have been developed. However, the lack of standards and calibration for these strain-sensing systems is severely limiting capital investment in this technology. NPL has developed its understanding of the science behind this technology, through a strategic research project (**NPL Report CMMT(D)205 1999, NPL Report MATC(D)13, 2001**) that resulted in linear models, visual realisation of a simple demonstration of the concepts and a working prototype demonstrator. Following on from this work, NPL won additional DTI support to investigate issues surrounding calibration of FBS with in-kind support from the UK's Smart Fibres Ltd. This report describes the results from this DTI cofunded New Metrology Work 6NMW0403 project.

The measurement of strain or displacement using fibre optic sensors involves a complex procedure of temperature compensation and high order non-linear data analysis. Even after this is carried out doubt is still felt by the community (**FOS-EN meeting Brunel University, 26-27 June 2000**) in terms of calibration and standardisation. These issues have provided the rationale behind this project.

As well as NPL's expertise in structural health monitoring MATC has also developed measurement methods that characterise piezoelectric materials. The measurement of displacement has been carried out using a multitude of techniques including capacitive, optical and others. In this project, a small device has been designed to accommodate the optical sensors and calibration sensors in close proximity within a controlled environment. In this way, true strain may be compared to the optical sensors and adequately separated from temperature effects.

The device has been constructed at NPL and tested on optical sensors that were purchased or on loan from supporting companies. The device could eventually be used as a measurement services tool available to UK industry. Beneficiaries will include the rapidly expanding sensors community within the United Kingdom. The use of sensors pervades all industry, and the adoption of optical techniques is viewed as the next step in highly integrated, multiplexed, high bandwidth sensory systems.

2 FIBRE BRAGG SENSORS

2.1 HISTORICAL VIEW OF THE TECHNOLOGY

Optical fibre first became widely available in its present form in the late 1970s. Each fibre consists of a glass, typically about 125 microns in diameter, which acts as a low-loss waveguide for optical signals. The core of the fibre is a glass that has a refractive index higher than that of the cladding region surrounding it. This difference is normally achieved by doping either the core or cladding with varying amounts of a metal such as germanium. An optical signal of the correct wavelength range, if launched into the core, will be confined within the core and will propagate with an attenuation that can be less than 0.2 dB/km. If the core diameter is made sufficiently small compared with the wavelength (about 8 micron for a

wavelength of 1 micron), only a single longitudinal mode will propagate, thus producing a single-mode fibre (**Nash (1998)**).

Low attenuation and very high bandwidths stimulated the development of optical fibres for the telecommunications field. However, it was recognised quite early that external influences, such as strain, temperature and acoustic signals, could affect light travelling through a fibre in ways that had the potential to produce extremely sensitive sensors. It was evident that if these sensing schemes could be combined with other properties of optical fibres, the potential existed for compact, tough sensors that could be interrogated remotely and could combine very large amounts of information into a single data channel.

The polymer cladding around an optical fibre protects it from being flawed by abrasion, which, when subjected to an environment like moisture, weakens the fibre and accelerates crack growth. In addition, the polymer acts as a stress absorber to reduce any bending in the fibre. This will reduce transmission losses. For strain sensing, however, the lower elastic modulus of the polymer coating affects the transfer of strain from the surrounding host material to the optical fibre. Subsequent data analysis can minimise this effect or else it can be reduced by keeping the polymer cladding as thin as possible or using relatively stiff polymers.

Fibre cables can have an additional plastic jacket outside the thinner coating for further protection. Fibre optics may be classified as intrinsic if the effect of the measured light parameter takes place in the fibre. The sensor is considered to be extrinsic if the fibre carries the light from the source and to the detector.

Fibre sensors are also described as either localized (point), or multiplexed. Localized or point sensors detect variations only in the vicinity of the sensor. This aids in determining where strain, temperature, pressure, etc is changing, but, if many individual sensors are required, can lead to a large number of fibre leads and connections. Some localized sensors can be multiplexed, where multiple localized sensors are placed at intervals along the fibre length (**Merzacher et al. (1996)**)

2.2 CLASSES OF OPTICAL FIBRE SENSORS

Optical fibre sensors can be classified according to the particular manner in which the external influence affects the propagation of light. Amplitude, interferometric (phase), colour (wavelength) and polarimetric sensors have all been successfully demonstrated (**Dakin et al. (1988)**).

Therefore, there are two classes, intensimetric and interferometric, for fibre optic fibre sensors. Intensimetric sensors are based on the amount of light detected through the fiber. Optical time domain reflectometry (OTDR) can be used in addition to locate where the fiber broke. Strain sensors based on intensity variation due to microbending losses have also been developed; however, they are relatively insensitive, inaccurate and have a limited range of detection. A development of this is the statistical mode sensor (SMS), which is a more sophisticated intensimetric optical fibre (**Huston et al (1993)**).

Interferometric sensors have been developed for a range of high-sensitivity applications, such as acoustic sensors (hydrophones) and magnetic field sensors, and are usually based on

single-mode fibre. Interferometric sensing is generally the most sensitive and is commonly used. However, another sensor, based on Fibre Bragg Gratings (FBGs), has recently attracted attention. Please refer to **NPL Report MATC (D)13, 2001** for more information on the various optical sensor types.

2.3 BRAGG GRATINGS

A fibre Bragg grating (FBG) is a multiple reflecting structure that consists of a periodic refractive modulation produced within a length of the fibre core. The modulation is written into the core using UV holographic or phase mask techniques (**Bennion et al. (1996)**).

Fibre Bragg gratings act as a wavelength-selective filter because all propagating wavelengths pass through the grating with no change of signal. Only wavelengths that satisfy the Bragg condition are influenced as they add coherently and are strongly reflected, see figure 1.

The Bragg grating acts as a *notch filter* for the incident spectrum of light. A change in grating period results in a change in the reflected wavelength. Therefore, Bragg gratings are susceptible to externally applied mechanical loads. Strain and temperature affect the response through the strain-optic and thermo-optic effects. Both physical effects also affect the response by the expansion or contraction of the grating. The effects are modelled for wavelength shifts using the equation

$$\frac{\Delta\lambda}{\lambda} = 0.79\varepsilon + \xi\Delta T \quad \text{Equation 1}$$

where:

ε = axial strain in the optical fibre core

ΔT = change in temperature

ξ = thermo - optic coefficient of the fibre

The thermo-optic coefficient of the fibre is $6.3 \times 10^{-6} / ^\circ\text{C}$. A measurable shift in wavelength being caused by either strain or temperature variations makes Bragg gratings very useful for sensing applications. With small packaging and processing techniques, the independent effects of temperature and strain can be separated. Also, the Bragg gratings can measure other parameters such as acceleration, and electric and magnetic fields (**Nash (1998)**).

Phase mask techniques have now become the preferred method for grating fabrication as they use low coherence industrial lasers and simple mechanical alignment which allows low cost manufacturing. The small size of Bragg gratings, linear response, totally passive operation, ability to multiplex many sensors along a single fibre and the stated properties, make Bragg gratings ideal for many applications (**Merzacher et al. (1996)**).

2.4 THEORY OF FIBRE BRAGG GRATING STRAIN AND TEMPERATURE SENSITIVITY

An increase in the grating element spacing, S arises from an elongation (or strain) of the FBG that results in a corresponding change in its refractive index due to the photoelastic effect. In

addition, the thermal response originates from the thermal expansion of the glass fibre in the vicinity of the FBG and the temperature dependence of the refractive index. This interrelation between strain and temperature on the reflected wavelength eventually measured provides the most severe of metrological challenges facing this technology for sensing applications.

The Separation of true strain from the non-linear optical changes with temperature is central to the use of Bragg grating technology for distributed strain sensing applications. In many cases, this is carried out with the use of additional temperature sensors position next to the fibre sensor. Other techniques of temperature compensation have been investigated and form the basis behind NPL's demonstrator system described in **NPL Report MATC (D)13, 2001**.

In detail the mathematics that describes the strain and temperature sensitivity and compensation is now given:

The Bragg wavelength λ is given by

$$\lambda = 2 \cdot n \cdot S \quad \text{Equation 2}$$

where n is the fibre refractive index and S is the grating element spacing. Now

$$n(\epsilon, \Delta T) = n_0 + B_\epsilon \cdot \epsilon + B_T \cdot \Delta T \quad \text{Equation 3}$$

where terms relating to the change of real strain due to expansion has been neglected.

where ϵ = strain, n_0 = effective index.

$$B_\epsilon = \frac{-n_0^3}{2} [\rho_{12} - (\rho_{11} + \rho_{22}) \cdot \nu] = -0.3151 \quad \text{Equation 4}$$

Taking values from the literature for typical germanosilicate optical fibre $n_0=1.482$, $\rho_{11}=0.113$, $\rho_{12}=0.252$, $\nu=0.16$ (**Othonos 1999**)

Combining these equations we have

$$\frac{\partial \lambda}{\partial \epsilon} = 2 \cdot \frac{\partial n}{\partial \epsilon} \cdot S + 2 \cdot n_0 \cdot \frac{\partial S}{\partial \epsilon} = \lambda_0 \left(1 + \frac{B_\epsilon}{n_0} \right) \quad \text{Equation 5}$$

where λ_0 is the Bragg wavelength at zero strain

$$\left(1 + \frac{B_\epsilon}{n_0} \right) \text{ is called the Gauge Factor and is } = 0.7874 \text{ for parameters above.}$$

Putting in the value for our grating where $\lambda_0=1554$ nm we have a theoretical strain sensitivity of 1.22 nm/m ϵ .

Now we also have,

$$\frac{\partial \lambda}{\partial T} = 2 \cdot \frac{\partial n}{\partial T} \cdot S + 2 \cdot n_0 \cdot \frac{\partial S}{\partial T} = \lambda_0 \left(k_T + \frac{B_T}{n_0} \right) \quad \text{Equation 6}$$

when the grating is unstrained and free to expand, where k_T is the thermal expansion of silica $= 0.55 \times 10^{-6} / ^\circ\text{C}$ and B_T is the thermo-optic coefficient which is approximately $8.6 \times 10^{-6} / ^\circ\text{C}$. This leads to a theoretical temperature sensitivity of $9.87 \times 10^{-3} \text{ nm}/^\circ\text{C}$.

This is telling us that wavelength measurements incorporate the effects of strain (both imposed and from thermal expansion) and the effects of the non-linear properties of refractive index.

This results in the strain temperature to wavelength relationship that is linear and may be written as:

$$\frac{\Delta\lambda}{\lambda} = A \cdot \varepsilon + (\alpha + \zeta)T \quad \text{Equation 7}$$

where A is a constant (called the Gauge Factor of the fibre), α is thermal expansion coefficient of the fibre grating and ζ is the thermal optic coefficient (**Magne 1997**).

Thus, as is the case for many optical measurement sensors, the measurement of the centre wavelength shift does not discriminate between strain and temperature fluctuations when only one sensor is used. There are various methods that have been developed to separate strain from temperature and are discussed in the book (**Othonos 1999**). Basically the methods either rely on the use of two fibre sensors that do not experience the same combined fluctuations or via measurements at two different wavelengths or two different optical modes in which the response from temperature and strain are different. In dynamic applications where the temperature fluctuations are always $\gg$ strain changes then the effects of temperature are clearly less of a problem.

It is interesting to note that FBG can also be used to measure pressure (fractional changes in length of the fibre $\gg$ changes in its diameter) and magnetic field (through the Faraday effect).

3 PROJECT OBJECTIVES

This project had aims to identify the calibration challenges afforded by FBS and to develop measurement capabilities that would address the issue of calibration as single fibres and also combined as embedded fibre patches. A secondary aim was to utilise the calibration jig to characterise some of the functional properties of a new class of smart material – piezoelectric *fibres*.

Previous work at NPL [**NPL Report MATC D(12) 2001**] has highlighted some of the calibration problems associated with FBS's. One major issue included the erroneous assumption of using published and accepted materials parameters used to evaluate the various Gauge Factors (equation 7). These values of refractive index, and thermo/strain-optic coefficients typically resulted in an inaccurate calibration of the (independently) measured strain to wavelength. Another issue is the calibration of wavelength to voltage output from the FBG interrogation unit. If the calibration is not accurate then any strain measured using the

interrogation unit would be offset by an arbitrary amount. The complexity of this calibration can then be clearly seen and is composed of two parts:

1. the various materials properties that determine the shift in wavelength with strain and temperature
2. the various interrogation units calibration of wavelength to voltage output that is an indication of wavelength shift

Both issues have been addressed in this project.

4 EXPERIMENTAL PROCEDURE

4.1 DEVICE DESIGN

The calibration issues amounted to the following:

1. an accurate measurement of displacement and hence strain that would be used as the calibration of the FBG sensors strain output
2. an accurate measurement of load applied to the fibre would offer an additional check on fibre strain through the materials elastic modulus
3. an accurate measurement of the temperature of the fibre and calibration jig would provide the effects of temperature on the fibre optic sensor output

The design is based on a simple structure that applies a load to the fibre in a controlled fashion. The load is measured using an in-line load cell and the strain is measured using capacitance gauge methods – again in-line. The force is applied through the fibre using ceramic piezoelectric actuators situated off-axis to the fibre axis. The general design is sketched in figure 2 and the component parts are reproduced diagrammatically in Appendix 1.

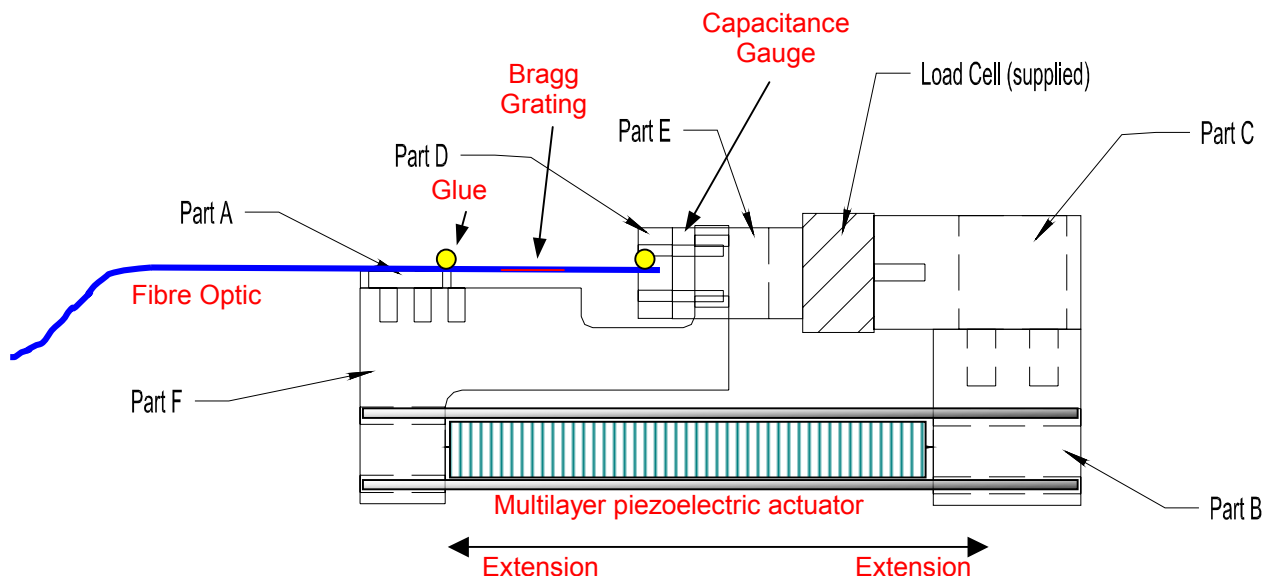


Figure 2: Schematic of whole assembly of Fibre Optic Sensor Calibration Jig

The capacitance gauge measures displacement, which is then converted into strain using knowledge of the original length between the fixed points of the optical fibre. The load cell is a resistive strain gauge type and has a stiffness less than that of the surrounding steel clamp. The clamp is made from 316-type stainless steel. This choice is suited for higher temperature measurements and avoids any problems associated with corrosion. The fibre is presently fixed using cyanoacrylate adhesive onto two steel flat supports that have been carefully machined so as to be in-line. Ideally, the fixation of fibre would be carried out using a simple clamping arrangement. The system is situated within an environmental chamber in the vertical disposition that allows easy routing of the fibre. Application of a high electrical voltage to the piezoactuator causes the fibre to become stretched. The FBS is connected either to an Optical Spectrum Analyser (OSA) or other commercial or laboratory based wavelength discriminating interrogation system. The strain measured from the FBG is then compared to the displacement measured from the separation between the faces of the capacitance probes. Additionally, the load cell, measuring load accurately, may be used to construct stress-strain plots and from a knowledge of the various component and fibre stiffness may be precisely calibrated.

4.2 FIBRE GRATING CALIBRATION SPECIFICATION

Fibre sensor

Gauge length	30mm
Fibre diameter	125 μm
Modulus	72GPa
FBG centre Wavelength	1309.7nm (for fibres used)
FGB Gauge Factor	ranges from 0.7 to 0.9, typically 0.78 – see equation 5.

Approximately, 5% maximum strain before failure
 Corresponds to 10,000 microstrain maximum
 System resolution: 1 μ strain

Displacement

Resolution 0.03 μm
 Range 300 μm
 (1 part in 10,000)
 Capacitance Gauges have approximately 100 μm range
 100 μm on 30mm is 1/300 strain = 0.3% or 3333 microstrain

Load

Maximum 8.8N approx 1kg
 Resolution approx 1mN (0.1gram)
 Load to give 0.3% on 125 diameter = 2.9N or ~500g.

4.3 EXPERIMENTAL PROCEDURE

The environmental chamber is a Gwent Electronics Ltd system Model XX, capable of precise temperature and humidity control from -60°C to $+150^{\circ}\text{C}$. A computer software program has been written (National Instruments: LabView) to control the piezoactuator voltage amplifier

and the environmental chamber and to log temperature, load cell voltage (load), time, FBG voltage (wavelength or strain), capacitance gauge voltage (displacement).

The Fibre sensor interrogation unit was based on the FLS3100-SA ElectroPhotonics Corporation, Canada (supplied in the UK by Laser Lines 2000), a single channel high precision strain/temperature measurement device that was used throughout the NPL Strategic Research project 9SRP6010. Two channels were purchased and incorporated within an industry standard rack mount. Here, the wavelength shift of up to two FBG's could be monitored and a voltage output could be recorded. Thermocouple inputs were also incorporated. The voltage/wavelength correlation was defined as a high order polynomial because the voltage output was not a linear function of wavelength shift. This formed the intrinsic calibration of each interrogation unit, as defined by the manufacturer. (Note: The company Electrophotonics Corp. are no longer operating and Laser Lines 2000 are no longer supporting this product. However, UK products exist – please refer to Appendix II.)

The optical fibre used is standard telecommunications fibre that has its core doped with Ge. This doping causes the silica optical fibre to become photosensitive and thus permits the index of refraction to be suitably modulated (using various laser techniques) on the scale of a few mm. This creates the Bragg Grating. The fibre is then coated with a methylcellulose or acrylic polymer that acts to protect it against mechanical abrasion, which would otherwise result in a dramatic loss of mechanical strength. The fibre diameter is approximately 125 μm and once the cladding is applied the overall diameter increases to 250 μm , figure 3. The actual volume created by the laser modulated Bragg Grating is very small and the effective diameter of the refractive index modulated region is much less than the core diameter of 125 μm .

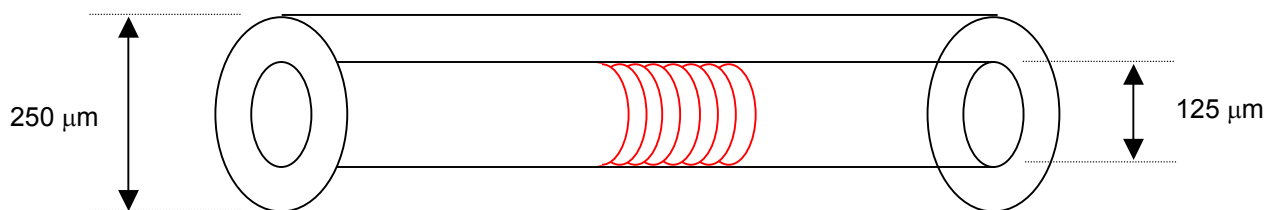


Figure 3: Illustration of cladding and fibre diameters for FBS's.

At the start of experimentation the effect of the polymer cladding on the stress transfer through to the optical fibre and hence the Bragg sensor was not assessed. The fibre may be attached to the jig using epoxy or, better, using a purpose built clamp. The cladding may also be physically or chemically removed before gluing or clamping. In order to complete these tests in as industry friendly a way as possible the cladding was not removed prior to fixation using cynoacrylite.

At zero applied load (and hence zero strain) the capacitance displacement sensor output was measured along with the temperature, load cell output and Fibre Sensor interrogation unit voltage output. Load was then applied in a slow saw tooth ramp by increasing the voltage on the piezoactuator and the data recorded.

5 RESULTS AND DISCUSSION

5.1 LOAD CELL CALIBRATION

The system was positioned vertically and one side was loaded up using standard reference masses and load was calculated by $\text{Force} = m \cdot g$ (with g = gravitational force constant $\sim 9.8065 \text{ m.s}^{-2}$). The graph in figure 4 shows the calibration curve, with the output from the load cell conditioning unit being linear with applied force.

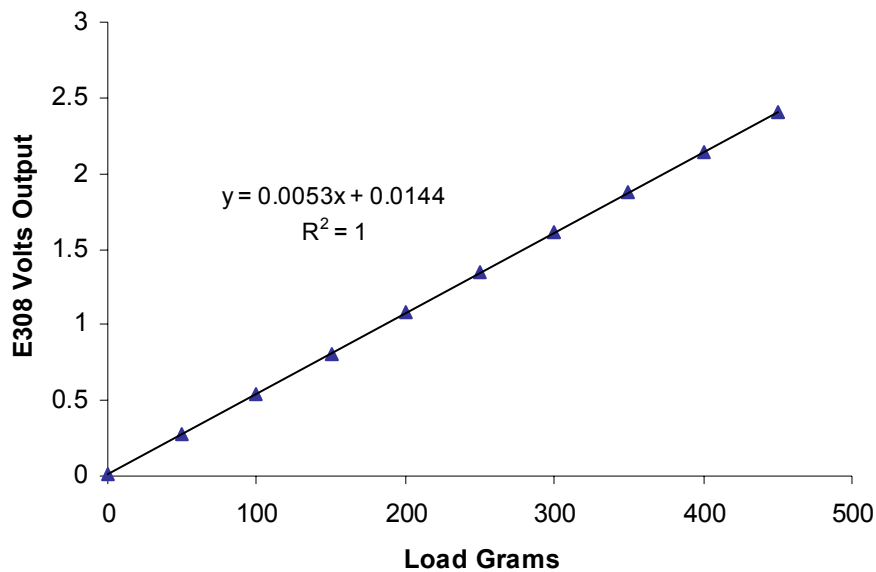


Figure 4: Load cell calibration

5.2 INTERROGATION UNIT CALIBRATION

The interrogation unit had been supplied with its own calibration, which was dependent on the various factors including centre wavelength of the Bragg Grating. The wavelength to voltage output calibration was a 20-order polynomial and conversion to strain was simply through equation 7 (for no temperature compensation) using the FBG Gauge Factor, figure 5, for the FBG sensors we used. Two curves are drawn, one representing the calibration for wavelength and the other for strain for one of the interrogation units incorporated within the laser Lines 2000 system (unit 010030). Additional calibration curves were drawn for the second interrogation unit, figure 6.

The fibres used were provided by Oxford Fibre Optic Tools Ltd (now Indigo Ltd) with a mean centre wavelength, λ_0 , of 1309.7nm. From the calibration curves, this places our working range at approximately 2V (as expected since the calibration curves are based on λ_0) but with tensile strains generating voltages less than this down to 0V. This has two implications: 1. The measurement range is much reduced and 2. The calibration profile is highly non-linear in this regime. The choice of centre wavelength clearly needs to take these factors into account but the experimental data presented in this report is still valid, although suffering from slight increased levels of uncertainty.

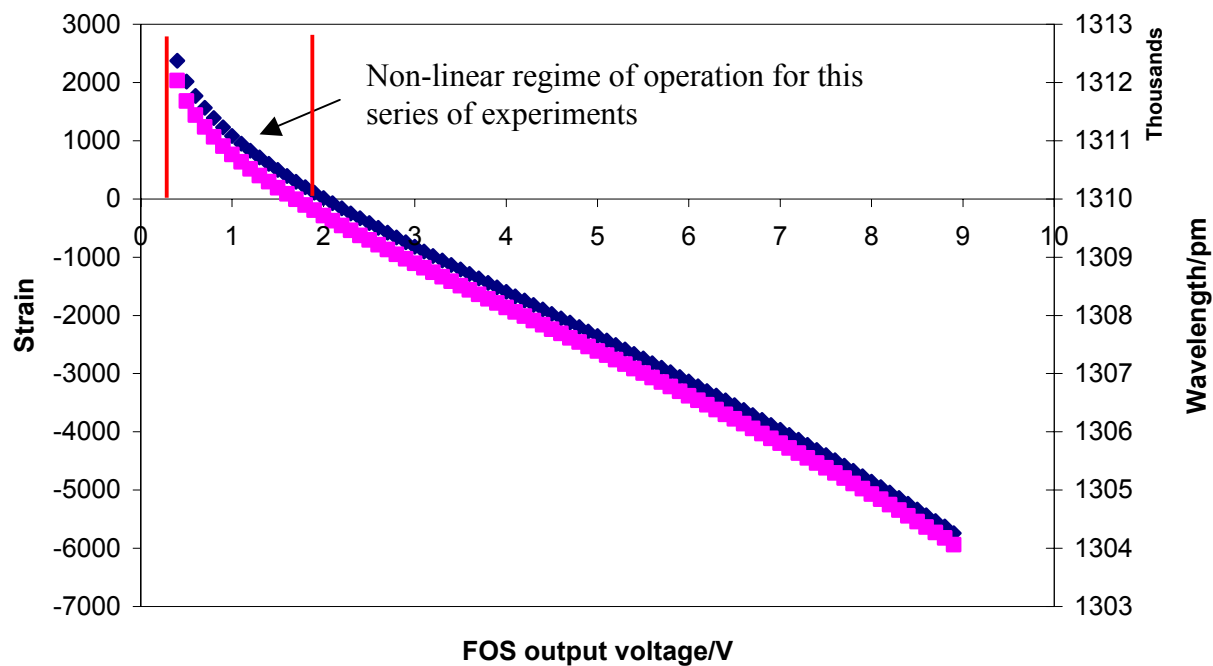


Figure 5: Calibration graphs for the interrogation unit used in NPL's Laser Lines 2000 system.

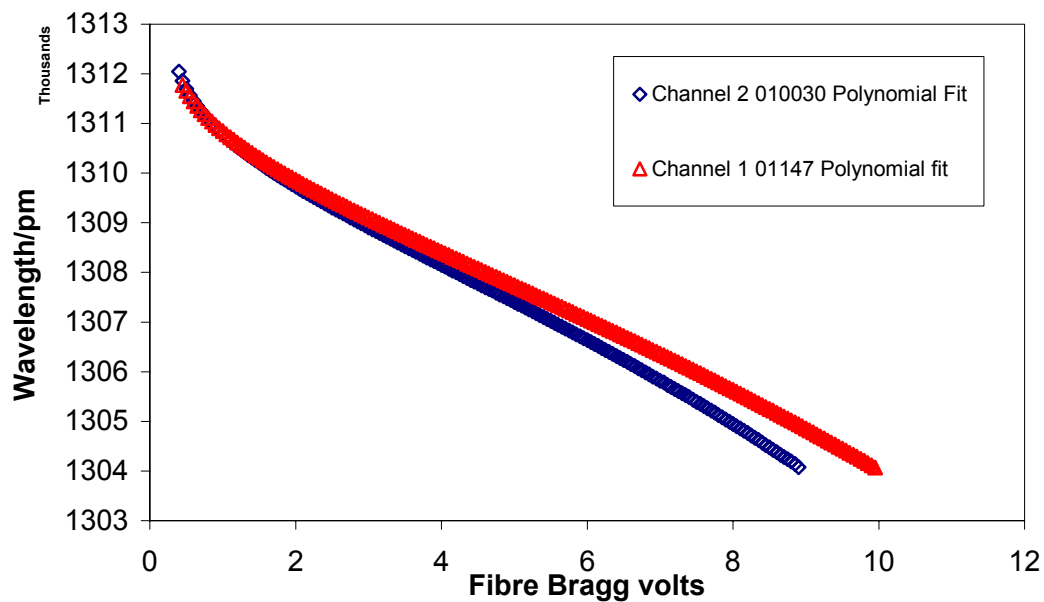


Figure 6: Calibration curve for wavelength for both FLS3100 units

5.3 FIBRE CALIBRATION TESTS

The Gauge Factor relevant to the FBG sensor used was theoretically calculated according to equation 5, and found to be 0.787. The data (#122/21°C) in figure 7 shows the strain measured using the capacitance gauge and that calculated using the FBG against voltage applied to the piezoactuator. Two important issues are observed: 1. The capacitance gauge data and FBG data are both approximately linear with electric field and hence load (but see later) and 2. The FBG data absolute levels of strain are only about half that measured using the capacitance gauge.

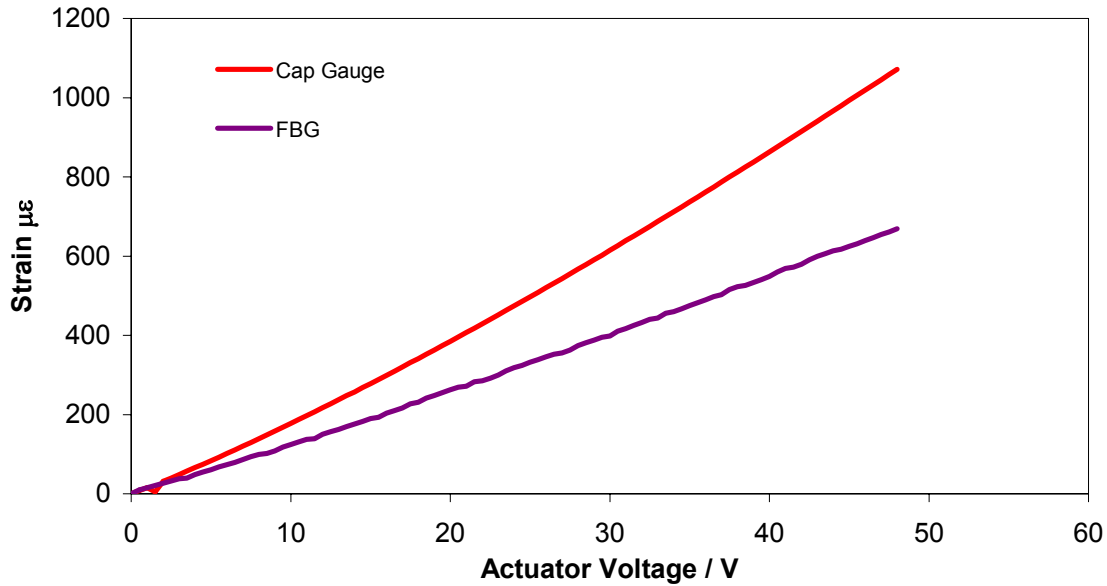


Figure 7: Capacitance gauge strain and FBG strain measurements with applied actuator voltage

The FBG strain calculated in the curves in figure 7 are based on published values of the effective refractive index and strain-optic coefficients (**Othonos 1999**, **Bertholds 1988**) that yield the Gauge Factor for each fibre sensor. However, the exact values for the Gauge Factor are also often reported to lie anywhere between 0.7 to 0.9 in extreme cases (**FLS 3100 Manual 1998**). Thus it is possible to adjust this value taking into account that generally we know the elastic modulus of the glass fibre to a greater degree of accuracy than these optical properties. The elastic modulus for silica glass is (72 ± 2) GPa (**Tennent 1971**) which may be used as a first estimate of the modulus expected from a measure of the gradient of the FBG curve in figure 8.

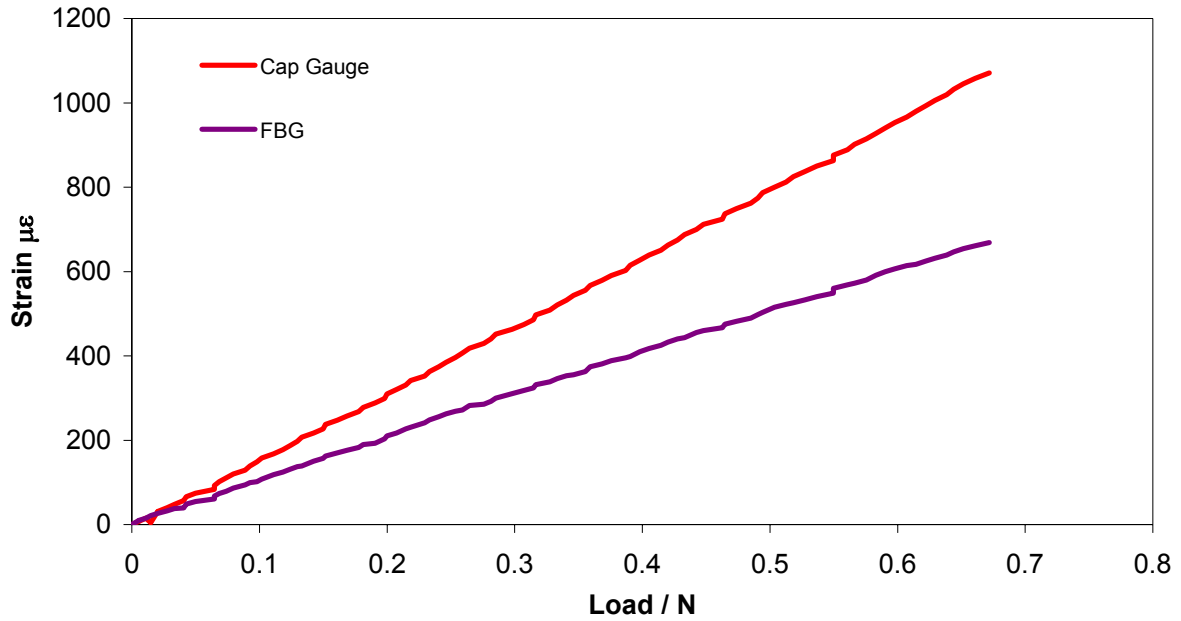


Figure 8: Capacitance gauge strain and FBG strain measurements with applied load

The gradient is $999.95 \text{E-}6 \text{ N}^{-1}$, yielding a value of modulus of: $E = 1 / (999.95 \text{E-}6 * \text{Area}) = 1 / (999.95 \text{E-}6 * \pi * (125/2 \mu\text{m})^2) = 81.5 \text{ GPa}$. (This is calculated for a silica fibre diameter of $125 \mu\text{m}$). Now, although the load is fully transferred through the fibre it is important to realise that the fibre not only contains its inner silica core but also has an outer cladding, $250 \mu\text{m}$ in diameter surrounding it. The effect of the load transfer through the optical fibre cladding may be investigated if we calculate this based on methods of mixture, appendix II. Using values of radius of core = $125 \mu\text{m}$, radius of outer = $250 \mu\text{m}$, $E_{\text{core}} = 70 \text{ GPa}$, and $E_{\text{cladding}} = 1 \text{ GPa}$, then the effect is to decrease the load through the glass inner core by approximately 4.2%, resulting in a comparable reduction in the fibre optic's effective modulus. Thus the new 'effective modulus' is now $72 + 4.2\% \sim 75 \text{ GPa}$. The difference between the measured modulus and the effective modulus can now be calculated as $81.5 - 75.0 = 6.5 \text{ GPa}$, a difference that can be accommodated by adjusting our value of Gauge Factor. This would make our adjusted value of the Gauge Factor to equal ~ 0.724 . This is depicted in the graph of figure 9.

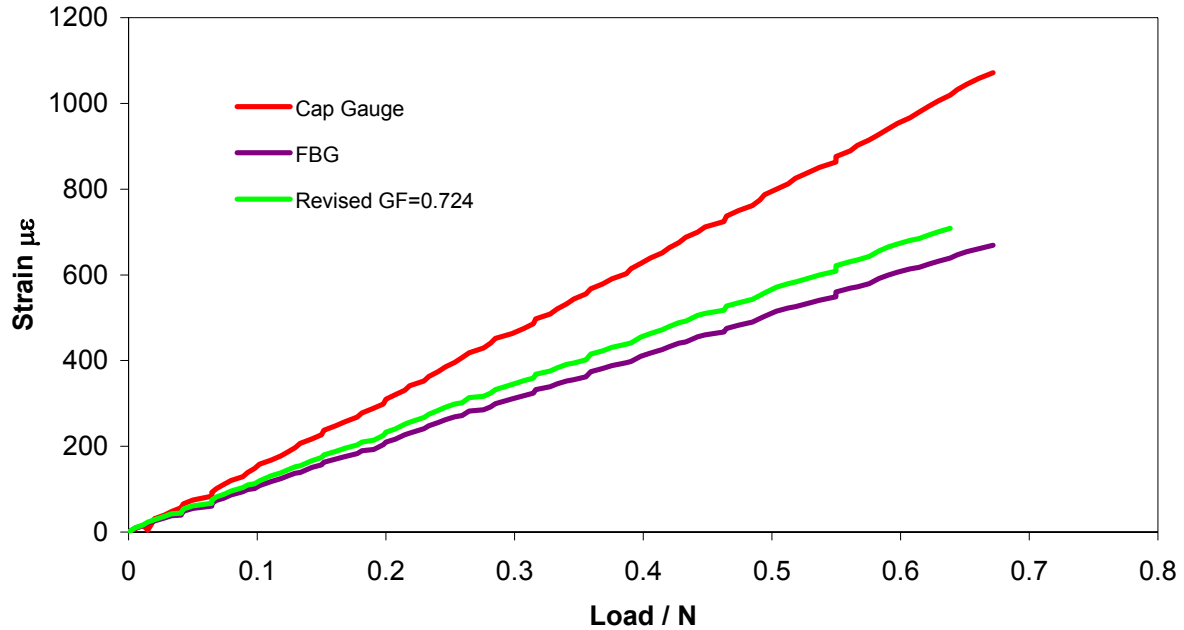


Figure 9: Capacitance gauge strain and FBG strain measurements with applied load adding new strain/load line for amended Gauge Factor taking into account modulus of silica and effect of cladding.

Even taking into account the variation in GF the values of strain measured using the capacitance gauge are still $\gg$ those taken using the FBG system. After the capacitance gauge was re-calibrated and the results showed no change then the effect of the cladding and glue compliance was postulated as a potential contribution to the excess displacement measured. Evidence comes from a test of the rate at which the strains changed with time at constant applied voltage measured using the FBG and capacitance gauge, figure 10.

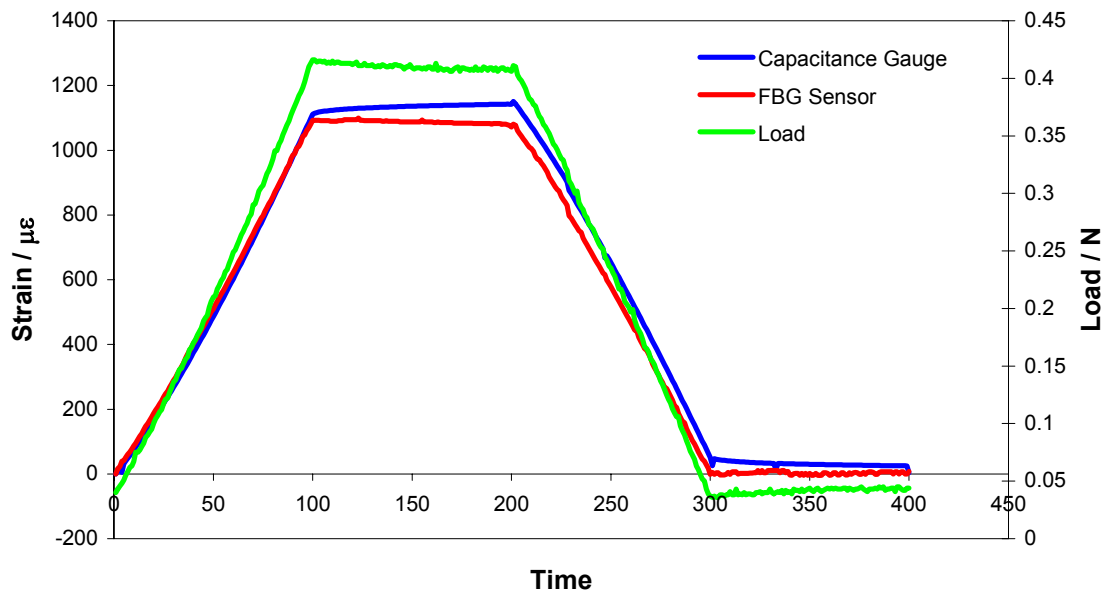


Figure 10: Rate of change of strain and load with time indicating the possible influence of a compliant relaxation phenomenon occurring in the system.

In this experiment a voltage ramp was applied to the piezoactuator and once it had reached a preset value the voltage was held fixed. The strain and load were continuously measured as a function of time. From figure 10, it is clear that the capacitance gauge signal increases signifying an increase in the separation between the probe plates whilst the FBG signal decreases indicating a reduction in strain with time. Note, as the FBG sensor strain decreased with time so does the load indicating the relaxation of a compliant boundary between glass fibre and loading points, possibly caused by a combination of glue and cladding.

The system developed may also be used within the environmental chamber at different ambient temperatures. Figure 11 demonstrates this capability, although until the calibration issues are resolved the absolute values of strain are left arbitrary.

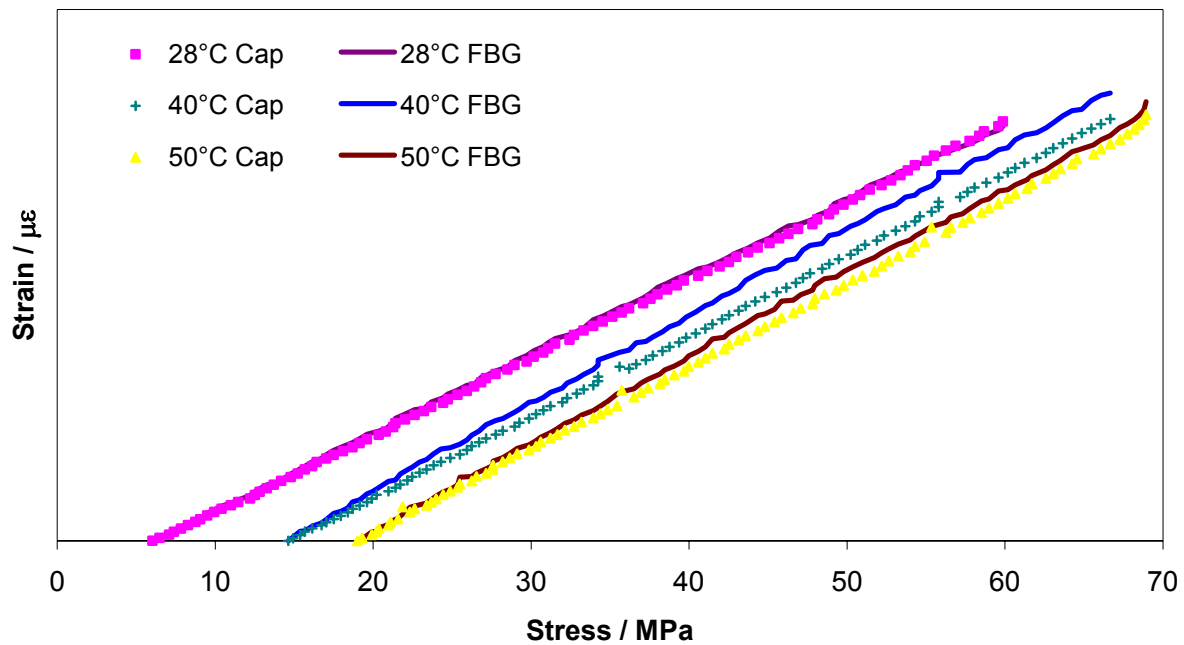


Figure 11: Measurements carried out at different ambient (constant) temperatures. Note, the values of strain for the FBG system are arbitrarily chosen so the maximum strains match those from the capacitance gauge, for readability.

A final point worth mentioning is the fact that a piezoelectric actuator is a non-linear device. This means that, in this context, the displacement produced is not a simple linear function of applied voltage. Additionally, the effect of reversing the voltage does not bring the actuator back down its original displacement path but rather down a hysteretic path. This is shown in the plot of capacitance gauge voltage against actuator applied voltage, in figure 12.

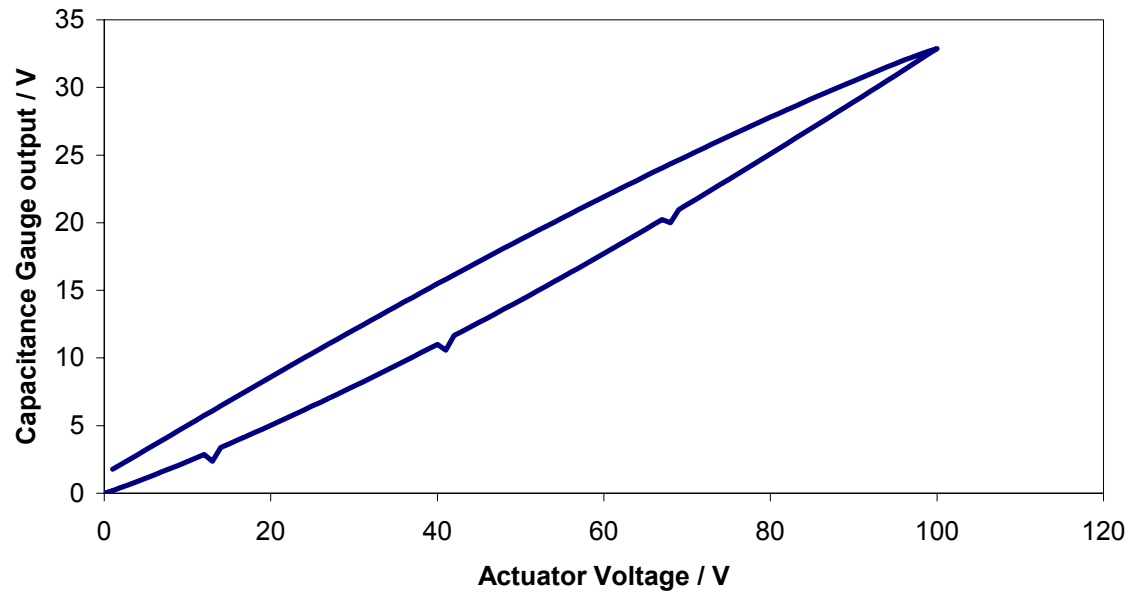


Figure 12: Hysteresis in Piezoelectric actuators.

This characteristic is expected from the non-linear properties of piezoelectric ceramic materials.

6 CONCLUSIONS

A novel calibration jig has been designed, built and used to initiate a new area of work at NPL concerned with the calibration of Fibre Bragg Grating sensors that are used as strain sensors in many applications. Individual fibres have been used in this work to develop a better understanding of the major metrology issues involved. The activity has led to the development of a potential new Studio project aimed at helping UK industry adopt this new technology by introducing standards and calibration services.

7 REFERENCES

NPL Report CMMT (D)205, 1999

NPL Report MATC (D)13, 2001

Othonos and Kalli, Fibre Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing, Artech House optoelectronics library, Artech House 1999.

Nash P., Optical fibre sensors for anti-submarine warfare applications, Journal of Defence Science Vol. 3 No. 2 (1998), pp.197- 206

Merzacher C. et al., Fibre optic sensors in concrete structures: a review, Smart Materials and Structures Vol. 5 (1996), pp. 196 – 208

Dakin J. and Culshaw B., Optical fibre sensors: principles and components, vol 1. Artech House (1988).

Huston D. et al., Dynamic testing of concrete with fibre optic sensors, Application of fibre optic sensors in engineering mechanics (ed. F. Ansari) pp. 134 -143

Bennion et al., Tutorial review: UV written in-fibre Bragg gratings, Optical and Quantum Electronics 28 (1996).

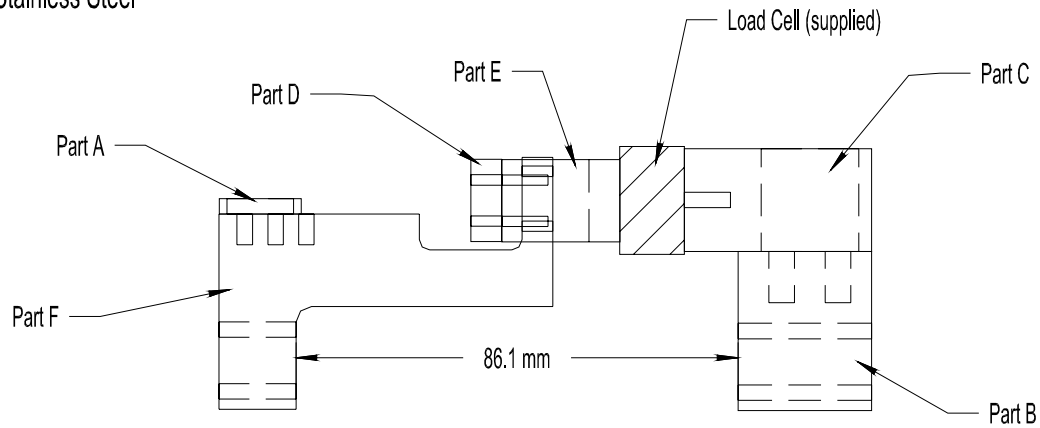
Magne, S., Rougeault, S., Vilela, M. and Ferdinand, P., State-of-strain evaluation with fiber Bragg grating rosettes: application to discrimination between strain and temperature effects in fiber sensors. Applied Optics, 36,36, pp.9437-9447 (1997).

Bertholds A. and Dandliker R, Determination of the individual strain-optic coefficients in single-mode optical fibers, J. Lightwave Technol., 6, 17-20 (1988).

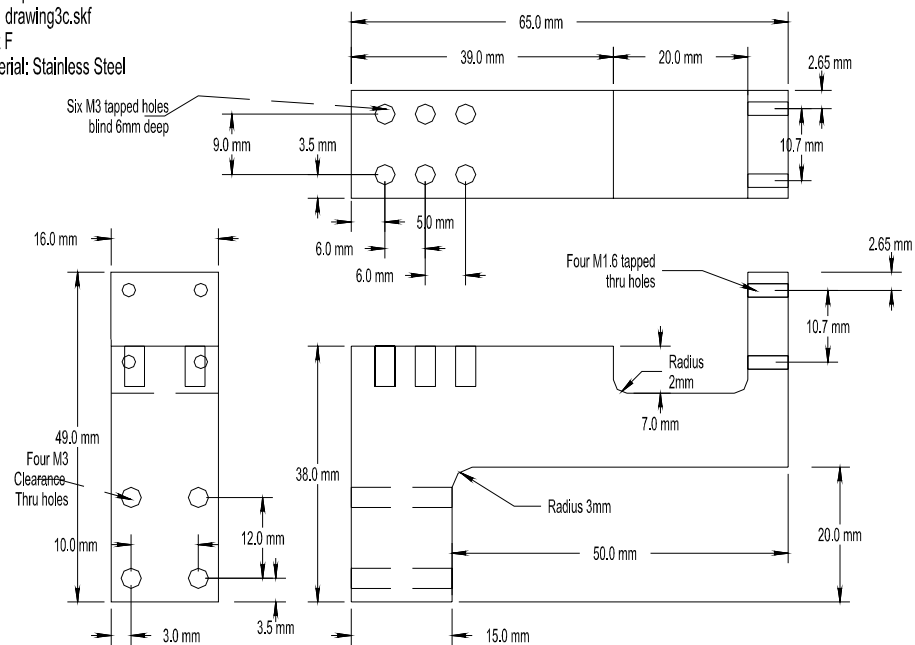
Ed. Tennent, Science Data Book, ISBN 0 05 002487 6, Oliver & Boyd, Edinburgh (1971).

APPENDIX I: DIAGRAMS OF COMPONENT PARTS OF THE CALIBRATION JIG.

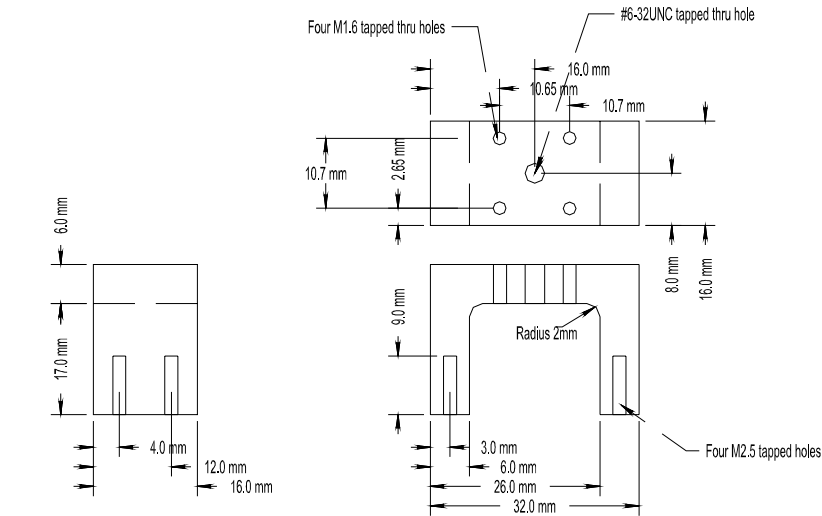
Fibre Optic Puller
 File: drawing3456.skf
 Assembly Side View
 Material: Stainless Steel



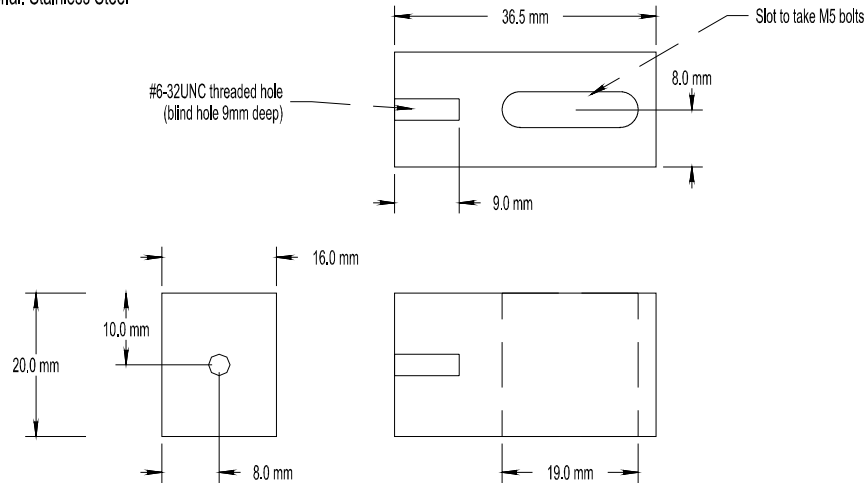
Fibre Optic Puller
 File: drawing3c.skf
 Part F
 Material: Stainless Steel



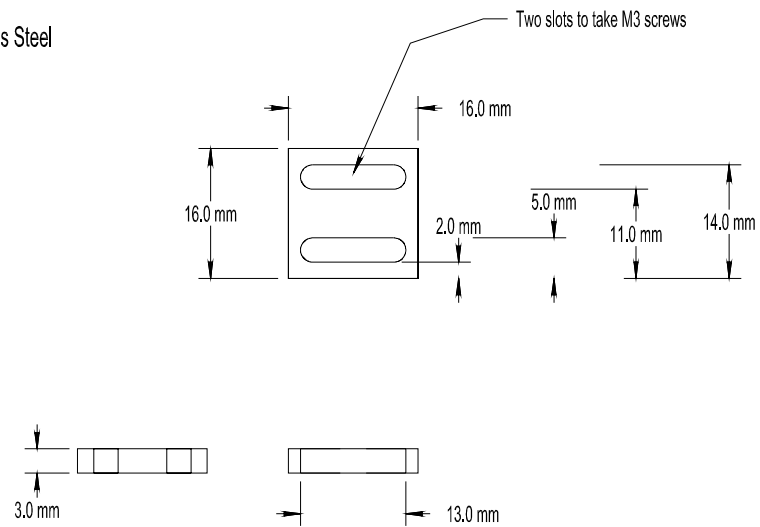
Fibre Optic Puller
File: drawing4.skf
Part E
Material: Stainless Steel



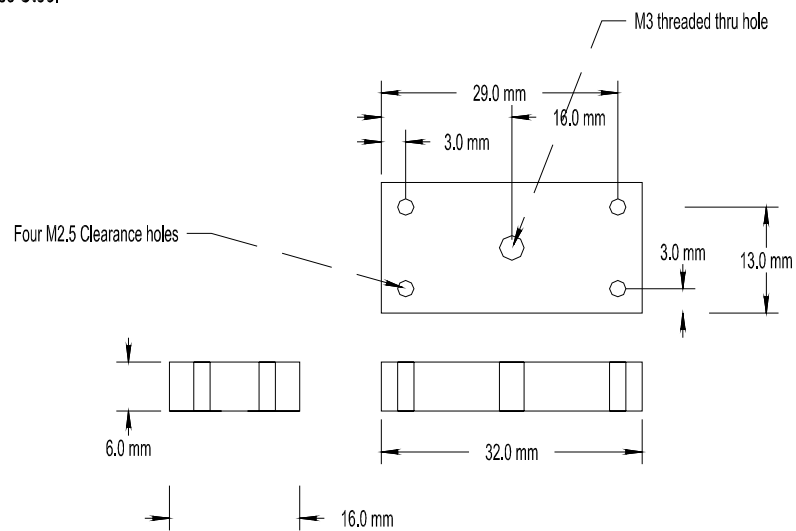
Fibre Optic Puller
File: drawing6.skf
Part C
Material: Stainless Steel



Fibre Optic Puller
 File: drawing3b.skf
 Part A
 Material: Stainless Steel

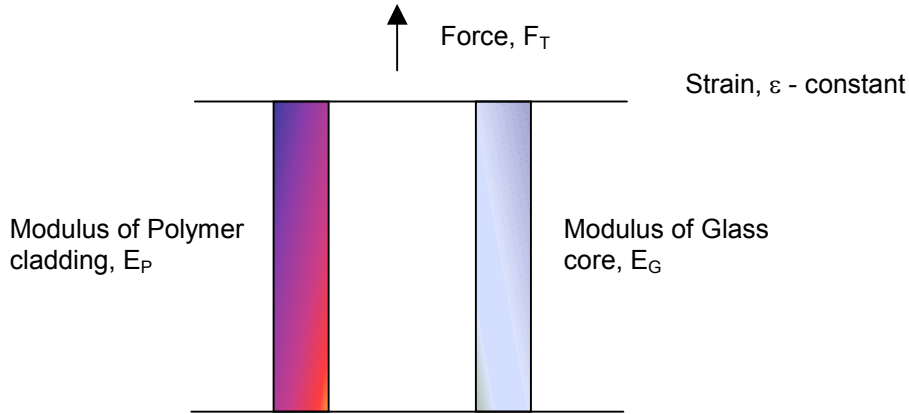


Fibre Optic Puller
 File: drawing5.skf
 Part D
 Material: Stainless Steel



APPENDIX II: METHOD OF MIXTURES CALCULATION FOR LOAD TRANSFER THROUGH OPTICAL FIBRE

Consider the polymer-clad fibre to be modelled using two rods, one made from glass and one from the polymer. Both rods must support the load and we assume that the resulting strain is equal in both rods – that is the stress state in each rod differs. Then, it follows:



$$\frac{F_G}{A_G} = E_G \varepsilon$$

$$\frac{F_P}{A_P} = E_P \varepsilon$$

$$\frac{F_P}{E_P A_P} = \frac{F_G}{E_G A_G}$$

also, $F_P + F_G = F_T$ so $F_P = F_T - F_G$

so

$$\frac{A_P E_P F_G}{A_G E_G} = F_P = F_T - F_G$$

$$F_G \left[1 + \frac{A_P E_P}{A_G E_G} \right] = F_T$$

$$\text{so, } F_G = \frac{F_T}{\left[1 + \frac{A_P E_P}{A_G E_G} \right]}$$

and from the radius of each fibre core, r_1 and outer cladding, r_2 this becomes:

$$F_G = \frac{F_T}{\left[1 + \frac{(r_2^2 - r_1^2) E_P}{r_1^2 E_G} \right]}$$

Typical values are:

$$R_2 = 250 \text{ } \mu\text{m}$$

$$R_1 = 125 \text{ } \mu\text{m}$$

$$E_P = 1 \text{ GPa}$$

$$E_G = 70 \text{ GPa}$$

APPENDIX III: SUPPLIERS OF EQUIPMENT

Please note that there are many other suppliers for the components needed to construct such a system. The suppliers that NPL used are listed below.

NPL Engineering Services

www.npl.co.uk

Morgan Electroceramics

www.morganelectroceramics.com

Ceramtec

www.ceramtec.com

Smart Fibres Ltd

www.smartfibres.com

Oxford Fibre Optic Tools Ltd

www.oxfordfibre.com

Indigo Company

www.indigo-photonics.com

Queensgate Ltd

www.nanopositioning.com

Software

National Instruments, Newbury, Berkshire, UK

<http://www.ni.com/>

LabView ® software

NPL written software © NPL

Other web based resources:

Institute of Physics, UK web site devoted to optical photonics:

<http://optics.org>

European Fibre Optic Sensors Network

<http://fibre.fos-en.net/>