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# EVALUATION OF ELECTRICAL AND OPTICAL FIBER BASED STRAIN GAGE SENSORS PERFORMANCE IN DIFFERENT ENVIRONMENTAL AND LOADING CONDITIONS

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***Abstract.*** *This work presents the results obtained from specifically designed specimens intended for performance comparison between electrical and optical fiber based strain gages under different environmental conditions and bonding techniques. The results from both sensors were compared with each other and with those ones obtained via Finite Analysis Method. It had been used two different bonding techniques, both based on those widely used in electrical strain gage technology. The specimens were exposed to environments with a 55°C average temperature, high relative humidity of about 96%, UV radiation from a 450W xenon lamp and salt spray tests. Static loadings were applied at the specimens on the beginning of the tests and repeated at the end of every exposition interval for the different environments in order to verify the performance degradation of the sensors installed with different bonding techniques. At the end, the specimens were subjected to cyclic tensile and compressive loadings, so that was possible to evaluate its decaying resulted from this kind of usage. The resulting data from each test were analyzed taking into account stability criteria. Finally the pros and cons perceived from the tests were tabulated for each sensor technology*.

***Keywords:*** *Strain measurement, stain gage, FBG sensor*

## 1. INTRODUCTION

Mechanical strain testing using strain gages is well known in engineering applications. New sensors for mechanical strain testing using optical fiber are now available (Lee, 2003). One sensor type is the FBG sensor (Fiber Bragg Grating) which is based on a construction of an interference grating in the fiber core. The FBG sensor is constructed in the optical fiber core using ultraviolet (UV) light interference which changes de core refractive index according to applied UV interference pattern (Hill and Metz, 1997).

Once the FBG sensor is expose to a broad band light source, its interference grating will reflect a specific wavelength and the broad band light spectrum forgoing will be subtracted from this reflected spectral component. When the FBG sensor is subject to strain, its dimension will change and affect grating structure in the fiber, so that the pick wavelength of reflected light will change and its drift is proportional to the applied strain (Hill and Metz, 1997; Guan *et al.*, 2000). Other parameters can affect the reflected light pick wavelength such as dimensional changes due thermal expansion, which indicate the need of temperature measurement during strain evaluation, and the light source polarization behavior, which could be controlled by FBG interrogation system (Hill and Metz, 1997).

FBG sensors have been used because of its benefits concerning electromagnetic interference immunity, the use of light energy in the sensor, the use in explosive environment and the use of multiple sensor as a net or in in a single fiber (Chan *et al.*, 2006; Haase, 2007).However, the use of strain sensor needs attention considering the attachment procedure from the sensor to the structure, which depend on the type of adhesive used, how long the sensor will be used and the special protection applied to the sensor and its adhesive (Montero *et al.*, 2011).

To evaluate the use of FBG sensors and its adhesive procedures a specifically designed specimens are constructed, so that it is possible to compare between electrical and optical fiber based strain gages under different environmental conditions and bonding techniques. The specimens were exposed to environments with a 55°C average temperature, high relative humidity of about 96%, UV radiation from a 450W xenon lamp and salt spray tests. It is important to say that the purpose of this work is to identify significant performance deterioration of sensors. In this way besides some results presents numerical representativeness, they are not studied as deeply as other ones whose have more significance on Structural Health Monitoring field.

## 2. METHODOLOGY

The designed specimen for comparison between electrical (ESG) and optical fiber (FBG) based strain gages was performed so as the region where the two gage types are bonded had constant and uniform strain distribution which reduce positions errors when sensors were bonded. An additional issue of specimen was its shape that improves the sensitivity to applied load and allow the static load test be performed by weight and the dynamic load test by a low power electrical motor.

The specimen where the gages were bonded is a triangular aluminum plate. Its draw and dimension are presented on Fig. 1. The specimens were exposed to environments with a 55°C average temperature, high relative humidity of minimum 90% (and 96% of average), UV radiation from a 450W xenon lamp at the distance of (528±4) mm and salt spray tests. The environmental test conditions were based in the laboratory experience observed during more than 30 years of field measurements. Though the exposure periods for each environmental condition were not the same, it should be noted that only elementary sensor protection was applied for critical tests such as salt spray, which aim to simulate occasional exposure to this condition, meanwhile a full sensor protection is applied. Correlation between laboratory irradiation exposure test and natural exposure are not direct and depends on material properties (ASTM, 2010), the specimen UV radiation measured was $47\mu W_{eff}/cm^2$ according to ICNIRP (2004).Static loadings were applied at the specimens on the beginning of the tests and repeated at the end of every exposition interval for the different environments in order to verify the performance degradation of the sensors. Dynamic load were applied using cyclic mechanical excitation to the plate, this device is presented on Fig. 2. The parameters were adjusted on their best to present a sinus mechanical excitation to the plate, this device is presented on Fig. 2. The parameters were adjusted on their best to present a sinusoidal excitation with 1.6Hz and to impinge a deformation in the order of 1000 µs on the strain sensors.

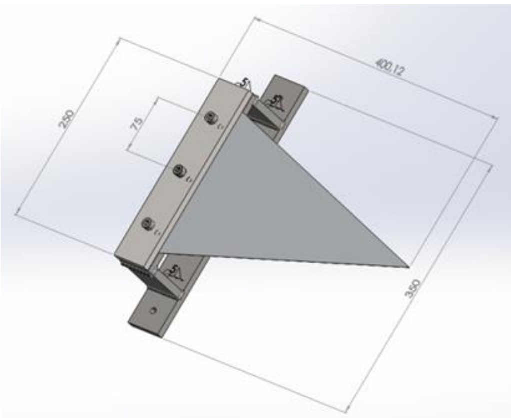


Figure 1. Designed specimen for comparison between electrical and optical fiber based strain gages.

Figure 2. Dynamic load Apparatus

There were fabricated 3 specimens subjected to different environmental conditions according to Tab.1 and some specimens were sequentially exposed to different environments.

Table 1. Specimen environment exposure conditions.

| Specimen Number | Environmental Conditions | |
|---|---|---|
| | First | Second |
| CP01 | 263 days (approx. 6300h) at 55°C | 1.000.000 cycles @ 1000µs of amplitude and sinusoidal wave |
| CP02 | 218 days (approx. 5200h) @ 90% RH minimum | - |
| CP03 | 72h UV | 24 h salt spray |

### 2.1 Computational Simulation

A computational simulation of designed specimen was performed using the finite element platform NASTRAN. Even though the simplicity of specimen geometry, the simulation was used to evaluated the uniformity of strain distribution in the sensors bond area. Figure 3A presents an overview of simulation results. The strain values in the sensor area were presented in Fig. 3B which is a zoom of Fig. 3A sensor area. The results of strain simulation in the sensor area indicated that strain values are constant for sensor bond position.

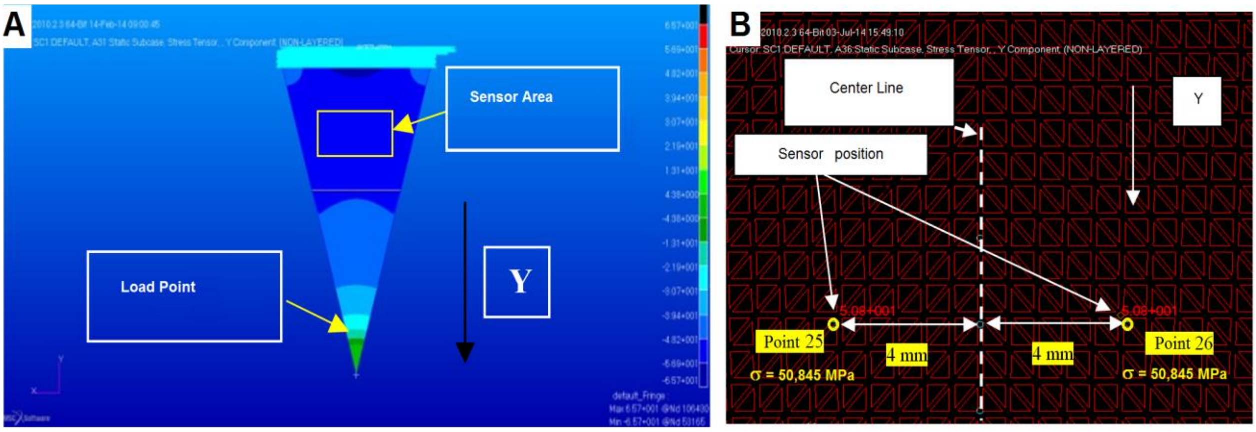


Figure 3. A) Computational simulation for strain of designed specimen. The color bar indicated the strain level.
B) Strain values in the sensor area.

### 2.2 Specimen Instrumentation

The electrical and optical fiber based strain gages were bonded in the points 25 and 26 indicates in the Fig. 3B. Two different types of adhesive were used cyanoacrylate and epoxy which are adhesive well known in strain gages applications. Both type of sensors received the same adhesive procedure which are based in electrical stain gages recommendation, the same surface preparation and the same sensor protection with a microcrystalline wax.

The electrical strain gages used are the model KFG-3-120-C1-23L2M3R manufacture by Kyowa and optical fiber are the model OS 1100 manufacture by Micron Optics. An instrumented specimen is presented in the Fig. 4.

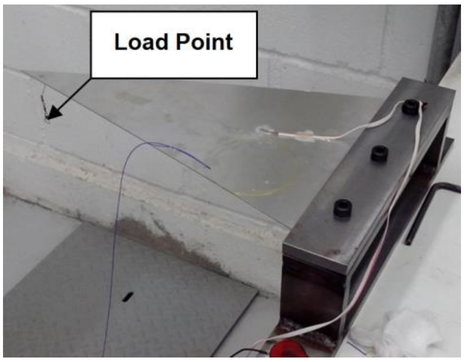


Figure 4. Instrumented specimen in the static load workbench.

## 3. RESULTS

Figure 5 shows the correlation between responses from the two sensors here analyzed to tensile and compressive loadings. The plots are based on a randomly chosen sample taken from CP02 data series. One reason to the 5% sensitivity variation between sensors is the FBG gage factor, which was assumed to be 0.864, may not present exactly such value. It is clear that there are many other actors in the sensitivity errors, but they are neither depicted nor explored at this work, since its aim is to investigate the sensors' performance degradation when exposed to different environmental conditions.

In the first experimental phase, the sensors were bonded to an aluminum plate using an ordinary cyanoacrylate adhesive. After the sensors were been protected with microcrystalline wax they were connected to the conditioning systems in order to get the initial reference. The time series on Fig. 6 and 7 represent a total of 263 days, or 6312 hours exposure to 55°C chamber temperature. At an average period of 15 days the specimen was subjected to three series of tensile and compressive loadings. The average value of these three loadings is plotted in the Fig. 6 and 7.

Figure 6 shows the sensors' performance when subjected to tractive loadings and Fig. 7 shows its performance on compressive loadings. The first thing one can perceive is the deformation peak in the FBG sensor curve. It was left intentionally to show a problem occurred with the sensor system. Despite this point is an average of three measurements and has a small standard deviation value (714 ± 0.82) με, it represents a connection problem between the transmission fiber, optical connector and interrogation system. In order to fix it, the optical connector has been replaced. After this procedure, the measured values came back to the expected ones.

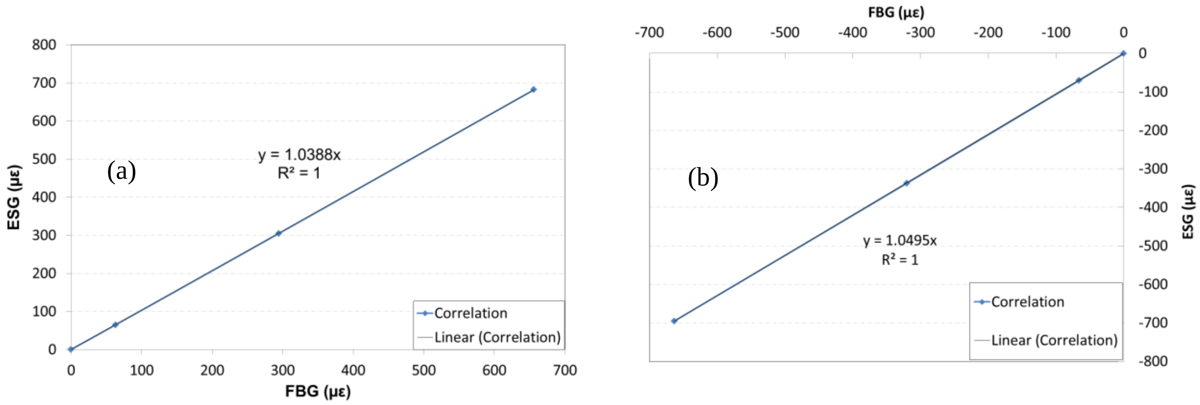


Figure 5 – Sensors correlation under tensile (a) and compressive (b) loading.

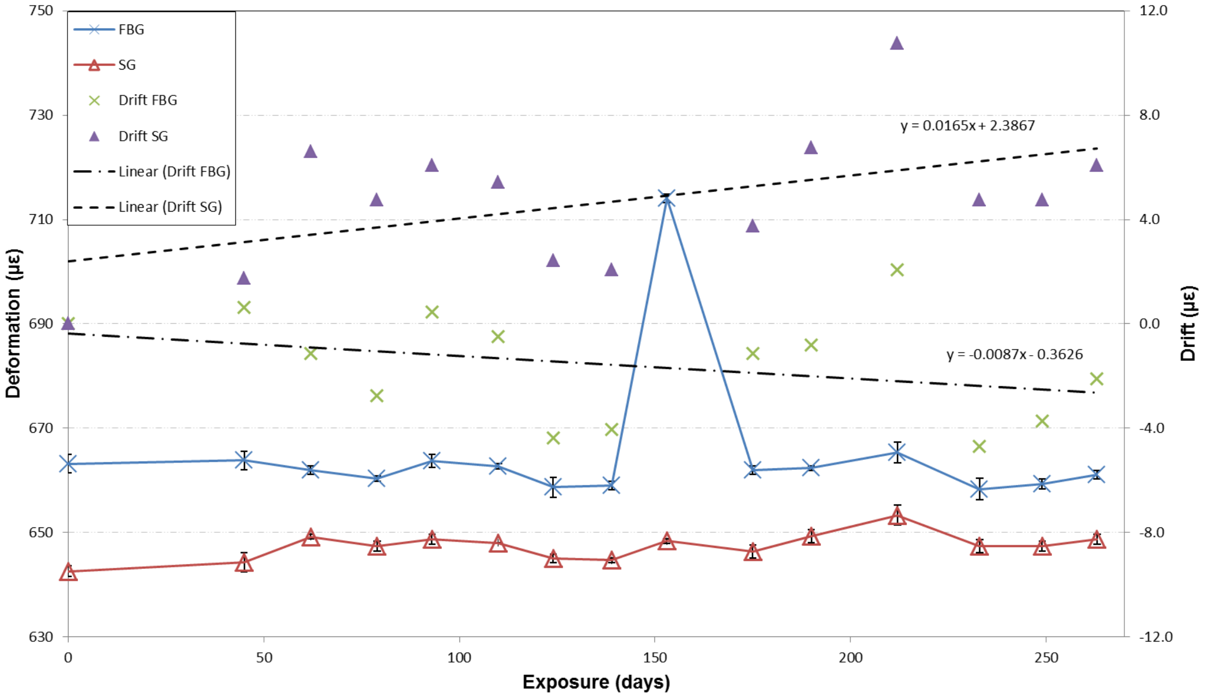


Figure 6 – Tensile loading performance of sensors when subjected to elevated temperature. Continuous lines are related to the left Y-axis and dotted lines are referenced to the right Y-axis.

The drift on sensitivity due to ageing of the sensors was calculated as a difference between the values obtained at each sample interval and the initial one. A linear trend line of the drift was then calculated for each sensor. It is worth to say that the point related to connection malfunction was not taken into account for the trend line calculation. Figure 6 shows the time history, the calculated drift points and finally the calculated trend curves for each sensor.

Figure 7 shows the results from this procedure applied to the data collected during compressive loadings on this specimen. The overall behavior of the sensors remains the same as that one they presented when subjected to tensile loadings i.e. : FBG sensor presents slightly higher sensitivity than ESG and the spurious point is present on FBG time series again, but the trend curves had their slopes changed in signal and/or modulus. In fact, the drift values obtained at present work suggests that a yet deeper investigation can take place on a future work. The calculated slope values for both loading cases, tensile and compressive, are summarized on Table 2.

Table 2 – Drift trend curve slope for each sensor and loading case

| Load case | FBG (με/day) | SG (με/day) |
|---|---|---|
| Tensile | -9x10$^{-3}$ | 17x10$^{-3}$ |
| Compressive | -6 x10$^{-3}$ | -4x10$^{-3}$ |

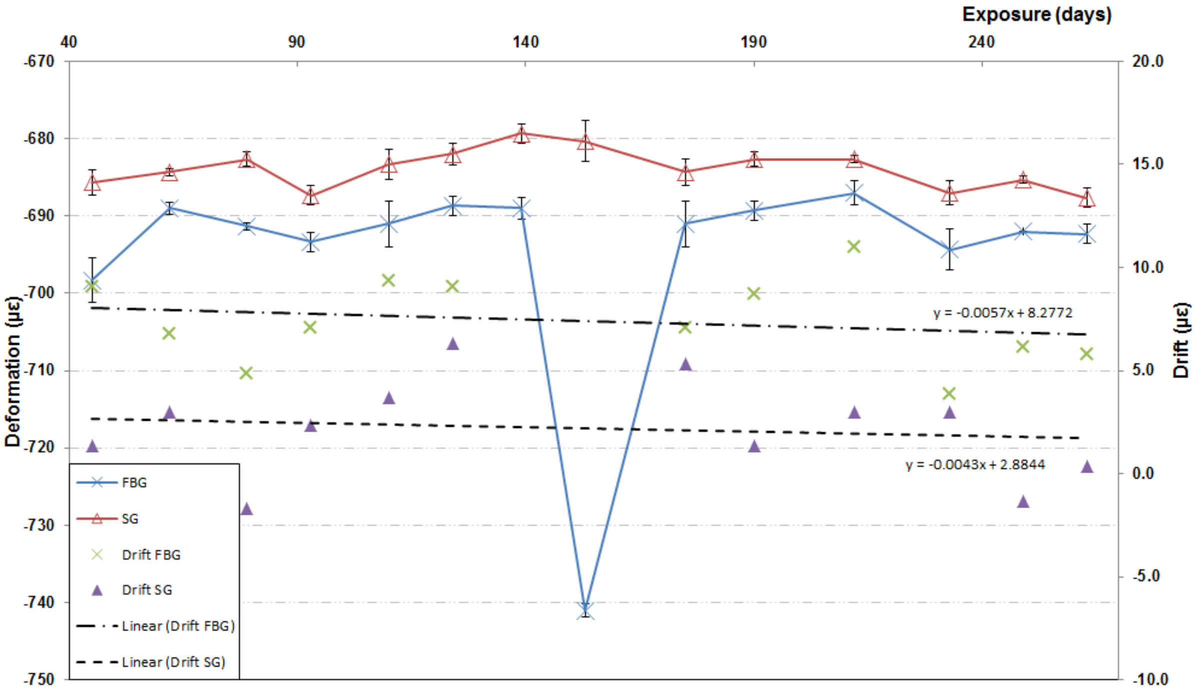


Figure 7 - Compressive loading performance of sensors when subjected to elevated temperature. Continuous lines are related to the left Y-axis and dotted lines are referenced to the right Y-axis.

In the second phase of the investigation, another aluminum plate was instrumented with one ESG and one FBG gage. At this phase, the sensors were bonded to the plate using a high performance epoxy adhesive specially developed for strain gages installation. Indeed, the bonding techniques used in this work came from the ESG area, and for the bonding of the FBG sensor they were used indistinctively. Subsequently sensors' protection with microcrystalline wax, they were placed on a climate chamber that was setup to 96 %RH for a period of 218 days, which corresponds to more than 5200 hours of exposure. The results are plotted on Fig. 8 and 9.

Using the same approach described earlier the ageing drift slope was calculated, and the results are summarized on Table 3.

Table 3 – Drift trend curve slope for each sensor and loading case

| Load case | FBG (με/day) | SG (με/day) |
|---|---|---|
| Tensile | 5x10$^{-3}$ | -1x10$^{-3}$ |
| Compressive | -8x10$^{-3}$ | -9x10$^{-3}$ |

It is noticeable, when comparing both bonding conditions (cyanoacrylate and epoxy adhesive) the sensor response changes slightly from one specimen to another and even between compressive and tensile loadings. There are several plausible causes for this behavior: small misalignments during bonding phase (Vishay, 2011), gage factor values uncertainty, errors related to nonlinearity of plate when subjected to large deformations (Zubin, 1998) among others. These error sources must be taken into account prior to the use of such sensors.

There were found differences less than 5% on sensors' measurements in this work with both bonding techniques but it is presumed that epoxy adhesives produces better results than cyanoacrylate adhesives, especially on long term campaigns. This suggests a future work on exposing a cyanoacrylate based instrumented plate to a high relative humidity environment.

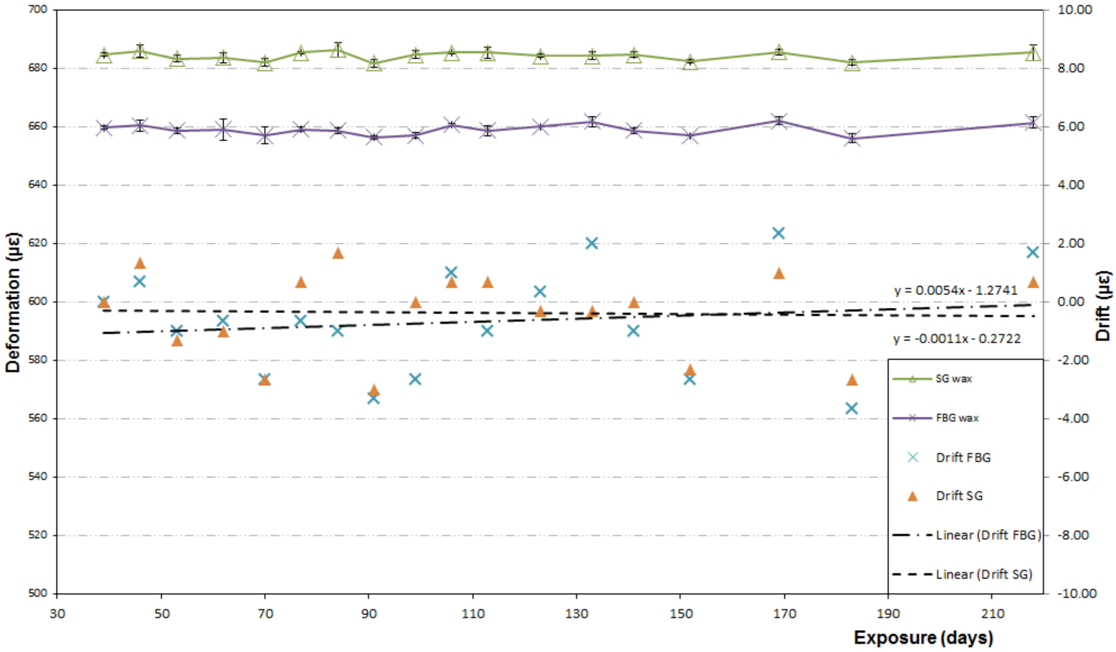


Figure 8 – Tensile loading performance of sensors when subjected to high relative humidity exposure. Continuous lines are related to the left Y-axis and dotted lines are referenced to the right Y-axis.

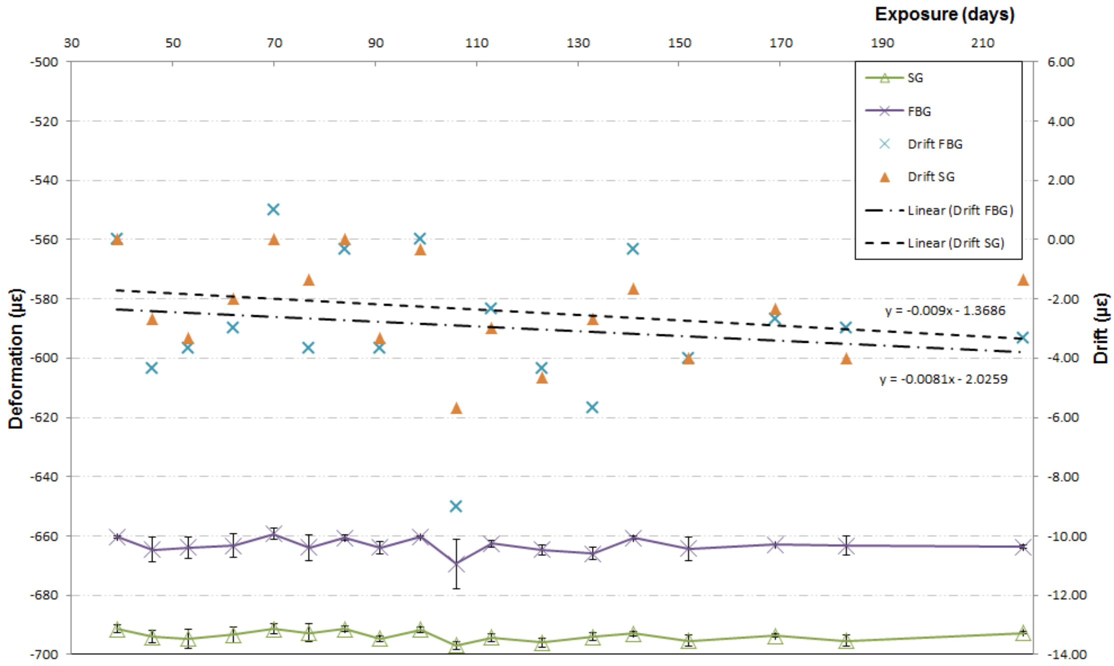


Figure 9 – Compressive loading performance of sensors when subjected to high relative humidity exposure. Continuous lines are related to the left Y-axis and dotted lines are referenced to the right Y-axis.

The third phase of project was constituted by the instrumentation of a plate with two groups of sensors: one group was integrally protected by means of applying microcrystalline wax, butyl rubber and an aluminum foil over the sensors (Group 1), and another group protected only with microcrystalline wax (Group 2). Each group has two sensors, one Electrical Strain Gage and a FBG Gage. All the sensors were bonded to the plate with epoxy adhesive. The plate was then exposed to UV radiation by means of a 450W xenon lamp (Fig. 10A) for a period of approximately 72 hours. After this exposure the electrical and optical connectors were protected, and the plate was put on a salt spray test machine (Fig. 10B). The results can be seen on Fig. 11.

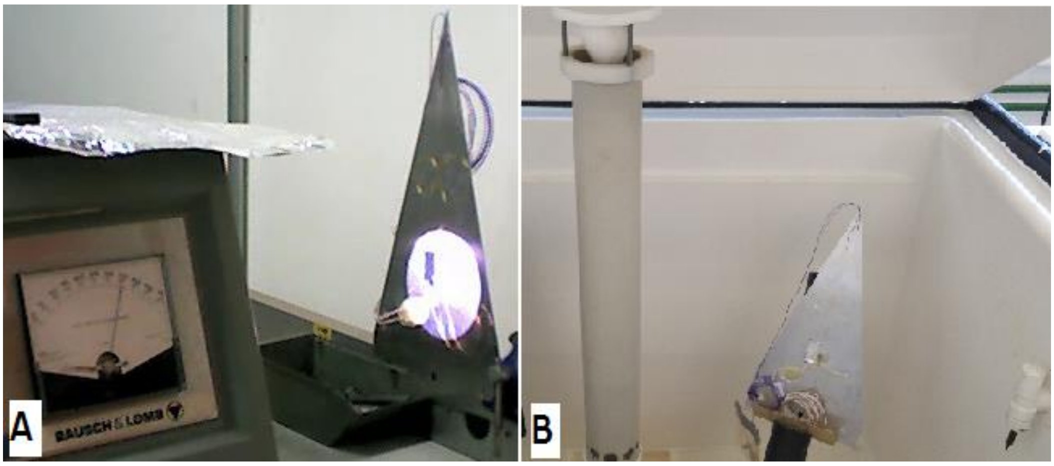


Figure 10 – A) UV exposure. B) Salt spray exposure.

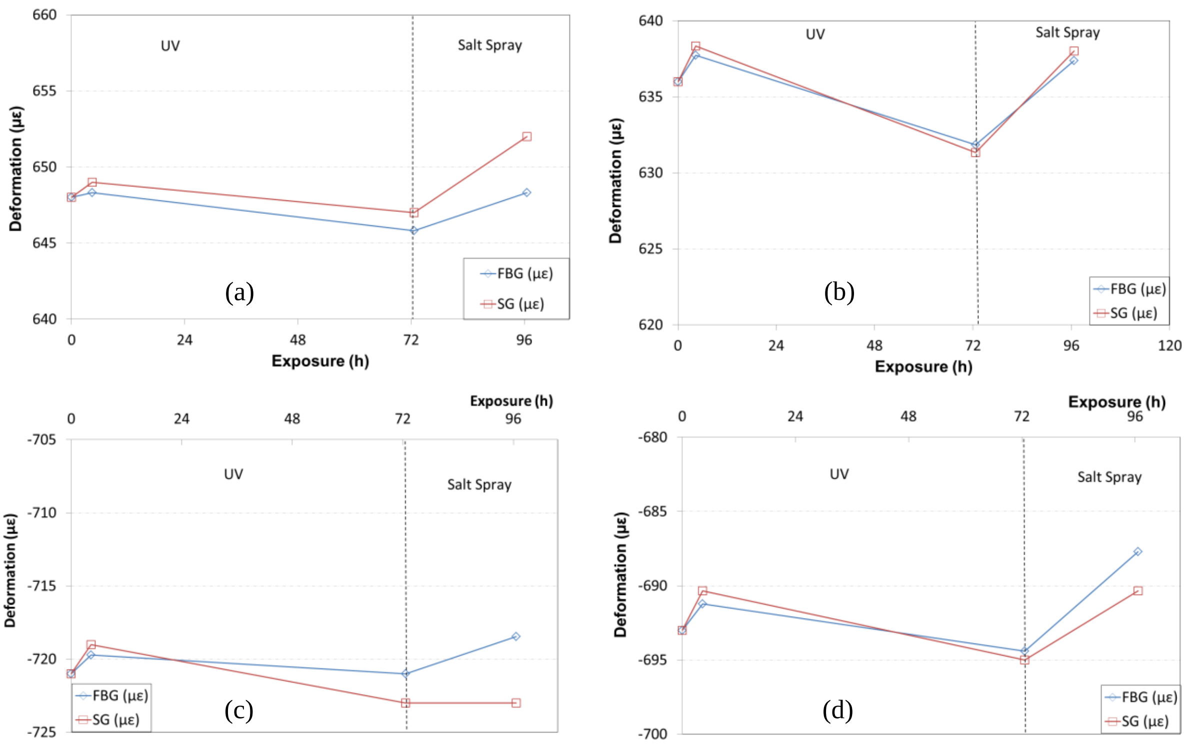


Figure 11 –Sensors' performance when subjected to UV and then salt spray exposure. Tensile loading: Group 1(a), Group 2(b); Compressive loading: Group 1(c) and Group 2(d).

The exposure to UV radiation didn't affect substantially sensors' response. It was expected that the iteration between UV radiation and materials used on FBG and optical fiber manufacturing could result on severe loss of performance due to cracks and/or changes of their optical properties. However it's possible to notice an increase on the difference between sensors' measurements when subjected to salt spray, even with a relatively short exposure time. There is just one situation when it was not possible to observe this behavior, which is plotted on Fig. 11(b) – Tensile loading on Group 2. In other words, the results from this phase suggest that long term salt spray tests may provide interesting degradation results.

In the fourth phase of project the specimen CP1 was mounted on an apparatus to be subjected to cyclic loadings. Here the aim is to investigate a possible deterioration on sensors' performance due to fatigue mechanisms. The plate was then subjected to 1 million cycles of a sinusoidal excitation with approximately 500 με of amplitude. Figure 12 shows the results.

Since the sensors were zeroed before the test start, it is possible to realize the average offset value is due to an asymmetry on the apparatus. It is noticeable the difference between FBG and ESG offset stability. While the average offset for ESG is (-43 ±5) με, FBG has (-38 ±30) με.

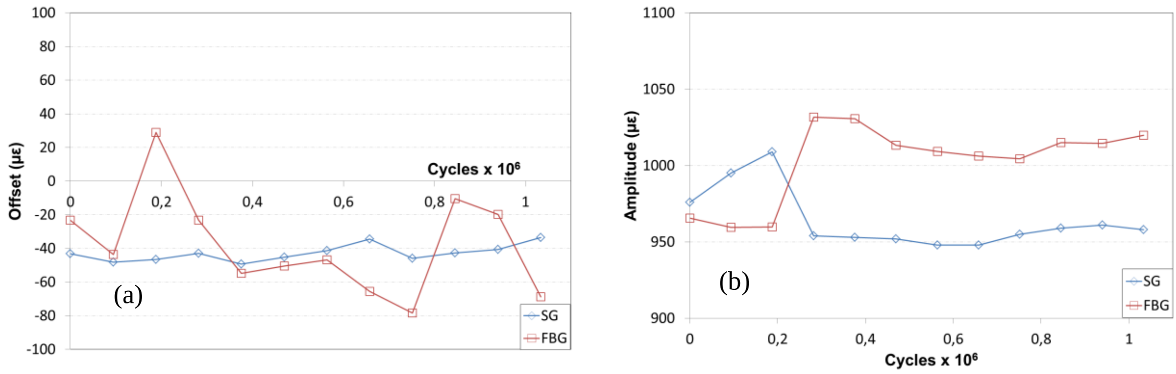


Figure 12- Performance of sensors bonded to CP1 when subjected to a cyclic loading: (a) Offset and (b) indicated peak-to-peak deformation.

The deformation in Fig 12B shows a change in sensors' response on the interval between third and fourth points. This change is related to an intervention made in order to retighten some loose parts of dynamic apparatus. Apart from this, both sensors, FBG and ESG presented good stability, without severe changes on their sensitivity.

## 4. CONCLUSIONS

The present work describes a comparison between two different strain measurement technologies: electrical strain gages (ESG) and optical strain gages (FBG). Since the use of ESG is by far a consolidated technology it is worthy to compare it with more recent technologies, like optical strain gages.

It was observed that commercial FBG sensors presented a performance comparable to the well stablished ESG sensors. To achieve this conclusion, sensors from both technologies were bonded to an aluminum substrate using well known adhesives and techniques then were exposed to various different environmental conditions: elevated temperature, elevated relative humidity, ultraviolet radiation and salt spray. It had been observed their performance under static loadings (tensile and compressive) and cyclic loadings.

It was found a malfunction on the FBG sensor related primarily to a connection problem, which was fixed by a connector replacement.

Finally, the authors conclude that FBG sensors behavior was similar to that of ESG concerning the installation technique, environmental degradation and their use can contribute to improve the monitoring of mechanical structures since they intrinsically present characteristics like EMI immunity, small signal attenuation and lack of local power necessity to supply the sensor, among others.

## 5. REFERENCES

ASTM. G151-10 "Exposing Nonmetallic Materials in Accelerated Test Devices that Use Laboratory Light Sources"; American Society for Testing and Materials; Philadelphia, PA (2010).

Chan,T.H.T. L. *et al.* "Fiber Bragg Grating sensors for Structural Health Monitoring of Tsing Ma bribge: Background and experimental observation". Engineering Strucutures, v. 28, 2006, p. 648-659.

Guan, B. *et al.* "Simultaneous Strain and Temperature Measurement Using a Superstructure Fiber Bragg Grating". IEEE Photonics Technology Letters, v. 12, n. 6, 2000, p. 675-7.

Haase, K. "Strain sensors based on Bragg gratings". In: 20th TC3 IMEKO International Conference, Mexico ,2007.

Hill, K. O.; Meltz G. "Fiber Bragg Grating Technology Fundamental and Overview". J. Lightwave Technology, v. 15, 1997, p. 1263-76

ICNIRP. "Guidelines on limits of exposure to ultraviolet radiation from 180 to 400 nm". Health Phys 87, p. 171–86 (2004)

Lee, Byoungho. "Review of present status of optical fiber sensors". Optical Fiber Technology, v.9, 2003, p. 57-79.

Montero, A. *et al.* " Fiber Bragg Gratings, IT Techniques and strain gauge validation for strain calculation on aged metal specimens". Sensors, v 11 ,2011, p 1088-1104.

Vishay Precision Group, " Errors due to Transverse Sensitivity in Strain Gages", Tech note TN-509, 2011, p. 91-99

Zubin, D. " Theoretical design of calibration beams for strain gauge factor measuring apparatus", J. Strain, 1998, p.99-107.

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