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ONLINE MONITORING OF COMPOSITE OVERWRAPPED PRESSURE VESSELS (COPV)

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Key words: Smart structures, Online monitoring, Composite Systems, COPV, Industrial applications.

Summary: Composite overwrapped pressure vessels (COPV) have been increasingly pointed to as the most effective solution for high pressure storage of liquid and gaseous fluids. Reasonably high stiffness-to-weight ratios make them suitable for both static and mobile applications. However, higher operating pressures are sought continuously, to get higher energy densities in such storage systems, and safety aspects become critical. Thus, reliable design and test procedures are required to reduce the risks of undesired and unpredicted failures. An in-service health monitoring system may contribute to a better product development, design and optimization, as well as to minimize the risks and improve the public acceptance.

Within the scope of developing different COPV models for a wide range of operating pressures and applications, optical fiber Bragg grating (FBG) sensors were embedded in the liner-composite and composite-composite interfaces during their manufacturing processes. The idea is to allow the online strain monitoring during preliminary testing and service-life. The ability of these measuring systems to effectively assess the strain fields has been investigated. Simultaneously, a finite element analysis (FEA) was made using the ABAQUS® platform. In this numerical analysis, accurate and realistic simulation of the different materials, geometry and loading conditions was approached. Particularly, the anisotropic nature of the wound laminate and the varying orientation of the fibers were attained. However, the cohesive zones were not attributed independent properties.

Comparison between experimental and numerical data was addressed. In general, although the experimental-numerical data agreement was not as good as desired, a preliminary insight to both the structural health monitoring (SHM) system and the numerical modeling approaches was actually achieved. Full characterization and validation shall be further addressed in the continuation of the present work.

The first set of results and difficulties on the development and implementation of this SHM system to COPV are presented and discussed in this paper.

1   INTRODUCTION

With the great demand for lightweight structures, the use of composite materials is widely expanding. Their high specific strength and stiffness gather preference over metallic ones in numerous applications. For instance, composite overwrapped pressure vessels (COPV), manufactured by filament winding, are among the most effective solutions for high pressure storage of compressible liquid and gaseous fluids [1-2]. Currently, COPV are already expressively used for LPG and other fuels storage, industrial gases storage, as fire extinguishers or air guns among other emerging applications.

In general, the COPV manufacturing process, which is typically based in the filament winding technique, can be separated in three sequential stages: (1) fibers impregnation in the case of thermosetting matrix (this can be made *in-situ* in the so-called wet winding or previously thus using pre-impregnated rovings), or heating/melting process when using a thermoplastic matrix; (2) winding the vessel through overwrapping the inner liner; and (3) composite cure process in the case of thermosetting matrix. In the winding stage, the fibers orientation is controlled by the coordinated movement of the fibers delivery head and the mandrel rotation. Due to cleaner and easier use of prepregs, these are increasingly reaching the commercial applications despite the fact that traditional wet winding is still the most used process.

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 [3-9], 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 their applicability for in-service SHM.

In recent years, fiber 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 used with the objective of monitoring COPV and assess their advantages and disadvantages for such SHM systems.

On the other hand, FEA is another powerful tool that allows to study and to analyze the behavior of complex structures such as COPV, as long as geometries, constraints, loading conditions and materials properties are correctly modeled. Despite the considerable experience and knowledge required to develop accurate and detailed models, the availability of computational platforms and its reduced cost when compared to fully empirical product developments, makes FEA very attractive for both knowledge improvement and product development. In specific, the numerical modeling of COPV requires a proper methodology that accounts for the fibers orientations in each region of each lamina of the laminate over a non-conventional surface, as well as proper contact conditions at the liner-composite and composite-composite interfaces. In practice, both experimental and numerical approaches have been improving significantly and helping to better understand the COPV behavior.

In this paper a SHM technology based on FBG sensors is applied and studied in COPV prototypes and tests results are presented and discussed. Simultaneously, an accurate numerical model, with fundamental inputs arising from experimental characterization of the materials and geometry of real prototypes, was developed in order to validate the experimental monitoring procedure, allowing to conclude about its own accuracy and applicability. In the following sections the working principle of the selected sensors, the numerical modeling approach, the manufacturing procedure and the results are presented. Conclusions are finally drawn and indications for the further improvement of these techniques are made.

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 fiber, by exposing the optic fiber to an interference pattern of intense 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 fiber with an FBG is illuminated by a broadband light source, the grating diffractive properties promote that only a very narrow wavelength band is reflected back (Figure 1).
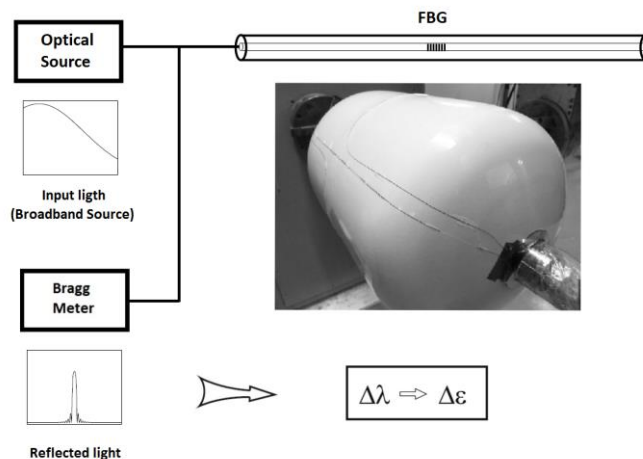

Figure 1 - Scheme of the FBG data acquisition apparatus, using a BraggMETER.

Gratings are simple intrinsic sensing elements that give an absolute measurement of the physical perturbation they sense. Their basic principle of operation is to monitor the wavelength shift associated with the Bragg resonance condition, being the referred shift

independent of the light source intensity [10-11].

When the fiber is stretched or compressed along its axis, the grating period changes. This modification is also observed to temperature fluctuations. The sensor working principle is modeled by the following relation [7]:

$$\lambda_B = 2n_{eff} \Lambda \tag{1}$$

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

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™. Multiplexed FBG sensors were used in order to evaluate the evolutions of the strain in different locations and orientations while using a reduced number of optical fibers.

The intrinsic high dynamic range and high output power of the BraggMeter allows for high resolution to be attained even for long fiber 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 callibration 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. $\varepsilon = 1\%$).

3   NUMERICAL MODELING OF THE COPV

The COPV model was developed considering an axisymmetric steel mandrel, with 1.87mm average thickness, in which a carbon-epoxy composite laminate is overwrapped. The real thickness profile along the generatrix was measured and inputted from a real prototype.

The winding angle and thickness of the composite layers were defined considering the real laminate. The first layer (hoop), which covers only in the cylindrical region, had 5.98mm thickness and winding angle of 90˚ (relatively to the longitudinal direction). Each of the five subsequent layers (polar) were defined with 1.03mm thickness (in the regular thickness zone) and winding angles of 12˚, 22˚, 12˚, 22˚ and 12˚, respectively. This laminate configuration represented the real ones applied in the manufacturing of the prototypes and thus accurately models the real laminate. In Figure 2 the overall geometry of the cross-section model is depicted.

The liner was meshed considering quadrilateral and triangular elements, available in the ABAQUS® standard library (axis-symmetric models), to obtain a mesh consisting on CAX8 (8-node biquadratic axisymmetric quadrilateral) and CAX6 (6-node quadratic axisymmetric triangle) elements. Each and every composite layer was individually built with proper interfacial boundaries and mesh attributes were defined. The elements assigned to the composite layer's mesh were the same as the ones used to mesh the steel liner, differing only in the constitutive elasto-plastic properties.

Being an axis-symmetric model, all the computation is realized over a virtual cross-section, where all degrees of freedom (DOF) in the 3D space are accounted in. Due to the symmetry properties, only a 2D cross section is needed to represent all results.
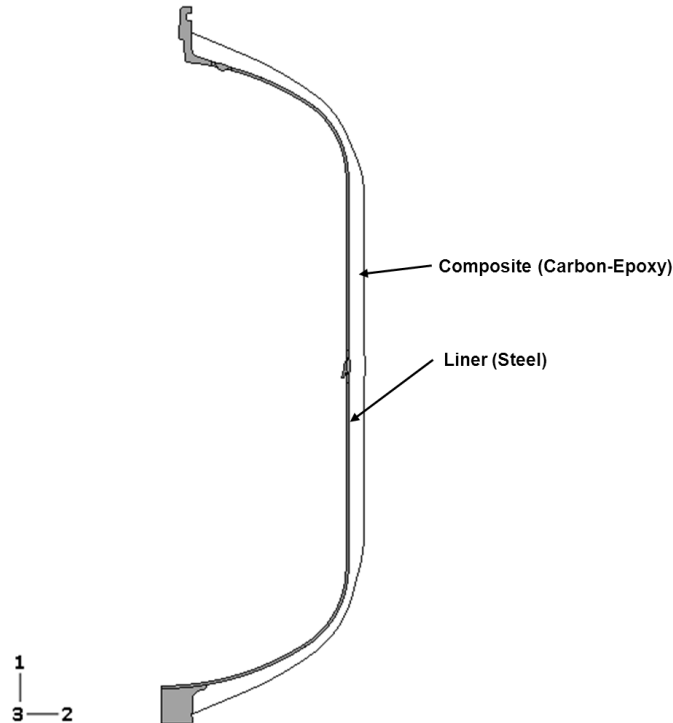

Figure 2 - Cross-section view of the COPV model. Liner and composite layers are identified**.**

The main materials properties inputted to the model corresponded to preliminary characterization tests and are presented in Table 1.Since no inclusions were considered, i.e., no sensors were embedded in the idealized mesh, the materials properties inputted in every locations of the model correspond to the stated properties of the host materials (isotropic steel for the liner and orthotropic composite bands in the composite layers).

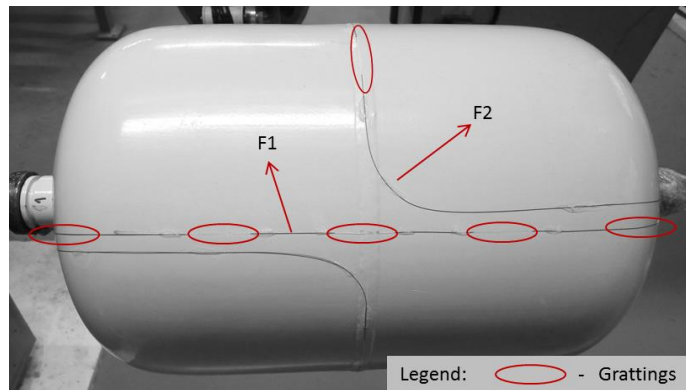Table 1 - Main material properties considered in the model.

Materials	Elastic Modulus [GPa]			Poisson's Ratio			Ultimate Strength [MPa]
Steel (CL-CT)	140.685			0.3			504.162
Steel (T)	238.244			0.3			457.765
Composite (carbon/epoxy)	E_1	E_2	E_3	v_{12}	v_{13}	v_{23}	n/a
	148.132	6.954	6.954	0.3	0.3	0.45	

A hydrostatic internal pressure loading condition was applied at the inner surface, truly representing the test loading conditions. Artificial boundary conditions were inputted through constraining the top "neck" in order to avoid numerical instability of the model.
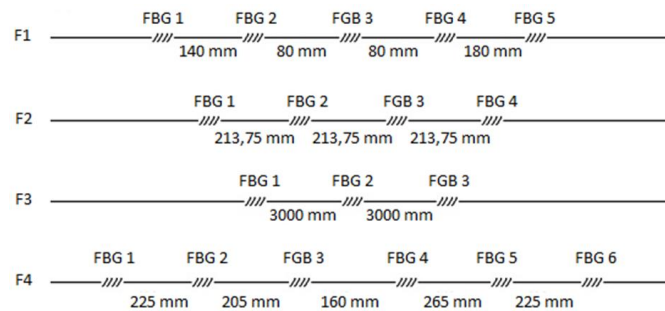
3   NUMERICAL MODELING OF THE COPV

The prototype manufacturing requires a previous study to define the best location of the FBG sensors implementation, the amount of sensors, as well as the parameters more important to for the monitoring process. The critical points, where strain achieves higher values, were located near the tops, neck and belly welding of the liner. These sections emerge due to geometrical specificity, local stiffness caused by the welding, and the fiber orientation.

The setup consisted on four multiplexed FBG sensors (F1-F4), being the gratings configuration presented in Figure 3 (b). The sensors named as F1 and F2 were placed between the steel liner and helical layer, allowing the measurement of strain variations that are propagated from the liner to the first composite layers. As shown in Figure 3 (a), F1 and F2 were strategically disposed in order to evaluate longitudinal and radial deformation, respectively. In a subsequent phase, F3 was conditioned between the first and the second circular layer, taking care to guarantee the superposition of the F3 grating with one of the F2 gratings. The F4 was positioned in the first helical layer.

(a)

(b)

Figure 3 - View of the FBG sensors positioning over the metallic liner (a) and scheme of the entire set of multiplexed fibers used for both liner-composite and composite-composite interfaces (b).

In a first stage of this study, uncoated FBG were embedded in the COPV prototype, in order to measure strain variations. During the cure process, when the compression is higher, most of the sensors were lost and the rest present a low intensity signal, as expected. In order to overcome this situation, the grating region was re-coated to strengthen that fragile area. Fibers were then strategically placed into the COPV.

Since the results obtained with the re-coated FBG were non-satisfactory, herewith only the procedure and results obtained with non-coated FBG are considered.

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4   NUMERICAL AND EXPERIMENTAL RESULTS

In this section a compilation of numerical and experimental results is presented in order to allow their comparison and critical analysis. In Figure 4 the strains at the liner-composite interface obtained in the numerical model as well as with the experimental measurements are plotted for four different locations-direction pairs. Namely, the longitudinal strains at 0.1, 0.2 and 0.4 relative length of the vessel, x/L, and the circumferential strains at 0.4 relative length of the vessel are presented. On the other hand, in Figure 5 the strains at the composite-composite interface are plotted for four different locations-direction pairs. Namely, the longitudinal and circumferential strains at 0.2 and 0.4 relative length of the vessel, x/L, are presented.

The selection of the location to study/measure was related with the symmetry and specific topologic conditions of the COPV prototypes. In fact, the location at 0.4 relative length is the nearest to the central weld possible spot to place FBG sensors. The location at 0.2 relative length corresponds to the middle of the cylindrical region in which both longitudinal and circumferential strains are easier to assess and thus compare the numerical and the experimental results. Some prototypes were produced and it was observed that some FBG sensors didn't survived. Taking into account previous studies, in the central weld area the compression stresses are higher. As expected, this behavior doesn't promote the survival of the optical sensors, contributing to the signal loss of the FBG.

The FBG results are already calibrated through a calibration rule developed by the authors and being published elsewhere [12]. The need for a calibration rule was identified from the ineherent mismatch between the strain measured (sensed) by an FOS and the actual strain experienced by the hosting media. There are several reasons for this mismatch. Our approach based in characterizing extensively the macroscopic mismatch over the applicable measurement range and establishes a calibration rule for each sensor-host material combination. The numerical results are in accordance with previous experience with other similar COPV. However, the agreement of numerical and experimental results is still not consistent. The strain-gauges used to further cross-validate the numerical and experimental methodologies proved to be disappointing so far, since only one out of four sensors provided apparently reliable output. It presented, however, strain values that were several times higher than expected.
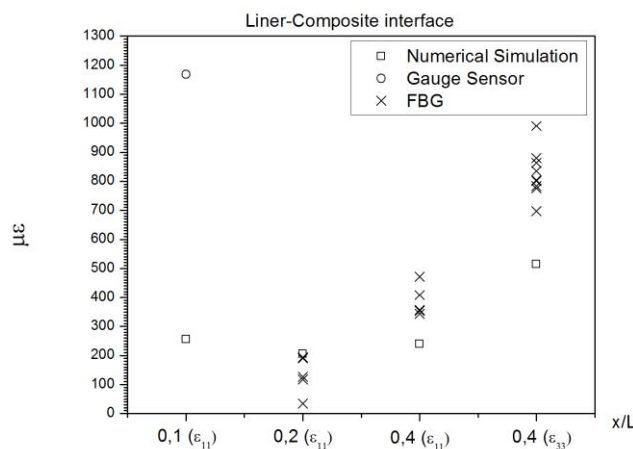

Figure 4 - Longitudinal (and circumferential) strains assessed numerically and experimentally for different locations at the liner-composite interface.
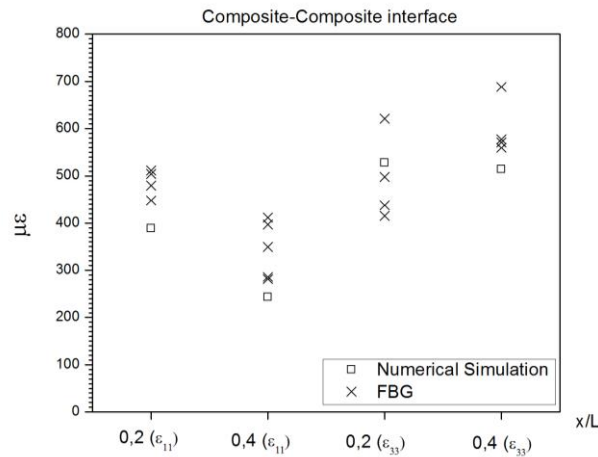
Figure 5 - Longitudinal and circumferential strains assessed numerically and experimentally for different locations at the composite-composite interface.

Further results and analysis will be presented throughout the realization of the remaining experimental campaign.

5 CONCLUSIONS

During the development of the present work, several conclusions were drawn. Namely, regarding the feasibility of the procedure of embedding FBG into a COPV, at the liner-composite and composite-composite interfaces, one may conclude that:

- FBG sensors are virtually non-invasive (when compared to resistive strain gauges, for example) and therefore very attractive for SHM of COPV. Local orientation mismatches or singularities in mechanical contacts may, however, impact their "blending" ability.
- FBG sensors are highly sensitive to handling and positioning, thus making them uncomfortable even for laboratorial studies like this one;
- the optical fibers placed at the composite-composite interface lasted longer during the several stages of the manufacturing and testing process due to the easier accommodation to the host material, since they were aligned with the surrounding composite fibers;
- also, the results obtained at the composite-composite interface presented better agreement between experimental and numerical;
- the optical fibers placed at the liner-composite interface were statistically more damaged (loss of signal) due to the fact that the inner metallic surface doesn't allow proper accommodation while the transverse (not co-aligned) composite fibers pressed them inwards, eventually compressing the optical fibers transversely. This resulted in fewer number of available data points;
- the calibration of the FBG results, using the calibration rule previously developed [12], approximated the experimental values to the numerical ones, mostly in the case of composite-composite interface. This complies with our previous experience, since

the calibration rule was developed for FBG fully embedded and co-aligned within a composite laminate;

- taking into account the experimental conditions, the use of re-coated FBG sensor is an advantage since it allows monitoring in more adverse conditions. Though, the results still could not correspond to the real strain variation, since the re-coating could reduce sensor sensitivity in particular situations. This aspect was studied in a dedicated program [13];
- the results have shown a reasonable agreement, since the same orders of magnitude were achieved in the first set of results.

In the scope of improving these results and analysis, further studies will be made, namely in terms of FBG positioning techniques and sensors reliability.

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