STUDY AND CALIBRATION OF FBG SENSORS FOR THE ACCURATE STRAIN MONITORING OF COPV

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Abstract
In this research programme methodologies to improve the accuracy in the results measured with embedded fibre Bragg gratings (FBG) sensors were studied and implemented in order to produce a composite overwrapped pressure vessel (COPV) prototype that incorporate a non-destructive sensing technologies. 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. In this paper, the experimental setup and procedure used to assess to the calibration rule is addressed and further detailed.

1 Introduction

Nowadays, with the great demand for lightweight structures, the use of composite materials is widely expanding. Their high specific strength and stiffness make composite materials preferred over metallic ones in a wide range of applications.

Higher operating pressures are continuously sought due to the need to achieve higher energy densities in storage systems. Therefore, safety aspects become critical and the lack of reliable models for short and long term mechanical behavior of COPV implies uncertainty and inhibits their faster penetration in the applicable markets. In situ SHM may allow to improve this knowledge, as well as to directly reduce the risks in the operation of these tanks. Non-destructive evaluation (NDE) techniques have been developed for pipe and vessels tests[5-11], including ultrasonic scanning, acoustic emission (AE), shearography, stimulated infrared thermography (SIT), electronic speckle pattern interferometry (ESPI), vibration testing, radiography and conductivity. However, these classical techniques have certain identified drawbacks related with in situ implementation and analysis, which restricts it's applicability for in-service SHM.

In recent years, fibre optical sensors (FOS) have been widely used in smart materials and structures. The small diameter of the optical fibers, their multiplexing ability, the effective insulation and immunity to electromagnetic fields are some of the attractive properties of these sensing technologies, making the FOS systems suitable for incorporation of a structure attributing it a "smart" characteristic through online monitoring. Due to these characteristics, in this research program FBG sensors were studied and calibrated with the objective of monitoring COPV and assess their advantages and disadvantages for such SHM systems.

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 to 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 [3]. 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 a perfect bonding or adhesion between the grating and the surrounding host material is also a factor that deteriorates the quality of the measurement. Since the 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 [4]

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 behaviours of the FBG sensors and the host material when subjected to UD (longitudinal) stress loading condition, in order to evaluate the mismatch between the real strain and the one measured by the sensor;

- to evaluate the effect of an alternative testing method in promoting the accommodation and stabilization of the sensor within the hosting material;

- 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.

2 Selected FBG Sensors

In the present study, single mode (SM) FBG were used and the output wavelength signal was acquired at 1Hz with a Benchtop BraggMETER FS 5200, a laser scanning measurement unit for interrogating FBG sensors, supplied by FiberSensing™. One single grating was used in each test specimen. The intrinsic high dynamic range and high output power of the BraggMeter allows for high resolution to be attained even for long fibre leads and imperfect connections. Also, the measurement unit includes a traceable wavelength reference and a Fabry-Pérot filter to act as wavelength reference grid, which provides continuous calibration to ensure system accuracy and a cleaner signal. The sensors used in this study had a valid measurement range of $\lambda_B^{\max} = 10nm$ (corresponding, through the sensivity factor, to aprox. $\varepsilon = 1\%$).

The sensor working principle is modeled by the following relation [5]:

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

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.

3 Manufacturing and Preparation of Test Specimens

To produce the specimens of unidirectional composite, attaining at replicating the manufacturing conditions, a dedicated setup was developed (Figure 1). This allowed to obtain specimens 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 100mm and width of 20mm. Each test specimen consisted of two layers of six rovings of carbon fibre/epoxy prepreg each. The properties of the prepreg material are presented in Table 1. Five valid specimens were manufactured accordingly with the following procedure.

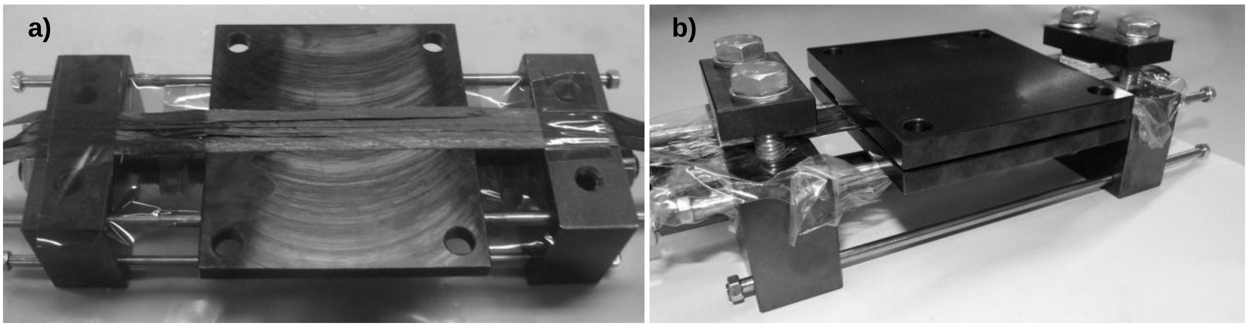

Figure 1. Specimens preparation setup. a) Positioning of carbon fibre prepreg rovings. b) Application of a longitudinal tensile force and geometry constraint to the specimen.

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

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

Firstly, one layer of six rovings was placed in the set-up and a FBG sensor was aligned and positioned in its the central line. This stage is depicted in Figure 1 a). Secondly, another layer of six rovings was placed on top of them thus fixing the FBG sensor in the middle position of the laminate regarding both the thickness and width. The ends of the specimen were then clamped.

Thirdly, as shown in Figure 1 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 @ 150ºC).

4 Experimental Procedure

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 Figure 2, 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. This first stage allowed to study and overcome the accommodation effect of the FBG sensor to the host material, through analyzing the linearity 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 proceeded. This testing procedure allows to verify if the linearity of the sensor response is achieved during the first accommodation cycles and also if it remains consistent throughout the process of deformation of the specimen up to failure.

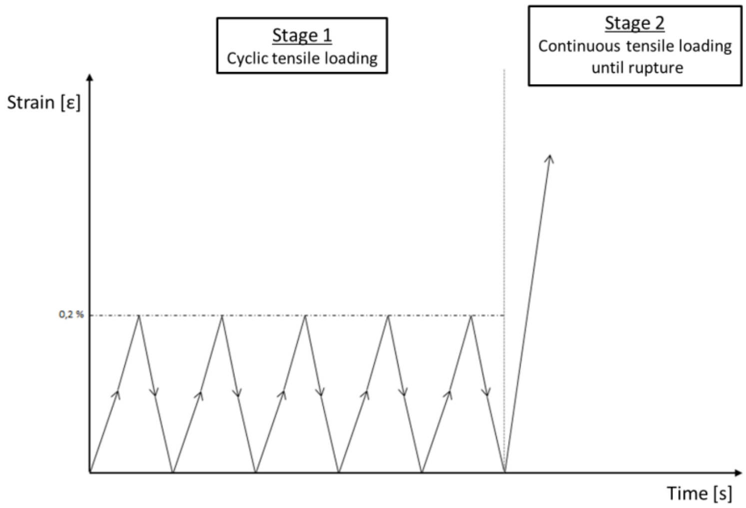

Figure 2. Schematic representation of the loading history imposed to the test specimens.

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 the strain sensed by the FBG sensor was acquired using a Benchtop BraggMeter FS 5200 supplied by FiberSensingTM and synchronized with the strain measured by a universal strain gauge extensometer assembled in the universal testing machine Instron 4507. Then the two values were compared in order to establish a calibration rule, that approaches with better accuracy the strain measured by the FBG sensor with the real behaviour of the host material.

5 Discussion of Results

In Figure 3, the data from the first stage (cyclic loading) of the tensile test is shown for one of the specimens, From the plot of the strain of the sample, ε_{sample}, versus the wavelength shift, $\Delta\lambda$, 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.

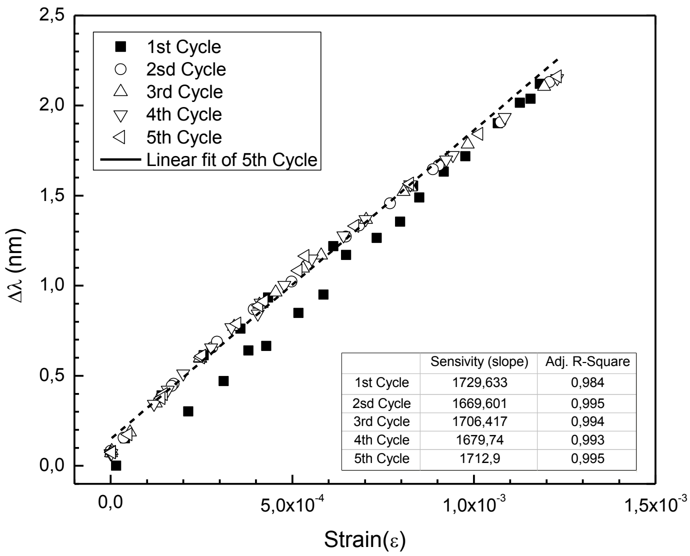

Figure 3. Wavelength shift from FBG sensor versus real strain on the specimen for the first stage of the UD tensile test.

It was observed an accommodation of the FBG to the host material, mainly in the first two loading cycles. From the third cycle onwards, the sensor response starts being linear, which was consistently observed in all specimens tested.

This 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 a complete straightness and perfect adhesion of both materials. For these reasons, in the first loading cycles, 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. The linear response that the FBG sensor outputs after a certain accommodation further supports this idea.

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]

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

where λ_B is the wavelength, Λ_B is the spacing between gratings periods , n_O is the effective index of the core and pc is the effective photoelastic coefficient of the optical fibre. For the FBG sensors used in this study, the wavelength-strain sensitivity at λ_B=1550 nm is 1,1 x 10-3 nm/με.[2]

From the data acquired with the Braggmeter and the Equation (2) it was plotted, in Figure 4, the evolution of the ratio, R_{sample}/FBG, between the strain of the sample and the strain measured by the FBG sensor during the second stage of the tensile test. As shown, the strain given by the FBG sensor is higher than the real strain of the specimen. However, with the increase of the strain in the sample, ε_{sample}, the strain measured by the FBG sensor, ε_{FBG}, approaches to a value closer to the real, thus making the ratio R_{sample}/FBG approaching the ideal value of 1. Nevertheless, in the relevant strain range, this ratio is never equal to unity and it is also not constant.

The relationship between the wavelength shift and the 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 materials[3] and the imperfect adhesion of the FBG sensor (and the whole optical fibre) to the host material.

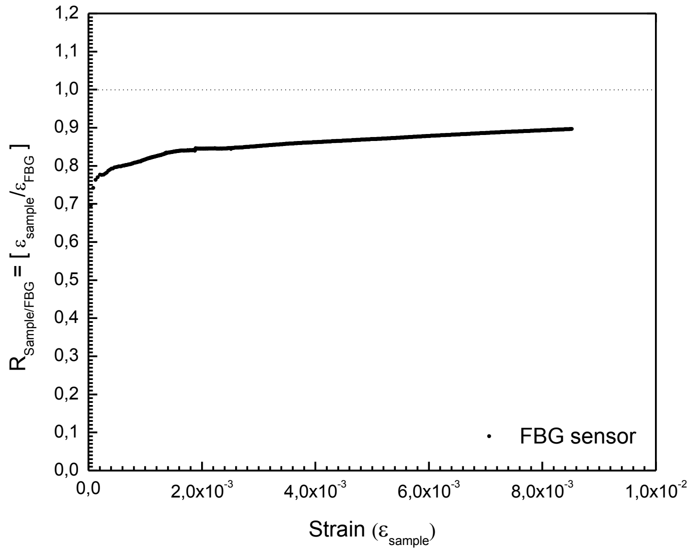

Figure 4. Evolution of the ratio between the real strain of the specimen and the strain measured by the FBG during the second stage of the tensile test.

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, and given by the following expression:

$$CF = 0{,}79 + 19.375 \times \varepsilon_{FBG} - 945.72 \times (\varepsilon_{FBG})^2 \tag{3}$$

The range of applicability of this correction factor is from $0{,}1\times10^{-3}$ 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 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 being 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, is required the accommodation of the FBG sensor to the host material, as seen previously, to obtain better results and a linear response from the sensor. For that, must be done a few cycles of loading 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 converts this value to Strain (not rectified) ε_{FBG}, as showed in the equation 3.

$$\varepsilon_{FBG} = S_{\Delta\lambda \to \varepsilon} \times \Delta\lambda = \frac{1}{1{,}1 \times 10^{-3}} \times \Delta\lambda \tag{4}$$

3. Calculate the factor of Correction "FC", given by the equation 4 defined by the 2sd order polynomial.

$$CF = 0{,}79 + 19.375 \times \varepsilon_{FBG} - 945.72 \times (\varepsilon_{FBG})^2 \tag{5}$$

4. Finally, correct the value of strain measured by the FBG sensor, using the equation 5, obtaining 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 doesn't accommodate or adhere perfectly to the host material during the preparation of the test specimens. The alternative procedure of imposing cyclic tension load (within the elastic domain of both the sensor and the host material) proved that the sensor can be accommodated after 2 or 3 cycles. After these the sensor returns the desired linear 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 the ones 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 in order to obtain a more accurate measure of the strain. This correction factor shall, thus, be used for as a calibration rule in measurements made in such materials. Since it is dependent on the grating length and relative stiffnesses 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.

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