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Technical Report

Manufacturing and testing composite overwrapped pressure vessels with embedded sensors

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ABSTRACT

In this research programme, methodologies for structural health monitoring (SHM) of composite overwrapped pressure vessels (COPV) were addressed. So, this work is part of the development of a COPV laboratorial prototype incorporated with non-destructive sensing technologies. The aim is to detect and identify critical aspects that can happen during operation, in order to reduce possible safety problems.

Fibre Bragg grating (FBG) optical sensors and polyvinylidene fluoride (PVDF) polymeric piezoelectric were the selected sensing technologies. These sensors were embedded in the liner–composite interface during its manufacturing and monitored the prototype while tested under cyclic internal pressure loading.

The measurements collected from the sensors were compiled with the analysis of test data and are presented in this paper. Also, the suitability of the two sensing technologies, issues related to sensor embedding and the monitoring strategy are discussed.

1. Introduction

Composite overwrapped pressure vessels (COPV) are among the most effective solutions for high pressure storage of compressible liquid and gaseous fluids [1]. Their characteristic high stiffness-to-weight and strength-to-weight ratios make them suitable for both static and mobile applications. However, since operating higher pressures are continually sought due to the need to achieve higher energy densities in storage systems, safety aspects become critical. Thus, reliable design procedures and non-invasive monitoring techniques are required to reduce the risks of undesired and unknown failures.

Non-destructive evaluation (NDE) techniques have been developed for vessels and pipe testing, including ultrasonic scanning, acoustic emission (AE), shearography, stimulated infrared thermography (SIT), electronic speckle pattern interferometry (ESPI), vibration testing, radiography, conductivity, etc. [2–7]. However, these classical techniques are not well suited for in-service SHM due to the difficulties of making *in situ* implementation and/or analysis. In recent years, in-service SHM systems for COPV based on FBG optical sensors have been studied and presented according to several aspects [8–15]. FBG have several attractive properties, such as small size, multiplexing isolation capabilities and immunity to electromagnetic fields, making them possible to incorporate a fibre optic sensor system in order to monitor a structure *in-loco*. All this is possible since an array of FBG sensors is capable of measuring, *in-real time*, several parameters such as load/strain, vibration, temperature [16–18].

Piezoelectric sensors, just like the FBG sensors, are an elected sensing technology used for smart structures, as well [19–22]. These materials make the continuous and active monitoring of a structure possible due to their direct (sensor) and converse (actuator) piezoelectric effect. These sensors are frequently used to measure the vibration dynamics of structures due to their double capacity (sensors/actuators), almost simultaneously. Piezoelectric sensing technology, such as polyvinylidene fluoride (PVDF) or ceramic, are most widely used because of their wide bandwidth, fast electromechanical response, relatively low power requirements, high generative forces and small dimension. Additionally, the voltage that is generated when it is pressed is storage sustainable and capable of recharging a battery (harvesting energy).

Qing et al. [23] report a work where thin films of piezoelectric ceramic sensors were used to diagnose a filament wound composite structure.

Contrary to FBG quasi-static sensors, piezoelectric sensors only respond to dynamic solicitations.

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In this work, a new approach where PVDF and FBG sensors are used was developed to monitor COPV. The applicability of both FBG and PVDF sensors to the online measurement of the COPV deformation was, thus, experimentally assessed. The COPV used were composed of a thin steel liner reinforced with glass-fibre/polypropylene (GF/PP). The sensors were embedded in the liner–composite interface during its manufacturing, previously to the winding stage. The prototypes were then tested under cyclic internal pressure loading condition and their behaviour was monitored using the two alternative sensor networks.

In this paper, the suitability of two different sensing technologies – FBG and PVDF – to support online SHM systems for COPV is discussed. Experimental test results are presented and analyzed. For each sensor type, a description of pros and cons, together with the monitoring strategies, is presented. The novel approach, using PVDF sensors, is compared to previous methodologies in both theoretical and practical issues.

2. Selected sensors

The hybrid network of sensors incorporates two different technologies: *optical and electric* sensors. In this study, FBG are used as quasi-static strain sensors, at room temperature. The PVDF are electric sensors and only respond to a dynamic solicitation. In the following paragraphs, the physical characteristic phenomena of each sensing technology are generally described.

2.1. Fibre Bragg grating sensor

FBG are formed when a permanent periodic variation of the core's refraction index is created along a section of an optic fibre, by exposing the optic fibre to an interference pattern of intense ultra-violet 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 promote that only a very narrow wavelength band is reflected back (Fig. 1).

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 [24]. The wavelength shift is independent of the light source intensity [25]. 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 output wavelength signal was acquired at 5 Hz with the BraggMETER equipment, developed by FiberSensing™ (see Fig. 1).

2.2. Polymeric piezoelectric membranes

The piezoelectric membranes that were used are the commercial piezoelectric polymers supplied by Measurement Specialties Inc Company, USA. The piezoelectric membrane consists of a 12 × 12 mm active area printed with silver ink electrodes on both surfaces of a 15 × 40 mm die-cut piezoelectric polymer membrane (see Fig. 2). Polarization is along the thickness and the piezoelectric stress constants are $g_{zz} = -330 \times 10^{-3}$ and $g_{zy} = -330 \times 10^{-3}$ $((\mathrm{v/m})/(\mathrm{N/m^2}))$ (Fig. 2). Theoretically, for this specific sensor where strength is applied in the (*y-axis*) direction, a voltage is generated across the polarization axis (*z-axis*). Furthermore, the amount of free strain is given by

$$V_0 = g_{zy} \times X_n t, \tag{1}$$

where t is the thicknesses of the polarized PVDF, X_n is the applied stress in the relevant direction and V_0 is the returned voltage after each applied stress. For this application, our concern was the selection of the piezoelectric sensor with the appropriate piezoelectric constant. So, the returned electrical signal is only for longitudinal deformations because other directions have null piezoelectric strain constants [26].

The black region, in the Fig. 2, corresponds to the sensor active area (silver electrode). The output signal was acquired using an ni-6229 multifunction data acquisition (daq) and the labview software.

3. COPV prototype manufacturing

COPV typically consist of an inner liner and an outer composite overwrapping layer. The inner liner ensures the vessel geometry and containment of the fluid being stored. The composite layer reinforces the liner and gives it ability to withstand higher pressures. The COPV prototype manufactured in this work was composed of an axis-symmetric thin steel inner liner (thickness = 0.7 mm), with two domes fabricated by a deep drawing process. The registered capacity was 24 l. The circular threaded filling hole is an insert welded to the top of one of the domes. In Fig. 3, we can see a schematic cut view of the COPV.

The various types of sensors were strategically placed over the liner in specific locations in order to sense the principal strains of the structure.

Given the axis-symmetry of the COPV, it is interesting to monitor two principal directions of strain: longitudinal and circumferential directions. Four FBG sensors were placed in the circumferential direction, as near to the main welding as possible. These were printed in one single optical fibre. Two other FBG sensors were placed in the longitudinal direction, along the liner generator profile. These were placed symmetrically to the COPV axis. Two PVDF sensors were placed in the longitudinal direction in symmetric positions. This positioning of the PVDF sensors was

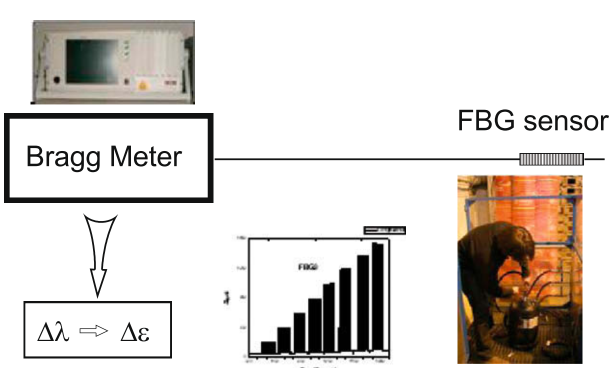

Fig. 1. FBG signal acquisition scheme.

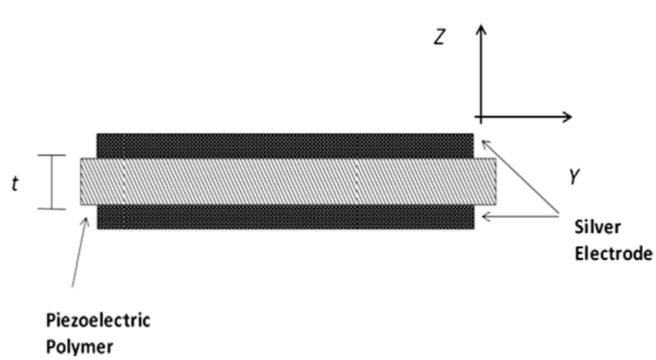

Fig. 2. Polymeric piezoelectric sensor scheme.

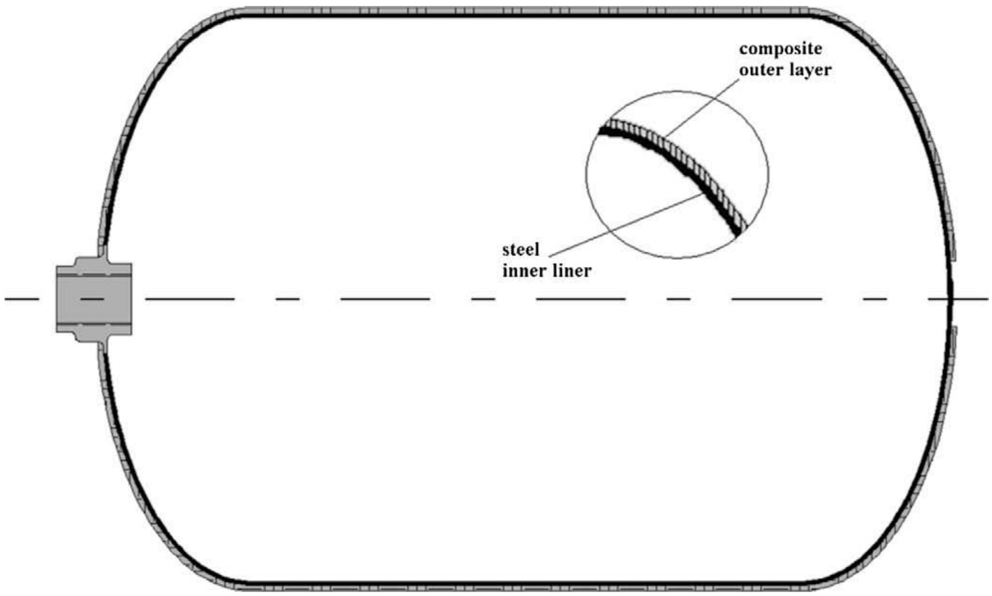

Fig. 3. Schematic cut view of a COPV.

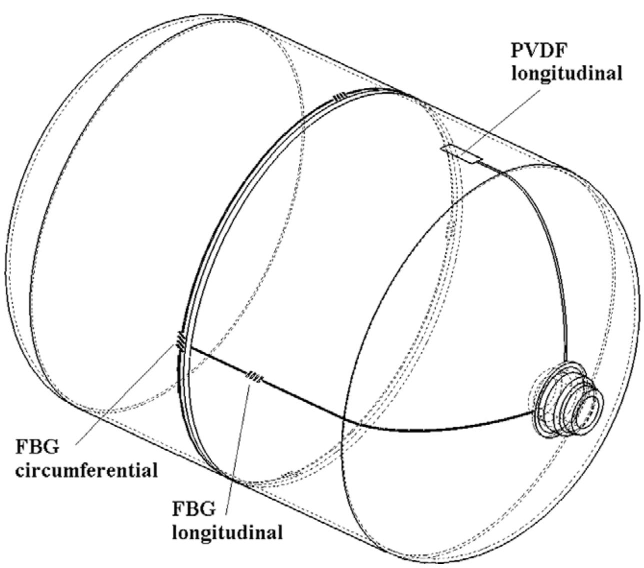

Fig. 4. Positioning of FBG and PVDF sensors onto the liner surface.

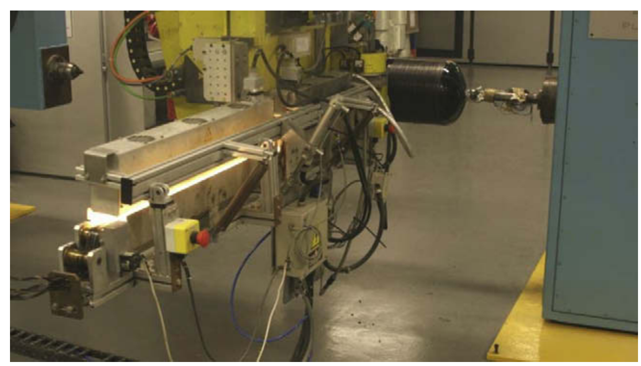

Fig. 5. Feeding the GF/PP filaments through the co-axial IR heater.

mainly limited by the reduced extent of their electrical connectors, thus allowing only to do their sensitivity analysis by comparing to the corresponding FBG placed sensors. In Fig. 4, a scheme of the arrangement is shown.

The composite layer was then wound over the liner and the sensors. A commercial commingled GF/PP composite was applied. Ten rovings (1870TEX) were configured in a 25 mm bandwidth winding band. The thermoplastic matrix was melted at 250 °C in a co-axial feeding IR heater and consolidated by cooling in the final geometry Fig. 5). The wound lay-up sequence was 90/±22/90.

These COPV are identical to commercial products that present a burst pressure of 105 bar and a fatigue pressure of 30 bar (12,000 cycles).

4. Experimental results

In order to observe the behaviour of both sensing technologies, cyclic internal pressure loading conditions were applied to the COPV. Consecutive series of 30 cycles with a prescribed maximum pressure and frequency of 0.24 Hz were conducted. For each new series, the prescribed value for the maximum pressure was increased in 5 bar. Nine series were conducted at maximum pressures from 5 to 40 bar. Moderate strain states were achieved, accomplishing the objective of evaluating the SHM methodologies under real in-service conditions of these COPV. Fig. 6 shows the test arrangement. The pressure history applied to the COPV is show also in Fig. 7.

In Figs. 7, 8a,b and 10, it is possible to observe that both technologies, optical (Figs. 7 and 8a,b) and piezoelectric (Fig. 10), sense and distinguish the different pressure stepped levels during the experimental tests. Table 1 reports the behaviour of FBG sensors for each cyclic loading step.

The FBG sensors placed circumferentially in the vessel reported a non-linear behaviour (see Fig. 9a). The FBG placed longitudinally demonstrated a linear response and a sensitive coefficient of 38 and 54 pm/bar (see Fig. 9b). On the other hand, the longitudinal FBG showed linearity even in the pressure release bottom trend line.

Moreover, in the circumferential direction, a compression state is observed at each pressure release in the cycle series led at maximum pressures of 10–25 bar. Further analyses focused in the vessel mechanical behaviour allowed us to conclude that the welding

Fig. 6. Test arrangement.

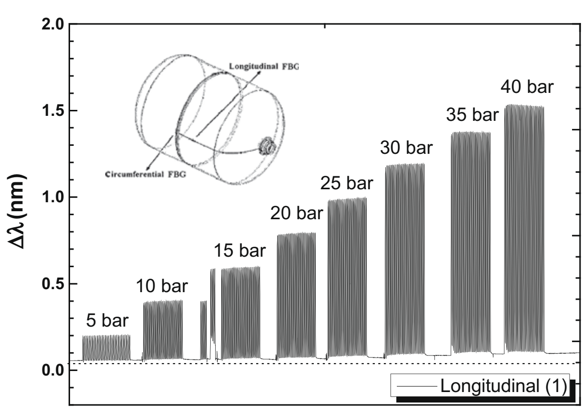

Fig. 7. Linear wavelength variation ($\Delta\lambda$), measured by the FBG sensor placed longitudinally for each pressure step during the fatigue tests.

region reaches plasticity at relatively low pressure values. Its greater stiffness forces the contiguous regions to bend when it expands (applying pressure) and this is not fully recovered when it retracts (releasing pressure).

The PVDF placed in the longitudinal direction of the vessel (Fig. 11) reported a non-linear behaviour for the pressure loading (see Table 2). Although the PVDF and the longitudinally placed FBG have differences, these can be possibly justified by the fact that, on one hand, the two sensors are positioned in slightly different locations and, on the other hand, the membrane behaviour of

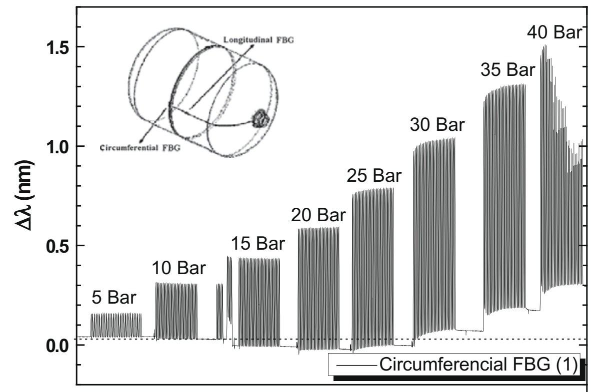

Fig. 8a. Linear wavelength variation ($\Delta\lambda$), measured by the FBG (1) sensor placed circumferentially for each pressure step during the fatigue tests.

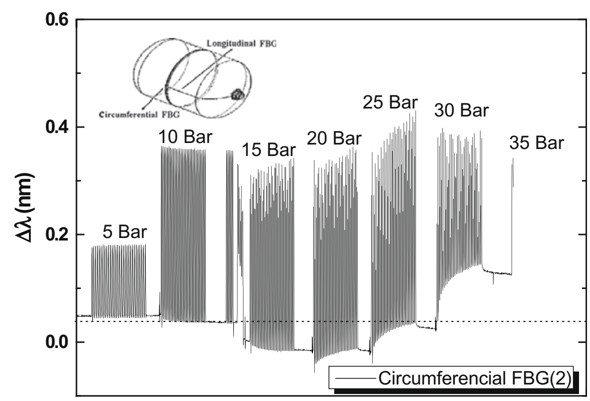

Fig. 8b. Linear wavelength variation ($\Delta\lambda$), measured by the FBG (2) sensor placed circumferentially for each pressure step during the fatigue tests.

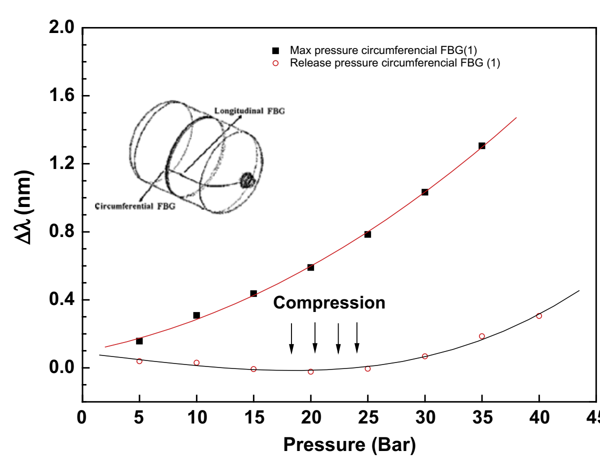

Fig. 9a. Wavelength variation ($\Delta\lambda$) in the circumferential placed FBG is proportional to the applied pressure and release.

the thin steel liner turns out to be more balanced and homogeneous at higher levels of strain, after an initial stage where local non-uniformities do to its manufacturing process prevail.

The longitudinal and circumferential FBG reported similar levels of strains during the first four and the last pressure steps and gradually diverged between the 15 and 30 bar stages (see Fig. 12). The minimum values sensed by both FBG sensors were

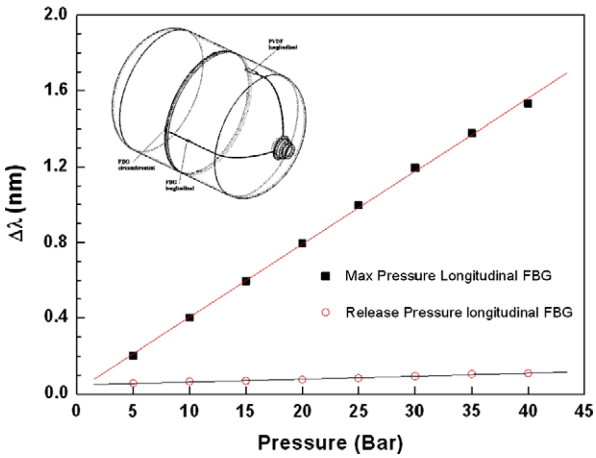

Fig. 9b. Wavelength variation (Δλ) in the longitudinal placed FBG is proportional to the applied pressure and release.

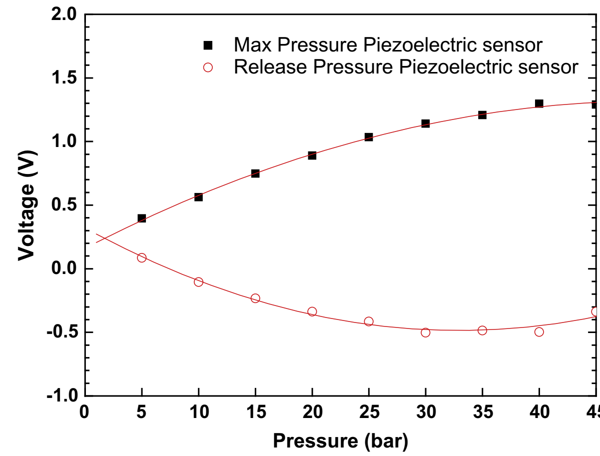

Fig. 11. Voltage variation (Δλ) in the longitudinal direction of the placed PVDF is proportional to the applied pressure and release.

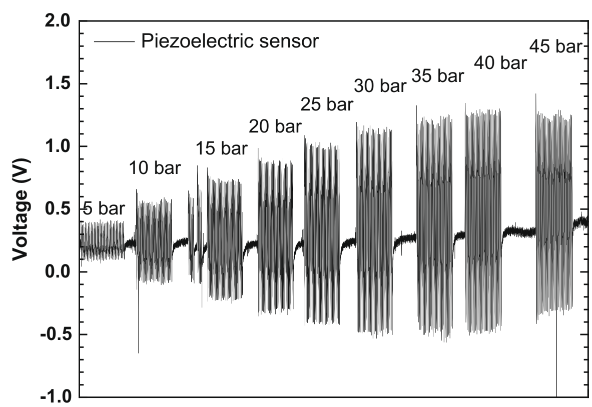

Fig. 10. Linear voltage variation, measure by the PVDF placed longitudinal for each pressure step during the fatigue tests.

equally 200 με in the first series (5 bar), but, in the final stage (40 bar), they presented values of 1377 and 1305 με, respectively. The PVDF theoretically present values between [34,599 and 112,770] kPa (see Fig. 13).

5. Discussion

From the analysis of the results, one can discuss the applicability of the studied sensor systems in SHM of COPV, as well as the behaviour of the COPV itself. In a preliminary assessment, the PVDF sensors proved to be applicable in SHM of COPV. This was supported by the good agreement of results for both FBG and PVDF in comparable sites (longitudinal direction). The PVDF withstand processing temperatures of up to 200 °C, which make them usable in both thermosetting and thermoplastic-based COPV. Moreover, they are easy to apply, relatively non-intrusive and allow the direct measurement of both longitudinal strain and normal (off-plane) stress.

The PVDF, as a dynamic sensor, showed good resolution in the identification of the pressure and consequent release in each step. However, the reported voltage is not linear to the applied voltage, but increases according to a polynomial equation (see Fig. 13).

Concerning to the FBG sensors, their application requires a more delicate collocation since they are very fragile. They are also more intrusive (visible indentations in the inner composite layers could be observed) and less capable of overcoming local geometric singularities like welding and hard curvatures.

Additionally, the circumferential and longitudinal strains showed to be of the same order of magnitude. Although this cannot be directly supported by other analytical means within this study, one can intuitively associate this to the membrane-like behaviour of the whole liner-composite thin shell in the lower pressure stages. As it is observed in the results, from the pressures stages at 25 bar, the circumferential strains diverge from the longitudinal ones which fit the experimental evidence of the failure mechanisms typically observed in the burst pressure tests led on these structures.

Interesting information was also assessed regarding the behaviour of the COPV in specific regions [27]. In fact, compressive

Table 1
Optical sensor behaviour for the different assays.

Optical sensors sensitivity calculated		Experimental	Error (square error, N)
Longitudinal FBG	Max pressure	38.54 pm/bar	$R = 0.9995$
	Release pressure	1.57 pm/bar	$R = 0.9921$
Circumferential FBG (1)	Max pressure	$94.4 + x(12.8 + 6.14E^{-7}x)$ pm/bar	$R = 0.99868$
	Release pressure	$86.86 + x(-7.99E^{-8} + 1.03E^{-8}x)$ pm/bar	$R = 0.98756$

Table 2
Piezoelectric sensor behaviour for the different assays.

Piezoelectric sensor sensitivity calculated		Experimental	Error (square error, N)
Longitudinal	Max pressure	$161.83 + x(46.1 - 4.581E^{-7}x)$ mV/bar	$R = 0.99807$
	Release pressure	$320 + x(-48.82 + 7.405E^{-7}x)$ mV/bar	$R = 0.98115$

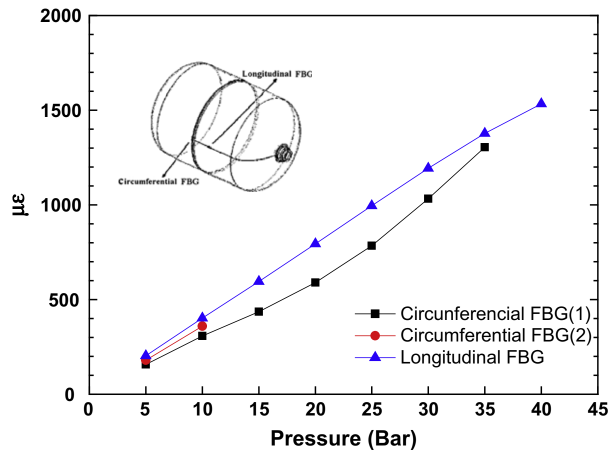

Fig. 12. Theoretic strain variation ($\Delta\varepsilon$) in the longitudinal direction of the FBG sensors proportional to the pressure applied to the vessel.

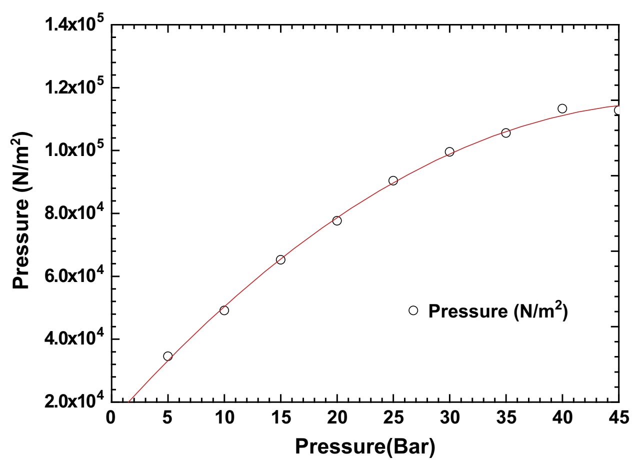

Fig. 13. Theoretic pressure variation ($\Delta\varepsilon$) felt in the longitudinal direction of the PVDF sensor proportional to the pressure applied to the vessel.

strains were observed in the welding at each pressure release, during the first pressure stages. Moreover, in the circumferential direction, a compression state is observed at each pressure release in the cycle series, which led to maximum pressures from 15 to 25 bars. This behaviour is explained by the plastic unrecovered deformation that occurs in the neighbourhood of the circumferential welding. Due to the greater stiffness of the welding section, its circumferential strains, when loading it (applying pressure), are less than those of the surrounding regions, leading to unrecovered plastic bending strains in these regions when unloading (releasing pressure). The welding surrounding region reaches plasticity at relatively low pressure values, leading to the abovementioned non-linear behaviour through the stepped increasing of pressure. This phenomenon could also be discussed in terms of the well studied *autofrettage* mechanisms, used in typical pressure vessels [28]. The results showed that the reinforced liner behaves non-linearly along the circumferential direction in the main welding region and linearly in the longitudinal direction along the domes.

6. Conclusions

By the end of this work, several aspects related to the applicability of FBG and PVDF sensor systems in SHM of COPV can be discussed, once they have been assessed through the present experimental programme.

In summary, two different technologies for online structural health monitoring (SHM) were studied in this composite overwrapped pressure vessel (COPV). When comparing these technologies, the FBG optical technology presents an alternative solution when compared the conventional piezoelectric. For dynamic measurement the PVDF technology presents good resolution and easy handling, thus being the main innovation introduced by this programme.

Despite these results, considerable effort must be addressed in future work. More testing campaigns and longer tests shall be conducted in order to study the long-term stability and reliability of the sensor systems. Embedment of sensors in different sites of the composite layer shall be addressed for the evaluation of eventual damage initiation and propagation in the composite. Numerical models, capable of being compared to experimental results, shall also be developed. All these issues will be addressed in the continuation of our work.

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