ON THE USE OF OPTICAL FIBRES WITH BRAGG GRATINGS FOR THE IDENTIFICATION OF PROCESS-PROPERTIES RELATIONS OF COMPOSITE STRUCTURES

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Abstract

The present paper deals about the use of optical fibers with Bragg gratings for the identification of process-properties relations for composite structures. This study relates a 6 year-experience in the field of process and mechanical characterization of composite parts. It highlights some major topics in terms of technological issues such as sensor integration, information discrimination and measurement accessibility. Results of process monitoring concerning autoclave cure and filament winding are shown through which initial states are identified. Finally, structural tests of instrumented parts are presented, showing the efficiency of the embedded sensors to allow test-calculation dialogues and thus properties identification.

1 Introduction

The PRO²COM research team (PROcesses and mechanical PROperties of COMposite structures) has been working on themes associated to the processing of composite materials using the main industrial manufacturing means such as an autoclave, a resin transfer molding unit (RTM) and a filament winding machine. Diverse and numerous research programs are undertaken around topics concerned with the influence of process parameters over material properties variability. Physico-chemical and mechanical studies of cured parts and structures may bring an important knowledge on the influence of the manufacturing conditions but they won't be able to precisely trace the material elaboration history. Indeed, the specific operating modes of these manufacturing means (high pressures, high temperature, rotation…) present technological difficulties to undertake in situ measurement acquisitions during the fabrication phase. The PRO²COM research team has been involved for many years in the use of optical fiber technologies to take on this challenge [1, 2, 3]. Advantage is taken of the composite material integration potential so that composite parts are instrumented with embedded optical fiber Bragg gratings (OFBG). The present paper starts by relating our finding and positioning over some of the major issues concerning OFBG embedment and measurement understanding. We then show how technological issues related to each manufacturing means are solved in order that OFBG's deliver an exploitable information. Some curves of strain assessment during manufacturing process are presented. Finally, themes concerned with material properties identification taking into account the influence of process parameters [4, 5, 6] are approached. They are based on experiments which are carried out over elementary coupons and also on representative industrial composite specimens. Instrumenting this kind of specimen is obviously more difficult because they present geometrical singularities and complex staking sequences but the knowledge of the material properties within these structures is the final target.

2 Sensor integration

Preliminary questionings concern the sensor integration in the host material. The interface OFBG/matrix quality and the effective load transfer were estimated experimentally through a series of SEM observations (see Fig. 1), and standard elementary tests including ILSS test (see Fig. 2) which are most revealing to detect any defect or weakness. Numerical 2D and 3D simulations (see Fig. 3) are also undertaken in order to estimate the thermo mechanical influence of the OFBG on its environment. Results show that the invasive character of the sensor is negligible and that the structural integrity of the instrumented part is not altered if the optical fiber is deployed parallel to the reinforcement fibers.

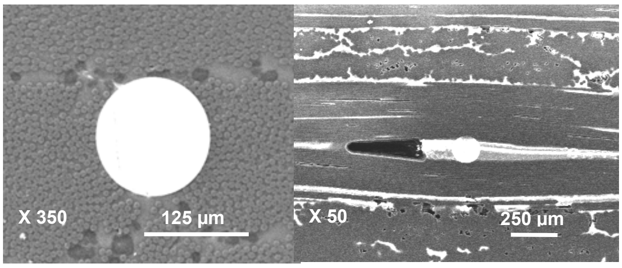

Fig. 1. SEM observations of an optical embedded with OF parallel to the reinforcement (left) and OF transverse to reinforcement (right)

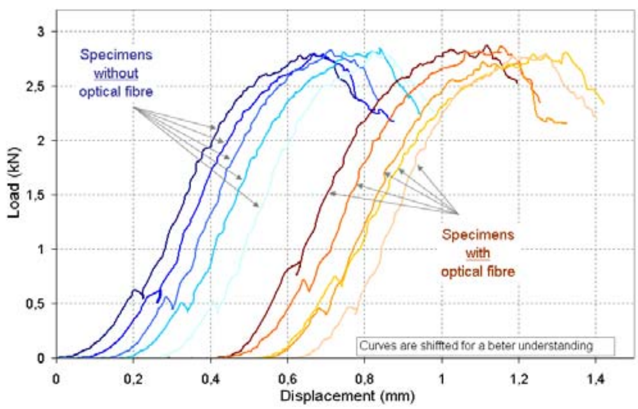

Fig. 2. Standard ILSS tests for carbon-epoxy coupons with and without optical fiber

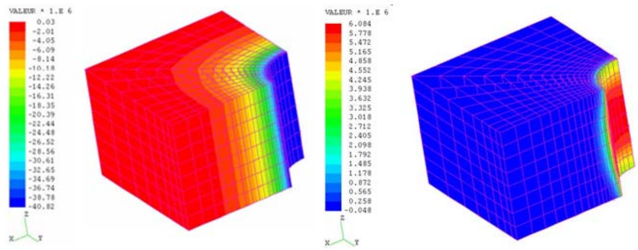

Fig. 3. Thermo mechanical numerical 3D simulations about effect of OF embedded parallel to reinforcement of UD carbon epoxy laminate with transverse stresses cartography (left) and longitudinal stresses (right)

3 Discrimination methods

Another major point of interrogation concerns the understanding of information delivered by the fiber Bragg grating (FBG) sensor. Indeed, during manufacturing processes or mechanical tests, several quantities (strain, temperature and pressure) may be acting on the embedded sensor at the same time. Various discrimination methods have thus been used and analyzed. Our work has focused on two different techniques. The first one is an association of a bare FBG with an encapsulated FBG (see Fig. 4). The second technique is an association of an FBG with a thermocouple. In both case the second sensor delivers the thermal component of the total information.

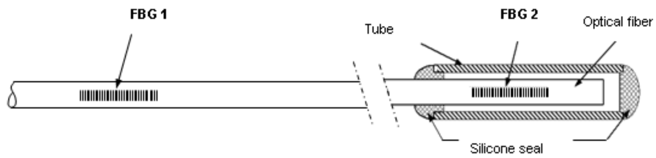

Fig. 4. Bare FBG associated to encapsulated FBG in order to discriminate strain and temperature

The first technique gives very accurate results in condition of varying temperature but the tube is to invasive to envisage mechanical studies. In case both thermal and mechanical studies are envisaged than, the second technique is more appropriated. However, it requires a very precise calibration procedure of the opto mechanical and thermal optical coefficients characterizing the FBG employed. This is undertaken in an oven equipped with an upper and bottom hole through which may go the OF, as describe in Figure 5.

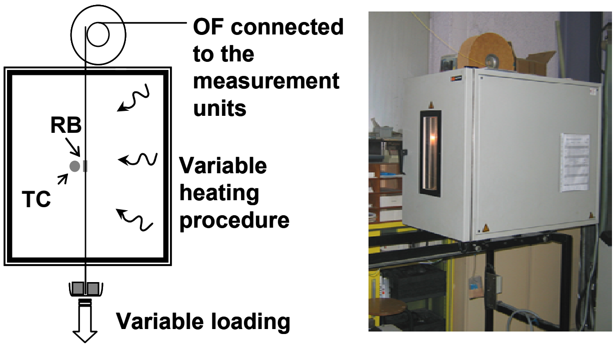

Fig. 5. Scheme and picture of the experimental set-up for the FBG calibration procedure

4 Measurement validation

This phase is carried out through a series of comparisons with other means of analysis. Thermal expansion measurements are considered with Thermo mechanical Analysis (TMA) or high temperature resistive strain gages. Mechanical measurements are also considered with traditional strain gages and with digital image correlation techniques. Moreover, both thermal and mechanical situations are simulated with numerical models. At the end, we obtain very satisfactory correlations between al these techniques as long as the optical sensor is mainly submitted to axial loading.

5 Autoclave Process monitoring

5.1 Technological issues

Many stages of this manufacturing process present situations that are a risk for the integrity of FO. Compacting, vacuuming, pressurizing are likely to subject OFs to more or less important foldings. Some may attenuate the reflected signal in some critical extend but they may even be responsible of fiber ruptures. The OF curvatures must be reduced as much as possible. Figure 6 shows a solution to minimize them by using beveled silicone foam.

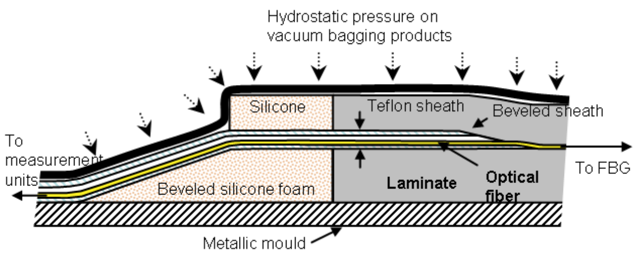

Fig. 6. Optical fiber ingress protection in prepreg before the autoclave curing process

For similar reasons a specific device was especially conceived to allow the passage of optical fibers through the wall of the autoclave (see Fig. 7). The major difficulty is to ensure a perfect sealing without breaking the optical fibers. The adopted solution is a silicone stopper placed in a tube crossing the wall of the autoclave. The stopper may be finely squeezed by means of a hollow screw.

Fig. 7. Autoclave set-up (left) and O.F. gate device (right)

5.2 Cure monitoring

The autoclave manufacturing process is particularly effective for high performance structures. This elaboration mode is largely used in the aeronautical and aerospace fields. The quality of the parts is obtained thanks to the association of three process parameters: pressure, vacuum and temperature. Each one of them has an important influence on the initial properties of the structure, such as the fiber content ratio, presence of porosity, degree of advance or level of cure residual stresses (CRC) which may have a considerable influence on the damage sensitivity of composite structure under loading. CRCs are closely related to the evolution of strains within the material throughout the process. Thus, we exploit the capacities of FBGs to undertake the cure monitoring of various specimens and to analyze the various phases of the autoclave curing process. The process induced strains curve concerning a specimen representative of industrial structural part (see Fig. 8) is shown in Figure 9. The FBG is positioned in the middle of the third ply of the thin zone of the structural specimen which counts a total of 20 plies.

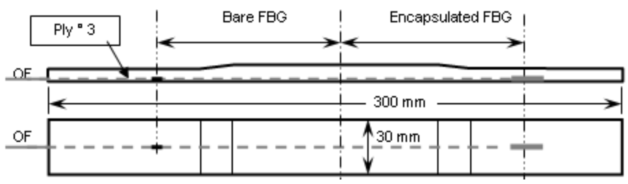

Fig. 8. Geometry of the structural specimen and FBG positioning

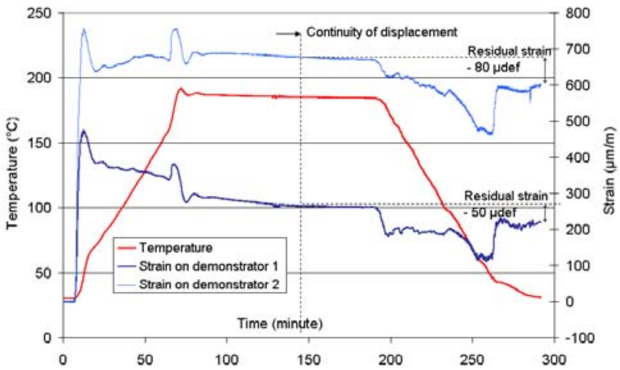

Fig. 9. Strain changes vs cure cycle for 2 structural specimens as described in Figure 8

Looking at Figure 9, it may be observed that, at the beginning of the cycle, the phase of setting under pressure and vacuum is clearly marked by a strong positive deformation. At this stage prepregs are relatively rigid and the stress fields which are exerted on the FBGs are not easily identifiable if one sticks to the optical answer. During the rise in temperature, the tensions on OFs seem to be released. Then strains stabilize until the beginning of the 180 *°C* isothermal shelf. There, an increase in the deformations appears and corresponds to the beginning of gelation. During the isothermal shelf the deformations are stabilized again even if one distinguishes a light reduction (contraction) which could be associated to chemical contraction. The out the preceding cure monitoring. The evolution of strain during the cooling phase is not made in a linear way. The material seems to contract with variable progressions. The dilatation of the mould on which the specimens are placed is certainly not foreign with this irregular change. A brutal change of orientation of the strain curves appears towards the end of cooling, at the moment when the pressure and the vacuum are released. This is explained by the release of the interfacial constraints between mould and specimen. At the end of the curing process, residual strain is estimated for both specimens.

This example highlights how FBGs are able to translate specific manufacturing phases such as temperature change, pressurization, vacuum setting up, gelation, mould-part interaction and build up of residual strains [3, 4, 6].

6 Monitoring of filament wound composite cylinders

It deals with the technological challenge and the development of specimens instrumented with embedded FBGs and thermocouples. The aim is to monitor the temperature and strain changes during the cylinder manufacturing process. Specimens are filament wound glass reinforced epoxy composites. Two technological problems have to be solved: the first question is how to collect data during fabrication and the second is how to withdrawn the specimen from the mandrel without damaging sensors. This first issue is solved through the development of a rotating interface between the filament winding machine and the composite cylinder in fabrication (see Fig. 10). The second issue is solved thanks to a specially designed split mandrel (see Fig. 11).

The filament winding machine rotary-static cable interface design leads signal transmission from rotary sensors (embedded sensors in the rotary specimen) to the static reading instruments. Detailed information can be found in [4].

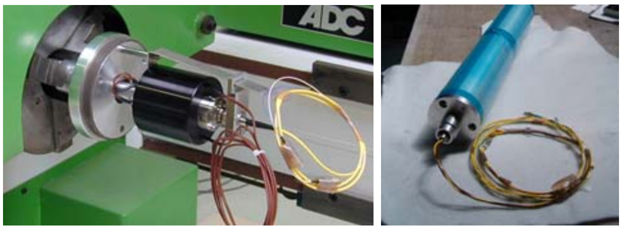

Fig. 10. Connector system on filament winding machine (left) and mandrel-connector system (right)

Fig. 11. Filament winding (left), split mandrel (center), and cable passage (right)

Cylinders are thin walled having a 4,42 *mm* thick, the reinforcement fiber is continuous glass roving (1200 *tex*), with a 3,5 *mm* width. The matrix system is a mixture of araldite LY 5052 and hardener HY 5052. Combined rotational and axial movements produce double helical trajectories and a rhomboid shape pattern. The winding has a pattern of 1 or 5 rhomboids in the circumferential direction. The 350 *mm* long is obtained with a machining operation. The number of layers is 7. At both ends of the cylinder, there are zones of reinforcing fibers with an angle of 90°. Fiber orientation has an angle of ± 55° which is a classical winding angle used for pressure vessels. Layer patterns are placed to be stacked coincident for having the same material through the thickness direction. Winding angles are strictly maintained for all layers, this produces a slight increase in cell size with thickness. Mean measured thicknesses are 4.4 *mm* and 12.6 *mm* for thin walled and thick walled cylinders respectively. The standard deviation for thin walled cylinders is 0.16 mm and for thick cylinders it is 0.26 *mm*. The specimens are wound and cured, at 50 °C for 15 hours. Fiber content ratios were obtained by burn off method giving a mean of 51 % with a 2.1 % standard deviation.

6.1 Winding phase

In such cylinders Fibers Bragg Gratings are aligned in axial and circumferential directions, and a thermocouple is placed next to each Bragg grating. Once the conditioned mandrel with the rotary interface and sensors is placed in the filament winding machine, the placement of the first layer is carried out. Next, sensors are placed over the first layer, one Bragg grating and one thermocouple in respectively the circumferential direction and in the axial direction. The second layer is carefully wound over the first layer covering sensors, and then the rest of the layers are placed like any other non instrumented specimen.

As indicated on Figure 12, the circumferential strain evolution during winding is a *historical file* of the winding process, where the most important events occurring during winding are recorded. The number of the waves and the period of them correspond to the number of layers and the time spent for winding layers.

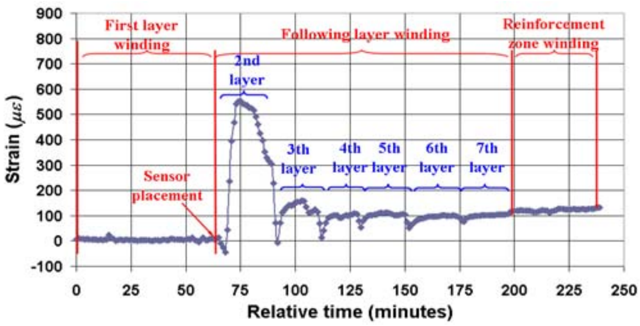

Fig. 12. Event detections during winding

The amplitude in signal reduces as the number of layers grows; one explanation for such tendency is the fact that each time a layer is placed, the radial distance between the sensor and the cylinder surface grows, so the sensors are each time less reactive to perturbations on the surface.

6.2 Curing phase

Tests are performed to measure in situ strain and temperature during cure (here for six nominally identical filament wound cylinders). Several *points* and *events* of the curing process are identified; these points can be grouped in two classes, one group is formed by points limiting the different phases, the second group is formed by points where material transformations occur. The characteristic points and event explanations are shown in tables 1 and 2.

Table 1. Process characteristic phase identification

Process phase identification	Phase description
1-2	Winding
3-4	Waiting phase between winding and curing cycle
4-5	Heating
5-6	Curing constant temperature phase
6-7	Cooling

Table 2. Phenomena and transformation identification

Characteristic point identification	Point description and occurring transformation
a	Point from which elastic response and thermo-elastic behavior begin to appear during heating
b	Point where axial strain shows a fast decrease, and may indicate a transformation. From this point there is no elastic response nor thermo-elastic behavior
c	Point at which a transformation occurs from semi liquid or liquid state in to a solid state. Material shows again an elastic and thermo-elastic behavior

Axial and circumferential mean strains of all specimens from optical sensors are plotted on Figure 13. Strain values at the end of winding segment are almost zero, this situation is expected because during winding resin is still liquid and no bound is present between resin and the optical fiber, so Bragg grating is only exposed to thermal excitation. At the beginning of the curing cycle (in oven), both strains climb as the temperature rise during curing cycle warm up. It corroborates the fact that during the test, incipient polymerization is observed at the end of the winding phase. A characteristic point is noticed before the end of the warm up segment (*point a*), where axial strain changes from a positive slope to negative, even if the warm up segment is not finished yet. This means that in axial strain the beginning of a material transformation is detected. This point is coincident with the gelation temperature of the resin system (58 *°C*). On the contrary, in circumferential strain this characteristic point is not detected, and circumferential strain follows temperature tendency to climb. It can be noted here, that the composite cylinder over the cylindrical mandrel is free of constrain in axial direction, but in circumferential direction the composite cylinder has to follow mandrel expansion during warm up, this may be the reason why the characteristic *point a* is not detected by circumferential strain response. During constant temperature segment in the curing cycle (*5-6*), axial strain decreases until zero, while circumferential strain remains almost constant, this response indicates a transformation within the material (axial strain releasing), which is supposed to be related with the polymerization process. During cooling down segment (*6-7*) both strains follow temperature evolution and one can suppose that polymerization has finished and strain evolution is due to thermo elastic behavior.

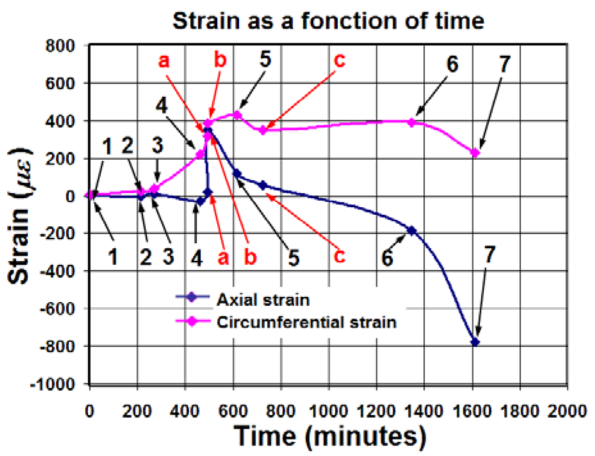

Fig. 13. Mean strains delivered by FBGs and characteristic points

After the curing cycle, strain values are different from zero, which reveals the presence of residual strains within the material. In axial direction specimens follow a contraction (negative strain mean value: –995 $\mu\varepsilon$) and in circumferential direction positive values indicate an expansion (mean value: 134 $\mu\varepsilon$), which is related to mandrel expansion because composite elongation in circumference is imposed by mandrel expansion.

7 Property identifications

As it has been shown the initial state of a structure may be approached thanks to FBG. Once the composite part is cured, the embedded sensors may be used to identify experimental values and properties. It may be a basis to elaborate test-calculation dialogues in order to identify material properties.

7.1 Autoclave cured composite parts

A test-calculation dialogue is undertaken successfully using as few FBGs as possible, in an economical way. In a more scientific way, we have investigated the experimental identification of the mechanical and thermally induced strain distribution throughout the thickness of a composite part (see Fig. 14, 15 and 16).

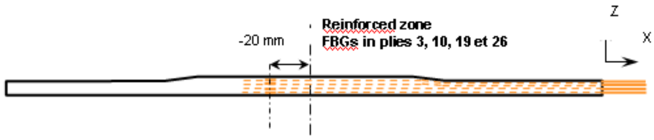

Fig. 14. Distributed instrumentation scheme in the reinforced zone of the structural specimen

In the same kind of specimen as described in section (*5.2*), we have inserted 4 OFBGs in the reinforced zone of the structural in order to estimate the through-thickness strain distribution. FBG are disposed as shown in Figure 14. This zone is composed of 28 plies and FBG are one on top of each other in plies 3, 10, 19 and 26. A 4-point bending test coupled with a numerical simulation enables to identify a correct set of properties, which presents discrepancies from the given manufacturer's set (see Fig. 15).

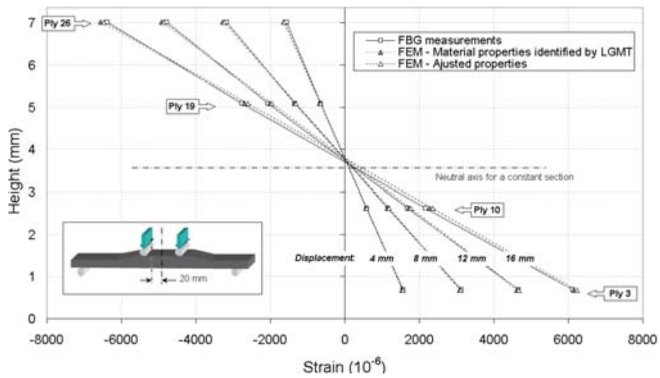

Fig. 15. Strain distribution delivered by FBGs in the reinforced zone during a 4 point bending test of a structural specimen

Through-the-thickness (see Fig. 16) thermal behavior of the material has been estimated thanks to reheating procedures in oven. Variable expansion coefficients have been identified.

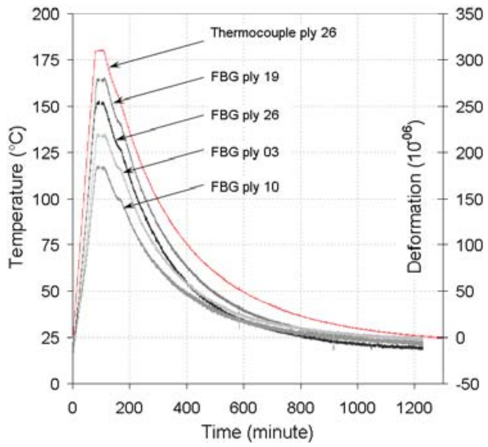

Fig. 16. Thermally induced strain distribution in the structural specimen

7.2 Filament wound cylinders

Specimen are tested under external pressure to validate embedded instrumentation during service and to continue the monitoring of a composite filament wound structure until failure.

The test was performed in the IFREMER facilities at Plouzané in France, using the hyperbaric testing chamber. For this test one closure is provided with a sealed passage tube to connect the optical fibers in the specimen interior to the chamber cover (see Fig. 17). This device was designed by IFREMER. Additionally specimen was instrumented with strain gages to compare with the Bragg grating results. These are bonded on the inner surface, three of them in the circumferential direction and one in the axial direction.

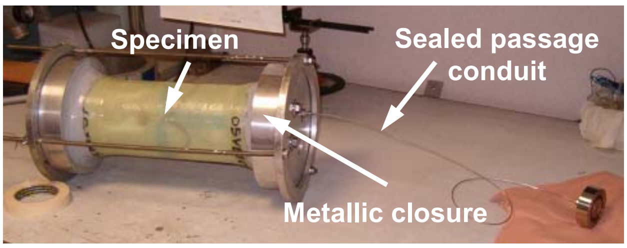

Fig. 17. Bragg grating and strain gage multi instrumented specimen conditioned for external pressure testing

Test is carried out by applying loading and unloading pressure cycles, having increments in pressure of 10 *bar*, starting at 10 *bar*. Results from this test show that specimen implosion pressure is 6,7 *MPa*, a 3 lobe buckling circumferential failure mode is observed, which is coincident with values obtained in previous tests of non-instrumented specimens [4] from which a mean value of a 6,5 *MPa* was determined with a standard deviation of 0,4 *MPa*. This result indicates that the embedded instrumentation has no significant influence on mechanical strength at implosion.

Bragg grating strain response and strain gage response show similar evolution. Bragg grating strain during the last three cycles presents a deviation compared with strain gages. As far as pressure-strain diagrams are concerned (see Fig. 18 and 19), critical pressure can be observed around 5,5 *MPa* (the pressure at which the pressure versus strain plot becomes non-linear). Beyond this point a Bragg grating hysteresis response is noted which is not detected by strain gages. A particular aspect of this phenomenon is that both gratings recorded it, and reacted in the same way, even though both are embedded in different places, both in the central section (half length), but at different circumferential positions. If this phenomenon is a local event (for example optical fiber and resin interface debonding), each grating would react independently.

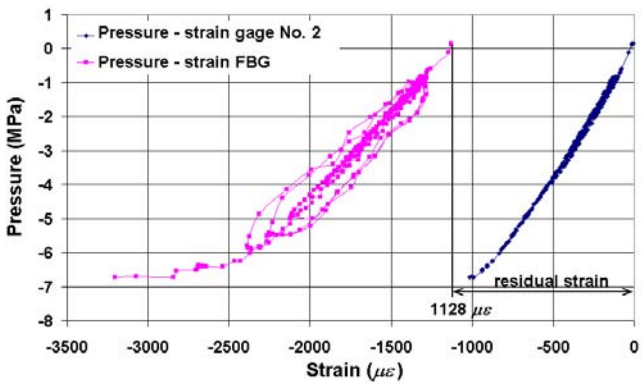

Fig. 18. Pressure - axial strain diagrams

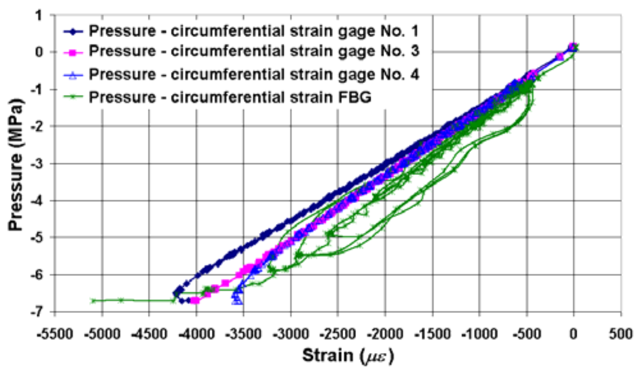

Fig. 19. Pressure - circumferential strain diagrams

7 Conclusion

Thanks to embedded FBGs, the possibility is now given to identify the material properties which exist in structures presenting singular zones (reinforced zone, ply drop off …). The gathered experimental information turns out to be very precious in a test-simulation dialogue [4, 5]. FBG's have a potential to become efficient multi-directional sensors and the PRO²COM research team is surveying this perspective. But today, it is at least possible to assure that FBG's are extremely useful and reliable sensors for process monitoring and further cured part analysis as long as optical fibers are deployed and tested in the appropriate direction and in non significant transverse and/or non uniform stress fields [1, 6].

The results from this test indicate that embedded optical fiber instrumentation allows real time material monitoring all over the structure and has no influence on failure, at least for the cylinder conditions studied here. So it can be said that embedded instrumentation does not appear to influence external pressure strength, this indicates no host material perturbation. Those aspects make in-situ fiber optic instrumentation a valuable tool to record the historical evolution of cylinder response, in terms of strain and temperature, from fabrication throughout the service life.

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