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AN EXPERIMENTAL APPROACH TO QUANTIFY STRAIN TRANSFER EFFICIENCY OF FIBRE BRAGG GRATING SENSORS TO HOST STRUCTURES

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Summary: This paper developed a method to evaluate the strain transfer efficiency of fibre Bragg grating sensors to host structures. Various coatings were applied to fibre Bragg grating sensors after being fabricated. They were epoxy, silane agent and polypropylene, representing different surface properties. A neat epoxy resin plate was used as the host in which the coated fibre sensors were embedded in the central layer. The tensile strain output from the FBGs was compared with that obtained from electrical strain gauges which were attached on the surface of the specimen. A calculating method based on the measured strains was developed to quantify the strain transfer function of different surface coatings. The strain transfer coefficient obtained from the proposed method provided a direct indicator to evaluate the strain transfer efficiency of different coatings used on the FBG sensors, under either short or long-term loading. The results demonstrated that the fibre sensor without any coating possessed the best strain transfer, whereas, the worst strain transfer was created by polypropylene coating. Coatings play a most influential role in strain measurements using FBG sensors.

keywords: fibre Bragg grating sensor, strain transfer efficiency, surface coating of optical fibres, interface strength

INTRODUCTION

Fibre Bragg Grating (FBG) sensors have been exploited as strain sensing elements for the application of smart materials [1] and large structural monitoring [2]. The fibre sensors are commonly either embedded into a composite structure during fabrication or surface-attached to metallic materials or existed structures by applying adhesives. In either case, the structure strain is transferred to the fibre sensors via interfaces between the host and the sensor. A surface coating is commonly required for mechanical protection and handling operation of the sensors, due to the fragile nature of optical fibres. The fibre surface coating serves as coupling layer, inevitably, the coating plays one of the most important roles in the strain transfer.

Polyacrylate is a most-common type of protective coating for telecommunication industry. As often required by splice connection in telecom, the applied coating is designed to have a certain degree of strippability. When the optical fibres are used as strain sensors, the coating is expected to have an intimate contact with the fibres offering with a strong interface. Therefore the requirement of coating characteristics must be different from the telecom applications. The strain transfer can be influenced by various coating characteristics: elasticity, surface chemical reactivity and coating thickness. Some analytical models were previously developed to examine the effect of the coating thickness and elasticity on the strain transfer [3, 4] by focusing on the elastic interactions between an embedded fibre and the host. Stress concentration due to the intrusive perturb of the embedded fibre, could be minimised by optimising the thickness and elasticity of the coating, which was illustrated by a FEM model [5]. Although these investigations have clearly indicated the importance of coatings to an embedded smart structure, there is insufficient experiment evidence to show the effectiveness of strain transfer when different coatings are applied. This paper was aimed to develop a quantified method experimentally evaluating the influence of the coatings on the strain measurement reliability by using FBG sensors.

EXPERIMENTAL DETAILS

Sensor fabrication and surface re-coating

FBG sensors were fabricated using the phase mask technique with UV irradiation at 266 nm on Fibrecore 1250 photosensitive fibres. The large absorption of the polyacrylate coating in the UV necessitates the local removal of the coating prior to UV irradiation. A 15 mm length of the coating was removed chemically by soaking in a proprietary paint-remover. The Bragg wavelength of the sensors was 1310 nm, with a 4.0 mm sensing gauge length.

After the fabrication of Bragg gratings, the stripped sections were recoated by three types of coating materials which were to provide different surface properties on the FBG surface: Redux 920 epoxy, silane agent and polypropylene. Redux 920 epoxy was manufactured by Ciba composites. It is a very tough resin with a failure strain of 8.4%, which makes it particularly suitable for surface protection. The epoxy type of the coating shall have a good compatibility with epoxy-based composites and adhesives. The bare section of optical fibres were covered with 0.12mm resin film, after being cured at 145° for 30 min.

Silane agent was commonly used to improve interface strength in glass fibre composites. There are many types of silane agents to suit different composite matrices. This investigation selected the trimethoxy silane containing three epoxide groups which were expected to have an interaction with the epoxide groups of the host epoxy resin during curing. Firstly, a solution containing 5% (in weight) trimethoxy silane and 0.1M acetic acid distilled water was prepared for the surface treatment. Then, the stripped section of the fibre sensor was dipped into the mixed solution for a few times. The fibre was dried at 100°C for 1h. A very thin silane film (<0.1μm, approximately) was formed on the surface.

The third type of coating was Polypropylene (PP), which can provide a flexible protective buffer for optical fibres. However, PP possesses an inert surface which resists bonding with other materials. In the investigation, the coating was used to produce a weak interface to provide a comparative reference with other surface coatings. To coat the optical fibre, a die was designed to use in conjunction with an extruder. Optical fibre was put through the die which filled with the PP melt. A 0.25 mm thick PP was applied to the stripped section of the optical fibres.

Fabrication of sensor-embedded specimen and mechanical testing

The fibre sensors including both recoated and un-recoated (bare) ones were embedded into a neat resin plate to examine the coupling effects between the host material and the FBG sensors. With the neat resin specimen, a uniform strain distribution is accompanied with the homogenous structure. The resin was RTM-6 epoxy, a monocomponent system, supplied by Ciba composites. The optical fibres arranged in parallel, at 15 mm interval, were mounted into the mid-layer of a steel mould filled with the resin. Then the resin was cured at 160° for 2 h. After curing, the casting resin plate was cut to strips each of which contained one optical fibre, aligned longitudinally, in the centre, as shown in Fig. 1. The strip specimen had a cross-section of 10 × 6mm, with a length of 150 mm. A strain gauge was bonded on the surface of each specimen. For each type of FBG surface, three specimens were fabricated.

These specimens were subjected to static tensile loading under a loading rate of 0.15 mm/mm.min while the strain was monitored by both strain gauges and the FBGs. In the investigation of the long-term performance, a 2.3kN load was maintained for over 30 h to monitor the strain measurement. This load level, equivalent to a stress of 30 MPa, induced the strain level around 1.05% on the specimen. A labview programme was developed to record experimental data at a designed sampling rate and a planned interval. The data recording took place every 10 min, lasting for 1 min. at a sampling rate of 10 Hz. The static testing used a continuous recording mode at a sampling rate of 20 Hz. The output from the optical sensors is the wavelength of the reflected peak from the FBGs. The interrogation system based on Fabry-Perot filter, used in demodulating the wavelength, and the conversion of the wavelength to strain can be found in reference [1].

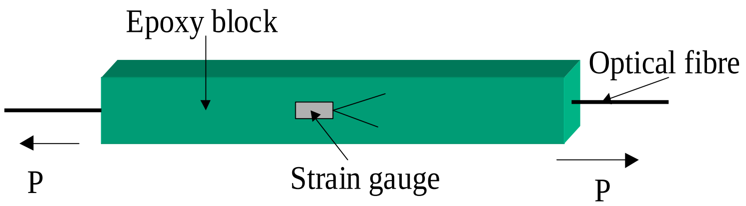

Fig. 1 Neat epoxy resin strip (150×10×6 mm) with an embedded optical fibre for tensile testing

CALCULATION OF STRAIN TRANSFER EFFICIENCY COEFFICIENT

To quantify strain transfer efficiencies of the different surface treatments, a strain transfer factor, *C*, was introduced. “*C*” is defined by minimising the difference of the strain measured by strain gauges and the term “$\frac{1}{C}\frac{\Delta\lambda_i}{\lambda}$” from the strain-induced wavelength shift, given by:

$$\sum_{i=1}^{n}\sqrt{(\varepsilon_{s.g_i}-\frac{1}{C}.\frac{\Delta\lambda_i}{\lambda})^2}=\min \qquad (1)$$

where $\Delta\lambda_i$ is the measured Bragg wavelength shift, λ is the Bragg wavelength at zero-stress, of the FBG sensors.
$\varepsilon_{s.g}$ is the strain measured by the strain gauge,
n is the total number of recorded samples, i is the ith sample.

The significance of Equation 1 is that the factor, C, can be found in each set of strain data to convert the ratio of wavelength shift over the zero-stress wavelength to the closest strain value of strain gauges. The strain measured from the strain gauges is assumed as an accurate value of the host materials, and used as a reference base for the equation.

The strain transfer coefficient, ξ, is defined by comparing the strain transfer factor, *C*, from Eqn 1, to the wavelength-strain factor, S_b, :

$$\xi = \frac{C}{S_b} \tag{2}$$

The wavelength-strain factor, S_b, is used to convert Bragg wavelength to strain, and is an intrinsic factor, dependent on the composition of the fibre core [1]. For the given FBG sensors, S_b was calibrated to be 0.76. When the coefficient, *C*, equals to 0.76, it is considered that a full strain transfer has been achieved from the host to the sensor. In this case, the strain transfer coefficient will be 100%. If the "*C*" is below 0.76, strain is not properly transferred. By inputting the recorded data from both the strain gauge and the FBG with a specific coating, into Equation 1, the strain transfer coefficients, ξ, can be determined from Eqn.2.

RESULTS AND DISCUSSION

Strain response to static tensile stress

The response of the embedded FBG sensor was monitored by the Fabry-Perot interrogation system while strain output by strain gauge was recorded by a PC, during tensile-loading of the neat resin blocks. The measurement results were plotted in Fig. 2, showing the strain values from various sensing elements responded to the same level of stresses. In general the results indicated that the FBGs experienced a lower strain than the strain gauges. The fibre sensor that was not recoated provided the best agreement with the strain gauge measurement, as seen two curves are almost overlapped. Other surface treatments on the fibre sensor exhibited a different extent of reduction of strain level. Polypropylene coating that created a poor interface between the fibre sensor and the host, yielded the largest reduction of the strain among all the FBGs. This shows that the interface plays a very important role on the strain measurement. The tensile modulus of the neat RTM-6 resin provided by its supplier is 2.89 GPa. Comparatively, the modulus, measured by the strain gauge was 2.86 GPa, which is adequately accurate. The second closest value to the provided modulus was 2.82 GPa, obtained by the un-coated FBG.

It should be noted that FBG sensors, geometrically, differ from thin foil strain gauge. Relatively high interfacial stresses to apply a strain to a fibre will be required because of the cylindrical geometrical shape which minimises the external surface area for a given cross-section. For foil strain gauge the shear stresses are relatively small, due to the thin-film feature. This conforms that the surface coating for a fibre sensor is extremely critical.

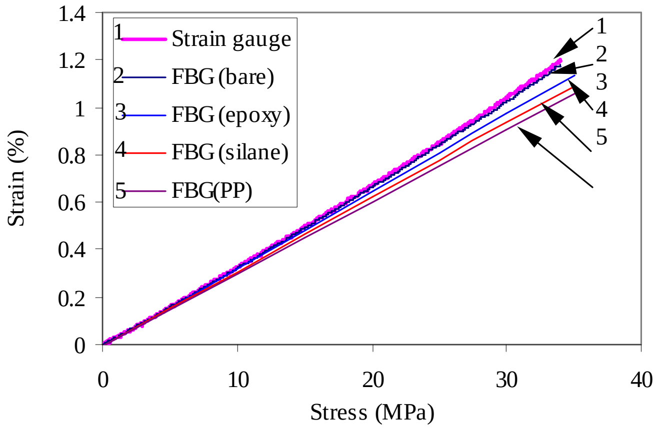

Fig. 2. Strain measured by various sensing elements under a static tensile loading

The Values of Strain Transfer Coefficient

By inputting data from Fig. 2 into Eqn 1 and 2, the strain transfer coefficient was obtained for the FBG sensors with different surface coatings as listed in Table 1. The results show that the bare FBG sensors have the best interface: up to 98.7% of the strain was transferred from the host to the sensor. The work by Habel[6] also demonstrated that the bare optical fibre had the highest interface strength when incorporated in a structure compared with any other coatings. The fibre recoated with epoxy appears as the second best (strain transfer reached 94.7%). As anticipated, fibres coated by PP provide the worst stress transfer response (only 88.2%). Silane coupling agents are commonly adopted in conventional glass fibre composites to improve interface strength. However, this technique has to be carefully applied. The compatibility of the coupling functional group (such as amino, methacryloxy, and epoxy etc) with the composite matrix is important to achieve good interface strength[7]. If the wrong type of coupling agent is chosen, or treatment methods are not appropriately applied, the interface strength could be even worse[8, 9]. The investigation illustrated that only 91% of strain transfer was obtained by using the trimethoxy silane. In this case the silane coupling was not adequately matched to the application situation. The degraded interface could be due to the type of the agent containing three epoxide groups with each molecule, which could create a spacial barrier for chemical interaction with the metrix.

In general, the measurement results from the coated optical fibre sensors are not satisfactory with the strain measurement requirement. The best measurement from the bare fibre sensor had a 1.3% deviation from the result given by the strain gauge. This deviation is believed to be introduced by the shear strain of the casting resin strip. As seen in Fig. 1, strain gauge was bonded on the surface, while the optical fibre was embedded into the centre of the specimen. There will be a shear lag transferring strain from the surface to the centre (at 3.0 mm away) in the neat resin strip. The absolute strain value was not particularly interested, as the work was to compare the strain transfer influence of different surfaces under the same experimental condition. If the sensing gauge of the fibre sensors is located closely enough to the location of a strain gauge, the measurement results could be precisely compared.

The values of the strain transfer co-efficient provide a straight indication of the performance of each coating in the strain measurement. Under the same experimental condition, the effect of various coatings on the strain transfer are clearly differenciated by the established quantified method. In a word, the coating applied on the FBG sensors should combine functions of both mechanical protection and high bond strength and stiffness.

Table 1: Strain transfer co-efficient comparison of FBG sensors with different surfaces

Surface coating	Bare	Epoxy	Silane agent	Polypropylene
Strain transfer coefficient, ξ	98.7%	94.7%	90.8%	88.2%

Strain Transfer Response to Long-term loading

The above results were based on the static tensile testing. It would be more important to understand the long-term strain transfer performance under stress. The strains of the strain gauge and the recoated fibre sensors were monitored over the loading time when the stress was maintained at 30MPa. Then, the strain transfer coefficient was calculated from the results, and plotted against the loading time as shown in Fig. 3.

The curves show a gradually increased trend over the first 20 hours of the loading history, after that, the values appear to reach a saturated level without noticeable further increase. As discussed previously, there existed a shear lag which influenced the strain transfer from the surface of the near resin strip to the fibre sensor in the centre of the specimen. During the first stage of constant loading, the strain of FBG sensors was gradually recovered from the shear lag, approaching to the value of strain gauge bonded to the surface. The ξ-value for 920-epoxy coated FBG sensor was increased from 94.7% at the beginning of the loading to 99.3% after 30h loading, while the value for the silane-coated FBG changed from 90.8% to 95.0%. The platform in the curves could indicate the absolute value of the strain transfer efficiency for the coatings, when the shear lag influence was minimum. From overall performance, it can be concluded that these two types of coating presented a reliable strain transfer function over the given loading period.

There is a sharp drop in the curve of the FBG recoated with PP, just after 6h loading. The falling point was due to the debond of the recoated fibre from the host. Even though, in the first 6h, the ξ value was slightly increased, following a similar trend to the other two types of the coatings. This effect was also own to the recovery of shear lag in the neat resin host. However, the poor interface between fibre/PP, or PP/host, was not capable of maintaining any strain transfer under long-term stressing, not excess of 6 hours in the case. Then the fibre sensor was debonded from the host, and lost the function totally.

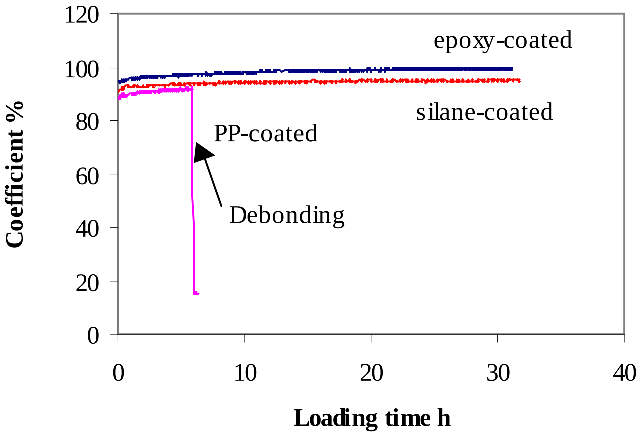

Fig. 3. Strain transfer coefficient over a long-term constant tensile stress

CONCLUSIONS

The results show that the developed method is applicable to quantify the strain transfer effectiveness of fibre Bragg grating sensors in strain measurements. The values of strain transfer coefficient clearly indicate the percentage of the strain which has been transferred from the host to the sensing gauge via different interfaces.

The influence of coating properties on the strain transfer was demonstrated and quantified. Although optical fibres without coating offered the best interfacial coupling with a host structure, practically the fibres have to be coated for protecting environment attack. Different coatings with a different degree of interfacial strength, significantly affected the performance of strain transfer. Ductile 920 epoxy appeared superior over other tried coatings, which showed a 99.3% strain transfer coefficient after the elimination of shear-lag effect under long-term loading. As demonstrated, a poor interface, such as created by polypropylene, only had a 88% of the efficiency, and lost functioning because the occurrence of debonding under a long-term constant loading. To achieve a successful strain measurement by fibre Bragg grating sensors, it is very critical that the fibre coating possessed functions of both mechanical protection and strong interfacial strength to the sensors and host structures.

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