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Comparison of epoxy and braze-welded attachment methods for FBG strain gauges

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Abstract—**This paper presents experimental results from fatigue and static loading tests performed on both epoxy and braze-welded FBG strain sensors. Most FBG attachment methods are relatively understudied, with epoxy the most commonly used. Long curing times and humidity sensitivity during curing render epoxy inappropriate for certain implementations. This work shows that a bespoke braze-welded attachment design is able to achieve a higher static failure limit of 22kN when compared to strain gauge epoxies, which fail at 20kN. Both methods demonstrate high fatigue life, with no significant deterioration after two million cycles. Epoxy swelling was observed when the sensors were held at a relative humidity of 96%, applying ~0.6 mϵ of tension to the FBG, whereas a braze-weld attachment was unaffected by humidity.**

Keywords—fatigue, static, epoxy, braze-welded, FBG, humidity

I. INTRODUCTION

Fibre Bragg gratings (FGBs) present many advantages over conventional electrical strain gauges due to their small size, robustness, immunity to electromagnetic interference and ability to multiplex [1-2]. FBGs also boast a long-life capability and have been used extensively for strain and displacement monitoring in many industries, such as civil engineering [3-5], aerospace [6], as well as oil and gas [7]; most of which use epoxy based attachment methods. In previous work, brazed metal packaged FBGs [8] were used to monitor prestress in concrete [9] and for displacement measurement in spalled concrete [10].

Prior to this work, an onshore wind turbine foundation with visible cracks was instrumented with FBG strain sensors to monitor long-term crack deterioration [11]. Attachment consisted of epoxying FBGs to carbon steel arms, allowing long-gauge crack displacement measurement. In the aforementioned work, sensors were built in the lab, thus epoxy curing was performed in a controlled environment. It is possible that a braze-weld attachment would provide improved characteristics, such as higher strain transfer or longer lifetime, however, rigorous testing would be required to determine this. Comparison between epoxy and braze-welded attachments for FBG strain measurement is not well documented. Commercially available sensor constructions are compared in [10], however internal designs of these are confidential. Effects of humidity on these attachment methods are unknown, yet this is of great interest due to the application of the sensors.

Work was carried out to determine if a braze-welded sensor can perform to the same standard as the epoxy construction in terms of both static limit and fatigue life. The two constructions were then tested within an environment of 96% relative humidity (RH). This environment was simulated by a potassium-nitrate solution within a container [12].

This paper is structured as follows: Section 2 provides an overview of the attachment methods alongside a brief introduction into FBG functionality. Section 3 presents results and discussions of the fatigue and static experiments, followed by a presentation of humidity results in Section 4. Findings are eventually concluded in Section 5.

II. SENSOR DESIGNS

A. Epoxy attachment

Figure 1 displays a typical epoxy attachment, the full length of FBG is glued to the steel plate to protect the fragile fibre. In some cases the FBG is spot glued at the ends only; however, this leaves the bare FBG exposed to environmental factors. FBGs reflect a small band of wavelengths, centred around the peak Bragg wavelength, λ_B. This peak is dependent on temperature and strain as illustrated in Equation 1,

$$\frac{\Delta\lambda_B}{\lambda_B} = K_\epsilon \epsilon + K_T T. \qquad (1)$$

Here $\Delta\lambda_B$ is the change in Bragg peak wavelength λ_B, K_ϵ and K_T are strain and temperature coefficients respectively, ϵ is the strain between FBG ends and T is temperature. A second, unbonded FBG is usually used for temperature compensation in order to isolate ϵ [1].

B. Braze-welded attachment

Similarly to [9], the braze-welded design consists of a metal coated FBG within a kovar capillary, brazed between two metal

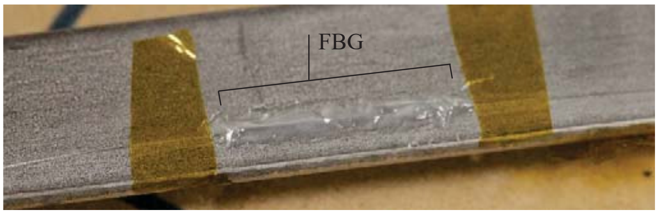

Fig. 1. Epoxy attached FBG.

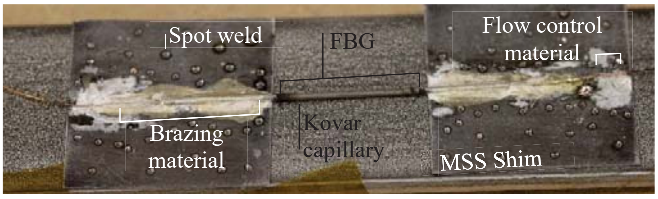

Fig. 2. Braze-welded attached FBG.

shims. In this work, the 0.05 mm thick carbon steel shims as reported in [9] were replaced with 0.2 mm thick magnetic stainless steel (MSS) plates as the sensors were welded to a flat surface. This provided additional corrosion protection. The capillary length of 25 mm was increased to 35 mm to provide a greater capillary-shim bonding area – compensating for the loss of ~360° attachment from bending the shim around the capillary. The applied capillary had an ID/OD of 0.2/0.7 mm.

The brazing process consists of centrally positioning the FBG within the kovar capillary. To minimise possibility of brazing defects and to reduce exposure time of the FBG to high temperature, the shim, capillary and fibre are brazed together. Stop-off brazing paste is applied to the shim to restrict the brazing area of the silver-based brazing paste. The entire ensemble is brazed using an induction coil as presented in [13]. Repeating for the second shim and spot welding using an electrical resistance spot welder creates the sensor illustrated in Fig. 2. The shims were squares of length equal to the steel plate's width of 20 mm. The distance in-between shims was therefore ~16 mm.

III. LOADING EXPERIMENT

FBGs were attached to a stainless steel (SS) plate of 600 mm length, 20 mm width and 3 mm thickness. Four commonly used strain gauge epoxies were tested during this experiment. MBOND AE-10 (MB) and Epotek 301 (E301) were room temperature cured for 24 hours, Epotek 353ND (E353) was cured at 80°C for 30 minutes and Epotek OG198-55 (EUV) was cured by UV light source for 10 minutes. Two further FBGs were affixed with MB (MB1 & MB2) for more detailed analysis as this was applied for the site installation in [11]. Two FBGs were braze-welded (BW1 & BW2 – Fig. 2), providing a total of seven FBG-based strain-gauge designs.

A. Fatigue

Initial testing consisted of sinusoidal cycling at 15 Hz on an Instron 8802 servo-hydraulic machine. One million cycles performed of 0-6 kN trough-peak loading on the SS plate corresponding to a strain of 0.5 mϵ before a further one million cycles were performed at 0-12 kN corresponding to a strain of 1 mϵ The former is equivalent to the maximum strain we have monitored in our previous studies of crack displacements in concrete foundations [11].

An FFT was used to extract the 15Hz loading cycle from the sensor data. Using the FFT magnitude provided an indication of the strain transfer for each sensor over time. Figure 3 contains both cycles with the amplitude of the 15 Hz loading signal apparent in sensor data – larger amplitude indicates higher strain transfer, whereas constancy suggests no performance degradation over time. Upon converting the change in wavelength to strain, using equation 1, it is seen that all sensors have strain transfers between 20 and 50%. However, this is assuming 100% strain transfer between machine and SS plate i.e. no slippage and that no bending occurred in the plate. It is expected that losses will occur from both aspects and thus strain transfer will be higher. For this work, the constancy of the strain transfer is more important, as it indicates fatigue damage occurring to any sensor. Note the following interesting effects: in linear elastic systems, doubling the load should double the strain (or slightly less if there are nonlinear strain losses). All sensors except EUV behaved this way, with EUV increasing by ~2.8 times. This suggests plastic deformation, or "stretching" may have occurred in this epoxy, but requires further testing. Both welded sensors showed very small variation (± 0.005nm) during tests, which could imply non-uniform attachment in welding.

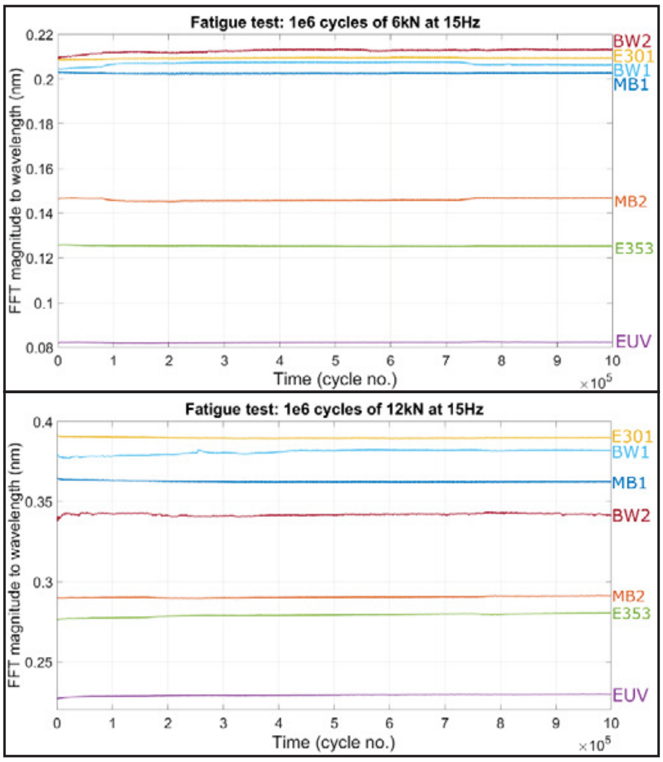

Fig. 3. Fatigue cycles of all sensors, showing the peak amplitude wavelength of the 15 Hz signal apparent in sensors. Doubling these amplitudes provides the peak-to-peak response of sensor to loads 6 kN and 12 kN.

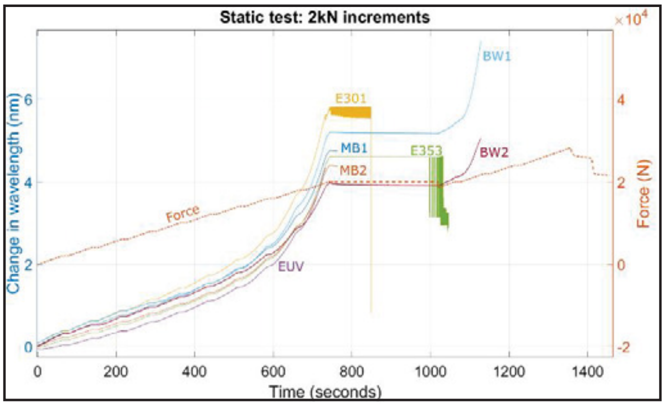

Fig. 4. Static fail test showing limit of each attachment method.

B. *Static*

Following the fatigue experiment, the SS plate was tensioned until failure. The purpose of which was to determine the static limit of attachment methods. Figure 4 shows the results. Both welded sensors failed due to capillary break at 22 kN, whereas all epoxies failed during the long 20 kN period. The high strains witnessed at these forces due to deformation of the SS plate are much higher than would be expected during operation. However, this showcases that the braze-welded design is able to withstand a higher stress before failing and thus provides a stronger bond.

IV. HUMIDITY EXPERIMENT

For the previous work discussed in [11], the sensors are functioning for long periods underground, and are thus subjected to high humidity levels. Prior to this experiment, bare FBGs were tested at high humidity, and displayed no peak wavelength shifts. Two sensors, one braze-welded and one epoxied with E301 were attached to 0.2 mm steel plates. These two attachment methods were chosen due to their similar performance during the fatigue experiment (Fig. 3). The FBGs were then temperature cycled to remove any relaxation effects and to determine the temperature coefficients, K_T (1). The strain sensors were manually strained by means of bending to around +1mϵ within a chamber consisting of a potassium-nitrate solution providing a relative humidity of 96% at 40°C [12]. Figure 5 shows sensor response over 140 hours subjected to 96%RH. Sensors were temperature compensated using a thermocouple of ±0.1°C accuracy. Results show the epoxy swelled within the high humidity, applying tension to the FBG of ~0.6 mϵ (~1nm change). The braze-welded construction exhibited minimal change in wavelength over time (< 0.02 nm), with some variation, perhaps due to temperature compensation errors.

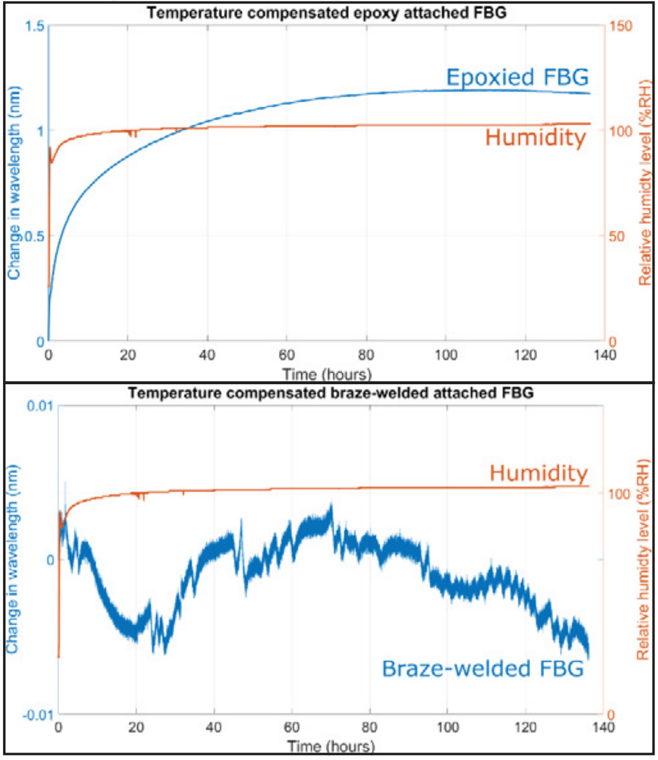

Fig. 5. Effect of humidity on epoxy and braze-welded attached FBGs. Please note the limits, 0-1.5 nm for epoxy and -0.01-0.01 nm for braze-welded. Hygrometer accuracy ± 3%.

V. CONCLUSION

In this paper, we have presented an experimental comparison between two attachment methods for FBG strain gauges. A bespoke braze-welded design outperformed commonly used strain gauge epoxies during a static failure test. Both methods showed no decay during a two million cycle fatigue test. A separate braze-welded sensor and E301 epoxy attached sensor were held at a very high relative humidity of 96%. The E301 epoxy showed signs of swelling, whereas the braze-welded sensor remained constant. In future, more epoxies will be tested to determine if this effect is unique to E301. This work illustrates the promising advantages of using a braze-welded attachment method for an FBG strain gauge within humid environments.

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