MONITORING OF STRAINS IN CFRP DURING MECHANICAL TESTING USING FIBER BRAGG GRATING SENSORS

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Abstract

Structural Health Monitoring (SHM) systems based on Fiber Bragg Grating (FBG) sensors are becoming more important for composite materials, against other conventional strain monitoring strategies. Their advantages include reduced sensor size, electromagnetic immunity, resistance to corrosion and fatigue, the possibility of performing simultaneously strain and temperature measurements and multiplexing, between others. FBG sensors can be embedded or bonded to the composite surface.

In this paper, mechanical tests are carried out on CFRP samples using different strain measurements configurations. Embedded and bonded (by adhesive or directly attached to the matrix resin on the sample surface) FBG sensors are used for recording strains during tensile, compression and flexion tests. Results are compared against conventional gauges and digital image correlation records.

1. Introduction

FBG are fiber optics sensors which present a Bragg grating. These sensors consist of a short length of optical fiber in whose core has been recorded a number of stripes (Bragg grating). The sensor behavior is analogous to a filter, reflecting a specific wavelength of light which illuminates the fiber optic and lets pass the rest of the spectrum [1]. The change of the reflected wavelength is proportional to the strain state of the structure.

Basically, there are two main methods to situate fiber optic sensors in CFRP/GFRP composite materials: (i) bonded to part surface, or (ii) embedded between layers inside the laminate.

Bonded sensors are glued directly to the surface of the specimen using adhesives. This technique does not interfere with the manufacturing process of the samples, being able to attach the FBG to cured structures. However, sensors are exposed to impacts or environmental conditions, and the accuracy of strain measurements depends on the adhesive properties and utilized bonding technique [2].

Embedding sensors in the specimen structure improves safety of sensors during part manipulation, although other problems derived from composite manufacturing could appear. For the positioning of the optical fiber sensors inside the laminate, it is necessary that the material is not cured, being also possible to monitor curing process [3-5]. In this case, the optical fiber must bear the pressure and temperature loads required for the manufacturing process. Another critical point is the “egress” strategy of the fiber optic from the laminate, due to the easy fiber breakage.

Other method consisting in simply bonding of optical fiber to matrix resin of raw laminate has been tested in this work (*Resin bonded* method). The fiber is then placed on the raw surface of the composite and fixed during curing. Since the fiber is partially integrated into the structure, the main safety problems are resolved during part operation, and compared with Embedded sensors, integration during manufacturing results on a simply task.

2. Experimental

2.1. Materials

12 CFRP specimens were manufactured by means of hand lay-up and then autoclave cured. 2 different geometries were considered: (i) 250 x 25 mm for tensile and flexion, and (ii) 150 x 100 mm for compression tests. The stacking sequence of the laminate was [45,-45,0,90,90,90,90,0,-45,45].

In each specimen, 3 FBG sensors were situated by different integration methods: (i) bonded to the surface using adhesive (Bonded), embedded between the first and the second ply (Embedded) and fixed to the surface by the matrix resin (*Resin bonded*). The direction of the fibers was parallel to the largest dimension of the specimens. A strain gauge was also attached to the samples surface for comparison purposes.

2.2. Mechanical testing

The equipment employed for mechanical tests was a universal testing machine Zwick Z100 and the data acquisition device MGC Plus. Additionally, digital image correlation ARAMIS system (GOM GmbH) has been used for full view strain records in tensile and compression specimens.

2.2.1 Tensile

Tensile tests were carried out until 15 kN, varying the displacement rate between 0.5 and 2 $mm.min^{-1}$.

2.2.2 Compression

Tests were performed using anti-buckling test tool. Similarly to the previous ones, a maximum load of 10 kN was selected and the displacement rate was varied from 1 to 2 $mm.min^{-1}$.

2.2.3 Flexion

Displacement rate was selected at 1 $mm.min^{-1}$ and the maximum load was gradually increased from 20 to 50 N.

2.3. Strain measurements

A SM125 optical sensing interrogator (MicronOptics) has been utilized for the processing of the optical signal (obtained from FBG sensors) and strain recording. The acquisition rate was set in 5 Hz for all tests. The utilized Bragg sensors consisted in OS 1100 (Micron Optics) with a wavelength range between 1510-1590 nm.

For comparison purposes, a strain gauge 1-LY61-3/350 (HBM) was glued to the sample surface. The records were registered by using MGC Plus (HBM) system, with an acquisition rate of 5 Hz.

Full strain records were obtained using an ARAMIS (GOM GmbH) digital image correlation (DIC) system. The acquisition rate was established at 5 Hz.

3. Results and discussion

3.1. Tensile

Figure 1 shows the reflected spectrum by FBG sensors during tensile tests. It can be observed the different shape of the signal depending on the integration method used to fix the sensor to the composite. Both sensors which have been exposed to the curing process (*Resin bonded* and Embedded) exhibit multiple peaks due to the change of sensor geometry caused by autoclave loading. On the other hand, the Bonded sensor presents a unique peak with much larger amplitude. The last effect simplifies the recording and processing of the FBG signal during strain monitoring. During tests, the maximum peak was followed using an automatic algorithm of detection.

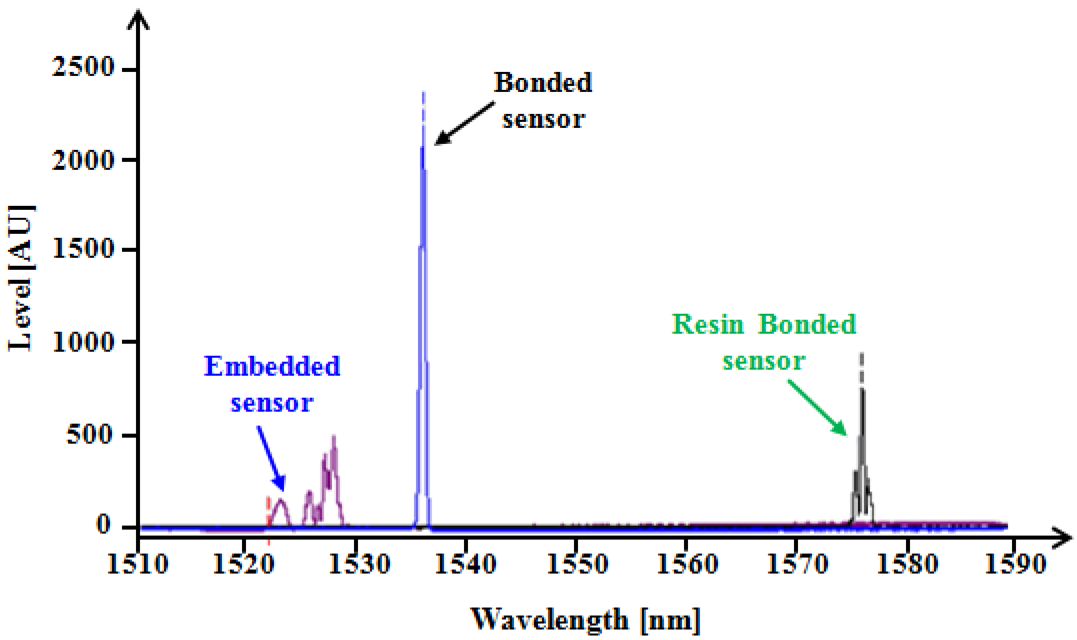

Figure 1. FBGS signals during tensile test.

The result of the tensile test at displacement rate of 2 mm/min is presented in Figure 2. A good correspondence between FBG sensors and strain gauge records is observed, where force vs. strain measures are mainly overlapped up to the maximum applied force (14KN). DIC curve was calculated as the average value of the strain in a rectangular region in the center of the specimen.

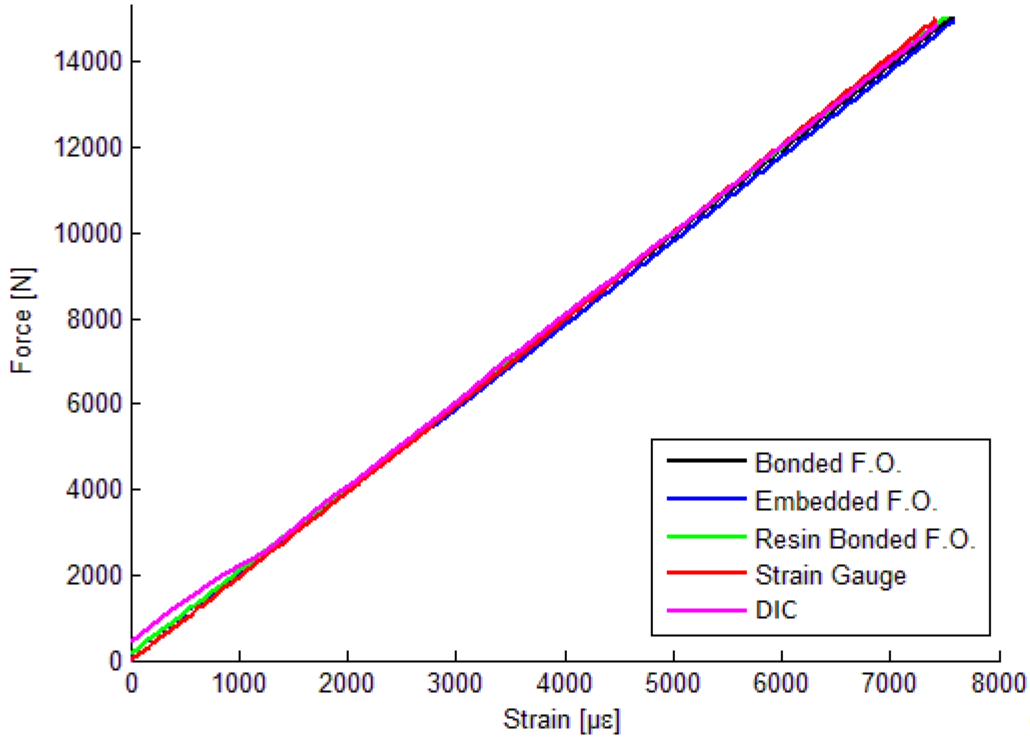

Figure 2. Stress vs. strain curves obtained during tensile testing by the different sensors (max. stress =15 kN @ 2 mm/min).

The relative difference between fiber optics sensors and the strain gauge at maximum load and different displacement rates are presented in Table 1. All of them present the same pattern, being the *Resin bonded* sensor the one showing the lowest difference (ranging from 0.3 to 1.9%). On the other hand, the Embedded sensor presents the largest difference, amounting up to 3.7% against the strain gauge. It should be noticed that sensors are located at different positions within the samples, which can lead in different records related with local strains.

Test	Displacement rate $[mm.min^{-1}]$	Relative difference against strain gauge [%]		
		Embedded F.O.	Resin bonded F.O.	Bonded F.O.
1	0.5	3.7	1.9	2.5
2	0.5	3.6	1.9	3.2
3	1	3	0.3	1.3
4	1	3.3	1.6	2.1
5	2	2.8	1.1	1.9
6	2	2.8	1.1	2.1

Table 1. Relative difference between fiber optic sensors and strain gauge measurement at tensile tests.

3.2. Compression

Records extracted from compression tests at 2 mm/min are depicted in Figure 3. Digital image correlation strains has been calculate at two locations: (i) DIC(1) corresponding to average of strain at sample center extracted from 5x5 mm^2 region, and (ii) DIC(2) calculated from similar area but located over of the *Resin bonded* sensor.

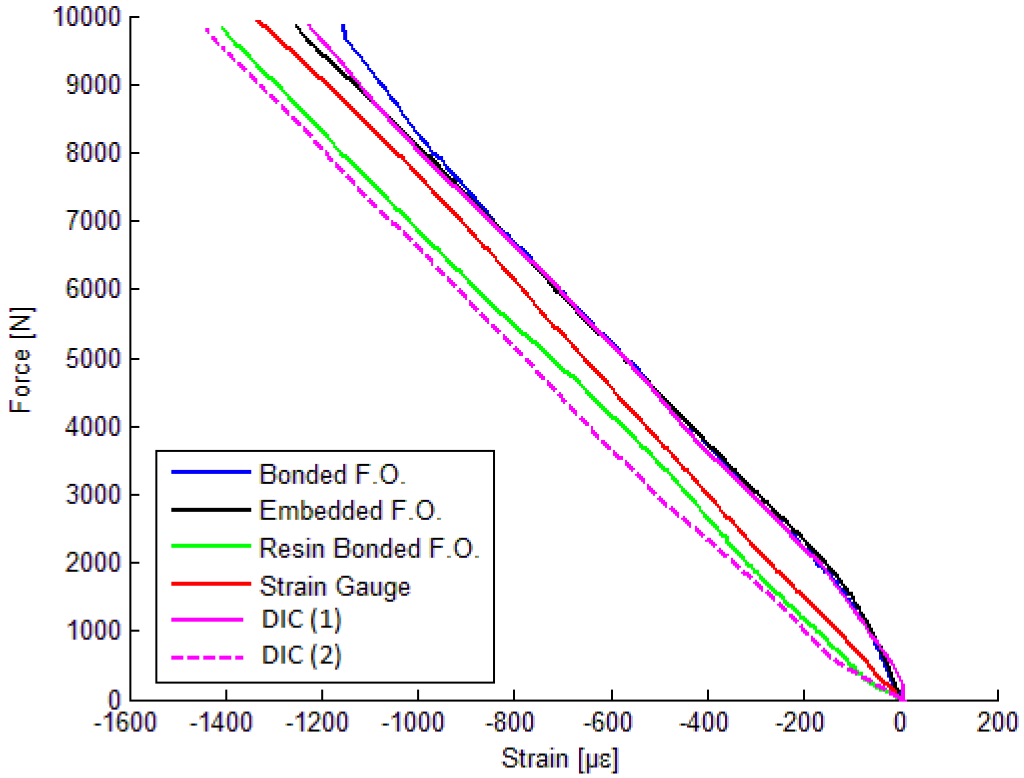

Figure 3. Stress vs. strain curves obtained during compression testing by the different sensors (max. stress = 10 kN @ 2 mm/min).

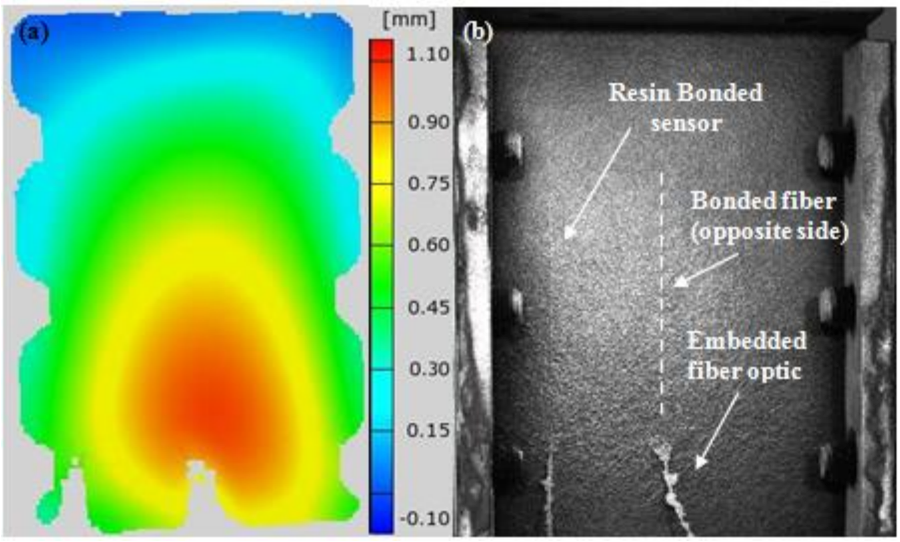

Figure 4. (a) Transverse displacement at the end of the compression test (10 kN at 2 mm/min) and (b) image of the sample.

Larger differences are displayed by the different sensors due to the buckling effect observed during the test, resulting in different strain values according to the position of each sensor. For this reason, the displacement of sample in the perpendicular direction (to the surface/load) has been monitored by DIC. The displacement map presented in Figure 4 (a), verifies the presence of the buckling effect, showing a maximum transverse displacements of 1.1 mm in the lower half of the sample at a load of 10KN. Despite this, Figure 3 shows a good adjustment between Embedded and Bonded sensors measurement (which are situated in the middle of the sample) and the DIC(1) values. A good adjustment is also observed between *Resin bonded* sensor and the DIC(2) measurements (both located in the same sample region). The position of the sensors can be observed at Figure 4 (b).

3.3. Flexion

For interpretation of results coming from flexion tests, it is first important to analyze the position of each sensor in the sample. Tensile and compressive loads are produced during flexion, varying considerably from convex and concave surfaces along the sample thickness. Depending on sensor location, the measures will vary significantly according to sensor distance to the neutral axis (at half thickness). For this test, 3 FBG configurations have been analyzed (Figure 5): (i) the Bonded sensor is located on samples surface together with the strain gauge for comparison purposes; (ii) then, the *Resin bonded* sensor is located within the first CFRP layer due to the applied pressure during curing process; (iii) finally the Embedded is located in a deeper thickness and integrated between layers 1 and 2.

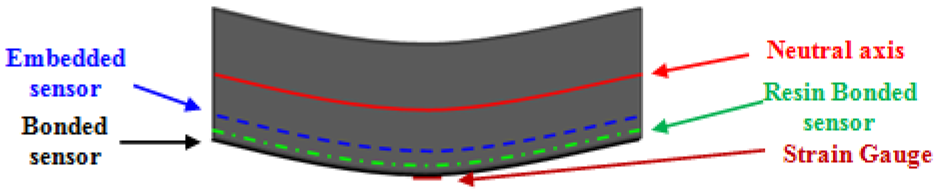

Figure 5. Schematic view for sensor location at flexion test specimen.

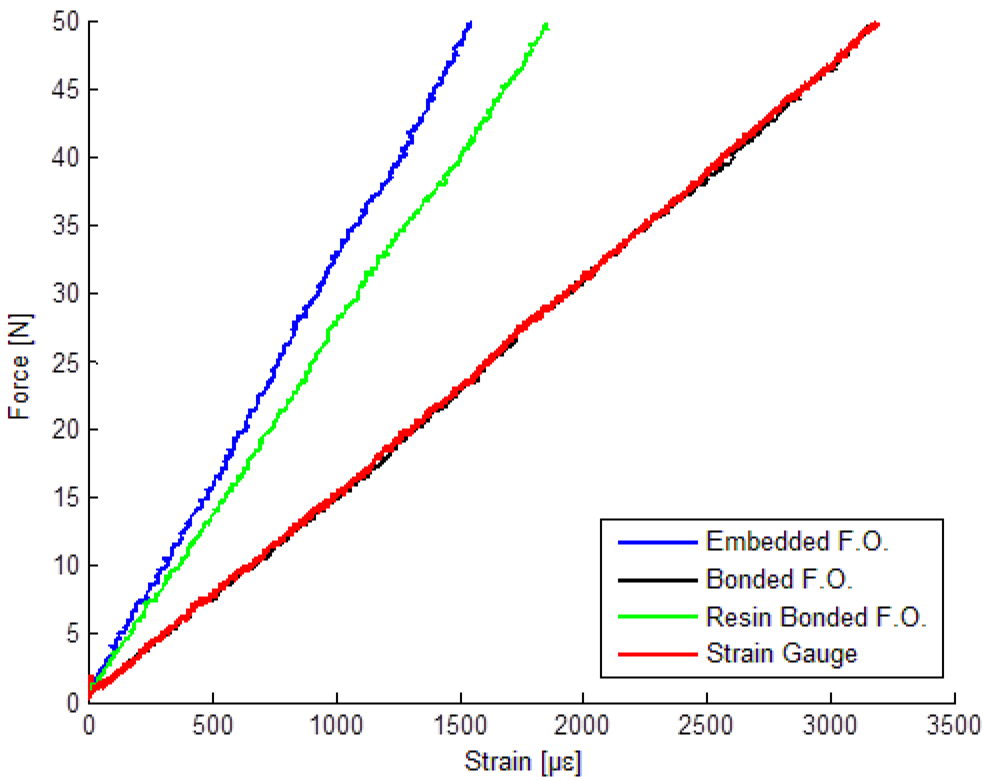

Figure 6. Stress vs. strain curves obtained during flexion testing by the different sensors (max. stress = 50 N @ 1 mm/min).

The effect of the sensor position is observed in the Figure 6. It demonstrates that the measures of the strain gage and the Bonded sensor match perfectly during testing (0.2 % difference in strain at maximum load of 50N), meanwhile the strain value registered by the other sensor decreases with their position across the samples thickness. For all above, the relative percentage difference between the strains recorded by the fiber optics sensors and the strain gauge, has not been calculated due to the variation of sensor deepness. The repeatability of the sensor measurement for each load has been checked.

4. Conclusions

A mechanical testing campaign has been performed to validate the strain measured by FBG sensors integrated by three different methods. The results obtained have been compared with a strain gauge.

The results of the tensile tests show the capability of FBG sensors to measure the strain state of the structure under, regardless of integration procedure of the sensor in the sample. A good repeatability of the records is register along all tests.

Due to the buckling problems presented by the compression tests, a comparative study could not be performed. The results are strongly affected by sensor location in the specimen. On the other hand, the records obtained from *Resin bonded* and Embedded match the ones registered by digital image correlation analysis at sensor position.

During flexion test, a clear effect on sensor location along the sample thickness is observed. In this way, different sensor integration strategies can be utilized for the recording of strains. This effect can be also utilized to detect the nature of strains: e.g. sensors embedded at neutral axis and bonded to samples surface will register similar strains in tensile tests, while in flexion the strain record of the last one will be neglected.

References

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