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On the improvement of strain measurements with FBG sensors embedded in unidirectional composites

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ABSTRACT

Optical fibre Bragg grating (FBG) sensors are now quite established and widely used in strain measurements of composites. However, insufficient understanding of the limitations of the embedment and measuring techniques often lead to inaccurate and inconclusive results. In this study, a novel method to improve the reliability and accuracy of the strain measurements on unidirectional composites using embedded FBG sensors was successfully developed. Using a carbon/epoxy prepreg system, test specimens were manufactured with longitudinally embedded FBG sensors. The combined behaviour of the sensors and the host material was characterized and a calibration rule (correction factor) was determined for the chosen material. The consistency of the results with both theoretical and empirical assumptions suggests that the proposed method is applicable to a wide range of FBG sensors and host materials.

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1. Introduction

The application of optical fibre Bragg grating (FBG) sensors in the structural health monitoring (SHM) of composite materials and structures has increased considerably in recent years. This is mainly justified by the attractive properties that these sensors present, namely, the small diameter of the optical fibre, the multiplexing ability, the effective insulation and immunity to electromagnetic fields. Therefore, this technology allows embedding of single or arrays of nearly non-intrusive sensors in the composite material to be monitored. By becoming part of the structure itself, these sensors are used for online monitoring and inspections during the whole service life of the composite structure. Fragile behaviour, coupled mechanical and thermal sensibilities, limited measuring range and difficult handling are some of the drawbacks of this sensor technology. Nevertheless, it is very promising and several authors have been studying and further developing it [1–5].

FBG sensors are quite well characterized, i.e., the relationship between the change in the wavelength of the reflected signal and the real strain imposed on the sensor is accurately determined and catalogued for each grating. However, the accuracy of the measurement in real applications strongly depends on the effectiveness of the strain transfer from the host material to the FBG sensors. The optical fibre and the host material in which it is embedded typically have different material properties (such as longitudinal stiffness) and, therefore, strain in both materials will not be equal when load is applied [6]. Since most of the physical changes that SHM aims at characterizing in composite laminates are primarily driven by the stress and/or load condition rather than strain, this aspect is of major relevance for the accurate evaluation of the laminate's condition.

The lack of perfect bonding or adhesion between the grating and the surrounding host material is also a factor that reduces the quality of the measurement. Since the

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surface sizing of the optical fibre may not be the most compatible with the matrix in which it will be embedded, deviations from the measured and the real strain field occur. Heterogeneity of the adhesion along the grating may even force the sensor response to become nonlinear in the measuring range, thus adding further uncertainty to the measurement [7].

In most of the applications of FBG to measure strains in composite materials, these issues are not taken into account and are neglected by most authors. Hence, the values retrieved from such measurements may be over or under estimating the real ones. Moreover, since normally the sensors are not calibrated for each material and/or application, the users are not aware of these errors in the measurements.

In this study, the application of FBG sensors to unidirectional (UD) composites to measure the longitudinal strain was addressed. The objectives were:

- to characterize the combined behaviour of the FBG sensors and the host material when subjected to UD (longitudinal) stress loading in order to evaluate the mismatch between the real strain and that measured by the sensor;
- to evaluate the effect of an alternative test method in promoting the accommodation and stabilization of the sensor within the hosting material; and
- to establish the calibration rule, i.e., the relation between the real and the sensed strains in the range of measurement for the particular chosen material.

In the following sections, the FBG sensors and the test materials applied in this study are indicated, the experimental procedure is described and the results are discussed in view of evaluating the reliability and applicability of the new method.

2. Selected FBG sensors

FBG are formed when a permanent periodic variation of the core's refraction index is created along a section of an optical fibre, by exposing the optical fibre to an interference pattern of intense ultra-violet (UV) light. The photosensitivity of silica glass allows the refraction index in the core to be increased by the intense laser radiation. If the optical fibre with an FBG is illuminated by a broadband light source, the grating diffractive properties are such that only a very narrow wavelength band is reflected back. In Fig. 1 a schematic representation of the data acquisition apparatus and a view of the test setup are presented.

Gratings are, therefore, passive intrinsic sensing elements that give an absolute measurement of the physical perturbation they sense. The basic principle of operation of the data acquisition hardware is to monitor and register the wavelength shift associated with the Bragg resonance condition [8]. The wavelength shift is independent of the light source intensity [9].

When the fibre is stretched or compressed along its axis, the period of the grating changes. The same is observed when the temperature fluctuates. The sensor working principle is modelled by the following relation [10]

$$\lambda_B = 2n_{eff}\Lambda \quad (1)$$

where λ_B, n_{eff}, and Λ are the reflected Bragg wavelength, effective refractive index, and the grating period, respectively. A change in the effective refractive index and/or the grating period will cause a shift in the reflected Bragg wavelength. This is the measuring principle upon which

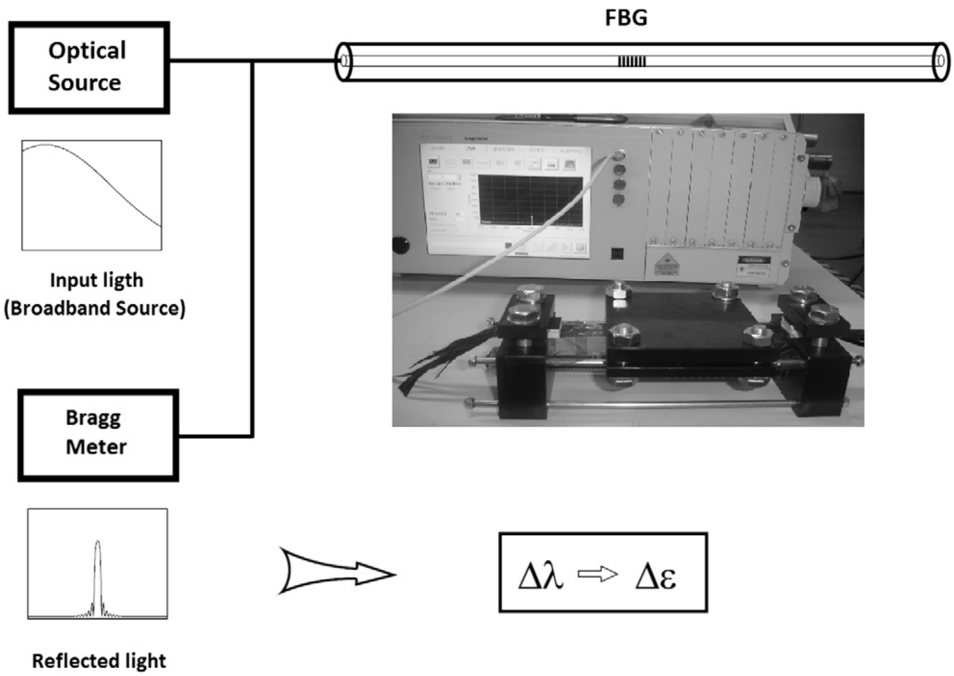

Fig. 1. Scheme of the data acquisition apparatus, using a Braggmeter.

physical quantities such as strain, temperature, force, and pressure can be measured by the FBG.

In the present study, single mode (SM) FBGs were used and the output wavelength signal was acquired at 1 Hz with a Benchtop Braggmeter FS 5200, supplied by FiberSensing™. One single grating was used in each test specimen, and all gratings were non-recoated in order to promote better strain transfer between the host material and the sensor.

3. Manufacturing and preparation of test specimens

To produce the specimens of unidirectional composite, as is shown in Fig. 2, two aspects were taken into consideration. First, this research topic was developed in order to study the applicability of an optical fibre bragg grating sensor in the structural health monitoring of a composite overwrapped pressure vessel (COPV), so a main concern was to produce specimens similar to the layers of composite material in the COPV produced by filament winding. A second important feature was the capability of replicating the manufacturing conditions; for that a dedicated setup was developed (Fig. 3). This allowed specimens to be obtained with precise and repeatable dimensions, and the capability to apply a longitudinal tensile force to the composite material and FBG sensor, leading to an optimum alignment and adjustment. The specimens were produced with a free length of 100 mm, 20 mm wide and 1.5 mm thick. Each test specimen consisted of two layers each of six rovings of carbon fibre/epoxy prepreg. The properties of the prepreg material are presented in Table 1.

Five valid specimens were manufactured in accordance with the following procedure.

Firstly, one layer of six rovings was placed in the set-up and a FBG sensor was aligned and positioned in its central line. This stage is depicted in Fig. 3(a). Secondly, another layer of six rovings was placed on top, thus fixing the FBG sensor in the middle position of the laminate with respect to both the thickness and width. The ends of the specimen were then clamped.

Thirdly, as shown in Fig. 3(b), a well-defined tensile force was applied by a normalized spring in the direction of the fibres and a geometric constraint was imposed in the free length region, leading to controlled and repeatable dimensions and alignment.

Finally, after the preparation steps, the samples were cured according to the temperature cycle specified by the manufacturer (90 min @ 150 °C).

4. Experimental procedure

In this study, a novel experimental procedure to test and accurately measure the longitudinal strain in UD composite laminates with embedded FBG sensors under tensile loading was developed and validated. The objective was to characterize and deal with the combined behaviour of the host material and the sensor in such a way that the eventual mismatch between both behaviours could be understood and realistic measurements achieved.

In Fig. 4, the two consecutive stages of the UD loading cycle are schematically plotted. In the first stage, the specimens were subjected to five cycles of tensile load. In each cycle the specimens were loaded at a displacement rate of 1 mm/min up to a strain of 0.2% and then unloaded to their initial state. The value 0.2% of strain was chosen through tests that proved that a strain value of 0.2% is enough to promote the sensor accommodation but not large enough to compromise the function of the FBG sensor and the structural integrity of the host material. This first stage allowed study of and to overcome the accommodation effect of the FBG sensor to the host material, through analyzing the hysteresis of the sensor response.

After this cyclic loading, the second stage of the traction test, in which a UD tensile load was continuously applied at the same rate until rupture, was carried out.

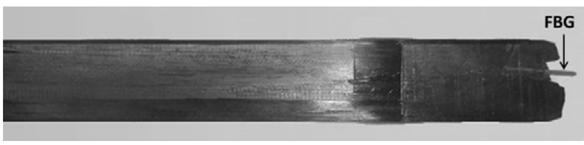

Fig. 2. Partial view of a test specimen with optical fibre embedded in the longitudinal direction.

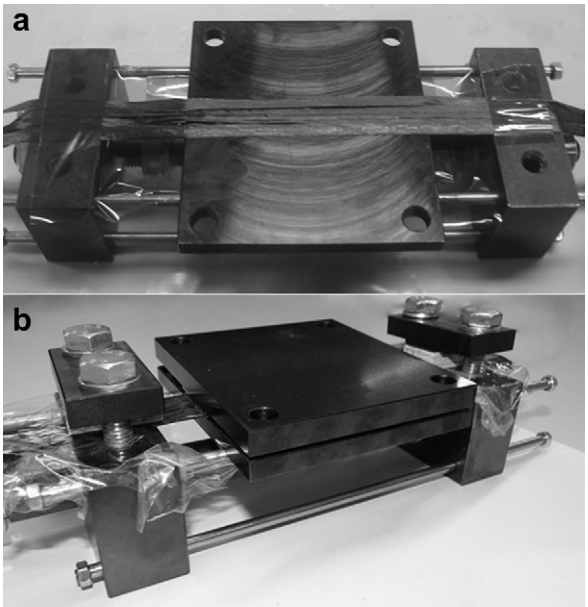

Fig. 3. Specimens preparation setup. a) Positioning of carbon fibre prepreg rovings. b) Application of a longitudinal tensile force and geometry constraint to the specimen.

Table 1
Properties of the carbon fibre/epoxy prepreg applied to the test specimens.

Filament diameter [μm]	7
Density [g/cm^3]	1.79
Tensile strength [MPa]	5000
Tensile modulus [GPa]	245
Specific electrical resistance [%]	2.1
Number of filaments per roving	24.000
Nominal linear density [tex]	1600

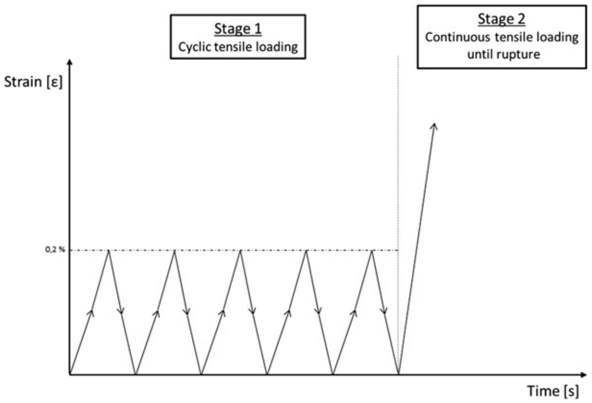

Fig. 4. Schematic representation of the loading history imposed to the test specimens.

Another important feature studied with this experimental procedure was the relation between the strain measured by the FBG sensor and real strain of the specimen. To perform this analysis as showed in Fig. 5, the strain sensed by the FBG sensor was acquired using a Benchtop BraggMeter FS 5200 supplied by FiberSensing™ and synchronized with the strain measured by a universal strain gauge extensometer assembled in a universal testing machine, Instron 4507. Then, the two values were compared in order to establish a calibration rule that aligns with better accuracy the strain measured by the FBG sensor with the real behaviour of the host material.

5. Discussion of results

In Fig. 6, the data from the first stage (cyclic loading) of the tensile test is shown for one of the specimens, From the

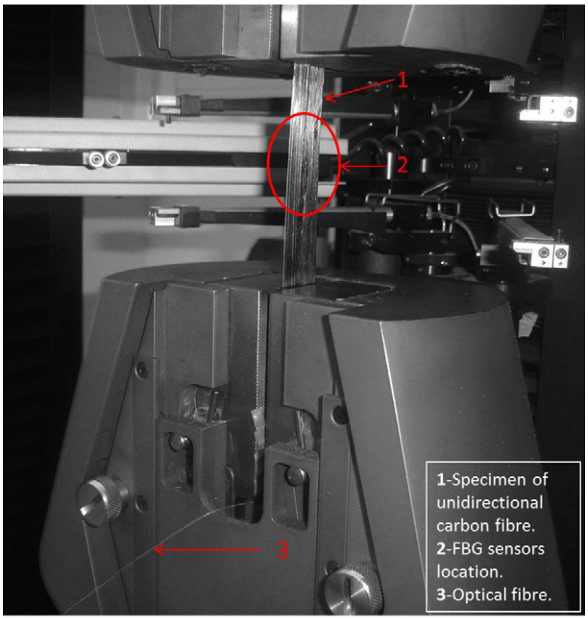

Fig. 5. View of the experimental setup for the tensile tests with FBG signal monitoring using the Braggmeter.

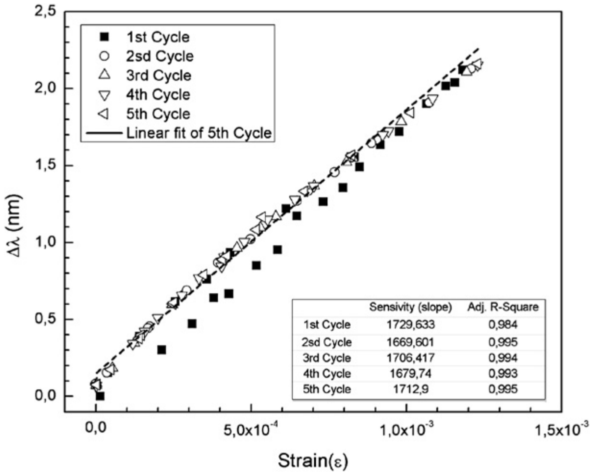

Fig. 6. Wavelength shift from FBG sensor *versus* real strain on the specimen for the first stage of UD tensile test.

plot of the strain of the sample, ε_{sample}, *versus* the wavelength shift, Δλ, of the FBG sensor embedded in the specimen. The sensitivity of the FBG sensor, $\Delta\lambda/\varepsilon_{FBG}$, is assessed through the slope of the linear regression of the data in each loading cycle. In Table 2, the averaged sensitivity and standard deviation for each loading cycle is presented for all the five tested specimens.

Accommodation of the FBG to the host material was observed, mainly in the first loading cycle. From the second cycle onwards, the sensor response starts being consistent without the presence of hysteresis, which was consistently observed in all specimens tested.

Data in Table 2, clearly shows the tendency of accommodation of the FBG within the host material after the first loading cycles. This phenomena occurs because during the process of embedding the FBG into the host material, it is technically impossible to promote complete straightness and perfect adhesion of both materials. For these reasons, in the first loading cycle, the sensor and the host material accommodated to each other, reaching an equilibrium that improved the correspondence between the sensed and the real longitudinal strains.

Upon completion of the tensile tests, the relationship between the longitudinal strain sensed by the FBG, ε_{FBG}, and the real longitudinal strain of the specimens, ε_{Sample}, was studied. By assuming that the tests were performed at a constant temperature and, therefore, no temperature effects were introduced in the FBG sensing ability, the wavelength shift, $\Delta\lambda_B$, is related to the longitudinal strain, ε, by the following equation [1]

Table 2
Average sensitivity of the FBG sensors in each loading cycle.

	Sensitivity ($\Delta\lambda/\varepsilon_{FBG}$)	
	Average	Standard deviation
Cycle 1	1797.65	61.69
Cycle 2	1687.71	47.32
Cycle 3	1721.31	19.61
Cycle 4	1709.63	32.09
Cycle 5	1727.64	12.53

$$\Delta\lambda_B = \lambda_B\left(\frac{1}{\Lambda_B}\frac{\partial\Lambda_B}{\partial\varepsilon}+\frac{1}{n_0}\frac{\partial n_0}{\partial\varepsilon}\right)\Delta\varepsilon = \lambda_B(1-p_C)\Delta\varepsilon \quad (2)$$

where λ_B is the wavelength, Λ_B is the spacing between gratings periods, n_0 is the effective index of the core and p_c is the effective photoelastic coefficient of the optical fibre. For the FBG sensors used in this study, the wavelength-strain sensitivity at $\lambda_B = 1550$ nm is 1.1×10^{-3} nm/με [11].

From the data acquired with the Braggmeter and Equation (2), the evolution of the ratio, $R_{sample/FBG}$ in Equation (3) between the strain of the sample and the strain measured by the FBG sensor during the second stage of the tensile test was plotted in Fig. 7. As shown, the strain given by the FBG sensor is higher than the real strain of the specimen. However, with increase of the strain in the sample, ε_{sample}, the strain measured by the FBG sensor, ε_{FBG}, approaches a value closer to the real one, thus making the ratio $R_{sample/FBG}$ approach the ideal value of 1. Nevertheless, in the relevant strain range, this ratio is never equal to unity and it is also not constant.

$$R_{Sample/FBG} = \frac{\varepsilon_{Sample}}{\varepsilon_{FBG}} \quad (3)$$

The relationship between the wavelength shift and its own strain sensed by the FBG is well established. Therefore, the differences between the sensed strain and the real strain in the composite specimen is mainly due to two reasons: the different stiffness of the sensor and the host material [6] and the imperfect adhesion of the FBG sensor (and the whole optical fibre) to the host material.

In order to develop a means to determine the real strain in the composite laminate from the effective strain sensed by the FBG sensor, a correction factor (calibration rule) was established from the experimental evidence. This correction factor was defined by the best fit of the data of the ratio $R_{sample/FBG}$ for the five specimens tested with a 2nd order polynomial. In Table 3 and Fig. 8, the coefficients and the plots of the 2nd order polynomial fittings for all the five tested specimens are, respectively, presented.

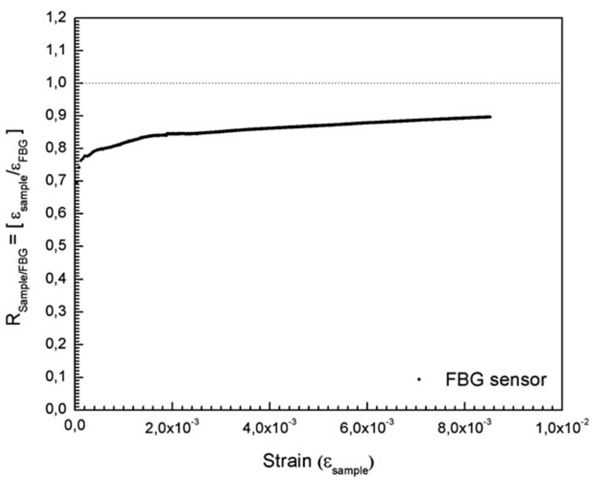

Fig. 7. Evolution of the ratio between the real strain of the specimen and the strain measured by the FBG during the second stage of the tensile test.

Table 3
Parameters of the 2nd order polynomial fit of the Ratio $R_{Sample/FBG}$ for the five specimens.

	Polynomial fit $R_{sample/FBG} = B_1 + B_2 \times \varepsilon_{FBG} + B_3 \times (\varepsilon_{FBG})^2$			
	B_1	B_2	B_3	Adj·R-Square
Specimen 1	0.79	19.375	−945.72	0.92
Specimen 2	0.81	19.792	−1471.91	0.79
Specimen 3	0.78	29.18	−2108.15	0.92
Specimen 4	0.81	42.50	−4548.49	0.88
Specimen 5	0.88	35.60	−2854.6	0.87

In our case study, the 2nd order polynomial of specimen number 1 was chosen, because it was the one presenting better agreement for all the relevant domain, thus suggesting better results.

The range of applicability of this correction factor is from 0.1×10^{-3} ε to 1×10^{-2} ε. However, in the range up to 1×10^{-3} ε it is not used, since considerable accumulated error and noisy results were consistently observed in this stage in the experimental data acquisition.

Also, this correction factor is only valid for this combination of FBG sensor and host material. Complimentary tests conducted with other host materials have shown that different ratios are observed for other combinations and, therefore, this calibration must be done for each new application.

6. Proposed method

6.1. *Experimental procedure to determinate the correction factor*

Next, the requirements and procedure to determinate the correction factor, that improves the strain value measured by the FBG sensor when embedded in a composite material are presented.

Minimum requirements in order to obtain valid results:

- Five or more, valid tensile samples with the set of FBG sensor/host material.
- Universal testing machine with automatic extensometer, that allows the acquisition of the strain of the specimen.

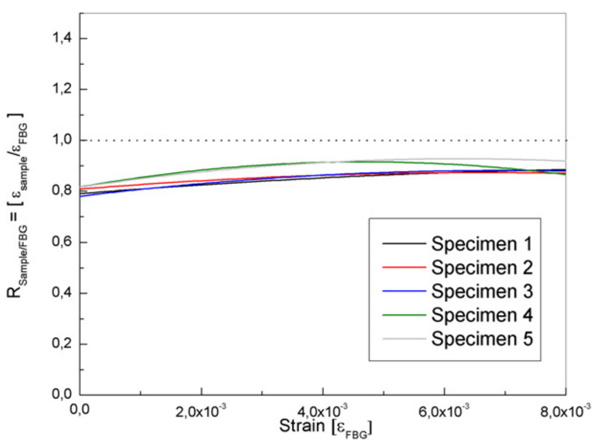

Fig. 8. 2nd order polynomial fits of the ratio data for all tested specimens.

The following steps must be taken to obtain the correction factor:

1. Execute a set of loading cycles with a low deformation in order to obtain accommodation of the FBG sensor to the host material, which improves the correspondence between the sensed and the real longitudinal strains.
2. Perform a continuous tensile loading until rupture, synchronizing the test with the acquisition of the strain measured by the extensometer of the universal machine and the FBG sensor.
3. Calculate the ratio, $R_{sample/FBG}$, between the strain of the sample and the strain measured by the FBG sensor.
4. Plot the evolution of the ratio, $R_{sample/FBG}$ against the strain measured by the FBG sensor, ε_{FBG}.
5. Define the correction factor by fitting the data of the ratio $R_{sample/FBG}$ for the five specimens tested with a 2nd order polynomial, and choose the polynomial which has the best approximation and smooth behaviour.

Note that the main purpose of the correction factor is, having access only to the information of the wavelength shift measured by the FBG sensor, achieving a more accurate stain value of the material studied. Therefore, the correction factor should be calculated through the curve $R_{sample/FBG}$ vs. ε_{FBG} in order to correct the strain value measured, even without access to the actual value of strain of the sample.

6.2. Procedure to obtain a more accurate strain in a random application using a FBG sensor embedded in the composite material

After the combined behaviour of the FBG sensor and the host material has been fully characterized, and the correction factor established, the procedure to measure a more accurate strain using a FBG sensor is given by the following steps:

1. First, the accommodation of the FBG sensor in the host material is required, as seen previously, to obtain better results from the sensor. For that, a few cycles of loading must be made with a low deformation in the set FBG sensor-host material.
2. Measure the wavelength shift, given by $\Delta\lambda$, using the acquisition system and convert this value to strain (not rectified) ε_{FBG}, as showed in Equation (4).

$$\varepsilon_{FBG} = S_{\Delta\lambda\rightarrow\varepsilon} \times \Delta\lambda = \frac{1}{1.1\times10^{-3}} \times \Delta\lambda \tag{4}$$

3. Calculate the correction factor “CF”, given by Equation (5) defined by the 2nd order polynomial presented in Table 3.

$$CF = 0.79 + 19.375 \times \varepsilon_{FBG} - 945.72 \times (\varepsilon_{FBG})^2 \tag{5}$$

4. Finally, correct the value of strain measured by the FBG sensor using Equation 6, to obtain a more accurate value of real strain of the specimen, given by ε'.

$$\varepsilon' = \varepsilon_{FBG} \times \frac{1}{CF} \tag{6}$$

7. Conclusions

From the analysis of the results, several conclusions were drawn. Namely, it became clear that the FBG sensor does not accommodate or adhere perfectly to the host material during the preparation of the test specimens. The alternative procedure of imposing a cyclic tension load (within the elastic domain of both the sensor and the host material) proved that the sensor can be accommodated after 1 or 2 cycles. After these cycles, the sensor returns the desired response and, therefore, better agreement between the measured and real strains is achieved.

Despite the accommodation of the sensor, the different material properties still prevent a perfect match between the real strains in the specimen and those outputted by the FBG sensor. This means that, in addition to the accommodation procedure, calibration must be done for each sensor/host pair. For the sensors and host material applied in this study a correction factor was determined and applied in order to obtain a more accurate measure of the strain. Since it is dependent on the grating length and relative stiffness of the optical fibre and the host material, this calibration must be done for each new application.

The practical implications of these conclusions are that, whenever a new application of FBG sensors to measure strains in composite structure is set, both the calibration and accommodation (through imposition of few loading cycles in the elastic domain) procedures must be done in order to have reliable measurement throughout the service life of the part or component to be monitored.

Future work will be a study to predict the difference between the real strain and the strain measured using the difference of the stiffness between the different components, host material and the sensor.

Acknowledgements

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References

[1] R. Oliveira, C.A. Ramos, A.T. Marques, Health monitoring of composite structures by embedded FBG and interferometric Fabry–Pérot sensors, Computers & Structures 86 (3–5) (2008) 340–346.
[2] J. Degrieck, W. Waele, P. Verleysen, Monitoring of fibre reinforced composites with embedded optical fibre Bragg sensors, with application to filament wound pressure vessels, NDT & E International 34 (4) (2001) 289–296.
[3] B. Glisic, D. Inaudi, Sensing tape for easy integration of optical fiber sensors, Composite Structures B (2003).
[4] K. Lau, L. Yuan, L. Zhou, J. Wu, C. Woo, Strain monitoring in FRP laminates and concrete beams using FBG sensors, Composite Structures 51 (1) (2001) 9–20.
[5] K. Kuang, R. Kenny, M. Whelan, W. Cantwell, P. Chalker, Embedded fiber Bragg grating sensors in advanced composite materials, Composites Science and Technology 61 (10) (2001) 1379–1387.

[6] G. Luyckx, E. Voet, W. Waele, J. Degrieck, Multi-axial strain transfer from laminated CFRP composites to embedded Bragg sensor: I. Parametric study, Smart Materials and Structures 19 (10) (2010) 105017–105026.
[7] A. Vieira, R. Oliveira, O. Frazão, J.M. Baptista, A.T. Marques, Effect of the recoating and the length on fiber Bragg grating sensors embedded in polymer composites, Materials and Design 30 (2009) 1818–1821.
[8] O. Frazão, R. Romero, F.M. Araújo, L.A. Ferreira, J.L. Santos, Strain-temperature discrimination using a step spectrum profile fibre Bragg grating arrangement, Sensors & Actuators A: Physical 120 (2) (2005) 490–493.
[9] O. Frazão, C.A. Ramos, N.M.P. Pinto, J.M. Baptista, A.T. Marques, Simultaneous measurement of pressure and temperature using single mode optical fibres embedded in a hybrid composite laminated, Composites Science and Technology 65 (11–12) (2005) 1756–1760.
[10] E. Chehura, A.A. Skordos, C.-C. Ye, S.W. James, I.K. Partridge, R.P. Tatam, Strain development in curing epoxy resin and glass fibre/epoxy composites monitored by fibre Bragg grating sensors in birefringent optical fibre, Smart Materials and Structures 14 (2005) 354–362.
[11] A.W. Morey, G. Melte, W. Glenm, Fibre Optic Gratings Sensors. Fiber Optic Lasers Sensors VII (1989). 1169-98-107.