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DEVELOPMENT OF LOW COST PACKAGED FIBRE OPTIC SENSORS FOR USE IN REINFORCED CONCRETE STRUCTURES

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ABSTRACT

There is an ongoing need to measure strains in reinforced concrete structures more reliably and under a range of circumstances e.g. long term durability (such as effects of cracking and reinforcement corrosion), response to normal working loads and response under abnormal load conditions. Fibre optic sensors have considerable potential for this purpose and have the additional advantages, including of immunity to electromagnetic interference and light weight (Grattan et al, 2000). This is important in railway scenarios and particularly so when the lines are electrified. Their small size allows for easy installation. However, their use as commercial ‘packaged’ devices (traditionally seen as necessary to achieve adequate robustness) is limited by their high cost relative to other sensor devices such as encapsulated electric resistance strain gauges. This paper describes preliminary work to produce a cost-effective and easy-to-use technique for encapsulating fibre optic sensors in resin using 3D printing techniques to produce a robust, inexpensive ‘packaged’ sensor system suitable for use with concrete structures. The work done to date has shown this to be a convenient and economical way of producing multiple sensors which were suitable for both surface mounting and embedment in reinforced concrete structures. The proof-of-concept testing to which the trial packages were subjected is described in the paper and the results indicate that 3D printed packages have considerable potential for further development and use in a variety of civil engineering applications, competing well with more conventional sensor systems.

KEYWORDS

Fibre optic sensor, encapsulation, 3D printing, reinforced concrete, strain measurement.

INTRODUCTION

There has long been a requirement to measure strains in reinforced concrete structures. Examples are seen in the monitoring of full scale structures, to measure performance and possible deterioration, load testing of full scale structures and a wide range of laboratory applications involving tests on all manner of structural elements such as beams, slabs, columns and connections. However, a prime requirement is that strain sensors must be robust as well as reliable if they are to function well in the long-term within the often harsh civil engineering environments that are experienced. Thus, sensor design is challenging and requires careful consideration and good, 'tailor-made' sensor systems for specific and difficult environments require considerable design effort.

Optical fibre sensor devices have great potential for use in civil engineering situations due to their immunity to electromagnetic interference, moisture resistance, relatively small size and compactness (Grattan and Sun, 2000, Surre et al, 2012). Fibre Bragg Grating (FBG) sensors are used widely and have proved to be extremely successful when used in a wide range of applications over recent years (Majumder et al, 2008, Grattan and Meggitt, 1995). However, by their very nature, they are fragile and thus, for use in civil engineering environments, they need to be correctly packaged (i.e. encapsulated) to resist the effects of climate and usage if they are to achieve the required level of robustness for use in different situations. Nevertheless, there is continuing interest in their use in a wide variety of structures (e.g. Kister et al, 2007, Grattan et al, 2011, Thakur et al, 2011, Banerji et al, 2014, Bravo et al, 2014).

A few years ago, the authors collaborated on a project using 'packaged' commercially sourced fibre optic strain sensors to monitor the behaviour of a multi-span prestressed concrete box girder railway bridge across Vasai Creek, north of Mumbai in India, funded by a UKIERI (United Kingdom India Education & Research Initiative) grant. The project remit was to demonstrate that such optical strain gauges could be rapidly installed on a major bridge under challenging field conditions and then used to obtain high quality strain data resulting from train movements. The bridge is shown in Fig 1. An inset to this Figure shows a detail of the optical gauges used which were commercially sourced and contained two FBGs inside a 250 mm long glass tube, one FBG for strain measurement and the other for temperature measurement (remembering that FBG strain readings must be compensated for temperature since they measure total strain i.e. mechanical strain plus temperature strain). The gauges were installed by being bolted to the surface of the concrete (but would also have been suitable for embedment in the concrete should this have been required). The tests, which have been reported in detail (Scott et al, 2013) were extremely successful but were constrained by the high price of the sensors, as each cost several hundred US dollars. Thus, a need for a reliable, robust, low cost optical sensor was demonstrated, the first stages in the development of which are reported in this paper.

PRELIMINARY TESTS

Background

The requirement was that the packaging for the sensors should be robust, easy to fabricate in a range of geometries and relatively inexpensive, yet able to offer high quality, reproducible measurements. Sensors had to be suitable for surface mounting as well as being able to withstand the rigours of being cast into concrete. In addition, because of the understandably conservative approach of the civil engineering industry, they should neither themselves be compromised by the highly alkaline nature of concrete nor be affected by this alkalinity in ways which would cause degradation of the concrete itself.

The use of 3D printing techniques seemed a promising way forward, particularly as the necessary facilities were already available in the laboratory and are relatively inexpensive to use. An initial trial, in which a 3D-printed package was created using photopolymer resin, was deemed sufficiently `encouraging (Wang et al, 2017) to warrant the further development work reported in this paper. This was funded by another UKIERI grant and was a collaboration between City, University of London, and the Indian Institute of Technology Roorkee.

Open Top Packages: Design and test setup

The packaging for the sensors was designed to be simple but robust. As a start, two very similar open top packages having the layout shown in Fig 2 were designed using *SolidWorks*. They were printed using standard photopolymer resin having a Young's modulus of 1.7 GPa. *formlabs Pre Form* was used to drive the *formlabs 1*+ 3D printer. Two 5 mm long FBGs were installed in each package, the one in Section B being glued to the package with Duralco 4525-IP for strain measurement and the other free (i.e. not glued) in Section C for temperature measurement, both being multiplexed on a single fibre. With reference to the figure, it can be seen that the cable leading to the interrogator exited the package along Section A. Protection of the strain FBG was achieved by filling Section B with Duralco adhesive. The temperature FBG was allowed to "float" in Section C.

A 60 mm x 60 mm square hollow section steel beam having a 3 mm wall thickness (i.e. a 60x60x3 SHS) was used for testing the packages. This was arranged in a commercial testing machine used for four point bending with a 1500 mm span between simple supports and a constant moment zone of 500 mm. Load was applied centrally with a spreader beam being used to distribute the load onto the two loading points. (as shown in Fig 3).

The two packaged sensors, created using the above approach, were glued to the mid-point of the beam. Adjacent to them a commercially sourced packaged electric resistance strain gauge (esrg) was glued which, overall, was 125 mm long, 13 mm wide and 5 mm thick. Gauge Resistance and Gauge Factor were 120 ohm and 2.1 respectively. A longitudinal groove had been carefully cut in both the top and bottom faces of this package in each of which were glued three bare FBGs multiplexed on a single fibre. Additionally, three bare FBGs, again multiplexed on a single fibre, were glued directly onto the top face of the beam adjacent to the packaged ersg. The aim was that readings from the packaged ersg would be used to benchmark the readings from all the FBGs. Fig 4 shows a detail of the sensor arrangement and the wavelengths of all the FBGs are listed in Table 1.

A series of load histories was applied to the beam to test sensor performance under cyclic and sustained loads to assess linearity under both loading and unloading situations and creep behaviour under sustained loads.

Data were collected using a Micron Optics sm130 interrogator with a sampling frequency of 1 kHz and an accuracy of ±2 pm. The interrogator had 16 input channels which enabled FBGs with similar wavelengths to be kept separate.

Results

The packaged ersg and the bare FBGs all gave essentially identical responses under all the loading conditions evaluated, each displaying excellent linearity, repeatability and absence of creep. The strain-monitoring FBG in the packaged sensor showed similar behaviour during loading and unloading but, although strains under sustained loads were of a similar magnitude to those for the bare FBGs, there was pronounced creep, as indicated in Fig 5 for load cycles to 5.0 kN (total load on the beam). The strain-monitoring FBG in the packaged sensor also displayed divergent behaviour on first loading (Fig 5). The temperature FBG in the packaged sensor remined very stable throughout the tests, indicating that no significant temperature change had occurred during the tests and thus no corrections were required.

Strain sensitivities of the FBGs were calculated by referencing them to the ersg results. Sensitivities of the temperature FBGs were known from prior work but not explicitly calculated since, in view of the stable laboratory environment, the authors were only interested in the wavelength shifts at this stage in the work. It would be straightforward to perform this calibration in future tests.

The strain sensitivity of the packaged FBGs was found to be significantly lower (0.68 pm/microstrain) than that for the bare FBGs (1.13 pm/microstrain). This lower sensitivity is not surprising when sensors are packaged in this way and the low stiffness of the resin used for the packaging was most likely the cause of the creep problem. Overall, however, low sensitivity was not seen as a problem as the sensors could be calibrated in advance of their use and thus these tests were deemed sufficiently encouraging to justify further development work being undertaken.

FURTHER TESTS: CLOSED TOP PACKAGES

Background

There were three aspects to this further work which used the facilities at both City and Roorkee. City designed and tested a more sophisticated packaged sensor, using a similar procedure to that described above, and then a batch of these sensors was produced and sent to Roorkee for further evaluation in a reinforced concrete beam test. In addition, Roorkee investigated the suitability of different cable types for use with sensors embedded in concrete.

Package Design

The new sensors were designed to have similar overall dimensions to the packaged ersg considered and used earlier. Since packaged ersgs are specifically designed for both surface mounting and embedment in concrete structures (without the need for bolted connections), it seemed sensible to manufacture the new FBG packages to have similar dimensions and surface characteristics for easy compatibility. They were printed in two parts with the dimension shown in Fig 6, a ‘top’ and a ‘bottom’, the two parts being glued together after installation of the gratings. Being completely enclosed made them more robust and thus more suitable for casting into a concrete beam although it was appreciated that there would likely be a reduction in sensor sensitivity. Tough photopolymer resin was used which was cured under UV light at a temperature between 40 to 50°C for one hour to give a Young's modulus of 2.5 GPa. Duralco 4525-IP was used to glue the two halves together. As before, two FBGs were installed in each package, the one in Section A being glued to the package with Duralco 4525-IP for strain measurement and the other free (i.e. not glued) in Section B for temperature measurement, both being multiplexed on a single fibre.

The first package was evaluated in the laboratories at City, using a similar sensor layout and test procedure to that described above, following which eight packages were manufactured and dispatched to Roorkee (Fig 7) for casting into the test beam. A further six packages were later manufactured and dispatched to Roorkee for use in cable resilience tests.

Laboratory Testing at IIT Roorkee

The test beam was 2.0 m long overall, 500 mm deep and 300 mm wide (Fig 8). It was reinforced with five No. 20 mm diameter ribbed high yield reinforcing bars, two in the top and three in the bottom (cover to the centre of the bars was 50 mm). It was tested in four point bending (Fig 9) with shear stirrups being omitted in the constant moment zone. The concrete was a standard laboratory mix having a target compressive cube strength of 25 MPa.

In the constant moment zone, a packaged sensor was tied (*not* glued) to each of the top reinforcing bars and to each of the two outer bottom bars, as illustrated by the inset in Fig 8. Also, packaged sensors were glued to the side face of the beam, level with the packages on the reinforcing bars. A standard patch lead, 125 µm in diameter, was used which was threaded through plastic tubing for additional protection where it passed through the concrete.

Load was applied to the two loading points via a centrally loaded steel spreader beam. The beam was loaded cycled to a total load of 200 kN in a series of increments, a full set of sensor readings being recorded at each load stage.

Three types of cable were trialled for the resilience tests, the standard patch lead used in the beam (without the protective tubing), a stiff, externally armoured version of this standard cable and a cable which was internally strengthened during the manufacturing process. This was achieved by having a fine, flexible, wire tube woven between the optical fibre and the outer polythene coating. Cables were cast into standard 150 mm test cubes (Fig 10) with bends being deliberately made very tight. It was intended that compression tests would be conducted on these cubes.

Results: Package Evaluation

As before, the response of the strain monitoring device in the packaged sensor was similar to that for the bare FBGs under all loading conditions. The sensitivities of the packages used were found to be 0.54 pm/microstrain in tension and 0.36 pm/microstrain in compression. Their behaviour in compression is compared with that for a bare FBG in Fig 11 which clearly indicates the effect of the package's reduced stiffness. Creep was also observed, although this was less pronounced than that recorded with the open top packages (Fig 11) and stabilised fairly rapidly (Fig 12). Once again, the FBG sensor used for temperature monitoring remained stable throughout the tests, reflecting the absence of temperature changes.

Bearing in mind that a stiffer resin had been used in this batch of sensors, the reduction in stiffness and the continuing presence of creep were both disappointing. However, overall, the behaviour of the sensor was still considered to be encouraging.

Results: Testing at IIT Roorkee

As in the first test carried out in the laboratories at City, the FBGs for temperature correction remained stable during the load tests, again indicating that temperature was stable (Fig 13). The FBGs used for strain measurement in the top (compression) zone of the beam, adjacent to the reinforcement, responded well to the pattern of the load cycling (Fig 13) although peak readings between the two sides of the beam differed somewhat, probably due to secondary effects caused by the alignment of the beam in the test rig and exacerbated by variations in compressive strength (and hence Young’s modulus) of the concrete across the width of the beam. However, calculations using a Young’s modulus of 31 GPa for the concrete (aligning with Eurocode 2, 2004) indicated strains of approximately 108 microstrain in compression and tension at the levels of the top and bottom reinforcement respectively. For a sensitivity of 0.36 pm/microstrain, this would be equivalent to a wavelength shift of 0.04 nm, shown as a series of horizontal bars in Fig 13, which was close to the mean value (0.045 nm) of the measured values. Variability in the compaction of the concrete around the packaged sensors may well have contributed to the discrepancy between their readings.

Behaviour in the tension zone was complicated by the development of a flexural crack at the centre of the beam as, with ribbed reinforcement, microcracking develops in the concrete each side of a crack leading to massive strain incompatibility between the reinforcement and surrounding concrete (Goto, 1971, Scott and Beeby, 2005, Scott and Whittle, 2005). Unfortunately, the packaged sensors at the bottom (tension zone) of the beam were positioned in this complex region but, as shown in Fig 14, on early loading prior to cracking, they still managed a small tensile response while, after cracking, they responded to the cyclic form of the applied load. Further investigation of these effects is needed (and planned) for future work.

Results from the cable resilience tests summarized above were conclusive since only the cable which was internally strengthened during the manufacturing process survived to give reliable readings.

FUTURE DEVELOPMENTS

The authors recognise that the work described in this paper is but the first stage in the development of packaged fibre optic sensors suitable for use in commercial civil engineering applications. Nevertheless, this early proof-of-concept work shows considerable promise and gives encouragement for further development work to be undertaken.

Experience gained from the work reported in this paper indicates that issues to be addressed further include the following items:-

- Significantly reduce the mismatch between the stiffness of the packaging material of the sensors and that of the concrete or steel which is the likely root cause of the creep problems. Possibilities include using PEEK (polyether ether ketone) or, perhaps more likely, ceramic resins. Additionally, reducing the thickness of the packaging is highly desirable and may be assisted by encapsulating the FBGs in the packaging at the time of printing.

- Perform durability tests of the package materials to assess resistance to an alkaline environment, moisture and wear.

- Ensure sensors and their cables can withstand the effects of the loads to which they may be subjected while in use, particularly if they are embedded in concrete.

- Ensure sensors perform the same in tension and compression, have improved (i.e. higher) sensitivities than the figures achieved to date and are consistent in performance between sensors of a similar type and size.

- Ensure similar behaviour between sensors which are surface mounted and those which are embedded.

CONCLUSIONS

A number of conclusions could be drawn from the outcomes of the above work, as follows:

- a need for low cost packaged fibre optic sensors for strain measurement in civil engineering applications has been identified, particularly for use in reinforced concrete structures.
- sensor systems of that type have been effectively packaged (encapsulated) in resin using 3D printing techniques, creating a low-cost and effective device for use in these applications.
- ‘proof-of-concept’ testing in the laboratories at City, University of London, and at the Indian Institute of Technology Roorkee has demonstrated the potential of the packaged sensors for strain measurement in representative civil engineering applications.
- further development work has been identified to enhance the sensitivity of the packages, possibly by using stiffer resin or ceramic materials, this forming the substance of future work.

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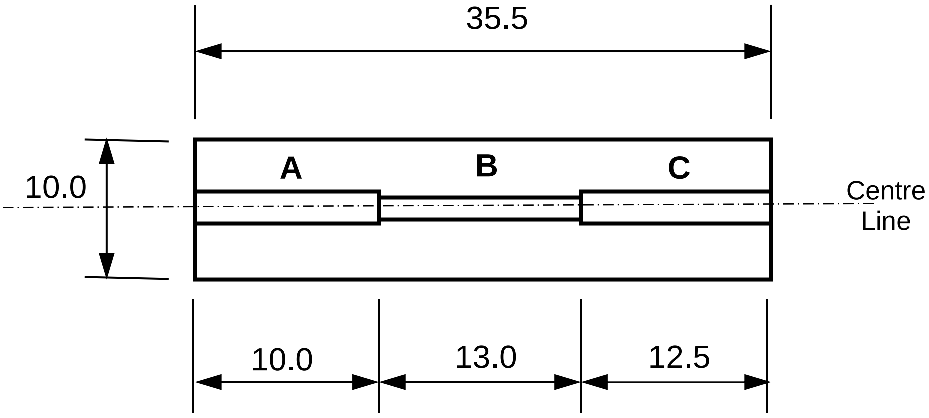
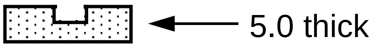
Figures

Fig 1: Vasai Creek Bridge (Optical Sensor Inset)



Plan



Section Through Area C

All dimensions in mm: Not to Scale
Symmetrical about longitudinal centreline
Thickness = 5 mm

A: Semi-circular duct 4 mm diameter
B: Semi-circular duct 3.5 mm diameter
C: Square duct 3.5 x 3.5 mm

Fig 2: Layout of Open Top Package

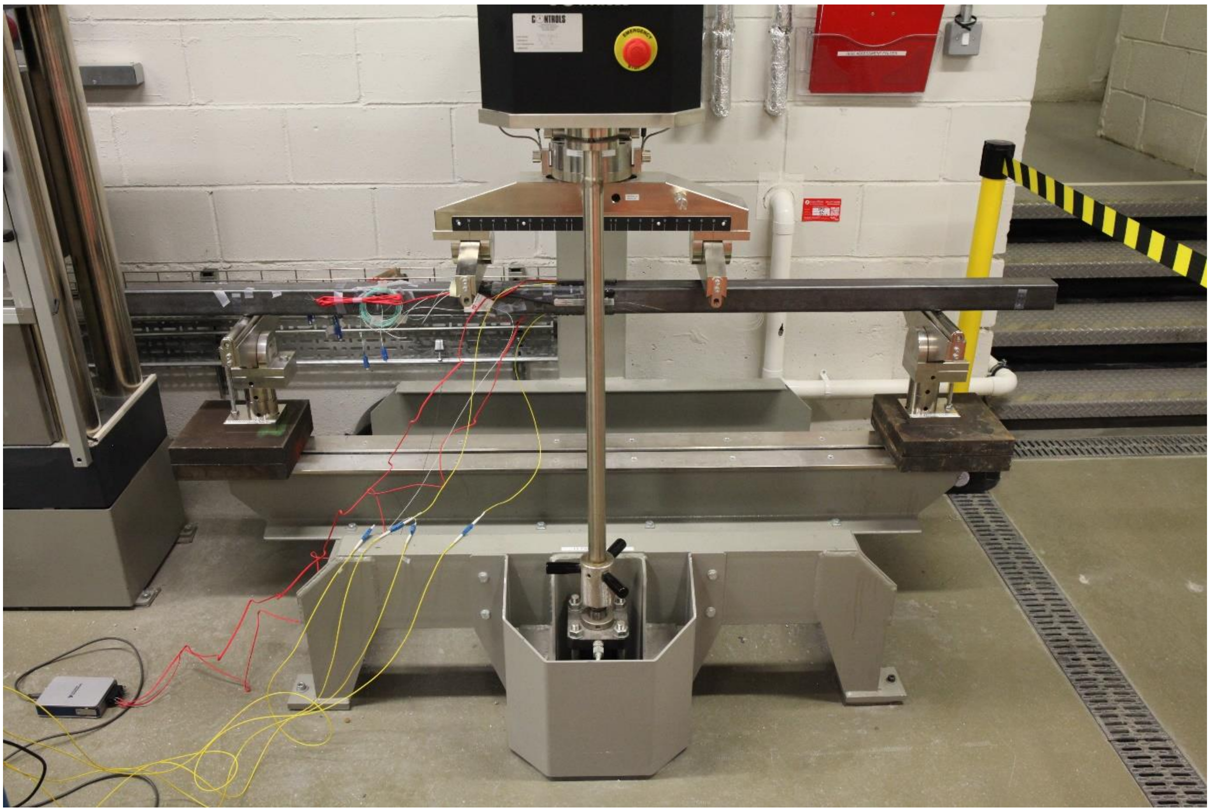


Fig 3: Test Rig for Sensor Assessment

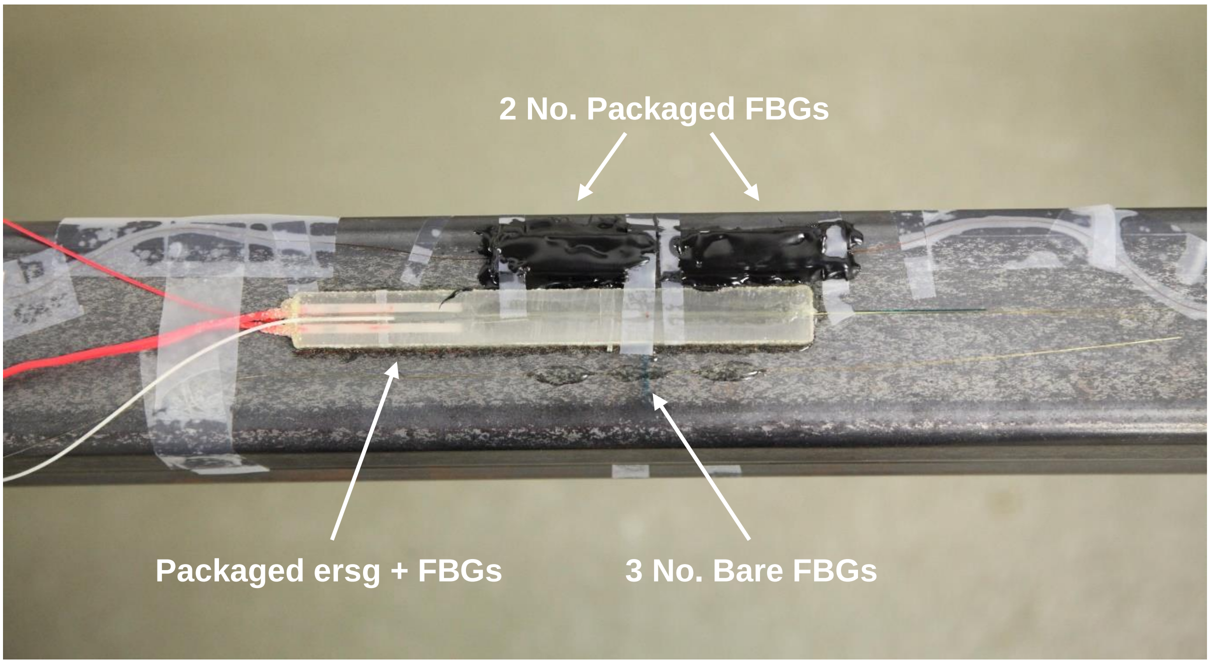


Fig 4: Detail of Sensor Layout on Steel Beam

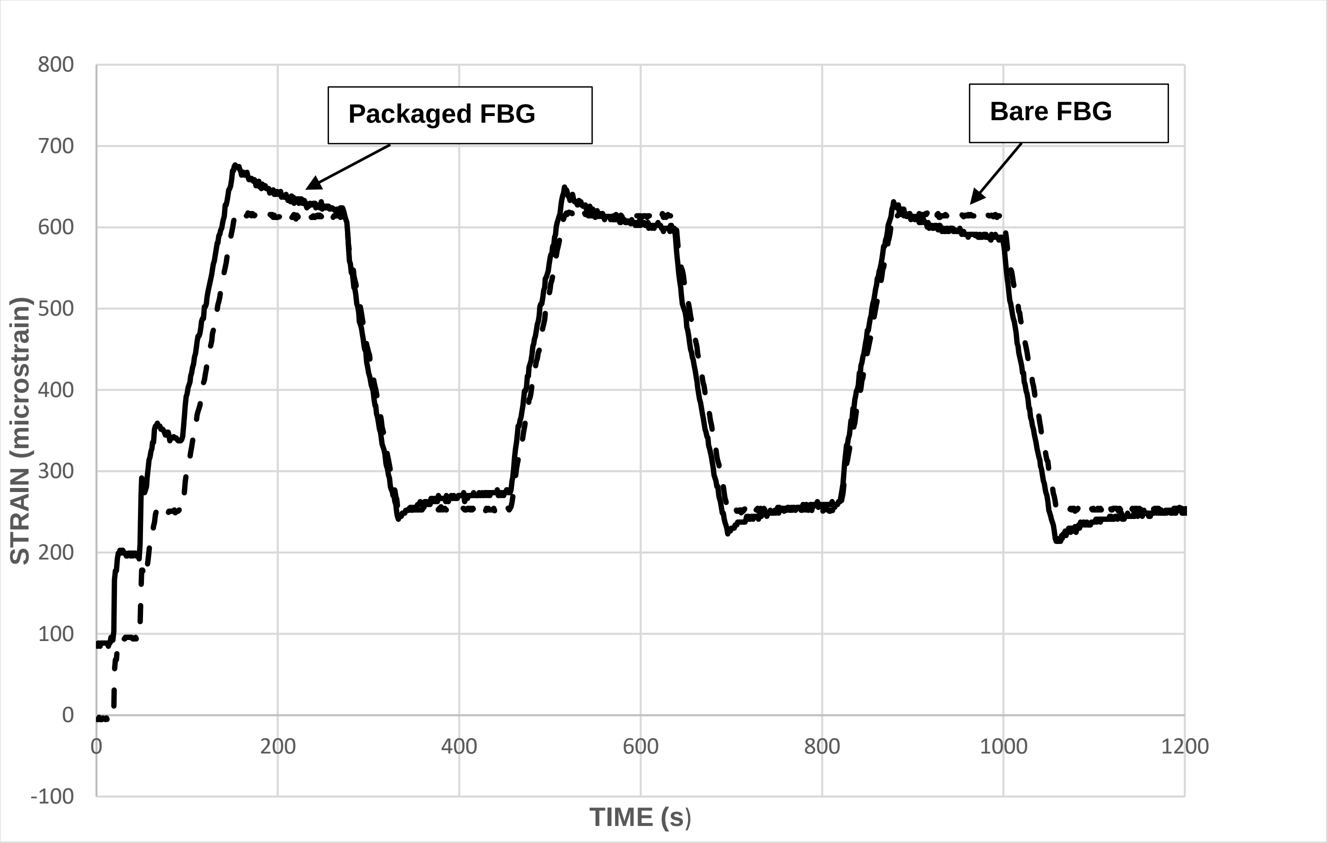
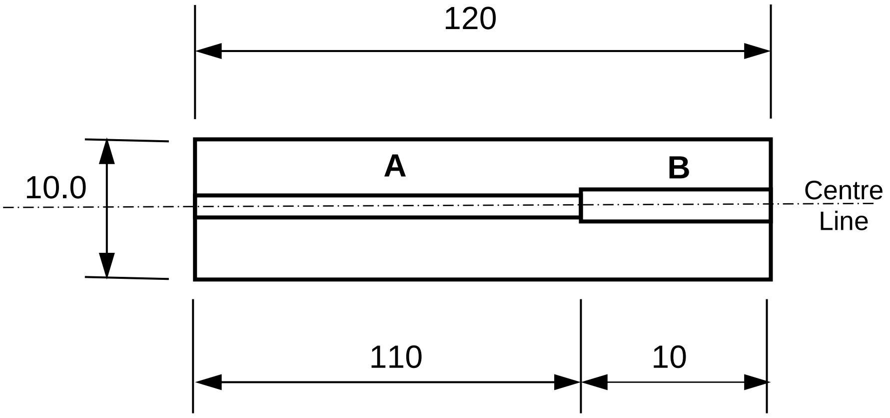
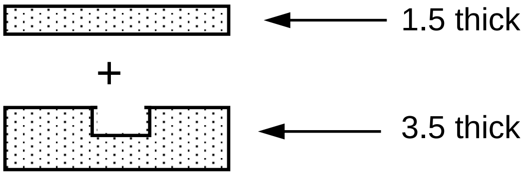


Fig 5: Open Top Package: Load Cycles to 5.0 kN



Plan of Bottom Component



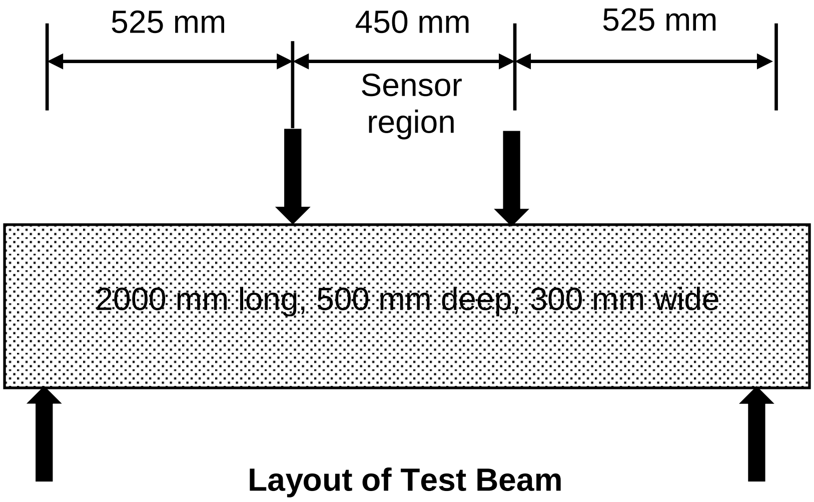
Typical Section

All dimensions in mm: Not to Scale
Symmetrical about longitudinal centreline

A: Semi-elliptical duct 1 mm wide x 1.5 mm deep
B: Square duct 3.5 x 3.5 mm

Fig 6: Layout of Closed Package

Fig 7: Packaged Sensors for IIT Roorkee



Layout of Test Beam

Reinforcement Cage
Longitudinal bars all 20 mm diameter
(Inset: Packaged FBG tied to bar)

Fig 8: Reinforced Concrete Test Beam at IIT Roorkee

Fig 9: Beam Test at IIT Roorkee

Fig 10: Cable Resilience Test Specimen During Casting

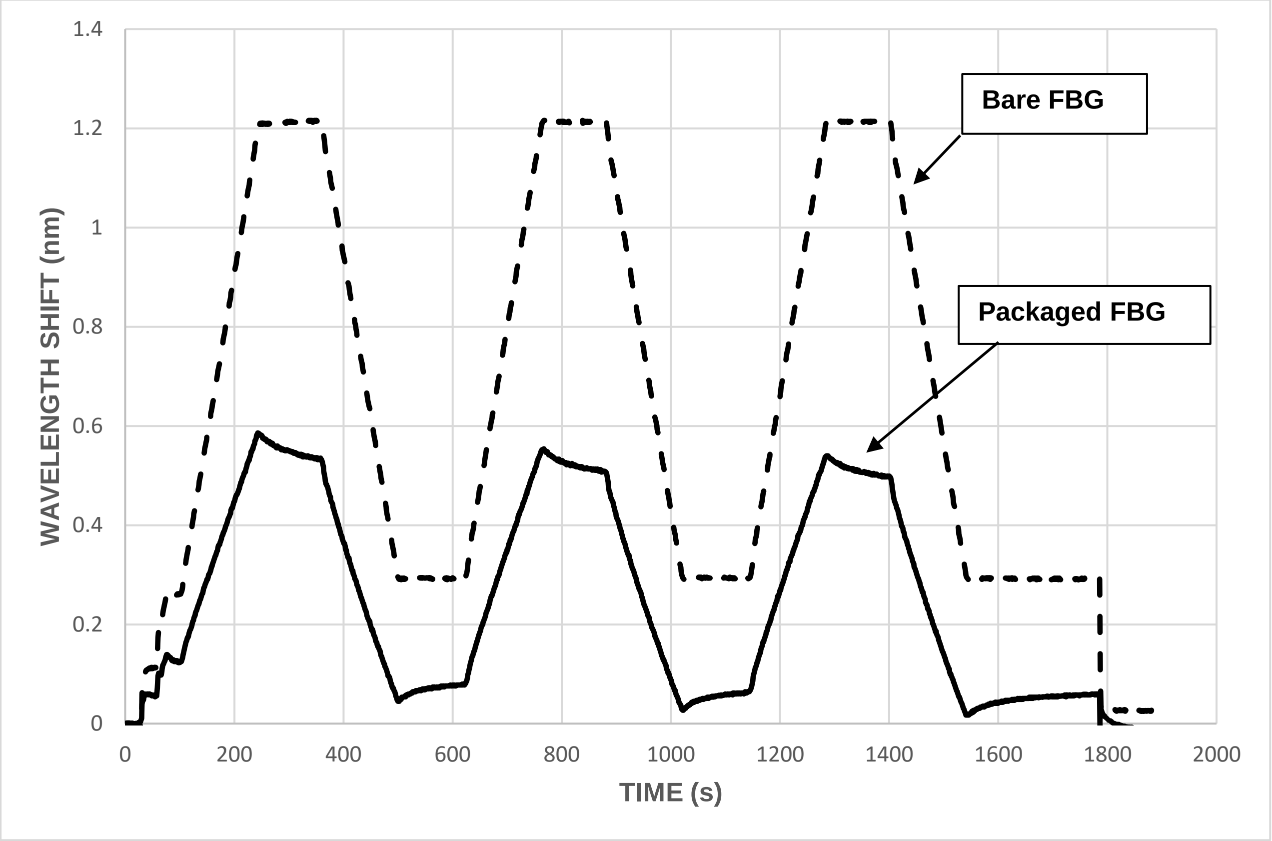


Fig 11: Closed Top Packages: Load Cycles to 5.0 kN

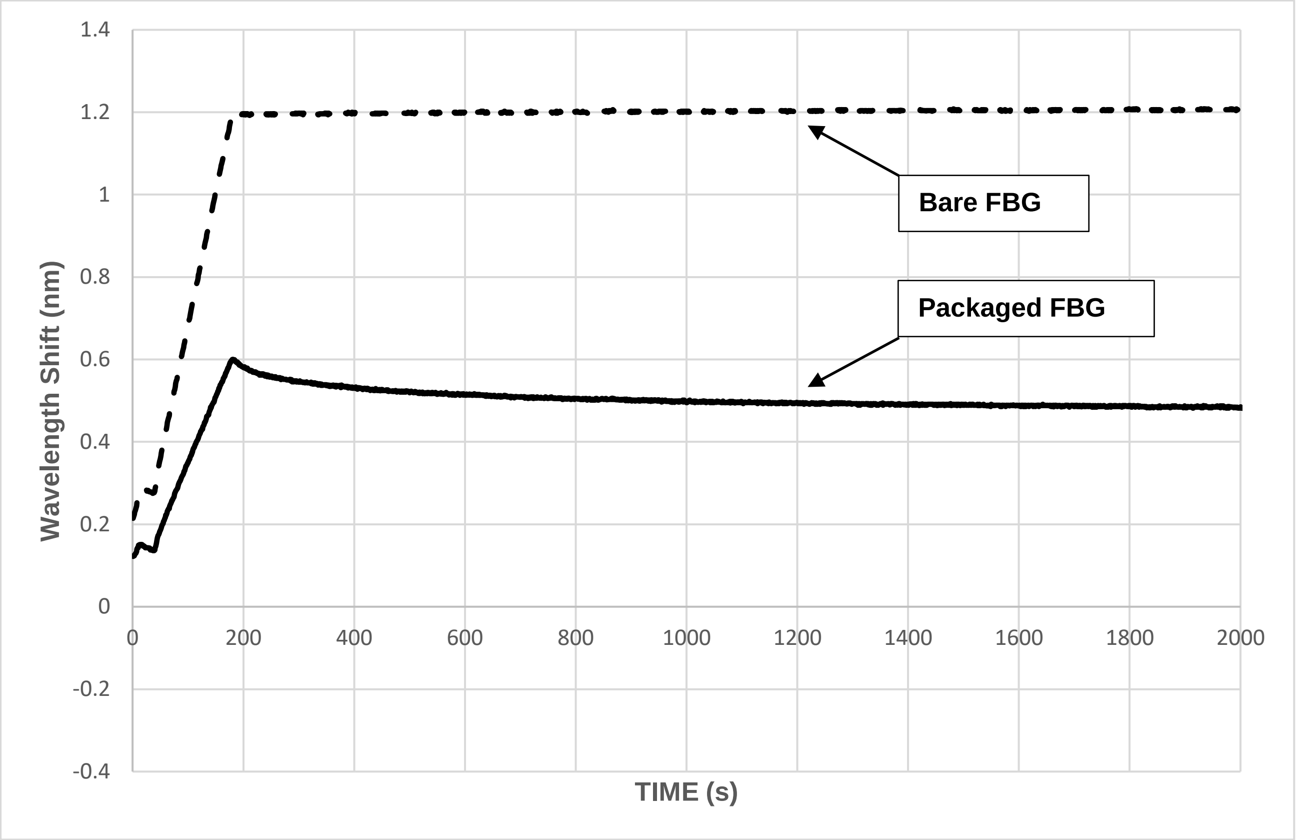


Fig 12: Closed Top Packages: Creep Behaviour at 5.0 kN

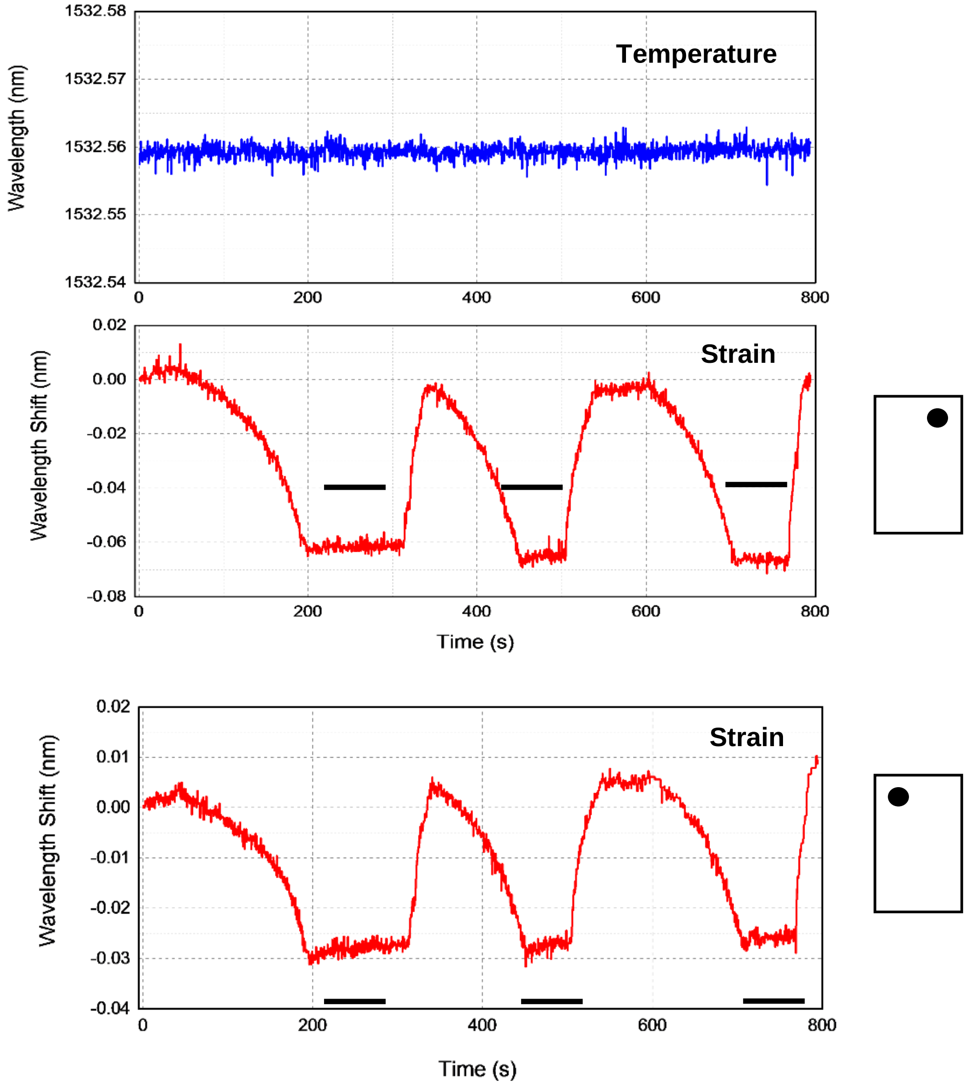


Fig 13: Results for Packages Adjacent to Top Reinforcement (Horizontal Bars Indicate Calculated Values)

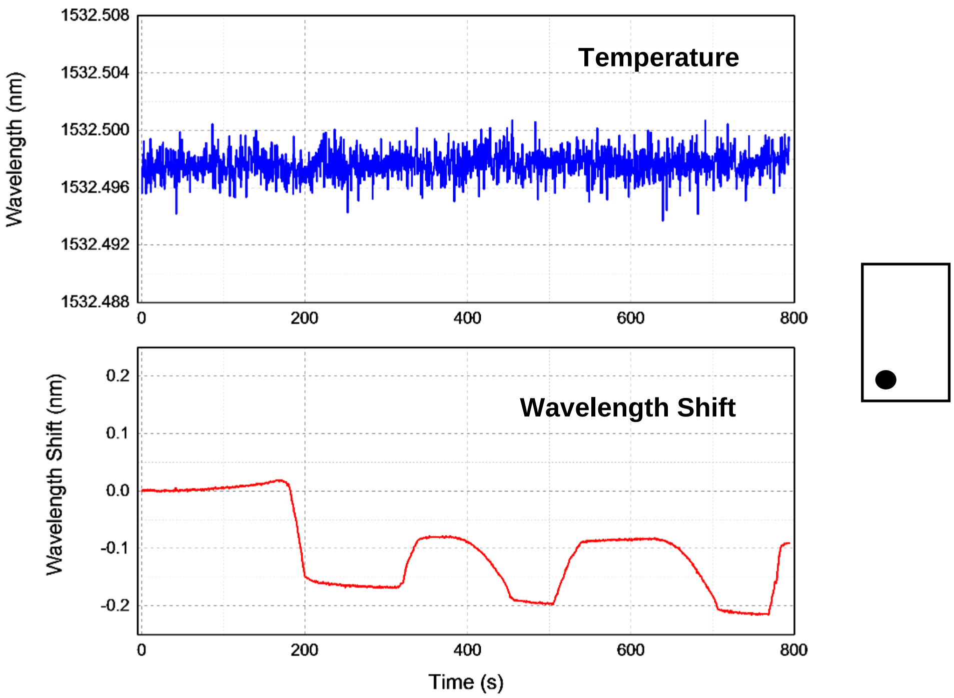


Fig 14: Results for Package Adjacent to Bottom Reinforcement

Sensor Type	Wavelengths (nm)
Bare FBG on steel beam	1537 1548 1558
Top face of packaged ersg	1537 1548 1558
Bottom face of packaged ersg	1537 1548 1558
Open top packaged FBG 1	1541* 1556
Open top packaged FBG 2	1541* 1554

* used for temperature measurement

Table 1: Wavelengths of Sensors Used in Open Top Packaged FBG Test