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Response of fiber Bragg gratings bonded on a glass/epoxy laminate subjected to static loadings

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Abstract

Fiber Bragg gratings (FBG) may be used to monitor strain over the surface of a structure as an alternative technology to conventional strain gauges. However, FBG bonding techniques have still not been established to yield satisfactory surface measurements. Here, two adhesives were investigated, one with low viscosity and the other with high viscosity for bonding FBGs on glass/epoxy sandwich skins. First, instrumented elementary specimens were tested under tension. FBG strain results were analyzed together with digital image correlation (DIC) measurements. The influence of the bonding layer on the measured strain and on the integrity of the sensor was investigated by considering different regions of interest. Next, an instrumented structural sandwich beam was tested under four-point bending. FBG rosettes were compared to conventional strain gauge rosettes. The high viscosity adhesive demonstrated behaviors that affected FBG accuracy. Brittleness of the bonding layer and poor interface adhesion were observed using DIC and X-ray tomography. By contrast, the low viscosity adhesive demonstrated satisfactory results. The FBG strain measurements appeared to be consistent with those of DIC. The accuracy is also adequate as the FBGs and the conventional strain gauges had similar results in three directions, under tension and under compression.

Keywords

Structural health monitoring (SHM), composite, laminate, sandwich, fiber Bragg grating (FBG), digital image correlation (DIC).

1. Introduction

Optical fiber Bragg gratings (FBG) are widely used in mechanical sensing of composite materials [1-3], mainly because of their resistance to high temperatures, allowing them to withstand the temperatures required in composite curing processes [4,5] and of their small size, allowing them to be embedded between laminate plies without significantly altering the structural integrity of the host material [6,7]. FBGs offer other advantages that make them ideal candidates rather than conventional strain gauges for structural sensing: they are immune to electromagnetic fields, they have the ability to be multiplexed, meaning that several sensors can be distributed on a single optical fiber, they provide an absolute wavelength reference making them immune to interruption and they may be used as very reliable temperature sensors [8,9]. These advantages suggest that FBGs can be used in long-term structural health monitoring (SHM) applications [10].

Composite materials are increasingly used in civil engineering. Among these materials, sandwich panels provide a promising self-standing structure for the roofs of large buildings. In some regions these structures are subjected to harsh environmental conditions (high heat combined with high relative humidity and strong winds). This calls for a reliable in-situ strain monitoring. Conventional electrical strain gauges could be used for such program but it

appears that it would imply an important number of cables, complex compensation procedures and the eventual influence of electromagnetic fields. The use of FBGs in this setting mitigated the likelihood of encountering these problems. In this case a major question relates to whether or not to embed the optical fibers. The large dimensions of such structures, the usual open mold contact lay-up environment and the frequent intense manufacturing flow process involved do not allow for precise integration of sensor arrays in sandwich laminated skins. Consequently it is reasonable to adopt a surface bonding technique to install the FBGs.

Surface bonding of FBGs leads to questions about strain transfer. To analyze the strain transfer mechanism from a loaded substrate to the optical sensor, theoretical approaches have been developed to provide prediction tools [11-17]. Numerical analyses using finite element modeling (FEM) are then proposed to validate the analytical models [11-14]. Only a few authors have validated their analytical approaches experimentally [13,15,16]. Ansari and Yuan [15] tested bonded coated fibers as well as bare fibers on an aluminum beam subjected to bending. They used a Michelson interferometry sensing technique. In this case, the sensor gauge length is much larger than the length of FBGs. They concluded that when optical fibers are used without any coating (bare fiber) a total strain transfer from substrate to sensor is obtained. Zhang et al. [16] compared two adhesive processes, epoxy resin and sprayed metal. FBGs were bonded on a galvanized steel wire. They reported that the geometry of the bonding layers, as well as their properties, have an impact on the measurement accuracy. Betz et al. [10] tested the viability of a surface-bonded FBG for a major aircraft company. The sensor was covered by a varnish build up. The results were validated by FEM and compared to conventional strain gauge measurements. The high potential of this installation technique was revealed due to its processing ease and practical advantages in comparison to embedding techniques.

In summary several studies suggest that the thickness between the sensor and the substrate should be as small as possible [12,16,17] and that the polymeric coating should be removed [15]. These studies also suggest that the bonded length should be longer than the sensor gauge length [12,16] to avoid misleading longitudinal strain gradients and that the overall bonding layer thickness must be reasonable to prevent distortion of the FBG's reflected spectrum [12,16,17]. Similar distortions may take place if the adhesive is too stiff and bulky [16]. If the stiffness of the substrate is low compared to that of the optical fiber strain transmission loss is possible [13].

Adhesion between the bare fiber and the protective material or the adhesive has not been the focus of much research. The theoretical developments cited above are generally based on the assumption that all interfaces are perfectly bonded so that displacement is consistent along the interfaces. Yet, a previous experimental study [18] clearly revealed that the protective coating was poorly bonded to the FBG, inducing important measurement inaccuracies.

There is limited research using experimental approaches that seeks to understand and validate the response of bonded FBGs. Motivated by the above considerations, an experimental investigation on the response of bonded FBGs on glass/epoxy composites was undertaken and presented in this paper. The adhesive systems chosen for the test were provided from a major strain gauge manufacturer. These adhesives are commonly used for bonding strain gauges to characterize materials under static and cyclic testing and are made to resist harsh environmental conditions to some extent. Given the installation conditions for sensors on roof sandwich panels, two adhesive solutions are proposed. The first one is a high-viscosity adhesive that is suitable for rough surface bonding and practical implementations. The second one is a low-viscosity adhesive that provides a recommended thin interface layer but that may necessitate polishing the substrate. To analyze the efficiency of both bonding systems two series of static tests were performed. The first consisted of tensile loading tests on two specimens made from the laminated skins of the sandwich. The objective of the tensile test was to compare the FBG results to full-field measurements from digital image correlation (DIC), to analyze the strain fields in the FBG-adhesive area and to evaluate the mechanical impact of the sensing system. Some additional analysis was possible using X-ray micro tomography. The second static test was a four-point bending test on a large instrumented sandwich beam. The goal was to validate the FBG measurements under condition of both adhesive solutions by a comparison with measurements from conventional strain gauges.

2. Material and samples

The reinforcement material and the matrix were chosen accordingly to a civil application of roof paneling of very large dimension. The results of a stress analysis of a sandwich solution provided an optimized design of the composite skins in terms of reinforcement quantities and orientation. Taking into account processing and

economical aspects, a tri-axial glass fabric that could be used in both normal and inverted position was found to be the most adequate.

The inner and outer face of the composite sandwich beam used in our test present a reinforcement stack of two layers of the same tri-axial glass fabric (TX 0/+45/90 - Saertex- 930 g/m²) to give a [(0/+45/90)/(0/-45/90)] sequence. The matrix was an epoxy resin (Ampreg 21FR - Gurit). The skin's mean thickness was approximately 2 mm and the glass volume fraction was 32 % when estimated using an acid digestion technique. The sandwich core was made of 150 mm thick PET foam (PETW/AC8 - Armacell). The manufacturing process consisted of hand lay-up and manual impregnation procedures in an open mold, followed by vacuum bagging and oven curing processes. Elementary specimens were cut from separately made skin laminates using a diamond disk. They were 120 mm long and 16 mm wide. The large structural sandwich beam was 3400 mm long, 450 mm wide and approximately 154 mm thick.

3. Instrumentation

3.1. Optical FBG sensing

An FBG reflects a part of the incident light signal that is represented by a spectrum of wave length [8,9]. It is characterized by a Bragg wavelength, λ_B , that corresponds to the spectrum peak. When the FBG is subjected to axial strain ε_{xx} or temperature changes ΔT , the peak shifts proportionally with these loadings. The Bragg wavelength variation can be expressed as:

$$\Delta\lambda_B / \lambda_B = K_T\Delta T + K_\varepsilon\varepsilon_{xx} \quad (1)$$

where K_T and K_ε are related to the sensor's sensitivities to temperature and strain, respectively. In this study the temperature component is neglected as tests are carried out at constant temperature. FBGs used here were 5 mm long and written on SMF28e standard fiber. The coating was removed along the FBG. A Micron Optics sm125 unit was used for the acquisition of peak changes and reflected spectrums.

FBGs used here were 5 mm long and written on SMF28e standard fiber. The coating was removed along the FBG. A Micron Optics sm125 unit was used for the acquisition of peak changes and reflected spectrums.

3.2. Adhesives

Two adhesives for extensometry applications were tested. According to the manufacturer, both adhesives were claimed to be adequate to resist long-term and harsh environmental conditions. That makes them viable candidates for our final structural monitoring. The main difference between the two adhesives is their viscosity. The first solution called system A is HBM X60. It is a pasty cold-curing two-component system made of methyl methacrylate. After rapid mixing of the two components, twenty to thirty seconds are necessary for curing. A typical thumb-pressure procedure is needed to bond the sensor. This system is very attractive for its ease of use even in the upside down position and for its fast curing. The second solution called system B is HBM Z70. It is a liquid cold curing single-component system made of cyanoacrylate. Curing is only possible on very thin adhesive films and at room temperature under thumb pressure for at least one minute. The second solution is less convenient from a practical point of view.

3.3. Sensor configuration on the elementary specimens

Two specimens, A and B, were instrumented with 5 mm long FBGs located in the center of the specimen and in the longitudinal direction. Adhesive systems A and B were used on specimens A and B, respectively. The bonding layer is extended several millimeters beyond each end of the FBG, as recommended in the literature [12,16]. To capture identifiable images for the DIC measurements, a randomly distributed speckle pattern was painted on the surface covering the bonded FBGs (Figure 1).

Figure 1. Schematics of specimens and detail of the speckle pattern on the bonded FBGs using (a) system A and (b) system B.

Repetitive observations by microscope of sections of bare optical fibers bonded on a glass/epoxy substrate revealed different geometries of the bonding layer (Figure 2). The adhesive system A almost covered the optical fiber (Figure 2a) while the adhesive system B bonded only to the lower half of the optical fiber and the layer width was only approximately twice the optical fiber's diameter (Figure 2b).

Figure 2. Microscope observations and schematics of a section of a bare optical fiber bonded on a glass/epoxy substrate, (a) with the high-viscosity adhesive and (b) with the low-viscosity adhesive.

3.4. Sensor configuration on the structural sandwich beam

As the objective of our study was to validate the use of bonded FBGs, conventional strain gauges were also used for comparisons. To obtain strain measurements in the three main directions, rosettes of sensors were used. The FBG rosettes were designed with a fourth FBG that would be free from mechanical stresses (not bonded) so that the temperature could be measured and compensation could be made for measured strain (Figure 3a). Rosettes of FBGs and strain gauges are positioned as follows (Figure 3 and 4):

- two strain gauge rosettes were bonded symmetrically on each side of the beam, on the central transverse line of the beam, 145 mm from the longitudinal axis. The adhesive used was system A.
- two FBG rosettes were bonded symmetrically on each side of the beam on the central transverse line, on the longitudinal axis using adhesive system A.
- two FBG rosettes were bonded symmetrically on each side of the beam on the central transverse line, 145 mm from the longitudinal axis using adhesive system B.

Figure 3. a) The FBG rosette configuration to measure strain and temperature. b) A schematic drawing of the symmetrical positioning of the rosettes.

Figure 4. FBG rosettes and strain gauge rosette instrumentation of the sandwich beam. a) Schematic view from the b) Photograph of instrumenting from beneath

Figure 4b shows the instrumentation bonding phase of the lower face of the beam. This uncomfortable position for the installer is representative of a real application from the inside of a roof. As expected it was easier to apply the high-viscosity adhesive than the low-viscosity adhesive. For the latter the use of a syringe and the capillary action helped to provide a satisfactory bonding.

4. Experimental set up and procedures

4.1. Tensile test on elementary specimens

The static tensile tests were performed with an Instron E10000 (Figure 5a). Although this machine was designed for fatigue testing, it can very conveniently be used for static testing as long as the maximum applied force is less than 7 kN. The DIC set-up consisted of a pco. Sensicam camera, providing 1376×1040 pixel resolution, equipped with bi-telecentric lenses (TC 23 016; Opto-Engineering). These lenses allow keeping the incident and reflected rays parallel, minimizing artificial strains resulting from out-of-plane displacements during the strain reconstruction by image correlation. These bi-telecentric lenses were an important feature of our test because the bonding layer, and to some extent the optical fiber, were obviously not in the same plane as the surface of the specimen. The interest of using high-quality bilateral telecentric lenses was demonstrated by Pan B. et al. [19]. Set up with a working distance of 45 mm allowing a field of view (FOV) of 9×7 mm the lenses enabled an optimum resolution. The displacement rate of the crosshead was 0.3 mm/min. To capture images at the steadiest moment, the tensile loading was held constant every 0.5 kN.

Figure 5. Experimental set up: (a) tensile test for the elementary specimens, (b) four-point bending test for the structural beam.

4.2. Four-point bending test on a large sandwich *beam*

The test was run in compliance with the ASTM C393 standard (Figure 5b). The distance between the central cylinders was 1000 mm and that between the outer bearings was 3000 mm. The cell force had a ± 200 kN capacity. The strain gauge acquisition was obtained with a Vishay 2100 gauge bridge and Vishay DO1 software. The optical acquisition equipment was the same as that used for the elementary specimen. The test was run continuously at 6 mm/min until rupture.

5. Results and analysis

5.1. Tensile test on elementary specimens

The numerical image processing was carried out with the VIC-2D® package. The subset size was 21 pixels and the step size was 5 pixels. To compare DIC results with FBG results, different regions of interest (ROI) were investigated. Two ROI sizes were defined on each sample. The first was a narrow ROI that provided a DIC mean strain measurement equivalent to that of FBGs. It was 5 mm long, like the FBG, and 0.7 mm wide. The second was a wide ROI that covered a major part of the bonding layer. It was 5 mm long and 3 mm wide. The goal was not only to compare the mean strain measurements, but also to detect any influence of the optical fiber and the bonding layer on the local behavior of the specimen. It is well known that the shape of the reflected FBG spectrum depends on the strain distribution along the FBGs. Therefore, a relation between the gradients obtained from the DIC and the spectrum distortions was expected. Such distorted spectrums may lead to strain measurement inaccuracies. Two ROI locations on each sample were therefore defined. The first region to be investigated was obviously located over the FBG. The second region was located beside the FBG and the boundary layer. The measured mean strain values from either the FBG or DIC did not necessarily relate only to the substrate's behavior. Measurements without the presence of an optical fiber would better reveal the pure substrate behavior. Comparisons would then clarify how the optical fiber and the bonding layer influence the behavior of the substrate. With this in mind, another ROI was investigated with the same dimensions, orientation and longitudinal position, but shifted transversally so that no part of the optical fiber or the bonding layer was included. In all, four ROIs were analyzed and the performance of adhesive system A and B were compared.

Specimen A. First, narrow ROIs were considered. With respect to loading, the change in the DIC mean strain in the FBG's ROI, the DIC mean strains in the substrate's ROI, and FBG measurements were plotted in Figure 6. The first observation was that the FBG stopped delivering information at 4.5 kN whereas the DIC curve continued until 7 kN. It was assumed that the FBG sensor broke for some reasons that were not clear at this stage of the analysis. The DIC measurements were obtained until the specimen ruptured. Comparisons were made between the trends of the three curves. FBGs give higher values than the DIC in the FBG's ROI and even higher than the DIC in the substrate's ROI. Generally, because of the strain transfer from the substrate (loaded part) to the adhesive layer and FBG, a lower mean longitudinal strain value should be measured on and close to the sensor. This assumption is confirmed in the literature both theoretically and experimentally [11-13]. Analysis of the longitudinal strain distribution helped to understand this apparent paradoxical behavior.

Figure 6. Load vs. strain for specimen A. Strains were obtained by the FBG and DIC in narrow ROIs.

Figure 7a shows DIC strain fields for both ROI at different load levels. Some strain gradients appear over the FBG as the load increases, whereas in the substrate's ROI the strain distribution is homogeneous.

In larger ROIs the strain fields obtained on both the bonding layer and the substrate are shown in Figure 7b. The strain gradients in the FBG area are even more obvious than in the narrow ROIs. However, the mean values extracted from these larger ROIs were not significantly different from those measured in narrow ROIs. The local high strain fields were likely responsible for the FBG rupture. The local maximum strain value at 5 kN was approximately 3 %, which is much greater than a glass fiber such as the optical fiber can withstand.

Figure 7. Specimen A. ϵ_{xx} strain fields according to load levels in the FBG area and substrate in (a) narrow ROIs and (b) wide ROIs.

To obtain more information on the specimen and bonding layer state after the test, an x-ray micro computed tomography (CT) inspection was carried out. As the specimen rupture took place just below the tabs, it was possible to investigate the center part of the specimen, where the FBG was bonded. A Bruker SkyScan 1172 micro CT unit was used, set to work at low resolution (1000 x 500 pixels). The 3D image reconstruction is processed with Nrecon. CT-Vox was used for volume visualization and Data-Viewer was used to obtain plan views (slices) in three directions. Before X-ray processing, the specimen was cut into a smaller sample that included the bonding area and this part was soaked in dye (1,4-Diiodobutane, 99 %, stabilized with cooper) for 24 h. Figure 8a shows clearly the bonding layer and the optical fiber inside it. It also shows that the FBG is placed between two longitudinal bundles of glass fiber. More importantly, some whitened areas on the top of the glue can be distinguished. Figure 8b is a view from below the bonding layer. It shows the optical fiber passing through and probable voids (air bubbles) under it. Figure 9 confirms this observation. The top view is showing a plan sections in the adhesive layer and the optical fiber. The optical fiber is clearly identified as the thick black line. This line is interrupted by a white trace (approximately 1 mm long) that gives an indication of the fiber rupture location. If we look at the view that is parallel to the longitudinal axis, we can see a macroscopic crack that corresponds exactly to the fiber rupture. Moreover, in the same view, we see an air bubble that is certainly responsible for initiating this crack. In the top view, dark grey zones are observed on the bonding layer corresponding to the white zones observed in the volume image (Figure 8a). One of these zones is clearly related to the fiber rupture. They are most probably cracks in the bonding layer. This assumption is confirmed by comparing the DIC strain fields that were observed at a load of 7 kN. The related mapping is shown next to the micro-CT plan view in Figure 9b at the same scale. It appears that the high gradients are situated exactly in the dark zones. Cracks formed in the adhesive and generated local strain gradient in the FBG itself. The reflected spectrum underwent distortion because of this non-uniform strain field. Further observations using CT-Vox and Data-Viewer did not provide evidence of substrate cracks in the other dark zones. This means that the high-viscosity adhesive fractured before the substrate itself, which is probably due to a very brittle nature of the adhesive. The top view in Figure 9a reveals important information about the efficiency of the adhesive. The white line mentioned above is in fact a gap between the two ends of the fiber. It means that the optical fiber was pulled away, and thus, there was a poor interface adhesion between the bare fiber and the adhesive.

Figure 8. X-ray micro tomography. CTvox 3D images of the instrumented region of specimen A: (a) view from the top, (b) view of below the bonding layer.

Figure 9. (a) X-ray micro tomography. 2D views in 3 directions obtained by the Dataviewer software and (b) the same scale DIC strain field obtained at 7kN.

The unexpected higher strain values in the FBG and the bonding layer shown in Figure 6 are explained by the cracks in the bonding layer. These cracks generated local high strain values that increased the mean strain value on the ROI. Moreover, the premature failure of the FBG is explained by the rupture of the optical fiber inside the brittle bonding layer. A complementary analysis was conducted by comparing the DIC strain fields with the FBG spectra. It is well known that the shape of the reflected FBG spectrum depends on the strain gradients along the FBGs [2,17,20] as well as in the transverse direction [2,16,21,22,23]. If those are severe, a critical distortion of the spectrum may occur, leading to strain measurement inaccuracies. Therefore, it may be relevant to compare the gradients obtained from DIC to the spectral shapes.

Figure 10. FBG spectra obtained at different load levels for (a) specimen A and (b) specimen B.

Distortions of Bragg wavelength spectrum are generally related to transverse stresses or non-uniform axial strain distributions. Transverse loading on an FBG is known to generate birefringence because the optical fiber tends to become ellipsoidal. In this configuration, two orthogonally polarized optical signals are reflected. The related wavelength spectrum will show two major peaks, more or less distinctively. Using FBGs written on highly birefringent optical fibers and a polarization maintaining source setup, Udd et al. [22] were able to measure multi-axial strain inside a stressed composite sample. In fact, they showed that the distance between the deformed spectrum peaks is proportional to the difference of strain in each related direction. More recently, Sorensen et al. [23] succeeded to capture the process induced transverse strains with a conventional FBG that was embedded in a thermoplastic composite, using a tunable polarization laser source. The polarized light was sent separately along each of the polarization axes to obtain two distinct peaks.

As regards surface bonded FBGs, the birefringent effect is much less significant because the thin layer of adhesive does not generate enough transverse stresses. This is observed even if the FBG is completely embedded into an epoxy adhesive layer [16]. In this configuration it is also noted that the transverse forces caused by shrinkage of the bonding layer are asymmetrical, thus don't allow for the determination of obvious major polarization axes. In

any case, before developing studies where effects of birefringence in FBGs are expected, an FEM analysis of the instrumented specimen under test would greatly help to determine the levels of transverse load.

The distortion of the spectrums is also attributed to eventual non-uniform distribution of strain along the optical sensor. Chen et al. [17] showed experimentally, as well as theoretically, that poor constancy in width and thickness of the bonding layer would affect the wavelength spectrum correspondingly. The same incidence is observed when the bonding layer is not long enough to bond the whole length of the FBG.

For the present study, considering the above comments, we will assume that the distortions of spectrum, if observed, are due to non-uniform distribution of strains along the FBG. Several methods have been proposed for the analysis of the spectral response of an FBGs subjected to non-homogeneous axial strain fields [17,20]. The objective is to reconstruct the spectrum using a theoretical opto-mechanical model by considering different strain distribution until the experimental spectrum is matched. The problem is that these approaches depend upon a priori assumptions on the strain profile. To overcome this problem, an optical low-coherence reflectometry (OLCR) base technique has been used [25] to investigate the true strain field and proceed by feeding the model with effective data.

A similar approach could be undertaken here as the real strain profile has been obtained through the high resolution DIC analysis along the bonded FBG. Using models developed by [20] or [17] the reconstruction of the wavelength spectrum may be carried out and compared to that delivered by the MicronOptics acquisition system. This should greatly improve the comprehension of the strain mechanism taking place in the bonding layer and how it is transferred to the optical sensor. The authors intend to develop this approach together with an FEM analysis in a next paper.

Figure 10a presents the FBG spectra at different load levels for specimen A. At the initial unloaded state the spectrum had a clear major peak although the spectrum was not very narrow and symmetrical. It is assumed that non-uniform strain gradients took place due to the bonding action. However, at low load states, since the major peak is clear, the measurements are reliable. As the load increased, strain gradients over the FBG (shown by DIC in Figure 7) grew and splitting of the Bragg spectrum took place until several peaks appear. Under these conditions, the information delivered in terms of axial strains cannot be considered reliable.

Specimen B. First, narrow ROIs are considered. With respect to loading, the change in DIC mean strain in the FBG region, DIC mean strains in the substrate region, and FBG measurements are plotted in Figure 11a. This graph shows different trends than those for specimen A. The FBG delivered data for the same duration as the DIC, i.e. until specimen rupture. The trends presented were as expected as DIC strains in the substrate region are greater than those in the FBG region and even greater than strains given by the FBG itself. However, discrepancies between measured values by FBG and those by DIC are important (approximately 27 % with DIC in the substrate region and approximately 17 % with DIC in the FBG region, as calculated at 5.5 kN). The strain fields in Figure 12a, it appears to be homogenous if the small range of color scale is considered.

Figure 11. Load graph vs. strain for specimen B obtained by FBG and DIC on a) narrow ROIs and b) wide ROIs.

In considering the wide ROIs for specimen A the changes in the mean strain vs. load is shown in Figure 11b. The curve of DIC mean strain in the FBG region almost perfectly matches the curve of strain measured by the FBG. Comparing DIC strains in the substrate region with DIC strains in the FBG region a discrepancy is observed but falls to 20 %. It is less than when using the narrow ROI, but still important. These results show the influence of the DIC

parameters. The right tuning must be found in order to provide representative values of the material's mechanical behavior. Observing the strain fields of the wide ROI, Figure 12b, we see that they are uniformly distributed. However, from one ROI to another, there are differences. The spatial variability of the material or misalignment in test setup may be responsible for these differences. An X-ray micro-CT of a sample cut from specimen B is presented in Figure 13. Like for specimen A, the observed sample is the instrumented area. The image shows that there is a bundle of fibers just below the FBG and that there is no bundle where the substrate ROI is located. This may indicate that material variability did lead to differences in the results. Note that Figure 13 shows no evidence of adhesive. This confirms the thinness of the system B bonding layer.

Figure 12. Specimen B. ϵ_{xx} strain fields according to load levels, over FBG area and substrate for (a) narrow ROIs and (b) wide ROIs.

The FBG spectrums are shown at progressive load levels in Figure 10b. At the initial unloaded state, the spectrum is clearly narrow, showing a major and unique peak. As the load increases the peak remains clear. The spectrum base widens progressively but does not affect the peak, especially at less than -3 dBm below it. Under these conditions, reliable information is delivered throughout the test in terms of axial strain. Note that the slight strain field gradient that appears in one side of the DIC images in Figure 12b is represented by the lateral widening of the spectrum base.

Figure 13. X-ray micro CT. CTvox 3D images of the instrumented region of specimen B.

5.2. Four-point bending test on a large sandwich beam

The test is performed until rupture. Figure 14 presents wavelength spectra recorded just before the end of the test from both types of adhesives and both faces of the beam. The spectra from the FBG rosettes bonded with the adhesive system A (Figure 14a) are distorted. This is especially true for the spectrum related to the FBG under compression (upper face of the beam). A main peak cannot be precisely defined. Consequently the measurements are not delivered in a reliable way. The FBG rosette spectrum bonded on the lower face (under extension) has very low amplitude. Micro-bending effects on the optical guide reduced the reflected signal. This is not detrimental to peak detection, although the 0° FBG spectrum is divided into several small peaks that may induce measurement inaccuracies. Figure 14b presents data from the FBG rosettes that were bonded with adhesive system B. The spectra corresponding to 0°, 90° and 45° FBGs are narrow and with high amplitudes. These FBGs delivered consistent measurements. These results indicate that the adhesive system B is preferable for monitoring the structural health of a composite structure. For this reason the following analysis will only deal with the FBGs that were bonded with this adhesive.

Figure 14. Spectra recorded just before the end of the test. The FBGs were bonded with the adhesive system A (a) and B (b).

To validate the accuracy of the strain values a comparison with conventional strain gauge data is made. Figure 15 presents changes in strain delivered by strain gauge and FBG in relation to time during the test. Figure 15a gives the results on the upper face of the beam and Figure 15b gives the results on the lower face. Clear and linear data were obtained from FBGs and strain gauges in all three directions, under compression as well as under tension. The maximum strain on the faces that the large structural beam was subjected to is 8500 $\mu\text{m}/\text{m}$ (FBG value). This is well below the capacity of the FBG measurement technique. There is satisfactory agreement between the measurements delivered by FBGs and those by electrical gauges. This holds for strain in all directions. The maximum discrepancy is approximately 6 %.

Figure 15. Strain and load vs. time during the four-point bending test on the sandwich beam. Gauge and strain results on the upper face of the beam (a) and lower face (b).

Summary and conclusion

Two adhesive solutions for bonding FBGs on GFRP were investigated. One was a high-viscosity system and the other was a low-viscosity system. Instrumented elementary specimens were tested under static tension and a structural sandwich beam was tested under four-point bending. In the first case, FBG results were analyzed together with DIC full-field measurements and in the second case, results from FBG rosettes were compared with those from conventional strain gauge rosettes.

The selection of a high-viscosity methyl methacrylate adhesive to bond FBGs on this material is not suitable. Brittleness and poor interface adhesion are observed with DIC and X-ray tomography. On the contrary, a low viscosity cyanoacrylate adhesive gives satisfactory results. The FBG strain measurements were consistent with those of DIC. Measurement accuracy is also found to be adequate as good agreement was obtained between FBGs and conventional strain gauges in all main in-plane directions. This was confirmed under both the tensile and compression conditions. The optical technology was validated as far as the static case was concerned.

As civil engineering composite structures are usually subjected to cyclic loadings and harsh environmental conditions, the next phase of this study will be to evaluate the behavior of the FBG rosettes bonded on glass/epoxy specimens during fatigue testing, under both constant and varying temperature conditions.

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