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Distributed fiber optic strain sensing for structural health monitoring of 70 MPa hydrogen vessels

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Abstract. We report on the development and testing of 70 MPa hydrogen pressure vessels with integrated fiber optic sensing fibers for automotive use. The paper deals with the condition monitoring of such composite pressure vessels (CPVs) using the optical backscatter reflectometry (OBR) applied for a distributed fiber optic strain sensing along fully integrated polyimide-coated single-mode glass optical fiber (SM-GOF). The sensing fibers were embedded into the vessel structure by wrapping them over the polymer liner during the manufacturing process of the carbon fiber reinforced polymer (CFRP). Detecting local strain events by the integrated fiber optic sensors can be an opportunity for monitoring the material degradation of CPVs under static and cyclic loading.

We present results of slow burst tests conducted on three 70 MPa hydrogen pressure vessels with integrated fiber optic sensors. The achieved outcomes confirm the suitability of the fiber optic sensors for condition monitoring of CPVs under pressure loads above the nominal working pressure of 700 bar.

The work described here stands in context of the European Horizon 2020 research project SH2APED focused on the development of an innovative hydrogen storage system composed of an assembly of nine 70 MPa tubular pressure vessels used as an automotive battery pack.

Keywords: fiber optic sensor, distributed strain sensing, composite pressure vessel, structural health monitoring, fiber-reinforced plastics

Introduction

Using hydrogen vehicles can be an important strategic solution on the way to convert the fossil fuel vehicle fleet to CO_2-neutral mobility. The development and optimization of composite pressure vessels (CPVs) for hydrogen storage in the automotive industry has the potential to revolutionize the transport sector. Modern type IV high-pressure CPVs for hydrogen storage consist of an inside polymer liner and fully wrapped carbon-fiber-reinforced plastic (CFRP) or glass-fiber-reinforced plastic (GFRP). The fiber-reinforced plastic vessels (FRP vessels) offer significant advantages over other pressure vessels

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including high tensile strength, resistance to corrosion and outstanding stiffness-to-weight ratio [1,2]. The resulting weight advantage underscores the hydrogen fuel economy.

Another economic aspect arises from the analysis of ageing processes of CPVs to increase safety of their usage over their maximum lifetime. Ongoing research activities comprise both the development of accurate and interpretable lifetime prediction models [3] and the use of modern non-destructive measurement approaches to monitor material degradation during the entire service life.

The non-destructive testing of CPVs can be realized by acoustic emission analysis [4], ultrasonic scanning [5] or computed tomography [6]. Another approach to determine the level of degradation or damage is given by testing the structural dynamic behaviour via an experimental modal analysis [7]. The requirement for quasi-distributed or even distributed monitoring can be met by using fiber optic sensors (FOSs). This type of sensors is becoming increasingly common due to their specific properties as their immunity to electromagnetic interference, suitability in explosive environments, small sizes, and long sensor lifetimes. The use of FOSs reaches from Fiber Bragg Grating arrays permitting quasi-distributed high-sensitivity strain and temperature sensing [8,9] to implementation of spatially resolved measurement methods [10-15]. The latter is usually based on optical backscatter reflectometry (OBR) using a swept-wavelength coherent interferometric technique [16]. The FOSs can thereby be directly integrated into FRP during the manufacturing process of CPVs.

The presented work deals with condition monitoring of tubular type IV CPVs designed as single components of an innovative hydrogen storage system to be optimized as a high-performance battery pack for vehicle installation. To account for the time-dependent degradation of the CPV strength, slow burst testing (SBT) [17] is preferred here. SBT offers a promising opportunity to investigate the suitability of FOSs integrated in CFRP for distributed strain sensing (DSS).

1. Distributed Fiber Optic Sensors for Monitoring of Composite Pressure Vessels

Continuous and gap-free monitoring of strain distribution enables reliable detection of material degradation. The strain distribution is thereby to be determined along a sensing fiber used as the FOS integrated into the CFRP. Taking into account the process requirements for the manufacturing of CPVs with FOSs, a polymide-coated single-mode glass optical fiber SM1500(6.4/125)PI made by Fibercore was selected here as a sensing fiber.

1.1 Installation of the Sensing Fibers

During the wrapping process at PONE facilities in Genk, Belgium, three sensing fibers were integrated in following composite layers of each CPVs according to the technical procedure developed in the preliminary stage:

- Fiber 1: in the first innermost helical winding (directly on the liner) – 6.5 circuits, i.e. 13 lengths from dome to dome
- Fiber 2: in the circumferential winding placed in the middle between inner helical windings and outer helical windings – single track from dome A to the opposite dome B
- Fiber 3: in the penultimate outer helical winding – 6.5 circuits, i.e. 13 lengths from dome to dome.

The sensing fibers joined the reinforcement carbon fibers during the manufacturing process at a point after the reinforcement fibers passed the resin bath, whereby the combined fibers were applied through the winding eye and on the vessel surface. All sensing fibers were intruded in and extruded from the CFRP at two opposite domes of each vessel allowing fiber optic measurements at both ends of the tested CPVs. Both the winding process and the subsequent annealing process by means of heating the CPVs with integrated FOSs were all accompanied by fibre optic control measurements.

1.2 Distributed Fiber Optic Strain Sensing

The SBT of CPVs with integrated sensing fibers has been monitored by DSS based on OBR [16]. The swept-wavelength coherent interferometric technique means that the measurement procedure is based on a wavelength / frequency sweep of the laser light source launched into the sensing fiber. Such approach allows to detect intensity profiles $I(f)$ of the Rayleigh backscatter as a function of the swept laser frequency f along the entire sensing fiber divided into customizable gauge lengths. The gauge length (≥1 mm) defines the segment size of the measured Rayleigh backscatter used to determine the cross correlate spectral shift Δf in relation to the reference data block. The determinable spectral frequency shift Δf is linearly dependent on the temperature and strain gradients enabling distributed temperature and strain measurements with the resolution of the measured values as fine as 0.1 °C and 1 µm/m, respectively. Generally, the longer the selected gauge length, the lower the two-point spatial resolution with simultaneous increase in temperature or strain accuracy and resolution. The spatial resolution of 2 cm applies to the results presented in Chapter 3.

2. Slow Burst Tests

All CPV specimens were loaded to failure at a pressure increasing at the rate of 3,5 bar/min. The use of such a low rate of pressure increase ensures approximately static conditions required when using OBR. Fig. 1 shows a CPV directly before SBT. The integrated sensing fibers are to be connected to the measuring device via standard fiber optic single-mode patch cables.

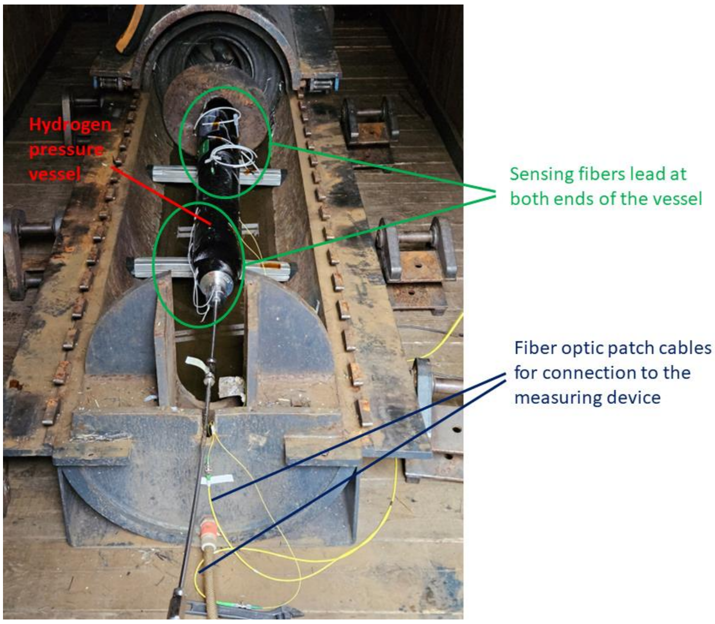

Fig. 1. 70 MPa hydrogen pressure vessel with integrated FOSs installed in the hydraulic burst testing facility.

One of the three tested CPVs (vessel A) was pre-treated in an ambient hydraulic cycle test (22,000 load cycles with 3 load cycles per minute varying between 20 bar and 700 bar) before conducting slow bursting.

The tested three CPVs (pre-treated vessel A as well as vessel B and C without pre-treatment) were placed individually in the hydraulic test chamber as shown in Fig. 1. The patch cables connected with the sensing fibers of the respective vessel were linked with the output ports of a fiber optic switch eol 1x4 IR Leoni. The input port of the switch was coupled to the OBR4600 controlled by a PC with a self-programmed software application (LabVIEW). The automatization software was designed for successive change of the output channel of the switch. Such approach permitted automatic long-term DSS measurements on all connected sensing fibers covering hundreds of load steps continuously increased up to the point of forced failure of the CPV under test.

3. Results and Analyses

The mechanical results of SBT are summarized in Table 1 and show that FOSs integrated into CPVs have no negative impact on the resilience and robustness of the tested vessels. The determined burst pressure exceeds the nominal working pressure by a factor of at least 2.2.

Table 1. Slow burst tests - burst pressure and damage locations

Vessel	Burst Pressure [bar]	Burst Location	Pictures
A	1560,2	Dome, close to cylinder	
B	1675,1	Cylinder	
C	1695,9	Cylinder & dome	

Fig. 2 and Fig. 3 present the development of the backscatter profiles of the sensing fibers integrated both in the circumferential (Fig. 2) and helical (Fig. 3) windings of the not pre-treated vessel B and vessel C. The backscatter profiles generally provide information about optical return losses caused by impurities, imperfections, irregularities, or defects along the tested optical fiber. They can be used to characterize local optical fiber faults due to splicing, bending, connector losses and fiber breaking. The pre-treatment in the ambient cycle test led in case of vessel A to pre-damage in the form of fiber breakage within the fiber section integrated into CFRP called here “sensor section”. This meant that the distributed strain monitoring of the entire sensor sections along all the three sensing fibers integrated in CFRP of the vessel A could not be guaranteed from the outset and is not considered further.

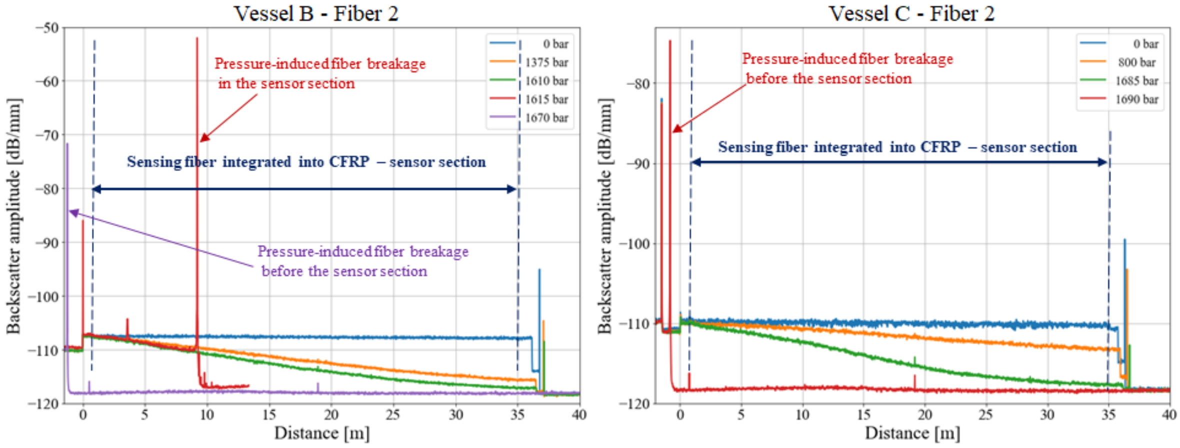

Fig. 2. Backscatter profiles of the sensing fibers integrated in the circumferential winding of the vessel B (left) and the vessel C (right) changing during the conducted slow burst tests.

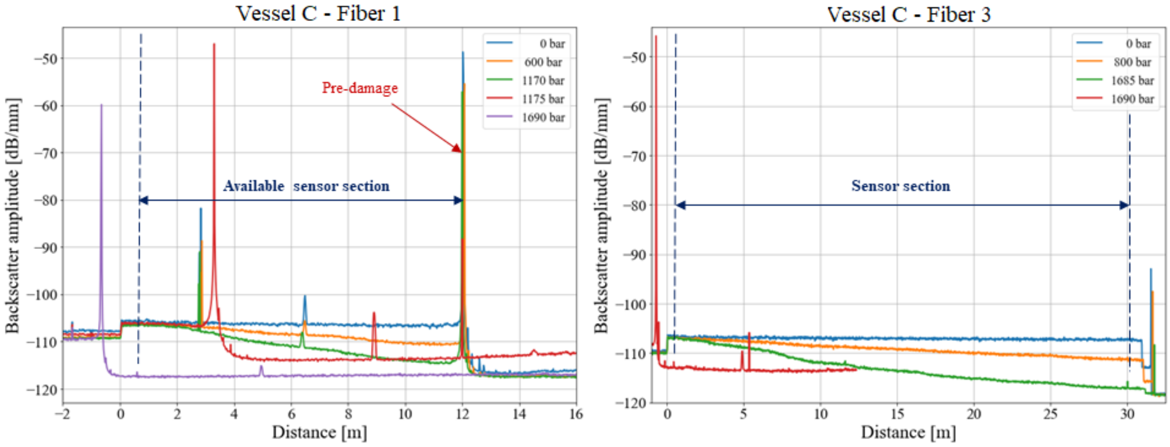

Fig. 3. Backscatter profiles of the sensing fibers integrated in the innermost helical winding (left) and in the penultimate outer helical winding (right) of the vessel C changing during the conducted slow burst tests.

The backscatter profiles shown above confirm the robustness of the selected sensing fiber type and the suitability of the investigated concept of FOS integration into CFRP.

The breakage of FOSs, as in case of Fiber 2 in vessel C (see Fig. 2 right) or Fiber 3 in the same vessel (see Fig. 3 right), only occured when the burst pressure was reached. The remaining two diagrams (Fig. 2 left and Fig. 3. left) prove pressure-induced sensor damage within the sensor section before the burst pressure was applied. The corresponding pressure values of 1615 bar for Fiber 2 in vessel B and 1175 bar for the pre-damaged Fiber 1 in vessel C are far above the nominal working pressure of 70 MPa (700 bar) of the tested CPVs.

The generally observed progressive decrease in backscatter along the sensing fibers (increase in optical attenuation) with ascending pressure is most likely caused by microbending effects. Such effects may make DSS calculation at extremely high-pressure values more difficult resulting in local outliers.

The results of the DSS measurements are represented graphically in Fig. 4 to Fig. 6. The pressure-induced strain gradients are illustrated here with a gradual increase in pressure $\Delta p = 5\ bar$. The n-th DSS measurement in the diagrams at the pressure p_n ($1 \leq n \leq 5$ in Fig. 4 and Fig. 6 or $1 \leq n \leq 21$ in Fig. 5) relates to a reference measurement at the pressure p_{Ref}. The following therefore applies to p_n:

$$p_n = p_{Ref} + n \cdot \Delta p$$

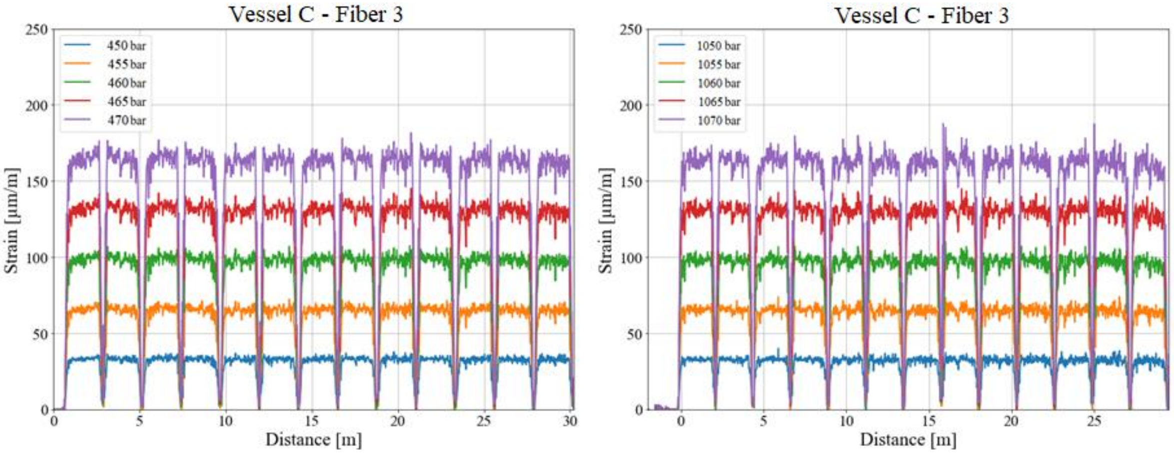

Fig. 4. Strain profiles of the fiber 3 integrated into the vessel C with increasing pressure.

All DSS measurement results indicate approximately linear strain response to pressure both for circumferential and for helical windings. As shown in Fig. 4 and Fig. 5, there are no strain gradients with increasing pressure in turning areas on both domes in helical windings.

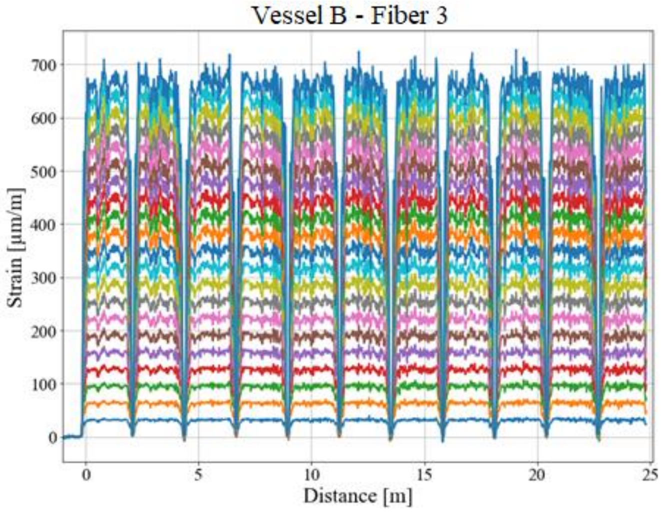

Fig. 5. Strain increase between 1500 bar and 1600 bar along the fiber 3 integrated into the vessel B ($p_{Ref} = 1495\ bar; \Delta p = 5\ bar$).

Fig. 5 proves the feasibility of the fiber optic DSS at high-pressure values, even at existing pre-damage of the sensing fiber 3 within the sensor section (11 of 13 lengths from dome to dome measurable). Such pre-damages can lead to higher reflections at the fiber breakage deteriorating the signal-to-noise-ratio.

As expected, the sensing fibers integrated into the penultimate outer helical winding (Fibers 3) have the lowest strain response to pressure. The rising microbending effects with increasing pressure also generate lower deviations of the measured distribution of strain gradients in the helical windings compared to the measured signals in the circumferential windings (Fibers 2).

The increase in strain near the opposite domes as well as the slight signal decrease in the middle of the sensor section as presented in Fig. 6 are related to design and manufacturing details of the tested CPVs.

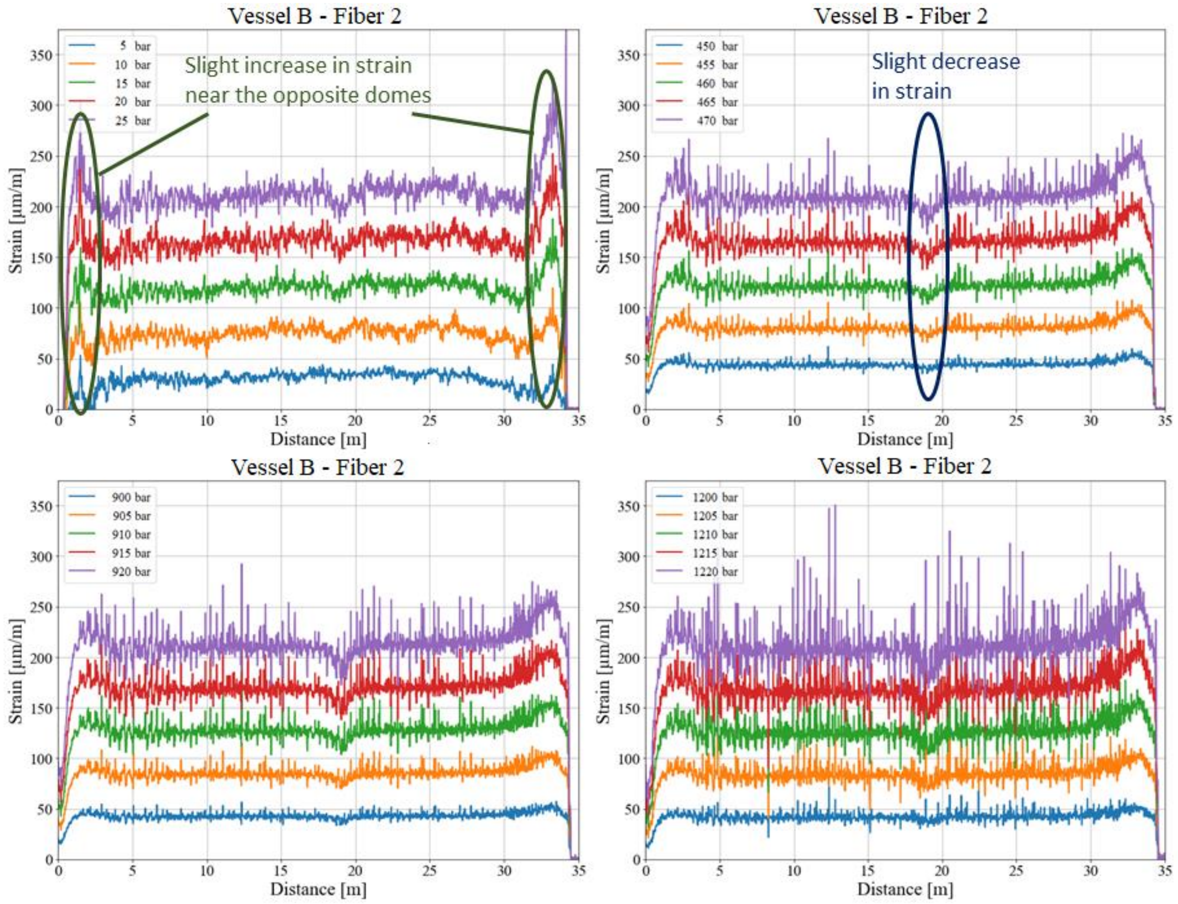

Fig. 6. Strain profiles of the fiber 2 (circumferential winding) of the vessel B with increasing pressure.

4. Conclusions

Distributed fiber optic strain sensing proves to be a suitable non-destructive method for condition monitoring of type IV CPVs. A faultless integration of sensing fibers directly on the liner into the first innermost helical winding of CFRP still remains challenging. The achieved results demonstrate the sensory capability for sensitive measurement of strain profiles above the nominal working pressure of 700 bar. The FOS strain response was found to be approximately linear in a wide pressure range.

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