Comparative analysis of instrumentation methods for characterization and monitoring of composite materials

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Abstract

The development of new composite materials requires for precise and trustworthy methods of material characterization. As such, the tools used alongside these materials must be thoroughly studied so that their applicability is well determined. Hence, in this study, two types of sensors, both aimed at measuring strains, and capable of being embedded within a composite material, are studied and compared. The main goal is to provide insight to the practical aspects of the usage of each sensor, such as the details that must be taken into account when using one or the other and in what implementations the choice of one type of sensor is more beneficial. To achieve this objective, samples of a composite material are assembled and tested. Due to the corporate interest within which this work occurred, material instrumented was comprised of a layer of brittle material combined, using epoxy, with a layer of reinforcement in the form of fiber glass. The sensors used were traditional metallic strain gages and fiber Bragg grating and were applied between each layer mentioned above. The conclusions include not only points originated from data that resulted from tests performed to the samples, but also discuss the influence that the handling each sensor requires upon installation should have on the decision of each technology to use and ways in which the sensors may be useful outside the material characterization problem.

Keywords: Strain Gage, Fiber Bragg Grating, Composite Materials

1. Introduction

The development of new composite materials requires the use of characterization tools that are capable of characterizing said material with precision. Since the behavior of these materials depends highly on the interactions between its components, it is advantageous to evaluate what is happening in the interface where these interactions occur. Hence, having arisen the need to evaluate a composite material made of a considerably heterogeneous and brittle element and a fiberglass fabric meant to reinforce it, strain sensors were embedded, during manufacture, in the interface connecting both components.

The use of the mentioned material is due to an interest in integrating materials of high aesthetic value in an industry where their mechanical characteristics do not meet the standards.

The strain sensors selected were of two distinct types: 1) Strain Gage (SG) 2) Fiber Bragg Grating (FBG). The installation of both kinds of sensors is aimed at evaluating the pros and cons of each technology throughout the entire span of the sensors presence, from handling during installation to performance during tests.

The main difference between the two types of sensors is their principle of operation. Whereas the SG acts as a resistor in an electrical circuit, having its resistance change with strain, the FBG is a sensor manufactured from optic fiber that reflects a wavelength that depends on the strain applied to the fiber.

The use of the SG requires the setup of a Wheatstone bridge that may contain up to 4 sensors. This circuitry requires electrical excitation and a method of reading the output voltage for the determination of the SG's resistance and consequently the strain applied. On the other hand, the FBG only needs the use of an interrogator, which emits through the fiber a light spectra in order to determine what wavelength is reflected and consequently what is the strain applied.

2. Experimental Procedure

The first step of manufacturing the samples was the installation of the sensors in the surface of the brittle element of the material. That is followed by the layup of the fiberglass fabric and epoxy. The samples become ready after undergoing a high temperature cure treatment. The work described in (1) shows that it is possible to monitor this type of cure process with a FBG installed, raising the question as to if in this configuration of composite material the FBG performs the same and if the SG has the same capability. Hence, during the cure cycle of the samples, the sensors' connectors are routed to the exterior of the controlled temperature chamber so that discreet readings can be made throughout the process. A total of 6 measurements will be made with each sensor, one at the start, one at the middle of the heating ramp and the rest at the constant cure temperature.

At this point in the experimental setup, some observations can be made regarding the preference of use of one sensor over the other. The installation procedure of the SG's, besides the bonding of the sensor to the surface, entails soldering connection wires to the sensor with a total of 4 lead wires going through the material. However, the FBG does not require soldering or more than one connecting wire. This brings up the argument for the FBG that it is simpler to install, hence less prone to errors in doing so, and because of that simplicity, parties interested in applying sensors in an automated procedure will have greater ease by using FBG's. Furthermore, soldering the lead wires of the SG adds thickness to the area near the sensor which resulted in added difficulties in the layup of the fiberglass and epoxy that were non-existent when installing FBG's.

After manufacture, the samples were submitted to a set of 4 point bending tests. These were performed according to the procedure described in (1). Following this method, each sample is tested twice, once with the instrumented side facing up and once with it facing down. Once the Load-Strain datasets are obtained (one for the sensor measuring a compression and another with it measuring tension), Equations (1)-(3) (from (1)) are applied in order to obtain, for that sample, values for the Young moduli in tension and in compression (E_t and E_c, respectively).

Furthermore, each bending test described is repeated in a second lot of tests so as to evaluate the repeatability of each sensor used.

$$\frac{\frac{P}{\varepsilon_t}}{\frac{P}{\varepsilon_c}} = \sqrt{\lambda} \qquad (1)$$

$$E_t = \frac{3m_t L}{8bh^2}(1+\sqrt{\lambda}) \qquad (2)$$

$$E_t = \frac{\frac{3m_c L}{8bh^2}\left(1+\sqrt{\lambda}\right)}{\sqrt{\lambda}} = \frac{E_t}{\sqrt{\lambda}} \qquad (3)$$

3. Data Acquisition Systems

As is mentioned above, each sensor has its own requirements for operation in terms of equipment. For the SG, an NI-9237 DAQ was chosen, a signal conditioner for Wheatstone bridges with the capacity to connect up to 4 bridges simultaneously. The FBG were connected to a Braggmeter interrogator, which also has 4 available channels. In this regard, it must be noted that the electric signal going from the SG sensors to its conditioner is subject to whatever electromagnetic interference is there in the area, resulting in a declining in the quality of the signal the further the sensor is to the conditioner. Since the FBG's operation is dependent on optical phenomena, this interference is not an issue and the sensor can be at distances or the order of magnitude of 1km without effect on the signal's quality. Also, even if the interrogator used has the same number of channels as the SG signal conditioner, several sensors can be applied to the same fiber up to about 100, allowing for a much larger number of sensors read with a single device.

Another very relevant aspect for the choice of one type of sensor over the other is the overall financial cost of the systems for data acquisition. Figure 1 compares the cost estimated for setting up 1, 20, 40, 60, 80 and 100 sensors for simultaneous acquisition in the case that SG's or FBG's are used, based on the cost of the

equipment used during this study. This approximation illustrates how an increasing number of sensors justify the use of FBG's rather than SG's which are financially preferable in small quantities. However, the values are a gross estimate since it is possible to lower dramatically the cost of the FBG interrogator with the purchase of other models with less channels, just as it is possible to lower the cost of the acquisition system for the SG's by compromising precision and resolution of data.

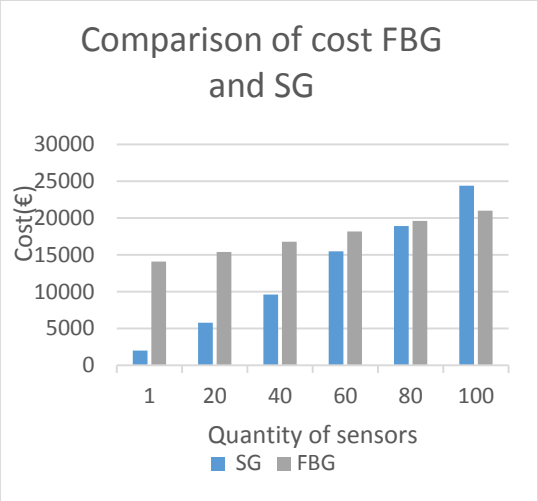

Figure 1 - Cost comparison between FBG and SG aquisition systems

4. Data Processing

In order to properly evaluate the performance of the sensors selected for this study, the approach on analyzing the dataset must be consider a number of points:

1) The three data sources (SG, FBG and Instron Load Cell) have different output data formats;
2) The time references are different between the data sources for the same test;
3) In between sensors of the same type, the initial offsets are not the same;
4) There are more output files than is practical to manipulate one at a time.

In order to manage these situations, a *software* tool was built specifically to handle large quantities of sensor data. A database was built to host in an organized fashion the information relating to each test and each sensor functioning within that test. To allow for user accessibility an interface was also provided.

This interface lets the user import sensor data to the database with tools that simplify the conversion of different data formats, it facilitates visualization and synchronization of data between sensors through direct interaction with the plotted data as well as immediate linear regression analysis of selectable ranges of the plotted data.

5. Data Results

The first set of relevant data is result of the acquisition done during the high temperature cure procedure of the manufacturing. The Figure 2Figure 3 present the 6 measurements taken with the SG's and FBG's. With the FBG's the same behavior as in (3) is verified since the data depicts a strain proportional to the temperature. However, the SG data does not correlate to the profiles presented in (3) or the data from the FBG's nor does it follow the same behavior between sensors. This leads to the conclusion that FBG's are more appropriate if the monitoring the cure process is of the interest of the manufacturer.

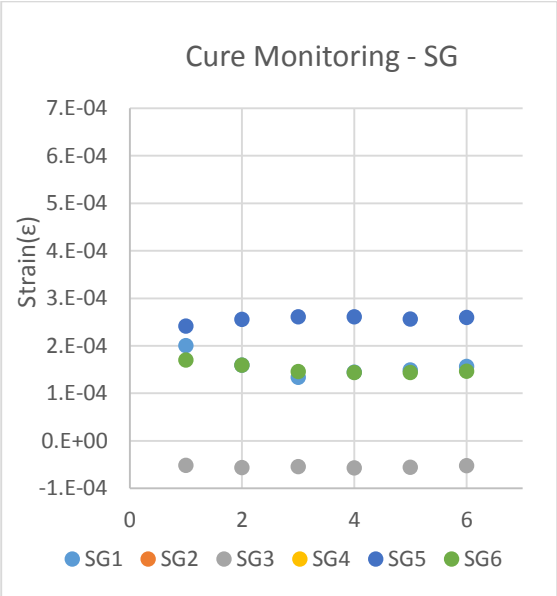

Figure 2 - SG Cure monitoring data

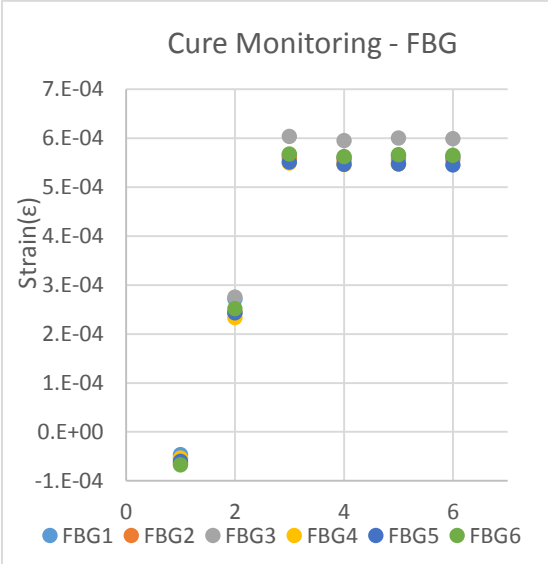

Figure 3 - FBG Cure monitoring data

The analysis of the data of the first lot of bending tests shows a tendency for the slope of the Load-Strain plots of FBG's to be repeatedly lower than those of the SG's, installed in the same sample, as is seen in Figure 4. A plot of the ratio between the slopes (Equation (4)) respective to each sample, as well as the overall average and standard-deviation, show clearly this tendency, which is possibly fruit of a systematic error occurring in measuring equipment used during fabrication or calibration of one type of sensors (Figure 5 - Ratios between slopes of SG and FBG, average and standard deviation of dataset).

$$ratio = \frac{slope_{SG}}{slope_{FBG}} \qquad (4)$$

The second lot of bending tests provides a dataset that lets determine the standard-deviation of the Load-Strain linear regression slope awarded to each individual sensor (Table 1). Despite the average standard deviation of FBG sensors being lower than that of SG sensors, the values fluctuate enough that in this situation, for the quality of the data, it becomes irrelevant which sensor is selected since both has very similar repeatability.

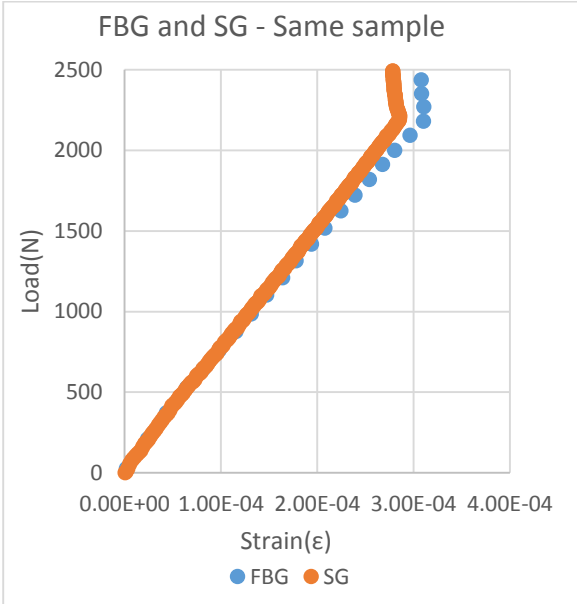

Figure 4 - Load-Strain for FBG and SG installed on the same sample

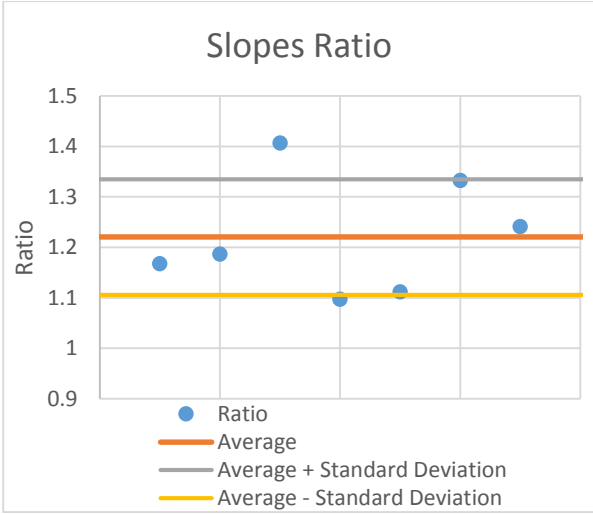

Figure 5 - Ratios between slopes of SG and FBG, average and standard deviation of dataset

Sensor	StandardDeviation (σ) [N]	Average Standard Deviation ($\bar{\sigma}$) [N]
FBG1 (fd)	4.73E+04	2.85E+04
FBG1 (fu)	1.87E+04	
FBG2 (fd)	4.77E+04	
FBG2 (fu)	2.12E+04	
FBG3 (fd)	3.19E+04	
FBG3 (fu)	2.51E+04	
FBG5 (fd)	7.90E+04	
FBG6 (fu)	7.17E+04	
SG1 (fd)	4.56E+04	3.92E+04
SG1 (fu)	3.01E+04	
SG2 (fd)	6.59E+04	
SG2 (fu)	3.28E+04	
SG3 (fd)	6.61E+04	
SG3 (fu)	1.85E+04	
SG4 (fd)	8.24E+04	
SG5 (fd)	9.51E+04	

Table 1 - Standard deviations of Load-Strain slopes for each sensor

6. Conclusion

In conclusion, it is found that FBG's are financially more applicable than SG's when the implementation at hand requires for the installation of a larger number of sensors, while the SG's are better suited for single measuring points or other small quantities. FBG's are also better suited for monitoring temperature driven processes applied to the material since in the case studied the SG's were not able to provide information of relevance. One situation that did not show better performance in either sensor was the 4 point bending test, where both types of instrument achieved similar behavior. Finally, the direct comparison between SG's and FBG's showed that there may be a systematic error related to the determination of the sensor's characteristics by the manufacturers.

References

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