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Deformation monitoring in prestressing tendons using fibre Bragg gratings encapsulated in metallic packages

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ABSTRACT

An investigation into the capability of deformation monitoring using fibre Bragg gratings encapsulated in metallic packages is presented in the paper. The proposed approach relies on a grating inscription into a metal coated fibre and brazing the fibre into a metal capillary using induction heating. A metal rod instrumented with encapsulated FBG strain and temperature sensors is placed in an electromechanical tester and stressed up 80 % of its ultimate tensile strength. It is demonstrated through a 60 h experiment that the sensors are capable of real-time deformation monitoring.

Key words: optical fibre bonding and sealing, induction heating, sensor encapsulation, deformation monitoring.

1. INTRODUCTION

The use of fibre Bragg grating (FBG) sensors for structural health monitoring (SHM) has been researched for years. Stress, strain, or force measurement systems employing FBGs have been proposed for aerospace[1-3], nuclear fission and fusion reactors[4-7], or bridge and concrete monitoring[8-11] applications. It is clear that in all these applications the sensor attachment must ensure long-term reliability even at adverse environmental conditions. Since the sensor exposure to high temperature, high strain or high dosage of nuclear radiation may lead to the degradation of the fibre and/or the grating structure[12,13], appropriate sensor packaging and attachment are crucial for its operation and lifetime.

To overcome the limitations of conventional epoxy-based FBG bonding and attachment methods, we previously developed a metal coated fibre sealing and bonding technique based on induction heating. The resultant joints performance was proven at high temperature (350 °C) and high pressure (15 kpsi) conditions[14,15]. We also showed experimentally that by selecting proper materials, such as kovar, brazing standard FBGs into metallic ferrules can be possible without any significant deterioration in the grating reflection[16]. Our recent work related to the high stress monitoring of prestressing tendons[17] employing the developed technology demonstrated an improved performance over the epoxy-based strain monitoring systems[17,18]. In this paper, a method of fibre Bragg grating encapsulation into metallic packages based on induction brazing and sensor attachment to a metal rod to measure high strain are proposed and investigated.

2. SENSOR ENCAPSULATION

A schematic diagram of an FBG strain sensor encapsulated in a metal capillary is shown in Figure 1. A previously developed optical fibre sealing and bonding technique employing induction heating was utilised to join the sensor components[14]. Firstly, a single-mode copper coated fibre was cut into meter long pieces. A 15-mm long section of the coating was removed from the fibre by submersing it in 65 % nitric acid (HNO_3). Such prepared fibres were than used for grating inscription and encapsulation.

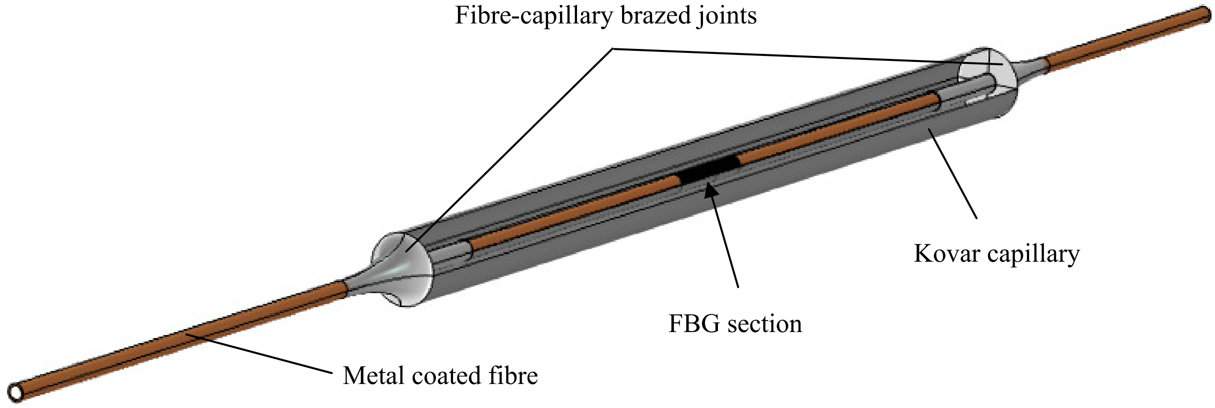

Figure 1. FBG sensor encapsulated in a metallic capillary.

The encapsulation process involved inserting a copper coated fibre with an inscribed FBG sensor into a kovar capillary, aligning the components, and brazing the fibre to the capillary using induction heating. During the joint fabrication, the capillary rested on a v-grooved ceramic bench while the fibre was held by two micro-positioning stages placed nearby both ends of the ceramic bench[14]. The length of the capillary was 20 mm and its ID/OD was 0.2/0.7 mm. The fibre outside diameter was 170 µm. The components were appropriately aligned so that the FBG section was in the centre of the capillary (Figure 1), and the fibre and capillary did not come into contact during heat processing. A small amount of flux and silver-based brazing paste were then applied at both ends of the capillary. The melting temperature of the brazing paste was 620 °C. To protect the FBG from excessive heat and deterioration, a heat susceptor was used at the joint location[14,17]. During the brazing process, a water cooled conductive coil was consecutively brought over each end of the capillary. To melt the paste and form the joint, a 370-kHz current of 200A was applied to the coil for 20 s. The assembly was then cooled down naturally to room temperature.

3. EXPERIMENTAL RESULTS

Following the encapsulation process, the FBG strain sensor was attached to a metal rod as shown in Figure 2. The rod was a plain strand wire made of steel Y1670C having a length of 0.5 m and 7 mm diameter according to British Standard BS 5896:2012. The FBG strain sensor was brazed to 0.5-µm thick metal foil strips and welded to the steel rod at both ends using an electrical resistance spot welder[17].

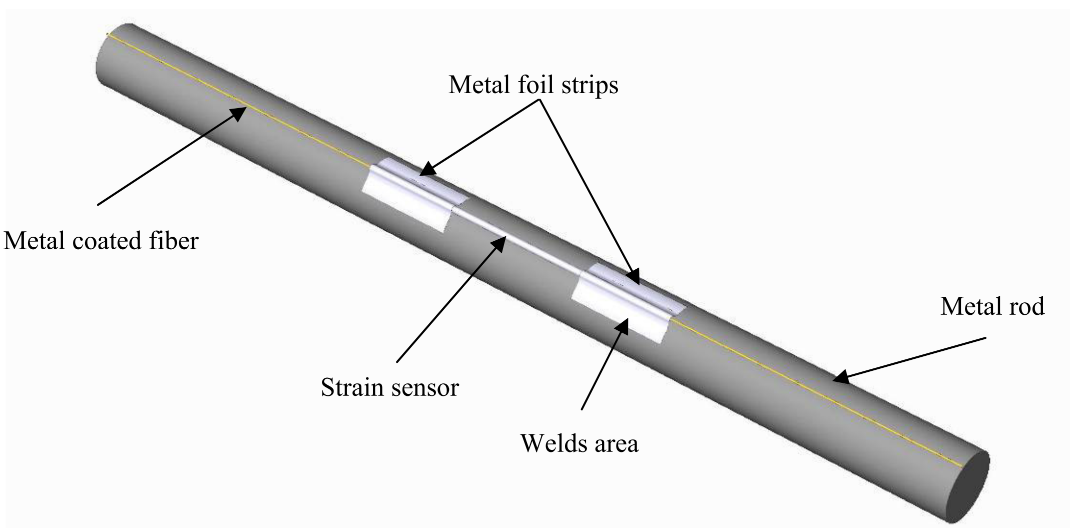

Figure 2. Diagram of an encapsulated FBG strain sensor attached to a metal rod.

It is well known that a standard FBG sensor responds to strain and temperature simultaneously. A relative change in the FBG peak wavelength, $\Delta\lambda_B/\lambda_B$, due to a change in strain, $\Delta\varepsilon$, and temperature, ΔT, can be expressed by $\Delta\lambda_B/\lambda_B = C_\varepsilon \cdot\Delta\varepsilon + C_T \cdot\Delta T$, where C_ε and C_T are the strain and temperature sensitivities. To distinguish between strain and temperature readings, an additional FBG temperature sensor located in proximity of the FBG strain sensor was used. The FBG temperature sensor was encapsulated in the similar way as the strain sensor but welded to the rod at one end only (Figure 2). Since the temperature sensor was strain-free, it allowed strain readings to be corrected by subtracting the wavelength shift due to temperature fluctuations[17].

To verify the optical sensors capability of deformation monitoring, a 60 h test was performed at a constant load of 50 kN using an Instron 5969 electromechanical tester. The instrumented rod was placed in the machine and a relaxation routine was performed prior to the long-term test by stress cycling the rod up to 1300 MPa (80 % UTS) four times to minimize any residual stresses induced during the sensors fabrication and attachment[17]. Following the relaxation, the load was increased at a rate of 10 kN/min up to 50 kN and kept constant for 60 h. It was then decreased to 0 kN at a rate of 10 kN/min. The FBGs having peak wavelengths of 1541 nm and 1564 nm were used for strain and temperature sensors, respectively. During the experiment, the sensors were monitored online using a Micron Optics spectral interrogation unit (sm125). The peak wavelengths of the FBG strain and temperature sensors along with the load and extensometer output from the Instron machine were recorded every half a second.

As it was previously demonstrated by the authors[17], a temperature sensitivity of the strain sensor was 20% higher than the temperature sensor due to the influence of thermal expansion of the steel rod for the presented sensor encapsulation and attachment method. Therefore, the influence of the ambient temperature fluctuations on strain measurements were corrected for using the results obtained during the previous thermal characterisation of the sensors. A comparison of the results obtained during deformation monitoring over 60 h at a constant load are shown in Figure 3.

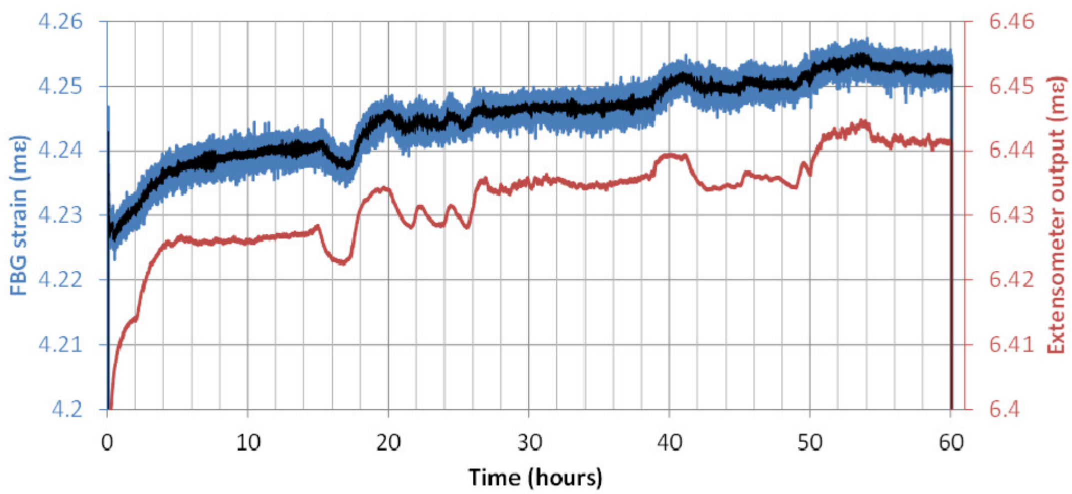

Figure 3. Comparison between FBG-based strain sensor and extensometer readings. The black curve superimposed on the FBG strain signal is a moving average of 10 samples.

It is clear from the above figure that the FBG strain sensor response is in good agreement with the records obtained from the extensometer. The small fluctuations apparent in the signals are most likely a consequence of the adjustments made by the Instron control software to keep the load constant at ambient temperature fluctuations. The magnitude of these fluctuations is within the machine calibration accuracy. The strain transfer between the rod and the optical strain sensor, estimated from the data presented above, equalled to around 66% which is in good agreement with the previous results[17]. Based on the experimental results, it can be concluded that the sensor was capable of deformation monitoring at high load of 50 kN equivalent to a stress of 1300 MPa, or 80% UTS, and thus may be a valuable tool in real-time monitoring of presterssing tendons.

4. CONCLUSIONS

An investigation into the capability of deformation monitoring using fibre Bragg gratings encapsulated in metallic packages has been presented in the paper. Following gratings inscription into metal coated fibres, the sensor encapsulation was realised by brazing the fibre into a metal capillary using induction heating. Encapsulated FBG strain and temperature sensors were then attached to a metal rod, placed in an electromechanical tester, and stressed up 1300 MPa, or 80 % UTS. It has been demonstrated by a 60 h experiment that the sensors are capable of real-time deformation monitoring and have the potential to constitute valuable tools in the SHM instrumentation.

ACKNOWLEDGEMENTS

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