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Optical fibre sensors for monitoring damage in historic tapestries

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Abstract

The application of silica optical fibre sensors (fibre Bragg gratings) to tapestries using a tapestry-like textile as a representative material is described. It is shown that the attachment method is crucial in the procedure and must be done without damaging the tapestry. The silica fibres are much stiffer than the tapestry yarn; the effect of this is investigated in the paper. The response of the optical fibre mounted on a tapestry like material is quantified in both quasi-static and creep conditions.

1. Introduction

Tapestries form an integral part of many historic house interiors. These hand-woven textiles are often large and often have intricate patterns that were very time consuming to produce. Tapestries were extremely expensive to commission and were often more highly valued than paintings. For example in 1528 Henry VIII bought a set of ten tapestries depicting the Story of David for £1500, while in 1538 Holbein, the King's painter, was paid £30 per annum. The conservation of tapestries is a key issue in the heritage sector. Specialists are employed to examine the condition of tapestries and recommend conservation strategies that do not alter their intrinsic characteristics or detract from their appearance and function. Textile conservators are experienced in visually assessing textiles for evidence of damage. The local environment is known to play a role in the deformation process and environmental monitoring and control, and condition assessment by visual inspection, is now routine. However conservators have never been able to quantify the strain imposed by the textile's own weight. In the case of a tapestry, this strain is presumed to be a significant factor in its deterioration. The effects of deformation under a constant load are well understood within engineering and procedures exist for monitoring deformation; a tapestry experiences similar deformations under the load resulting from its own weight.

Tapestries are produced by weaving on a loom where closely spaced, highly twisted yarns, known as warp yarns, are stretched and fixed in one direction. Less dense yarns are woven transverse to the warp yarns to produce the pattern; these are known as the weft yarns. In producing the pattern changes of colour are necessary so the weft yarns are often discontinuous and slits are formed; these are secured during weaving by interlocking weft yarns together or later by stitching. On completion the tapestry is hung so that the weft yarns support the weight of the tapestry, causing the self-loading of the tapestry in the direction of its weakest components and across discontinuities in the woven wefts. In the present work, to avoid using and destroying actual tapestries, tapestry-like textile samples are used for testing purposes that have been shown to adequately represent the tapestry behaviour [1]. The material is a plain-weave mass produced wool fabric with warp yarns made up of strong and tightly twisted threads and weft yarns made from soft and bulky threads, similar to the weft in tapestries. The thicknesses of yarns, amount of twist and weave density are the most important factors influencing the general mechanical behaviour of a woven textile fabric. In previous work [1] it was shown that the representative material models the behaviour of the tapestry well.

In engineering structural health monitoring [2] is an accepted approach to condition assessment of components and structures. The proposition is that the physical integrity of tapestries could be assessed by evaluating their condition in an identical way to structural monitoring in engineering. Full-field non-contact measurement techniques, such as electronic speckle pattern interferometry (ESPI) have been used in the cultural heritage sector to assess damage and deterioration; examples include panel paintings [3], mosaics [4] and frescos [5]. The technique seems ideal as it does not require attachment to the artefact. However, full-field interferometric techniques are susceptible to small vibrations and environmental changes. Furthermore, they require a change in the strain state and for tapestries this would occur naturally over a considerable period of time so accuracy of the positioning of the measurement system is an essential feature. A comprehensive review of the application of these techniques in the heritage sector has been carried out [6], which showed condition monitoring in galleries or on-site have been based on purely qualitative assessments. As the overall purpose of this work is to develop means on quantitative on-site (display) assessment a robust technique was necessary. In an initial feasibility study [1], two techniques were assessed using the representative textile samples with one weft fibre cut to simulate a discontinuity resulting from a colour change. It was concluded that the high sensitivity of electronic speckle pattern shearing interferometry (ESPSI) to very small out-of-plane deformations makes the technique unsuitable for tapestries. However a second technique using 3-D photogrammetry and digital image correlation (DIC) produced excellent results showing the strain concentrations around the damage. Presently DIC [7] is being investigated as a means of condition monitoring historic tapestries. In the previous work the 'contrast' required to aid the image correlation was facilitated by producing a 'speckle' pattern on the material using spray paint. Clearly this is undesirable on actual tapestry so work has been carried out that shows the contrast in a typical tapestry design in sufficient to carry out the image correlations; this will be described in a future publication [7].

As discussed above, one of the challenges in applying a full-field strain monitoring technique such as DIC is the necessity of moving and re-positioning of the measurement system between readings. The authors are currently working on a means to accurately reposition the system [7]. However, even if this is successful it would be impossible to use DIC to continuously monitor the condition of a tapestry and the requirement for digital cameras to be positioned to view the tapestry under investigation would detract from the visual impact of the tapestry. Furthermore in a gallery situation it would be difficult to prevent the viewing public from disturbing the cameras etc. Therefore it was considered desirable to identify a less visually intrusive means of continuously monitoring the tapestry behaviour. In the initial feasibility study [1] the integration of optical fibre Bragg grating (FBG) [8] sensors into tapestries was studied. These were chosen, as optical fibres are very small, non-intrusive and very light weight. In general silica FBGs can only respond to strains of up to 3%. It was determined in the feasibility study that the damage that could not be detected by the eye of the conservator occurred below 10%. Even though this is much greater than the range of an FBG, it was considered monitoring small changes in strain with such a device would be useful as a reference for DIC and if positioned judiciously it could be ensured that the FBG would not be damaged by larger strain. Furthermore in the future more flexible devices based on polymer optical fibres could be used.

In integrating the optical fibre with the tapestry it is crucial that no damage is caused to the tapestry. In the feasibility study [1] three techniques were examined: (i) bonding using a conservation adhesive, (ii) stitching using a standard stitch employed by conservators, and (iii) weaving into actual tapestry (with and without crimping the Bragg grating).(Clearly (i) and (ii) can be employed directly on historic textile; (iii) would require the manufacture of a monitoring patch.) The work considered the response of the Bragg gratings and the three attachment techniques to a quasi static strain applied to the materials. The bonded sensor showed a linear response to the applied strain and therefore is the most suitable. Both of the woven in sensors showed two linear regions, probably as a result of the straightening of the crimp in the fibre. The stitching did not providing any means of strain transfer. Even with the bonded optical fibre the strain transfer coefficient was low and when subjected to a long term creep tests the results from the optical fibre sensor showed an decrease in strain when it was clear that the strain on the representative material was increasing. A typical set of results is shown in Figure 1 for a strip of the representative material subjected to a uniform load of 20 N over a period of 100 hours. The strain reading from the FBG was calibrated using the strain transfer coefficient derived from quasi static test. The test machine cross head displacement was used to derive the applied strain during the creep test. It can be seen in Figure 1 that there is a monotonic increase in this value up to about 30 hours when the specimen is failing. The strain readings from the FBG show an initial increase due to the application of the 20 N applied load and then in general a decrease. The FBG reading also shows rapid decrease at the same time as the crosshead strain increases; this indicated to some extent that the FBG was sensing a phenomenon related to the mechanical behaviour of the material.

The present paper studies the application of silica FBGs to the representative material to further investigate and quantify the behaviour of silica fibres bonded to the representative material. It is known that the crosshead displacement strain measurements were inaccurate so the readings from the FBGs are correlated with strain values derived from DIC readings. This approach also has the added advantage that strain readings can be taken local to the FBGs. Two different adhesives are studied: a standard conservation adhesive and an epoxy resin. The performance of the FBG and its strain transfer coefficient when bonded to the representative material with both adhesives is derived from quasi static tests. Finally the performance of the FBGs bonded with both adhesives is studied in creep tests.

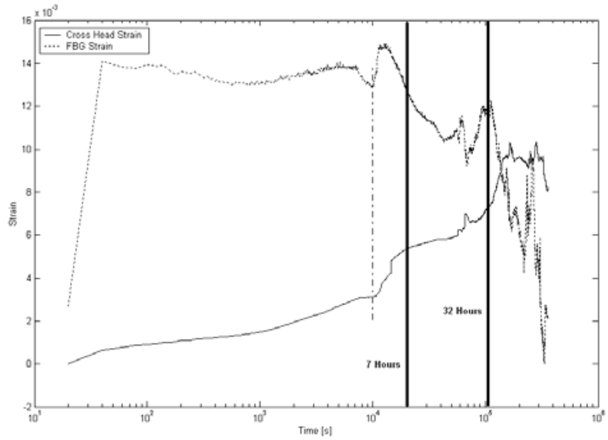

Figure 1: Strain vs. Log(Time) curve obtained under 20 N constant load for 100 hours

2. Initial validation of optical fibre and DIC systems

The system used to obtain the wavelength shift from the FBGs is a Swept Laser Interrogator (FBG-SLI) by Micron Optics. The swept laser illuminates the FBGs through the fibre couplers and each FBG reflects its corresponding wavelength. The detected spectral signals are processed and displayed using LabVIEW software. The resolution of measured wavelength is 1 pm, corresponding approximately to 1 με, i.e. 0.0001%. The FBG-SLI can simultaneously interrogate up to 256 FBGs in four fibres (maximum of 64 FBGs per fibre) with Bragg wavelength between 1530 and 1565 nm at a rate of 106 Hz. The DIC system used in this work is a StrainMaster from LaVision GmbH. Two 2 MPixel digital cameras take images of the specimen simultaneously using the camera controllers and the programmable timing unit (PTU). A series of images during a test are acquired, with the first pair images being the case of zero applied load. The acquired images are then processed and correlated with the zero load image using software DaVis Version 7.2 resulting in a series of whole field strain profiles of the specimen at each load increment.

Prior to applying the DIC and optical fibre sensors to the representative material the measurements from the FBG sensors and the DIC were validated against a known strain. This was done using conventional electrical resistance strain gauges and a long gauge extensometer. An aluminium alloy dog bone test specimen of 10 mm wide x 1.4 mm thick was equipped with a FBG bonded to one side (Bragg wavelength 1553 nm, gauge length 6 mm) and an electrical resistance strain gauge with a 7 mm gauge length on the other using M-Bond AE-10 two part epoxy adhesive. The specimen was mounted in an Instron 5569 test machine. The length between the grips was 156 mm. A 50 mm long gauge extensometer was mounted on the specimen. To facilitate the DIC, the surface of the specimen was covered in a speckled paint on the same side as the FBG. A constant displacement of 0.3 mm/minute was applied to the test specimen and the test machine crosshead displacement was recorded along with the applied load. The strain was also recorded directly from the extensometer using the test machine facilities at a rate of 10/sec. The strain obtained from the strain gauge was recorded using a Vishay 6200 scanner; the sampling rate was also 10/sec. The measured stress plotted against the strain from different sensors is given in Figure 2. The linear change of stress versus strain was calculated using Young's modulus of 70 GPa for aluminium and is plotted in the figure. It is clear that the data obtained from the sensors is very close to the theoretical value. However, in Figure 2 it can be seen that the strain values obtained from the crosshead displacement are of the order of 50% greater than that obtained from the other sensors. Such a large discrepancy was observed in a number of tensile tests carried out on the aluminium specimen, and it can be concluded that the strain values obtained from the crosshead displacement are incorrect. There are only two possible reasons for the errors; either the reading of crosshead displacement is incorrect, or the crosshead displacement is larger than that of the extension of the specimen between the two grips. The first reason was eliminated by measuring the displacement of the crosshead using an extensometer mounted between the grips without a test specimen. Therefore the errors of the strain from crosshead displacement are simply generated from the fact that the crosshead displacement is larger than the actual extension of the specimen. In addition to possible slippage of specimen in the grips, there are contributions to the displacement of crosshead from wedge jaws, couplings, etc, outside the specimen. The measured strain from FBG is approximately 9% greater than that from strain gauge. This results from mounting the extensometer; when the extensometer mounted on the other side of the specimen, i.e. where the FBG was bonded, the strain from FBG was smaller than that from strain gauge. For tests without the extensometer, the measured strain values from the FBG and strain gauge matched practically exactly. It is clear that the use of the extensometer induced a bending in the thin aluminium specimen, making the surface strain different on each side.

From this section of work it has been shown that measurements of displacement taken from the test machine are inaccurate. As it is not possible to attach an electrical resistance strain gauge or an extensometer to the textile or tapestry material, it will be necessary to use the DIC technique to validate the performance of the optical fibre sensor when mounted on the representative textile material.

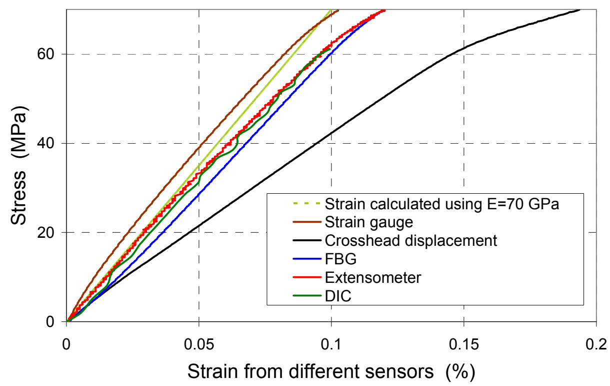

Figure 2 Stress-strain behaviour as recorded by the different sensors

3. Modification of material behaviour with bonded optical fibre

In this section of work the stress-strain behaviour of representative textile material with and without an optical fibre is investigated. Three types of narrow (14 mm wide x 0.6 mm thick) textile test specimens were used: *Specimen-1*: textile only; *Specimen-2*: textile covered with adhesive on one side; *Specimen-3*: textile covered with adhesive on one side where a 250 μm silica fibre (without a grating) was bonded parallel to the weft direction of the textile. The adhesive was a conservation adhesive (Mowilith DMC2), which has a polyvinyl acetate (PVA) base. The purpose of coating Specimen-2 with adhesive was to attempt to quantify any reinforcing effect of the adhesive. The specimens were mounted in wedge grips of an Instron 5569; the distance between the two grips was approximately 215 mm. A displacement was applied to each specimen in the weft direction, at rate of 15 mm/minute until each specimen failed. DIC readings were taken every 4 seconds as the load was applied from the side of the specimens 2 and 3 without adhesive; the weave pattern of the material was used for the correlation in all cases. The strain was calculated by taking the average of the DIC readings from the central area of each specimen. The stress-strain curves in Figure 3 show that Specimen-2 is a little stiffer than Specimen-1 (i.e. the textile only specimen) indicating that the adhesive has a small reinforcing effect. However the textile with the optical fibre (specimen-3) was much stiffer until the fibre fractured at strain of approximately 6%.

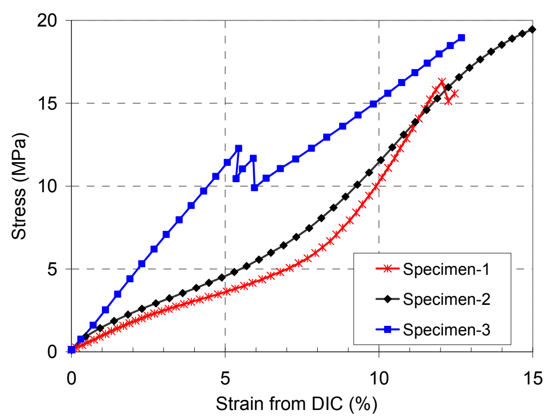

Figure 3 Stress-strain behaviour of textile with and without optical fibre

This section of the paper has shown that the optical fibre does have a reinforcing effect on the textile increasing its stiffness from about 80 MPa to 220 MPa. This will clearly have an effect on the strain local to fibre in a larger specimen and is one of the objects of the next section of the investigation described in the paper.

4. Quasi static tests with FBG sensors

Three types of representative textile test specimens were prepared: one with an FBG bonded with the DMC2 adhesive, one with the FGB bonded with a two part epoxy (Araldite 2015) and one using another conservation adhesive Vinamul 3252 which also has a PVA base. In all cases the test specimens were 50 mm wide x 0.6 mm thick. The FBGs had a nominal wavelength of 1540 nm and 6 mm gauge length; these were bonded centrally to the specimens and attached only over a length of 30 mm around the FBG. The specimens were mounted in an Instron 5569 test machine in wedge grips; the distance between the grips was 250 mm. A constant displacement of 15 mm/minute was applied to each specimen and DIC data were taken every two seconds throughout the test. When the applied load reached 30 N the test was stopped. Typical longitudinal strain data from a test with the DMC2 adhesive is shown in Figure 4. Here the area where the FBG is bonded is labelled AI and it can be seen

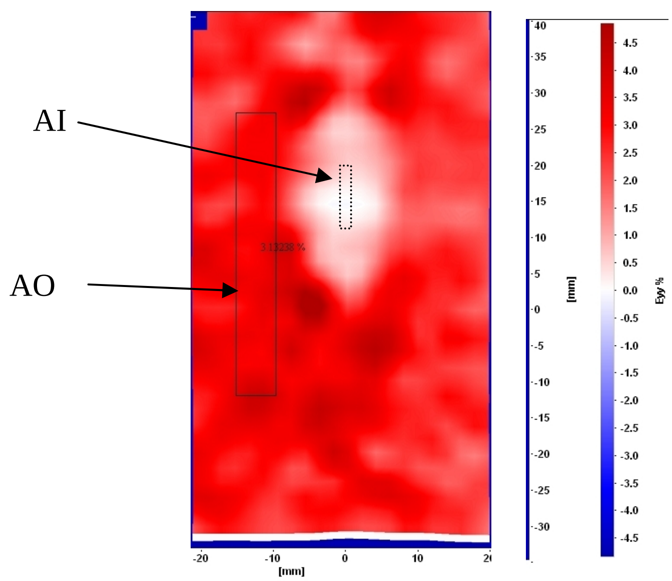

Figure 4 Longitudinal strain for specimen with FBG bonded with DMC2

that the strain at this position is much less than elsewhere in the specimen. This clearly shows the reinforcing effect of the FBG. Figures 5, 6 and 7 show the stress-strain curves for the three specimens with the FBG strain, the DIC strain recorded in area AI and the DIC strain recorded in area AO.

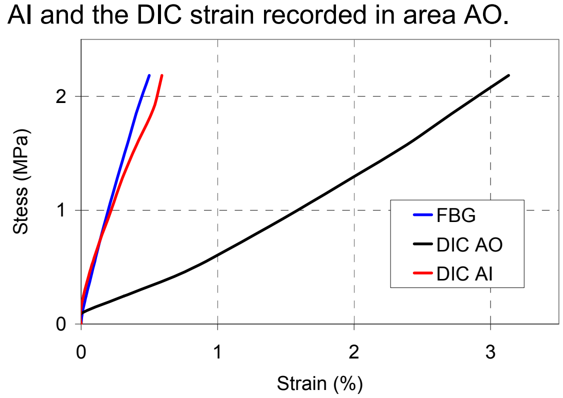

Figure 5 Stress-strain behaviour of specimen with FBG attached with DMC2 adhesive

In Figure 5 it is clear that the FBG strain and the DIC AI readings match practically identically. It was calculated that the strain transfer coefficient (i.e. $\varepsilon_{FBG}/\varepsilon_{DICAI}$) was approximately 0.8 compared to $\varepsilon_{FBG}/\varepsilon_{DICAO}$ which is approximately 0.2. Figures 6 and 7 show similar trends, except that there in not such good agreement between the FBG and the DIC AI readings. This was because with the DMC2 adhesive the FBG was threaded between the warp fibres clearly providing better contact and adhesion with the specimen. From this work it can be seen that there is considerable local reinforcement when attaching optical fibre sensors that affect the strain readings from the FBG. This has been quantified using the DIC and it has been shown that the FBG readings are accurate once the reinforcement is accounted for. This explains the very low strain transfer coefficients obtained in the previous work [1]. Clearly silica optical fibre sensors are not suitable for obtaining accurate strain readings from actual tapestry but the readings from such a gauge could be used as a reference measurement for the DIC during a long term test. Therefore the next section of the paper investigates the long term behaviour of the FBGs.

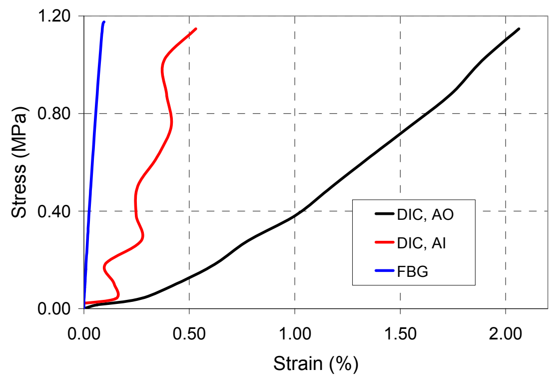

Figure 6 Stress-strain behaviour of specimen with FBG attached with Araldite 2015 adhesive

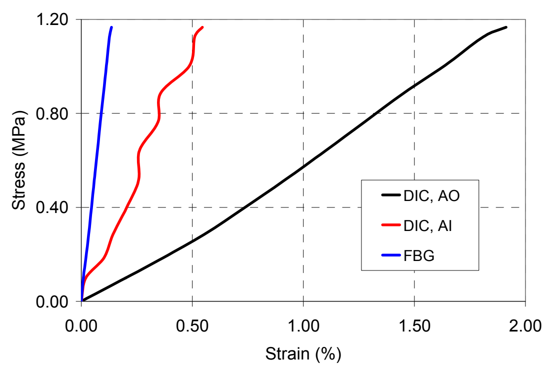

Figure 7 Stress-strain behaviour of specimen with FBG attached with Vinamul adhesive

5. Long term tests

To establish if the FBGs were sensitive to creep an initial test was carried out on a FBG directly, where a constant load of 7.2 N (579 MPa) was applied to the fibre containing a FBG using a dead weight. This was facilitated by attaching a length of cable with superglue adhesive along the fibre at each end of the fibre. Each section of fibre bonded to the cable was approximately 10 cm long. When a load is applied to the fibre, the applied strain will be measured by the FBG. In this way, any minor slippage between the fibre and the cable did not affect the measured values of strain. To compensate for the temperature and other environmental changes, another FBG with Bragg wavelength 1545 nm located close to the loaded FBG was used as a reference. The 7.2 N load was applied to the fibre over a period of 10 days. The change in strain in the FBG was recorded at intervals of 5 seconds for the first 96 hours and at intervals of 1 minute afterwards. No significant deformation was recorded over the ten day period therefore it was concluded that even a stress of 579 MPa does not cause a silica optical fibre to creep. Therefore it is considered that silica optical fibres are a good means of monitoring long term behaviour of a material.

In the long term tests it was decided to study only two types of representative textile material specimen: one with a FBG bonded with the Vinamul 3252 adhesive and the other with a FGB bonded with a two part epoxy (Araldite 2015), as the Vinamul yielded similar results to the DMC2 in the quasi-static test. The specimens were mounted in the Instron test machine in an identical fashion to the quasi static tests. A constant load of 30 N (1 MPa) was applied to the specimens and the strain monitored by the FBG and the DIC over 18 hours for the Vinamul adhesive and 44 hours for the Araldite; readings were taken every 6 minutes. During these tests the humidity and the room temperature were monitored and the FBG readings were corrected for temperature change using the reference FBG. Figures 8 and 9 show the results for the Araldite 2015 and the Vinamul 3252 respectively. It should be noted that in this presentation the FBG strain readings are on the left ordinate and the DIC readings on right ordinate. It is clear that in both cases the DIC readings provided from area AO give the highest strain and these increase with time. The increase for the specimen with the Vinamul bonded FBG is less than that for the specimen with the Araldite bonded FBG. It is interesting in the Vinamul test that both the temperature and the humidity are decreasing whereas they fluctuate in the Araldite test. The reduction in creep could therefore be attributed to the reduction in humidity; this is currently being investigated. For the DIC readings in area AI these are constant in the Araldite test but increase in the Vinamul test. Most importantly the FBG readings increase in the Araldite test but decrease in the Vinamul test. This latter finding echoes that of the initial work and therefore the decreasing readings must be attributed to the bonding method. The creep rates of a range of conservation adhesives is currently being studied and it is also being ascertain if an epoxy based adhesive could be used in a small area in actual tapestries.

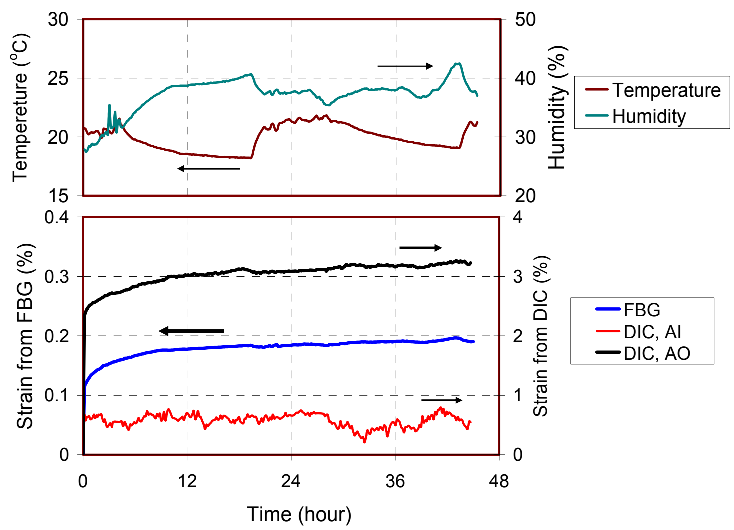

Figure 8 Results from long term test on textile specimen with FBG bonded with Araldite

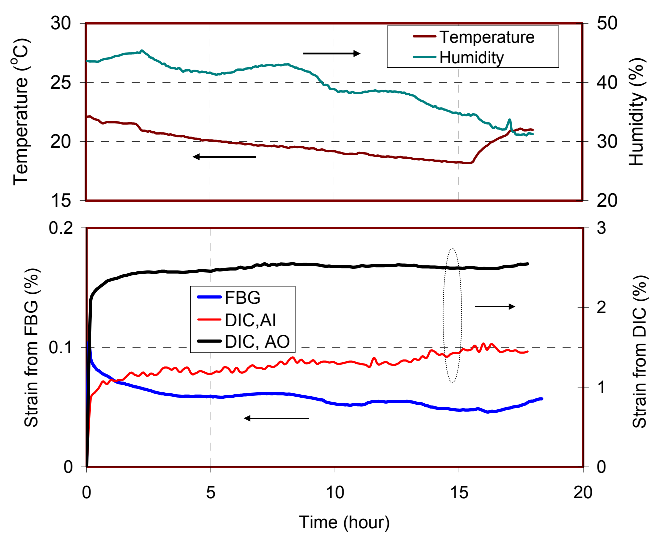

Figure 9 Results from long term test on textile specimen with FBG bonded with Vinamul

6. Conclusions

It has been shown that FBG sensors can be attached to textile fabrics without causing damage. However, the stiffness of the silica glass in comparison to the textile causes significant reinforcement. A strain transfer coefficient can be devised from quasi static tests that will allow quantitative strain measurement to be made. In long term tests it has been shown that adhesive material is an important factor when attempting to obtain quantitative measurements.

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