Monitoring the Loads Inside Adhesive Joints by Fiber Bragg Sensors

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ABSTRACT

In this work we propose to incorporate fiber Bragg gratings inside adhesive joints in order to measure compressive strains / stresses to which they are subjected. Since the only possible embedding geometry is in-plane (that is transverse to the direction of compressive and tensile loading), this is the geometry we investigate.

The joints examined were of the butt joint type, (Ultem 1000 adherents and epoxy adhesive - Epon 815C/Versmid 140) in which fibers with Bragg gratings were embedded. After curing, the joints were loaded by several compressive loads and the gratings' signals were studied.

The possibility to multiplex several gratings on one fiber was also examined, when five FBG sensors were incorporated inside each sample on a single fiber to estimate the stress and strain distributions in the adhesive plane. Linear correlation was found between the Bragg shifts and loads. The resulting outputs from the sensors were compared with a Finite Element Analysis (FEA) and reasonable agreements were demonstrated.

In addition, the influence of the embedded fiber on the adhesive strength was examined, resulting in no noticeable influence.

Our conclusions are that FBG sensing might be an excellent method for monitoring loads inside adhesive joints, as part of an all-inclusive structural health monitoring system.

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INTRODUCTION

In recent years several structural health monitoring (SHM) methods have been developed for civil engineering, space, automotive and other industries [1-4]. In some of these fields adhesive joints form integral parts of the structure, and monitoring their health remains a great challenge, mainly due to their small thickness. Fibers containing Bragg Gratings (FBGs) may very well suit this challenge, given their size and relative ease of embedding. Some works were already published regarding the use of FBGs to sense loads in adhesive joints, e.g. [5], and others to monitor debonding progress of adhesive layers [6].

In this work we propose to implement fibers with FBG chains inside planar adhesive butt-joints in order to measure the stresses and strains present in the adhesive layer. Usually FBGs measure strains along the fiber axis; however it is practically impossible to install the fiber in the direction of the compressive or tensile loading of the joint due to geometrical constraints, i.e. the adhesive layer thickness. Accordingly, we propose to embed the fiber in the adhesive layer plane so it will be loaded transversely (perpendicular to the fiber axis).

Since multiplexing FBGs on fibers is a common practice, we decided to use this feature in order to measure not only the loads in the adhesive but also their distribution.

ADHESIVE JOINTS PREPARATION

To check the validity of our proposal we prepared several 100mm diameter butt- joints, (Ultem 1000 adherents and Epon 815C-Versmid 140 adhesive). During the preparation process we embedded, in the adhesive of each joint, a fiber having a chain of five Bragg gratings. Note that not all of the fibers and FBGs were from the same manufacturer. The fiber paths in the adhesives, as well as the detailed embedding process, were carefully planned and performed. For example in some of the joints the fiber was just "sandwiched" between the two Ultem substrates, whereas in others, for comparison purposes, the fiber was laid inside a specially bored groove. Four types of joints were produced, as shown in Figure 1.

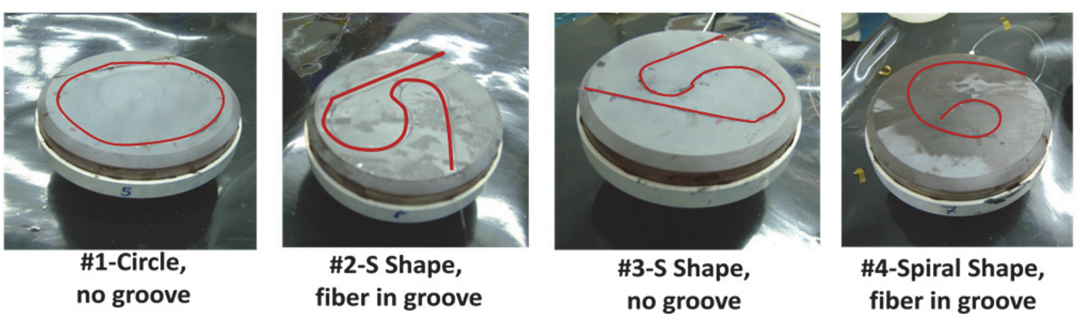

Figure 1. Ultem substrates during the embedding stage for the four joint samples. The fiber paths are highlighted in red. Scale: the joints' diameter is 100mm.

In each joint a single fiber was laid, having five FBGs with the following characteristics:

- Central wavelength (WL): ITU11, ITU21, ITU31, ITU41 and ITU51 (i.e., 1568.75nm, 1560.61nm, 1552.57nm, 1544.47nm, and 1536.65nm respectively).
- Spectral width (FWHM): 0.2-0.3nm
- Reflectivity: >95%

- Fiber: 9µm core, 125µm clad, 140µm polyimide coated.
- Physical center-to-center spacing of the gratings: 50mm

The final adhesive thickness was 200-250µm, somewhat larger than the fiber thickness, and similar to the usual thickness when no fiber is embedded.

As a first concern we assessed the influence of the fiber presence in the joints on their strengths. This has been performed by loading to failure both such a sample and a similar sample having no fiber. It was found that the fiber presence has no measurable effect on the joint strength.

EXPERIMENTAL SET-UP AND RESULTS

Each sample was placed inside a custom designed loading apparatus, capable of loading the samples, both in compression and in tension, up to 3,000Kg (~30,000N). The adhesive area in all of the samples was the same (78.5cm^2), thus the maximum force of 30,000N amounts to an average stress of 3.75 MPa across the joint.

Figure 2 shows one of the samples inside the loading machine and the peripheral equipment.

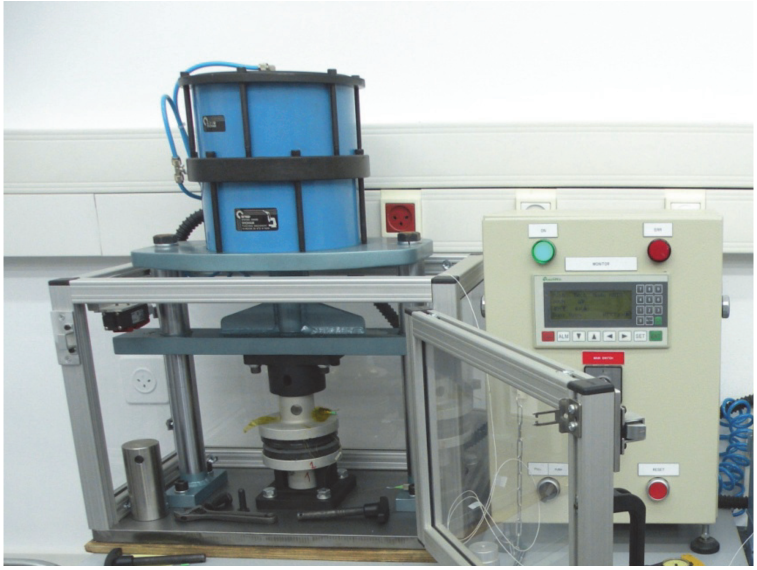

Figure 2. One of the joint samples in the loading machine, with the machine control panel on the right.

Each sample was first subjected to increasing compressive loads, with incremental steps of 500Kg (i.e. 0.63 MPa), up to the maximum load, when in each step an equilibration time of two minutes was allowed, after which all of the five FBG spectra were acquired. At the end of the loading process, a step-wise decrease of the load was applied to check for hysteresis effects. Thus, all samples were consecutively loaded and all the FBG spectra acquired. Figure 3 depicts typical spectra obtained, with shifts clearly visible.

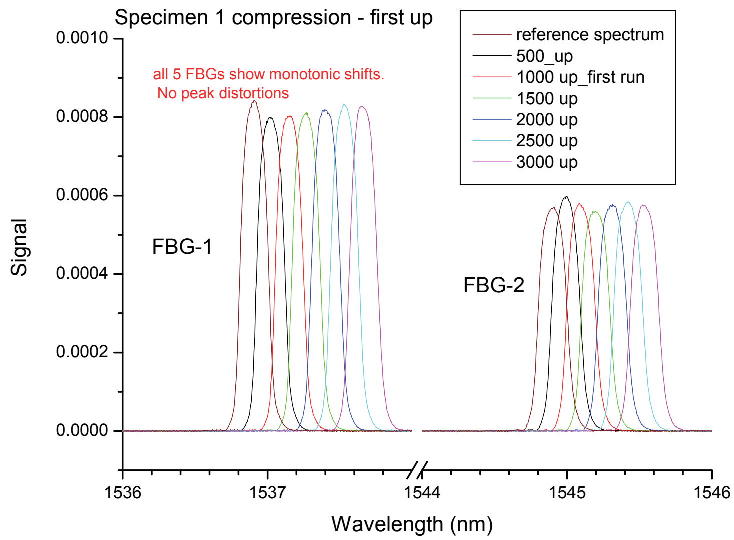

Figure 3. Typical spectra obtained from 2 of the 5 FBGs in sample 1. Note the wavelength shifts due to varying loads.

Note that no peak splittings were observed with these FBGs at the loads applied. When using smaller (40mm diameter) samples (not shown in this paper), the same loads produced 6-fold stresses, causing peak splitting phenomena, due to anisotropic effects in the FBGs.

For each spectrum, the five FBG peaks were determined and plotted versus the spatially averaged stress applied (i.e. total force divided by the joint area). Figures 4-6 depict the results obtained for three of the four samples.

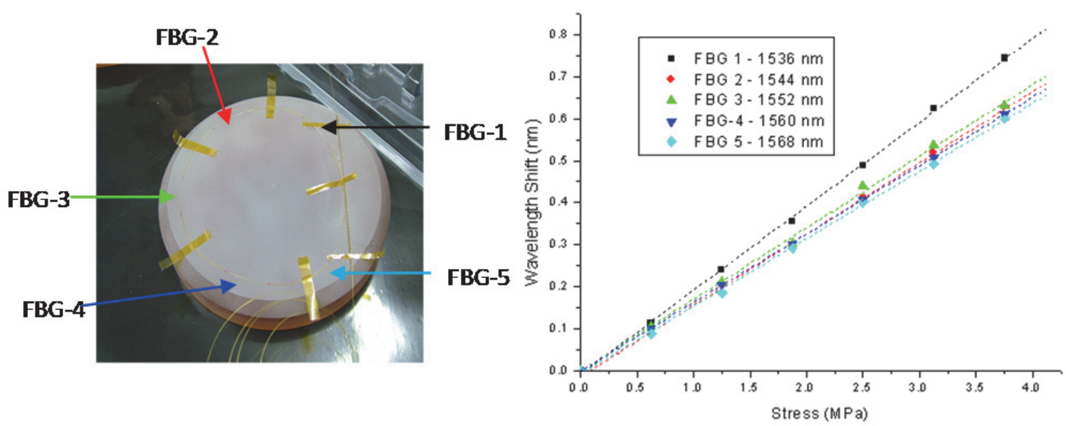

Figure 4. Sample 1: FBG locations (in a circle) shown before forming the adhesive joint and their peak shifts when load is applied to the joint.

In sample 1 (Figure 4), the fiber was laid directly on the substrate (i.e. no groove), in a circle of radius 40-45mm concentric with the joint. All the five FBGs were nominally at the same distance from the joint center. Accordingly, it was anticipated that they will experience the same loads and thus report the same wavelength shifts, which was indeed the case for four of them, with some 15-20% deviation of the fifth. Note that all the signals show linear dependence of the FBG wavelength shift with the applied load.

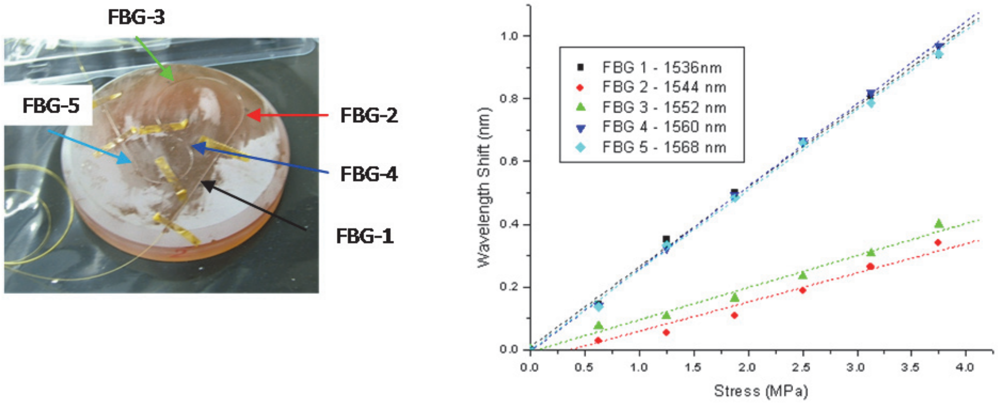

Figure 5. Sample 2: FBG locations (S-shaped fiber route, fiber lies in groove) shown before forming the adhesive joint and their peak shifts when load is applied to the joint.

In sample 2 (figure 5) the fiber was laid in an S-shaped groove, with FBGs 2 and 3 closer to the joint rim. As figure 5 demonstrates, these two gratings reported lower wavelength shifts, which is interpreted as lower stresses at their locations. This is consistent with our model which is described below. Regarding the other gratings, i.e. FBGs 1, 4 and 5, one might expect to see some differences (since FBG 4 is closer to the joint center than the other two). This is not observed in the figure.

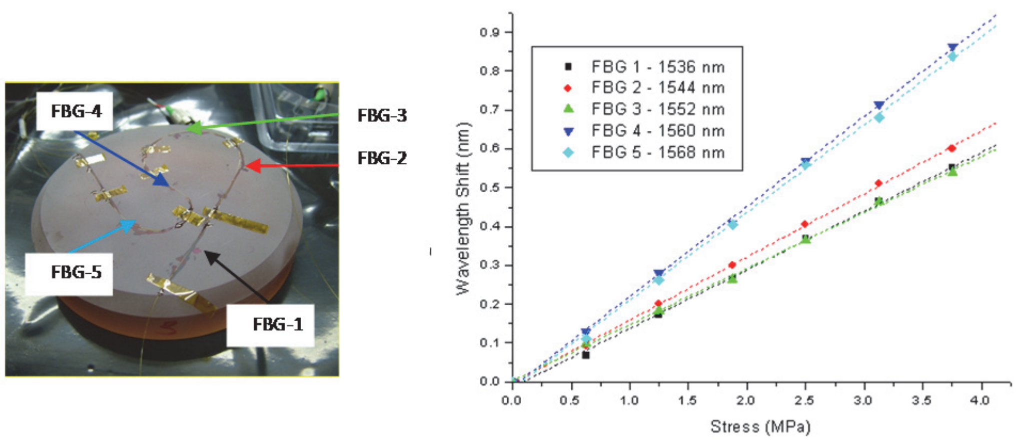

Figure 6. Sample 3: FBG locations (S-shaped fiber route, fiber lies on substrate, no groove) and their peak shifts due to load applied.

Figure 6 presents results from sample 3 which are very similar to the results from sample 2. The difference between the samples is that in sample 3 the fiber lies directly on the substrate (i.e. no groove as in sample 2). Also in this sample FBG-1 was closer to the joint rim than in sample 2. Basically the wavelength shifts are similar (though not identical) to those of figure 5, the main difference being with respect to the data of FBG-1. Comparing the results of samples 2 and 3 we can conclude that the issue whether the fiber is laid in a groove or directly on the flat substrate has some effect, though not a very significant one.

The results from the fourth sample had similar characteristics, with some of the gratings exhibiting peak splits as a result of the embedding process, due to anisotropic loads. Note that this occurred only for FBGs on fibers of a specific manufacturer, having different fiber materials and manufacturing processes.

As mentioned, hysteresis effects were also examined, resulting in effects on the order of 10%, with a maximum measurable hysteresis equivalent to approximately 250Kg (0.3 MPa) – see Figure 7.

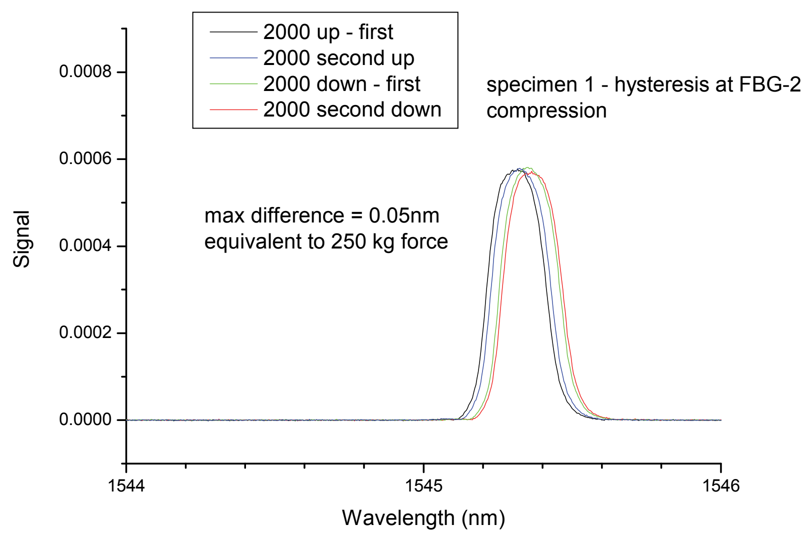

Figure 7. Typical hysteresis measured. Note the wavelength shifts between various cycles of increasing and decreasing loads.

COMPARISON TO MODELLING RESULTS

In order to gain more confidence in the translation of the measured wavelength shifts to local stresses, some modeling is desirable. Numerous works were published that cover the issue of modeling the response of embedded FBGs, though most were performed for FBGs embedded in composite materials, e.g. [7, 8]. We have applied to the joint layout an FEA model using the Cosmos modeling software [9]. An example is shown in Figure 8, for the case of sample #3, i.e. S-shaped fiber route, where the fiber lies directly on the substrate. The figure shows the stresses calculated from the different FBGs wavelength shifts, under 3,000Kg (3.75MPa) load, using two different models, and a solid line which is the output of the FEA along a radial axis of the joint In fact, the cylindrical symmetry resulted in the stress being a function of the radial distance only.

The first model assumes that the wavelength change in the grating reflection is caused by the adhesive layer straining the fiber along its axis due to the Poisson effect and by direct strain applied to the fiber by the compressive load which causes refractive index changes,. The second model neglects the effect of the direct compressive straining of the fiber.

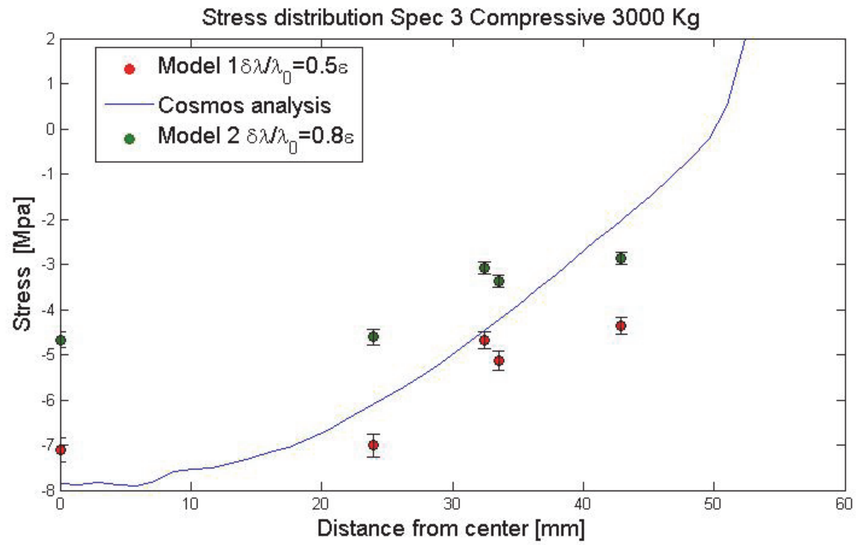

Figure 8. Stress distribution in sample 3 at maximum load (3.75 MPa). Solid line – FEA results, Dots – calculated results obtained from experimental measurement of FBGs wavelength shift utilizing Model 1 – Red, and Model 2 – Green.

Though we cannot claim perfect agreement, the predicted by a FEA and measured stresses agree to within 20-30%, enough to demonstrate the validity of the technique. Obviously more work is needed to obtain better agreement.

CONCLUSIONS

In summary, the following have been demonstrated:

- The validity of embedding fibers in adhesive joints with no significant impact on the joint strength;
- The capability of embedding fibers with several FBGs on each, at different locations in the joint;
- The capability of measuring compressive stresses at the location of each of the FBGs (and thus strain distribution in the joint surface);
- The issue whether the fiber is laid in a groove or directly on the flat substrate has some effect on the measurement, though not a very significant one;

There are still some issues that should be addressed:

- Demonstrating the validity of the approach also for tensile loads;
- Improving the agreement between the measurements and modeling;

To conclude, we have demonstrated the validity of using FBGs to measure stresses and stress distributions in adhesive layers or joints. This ability may prove important both for the development stages of adhesive assisted structures, and as a viable structural health monitoring instrument, with the understanding that in many occasions, breaks, knot releases etc. will manifest themselves in the stresses (or stress distributions) at such joints and thus will be detected.

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