

Structural Health Monitoring of Hydrogen Pressure Vessels using Distributed Fiber Optic Sensing

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Abstract. We report on distributed fiber optic sensing-based monitoring of hydrogen composite overwrapped pressure vessels (COPVs) to simultaneously increase the service life and mitigate maintenance costs. Our approach represents, to the best of our knowledge, the first application of distributed fiber optic sensing for COPV Type IV monitoring, where the sensing fibers are attached to the surface, rather than integrated into the composite material. Specifically, we attach an optical fiber of approximately 60 m to the vessel's surface, covering both the cylindrical and dome sections. We note that our fiber optic sensing technique relies on swept wavelength interferometry providing strain information along the entire length of the optical fiber with high spatial resolution on the millimeter scale. When the vessel is pressurized, the sensing optical fiber shows a linear strain response to pressure at every position along the optical fiber. After thousands of load cycles, the vessel finally fails with the optical fiber detecting and precisely localizing the damage in the vessel's blind dome area. Furthermore, we discuss the potential of state-of-the-art signal processing methods and machine learning for advancing predictive maintenance. This could reduce the number of regular inspections, mitigate premature maintenance costs, and simultaneously increase the vessel's remaining safe service life. We believe that the structural health monitoring of hydrogen COPVs with fiber optic sensors can enhance trust in hydrogen technology contributing to the energy transition in the future.

Keywords: Structural health monitoring, fiber optic sensors, hydrogen, composite pressure vessels, machine learning, predictive maintenance

1. Introduction

Over the last few decades, the performance and the range of applications of distributed fiber optic sensors (DFOS) have progressed significantly. Consequently, DFOS attracted a lot of attention in the field of structural health monitoring (SHM) [1]. SHM is of great importance to ensure safety and mitigate unnecessary maintenance costs. Specifically, DFOS have been widely applied in civil engineering to monitor structures like bridges, tunnels, and dams [2]. DFOS are also applied to monitor transportation networks, including railways and roads, and

proved effective in monitoring long pipelines of the oil and gas industry [3-5]. Furthermore, DFOS have been employed in the energy sector, to monitor wind turbines, subsea cables, and composite pressure vessels [6-9]. In the field of composites, in particular, DFOS with their small size typically in the micrometer range, offer significant advantages as they can be embedded within composite structures [10]. Embedded DFOS have already been employed to detect structural deformations in composites caused by delamination or impact damages [11]. Due to the reduced weight of pressure vessels made of composite materials, such as carbon-fiber reinforced polymers, these pressure vessels become more important for the storage of hydrogen.

Hydrogen could play a significant role in the transition towards a sustainable energy sector. DFOS, as an SHM method, can be applied to continuously monitor hydrogen pressure vessels to ensure safety and mitigate premature maintenance costs. Embedded DFOS have already been used for monitoring Type IV composite overwrapped pressure vessels (COPVs) that are designed for hydrogen storage with the results showing that DFOS provide signs of damages long before the vessel bursts [8].

In this paper, we use surface-applied optical fibers to monitor a Type IV COPV. In comparison to the previous approaches, where the optical fibers were integrated within the composite structure, the use of the surface-applied optical fibers reduces the application cost significantly. We describe the DFOS technique based on wavelength-scanning interferometry and the application of the optical fibers onto the COPV. The results present the strain response that is measured along the whole optical fiber when the vessel is pressurized, which can serve as an aging indicator. Furthermore, we show that after thousands of pressure load cycles, a leakage occurs. The surface-applied optical fibers were able to detect and localize the damage. Finally, the role and the benefits of machine learning in predictive maintenance are discussed.

2. Application of Distributed Fiber Optic Sensors

In contrast to point sensors, which measure only at predetermined positions, DFOS offer continuous monitoring capabilities since every point of the fiber is a sensor. We made use of a DFOS system based on swept-wavelength interferometry which is known as optical frequency domain reflectometry (OFDR). This technology is based on Rayleigh scattering and only needs access only to one end of the fiber. Details about the OFDR working principle can be found in [12]. OFDR measures variations of temperature and strain between a reference and a measurement signal. Fig. 1 shows a reference (blue) and a measurement (orange) OFDR trace. Once these traces are acquired, they are divided into segments with a length defined by the so-called gage length. In practice, this gage-length determines the spatial resolution. Afterwards, a fast Fourier transformation is applied to each segment and through cross correlation analysis the shift between the two signals is calculated. That shift is called frequency shift and is linearly proportional to temperature and strain changes.

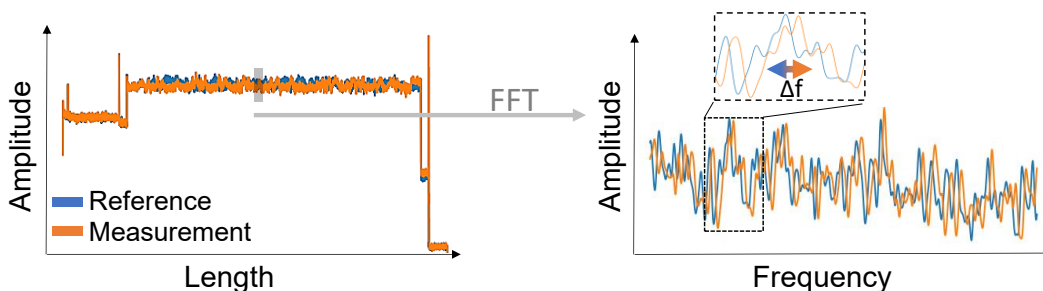


Fig. 1. Illustration of the optical frequency domain reflectometry (OFDR) signal processing.

For monitoring a Type IV COPV with a diameter of 228 mm and a length of 1510 mm (NPROXX GmbH, Heerlen, Netherlands), a 60-m polyimide (PI)-coated single-mode optical fiber (SM1500 (6.4/125)P, Fibercore, Southampton, UK) was used. This fiber variant is characterized by a core diameter of 6.4 μm , a cladding diameter of 125 μm and a coating diameter of 156 μm . Studies have shown that in contrast to a standard single mode fiber, this specific fiber contributes towards a higher backscattered amplitude due to the higher germanium doping and numerical aperture, which in turn results in higher strain accuracy [13].

As already mentioned, the optical fiber was wrapped on and glued to the vessel's surface. A schematic illustration of the COPV with the surface-applied optical fibers is shown in Fig. 2. The figure illustrates that the optical fibers were wrapped in a circumferential direction, which exhibits a higher strain sensitivity in comparison to wrapping along the axial direction [14]. We note that at the dome areas, the fiber wrapping is slightly different compared to the cylindrical part, as shown in Fig. 2. To ensure stability and protect the optical fiber from potential external damages, the optical fiber was glued using an epoxy resin-based adhesive, which after curing, was covered by a silicone layer.

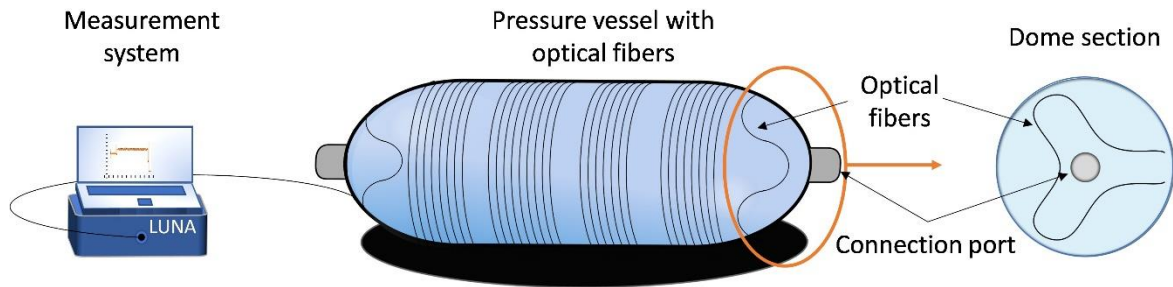


Fig. 2. Schematic illustration of the composite overwrapped pressure vessel (COPV) with hoop layers of surface-applied optical fiber wrapped around the cylindrical part. In the dome areas, optical fibers are positioned as depicted on the right.

The fiber configuration is as follows: First the sensing fiber goes from the measurement system (LUNA OBR 4600, Luna Innovations Inc., Roanoke, VA, USA) to the blind dome area, whereafter it covers the cylindrical part forming four distinct sections. The optical fiber ends at the dome area which is connected to the hydraulic pressure machine (PN020, Maximator GmbH, Nordhausen, Germany).

The COPV with the surface-applied optical fibers was exposed to approximately 60000 load cycles before a leakage occurred. Load cycles are characterized by periodic changes of the internal pressure between a lower and upper pressure level. In our measurement campaign, we set the lower and upper pressure levels to 0 bar and 800 bar, respectively. The hydraulic load test was performed initially at 50 $^{\circ}\text{C}$. However, in order to initiate a material failure, after approximately 22000 load cycles the temperature was increased to 65 $^{\circ}\text{C}$. We introduced pressure ramps at regular time intervals where the pressure levels were kept constant for a few seconds because the measurement system that we employed allows only quasi-static measurements.

3. Results and Discussion

Fig. 3 presents the strain profile along the entire length of the sensing fiber under a load of varying pressure levels. Sections of the fiber without a change in strain indicate areas where the fiber was not attached to the COPV. These sections were deliberately left strain-free to act solely as temperature sensors. In contrast, the fiber sections that show strain changes in response to pressure are those glued to the vessel's surface, as illustrated in Fig. 2. The four

central sections are characterized by significant strain changes. They result from the fiber being wrapped around the vessel's cylindrical part. The two sections at the start and at the end of the sensing fiber showing lower strain changes correspond to the dome sections. The dome section at approximately 2 m is the blind one, whereas the other at 56 m, is the one with the connection port.

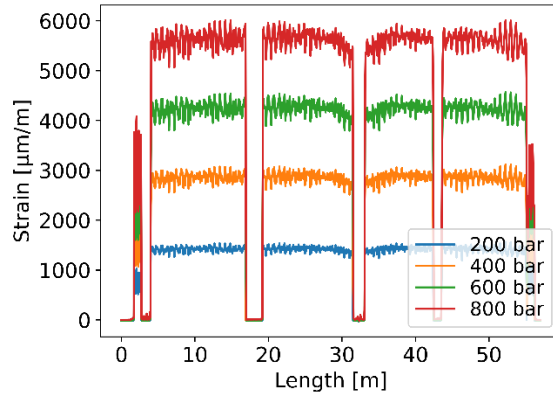


Fig. 3. Strain profiles along the optical fiber at different pressure levels.

A detailed view of the strain profile within the blind dome section is shown in Fig. 4. The grey and green dots correspond to the ingress and egress position, respectively. We observe that the positions close to the vessel's cylindrical part exhibit strain levels almost double than those close to the boss. In general, the measured strain depends on the thickness of the composite material and the wrapping angle of the optical fibers. Therefore, the fluctuations in strain within the dome area result from the complex structure and varying wrapping angles.

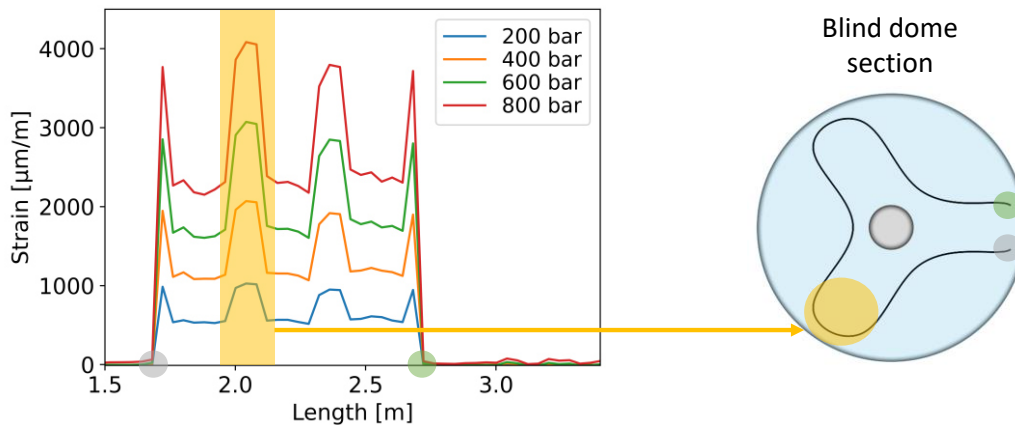


Fig. 4. Strain profile along the fiber that is wrapped around the blind dome area. The grey and green dots represent the ingress and egress positions.

The measured strain (ϵ) increases linearly with pressure as shown in Fig. 5a. As an example, at a position of approximately 10 m of the fiber length, the pressure sensitivity is estimated at $6.97 \pm 0.02 \mu\epsilon/\text{bar}$. However, during the measurement campaign we noticed, that the pressure sensitivity increases with the number of load cycles, which is attributed to vessel's aging. The pressure sensitivity over the whole measurement campaign until the vessel's failure is shown in Fig. 5b. We observe that at around 22000 load cycles there is a sudden increase in the pressure sensitivity. This coincides with the temperature increase from 50 °C to 65 °C. We need to note that the temperature effect was compensated by using the strain-free optical fiber segments (Fig. 3) and data from preliminary temperature tests conducted without pressure loads. These tests revealed that the optical fiber's temperature

coefficient is $-1.32 \text{ GHz}/^\circ\text{C}$, whereas for the surface mounted fibers, this temperature coefficient increases to $-1.91 \text{ GHz}/^\circ\text{C}$ due to the vessel's thermal expansion coefficient.

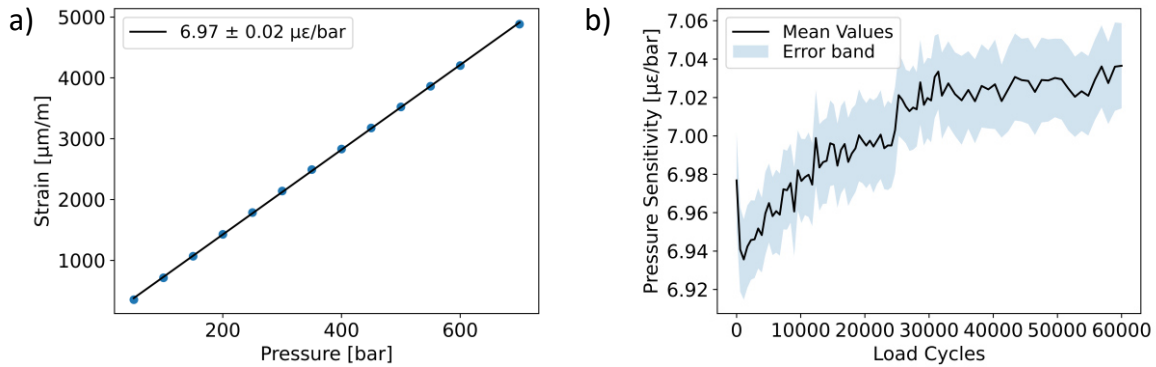


Fig. 5. a) Linear strain change with pressure of a fixed position at approximately 10 m. b) Mean pressure sensitivity between 9 m and 11 m over the whole measurement campaign.

After approximately 60000 load cycles, a leakage occurred, and the measurements were terminated. Fig. 6a shows a photograph of the internal view of the damage, which is located in the blind dome area. From this image, it is obvious that the damage involves the plastic liner. However, it remains unclear whether the composite structure is also affected. For this reason, X-ray computed tomography (XCT) was employed which revealed delamination within the innermost carbon layers as shown in Fig. 6b.

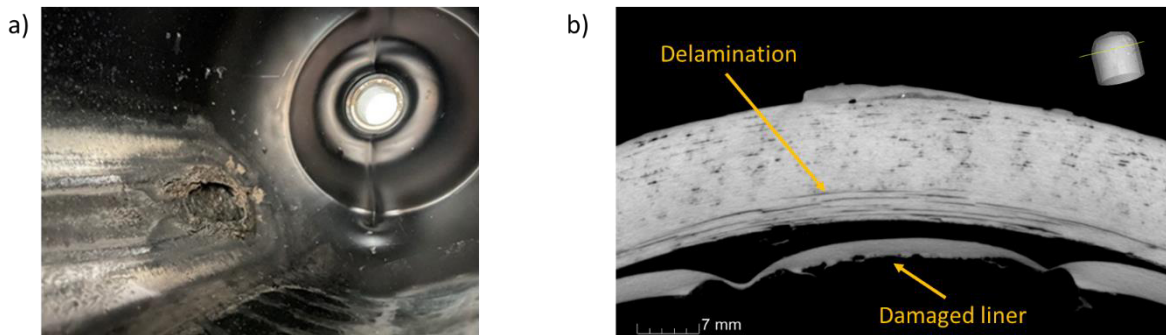


Fig. 6. a) Photograph of the internal view of the blind dome section, where a damage to the liner is visible. b) X-ray computed tomography (XCT) scan performed at the damage location. Apart from the liner damage, delamination within the composite structure is shown. The cut angle of the XCT scan is depicted in the upper right corner.

Fig. 7 shows two measurements of this area before and after the damage, where a clear strain difference becomes visible. We note that the two measurements were conducted under approximately pressureless conditions. The yellow frame is the same as shown in Fig. 4 and helps to correlate the positions between the two plots. The strain relaxation that is observed after the strain peak results from the complex composite structure and the varying wrapping angles as described previously. The results in Fig. 7 show that surface-applied optical fibers can successfully detect and localize even small-scale damages that includes mostly the liner and the innermost carbon layers.

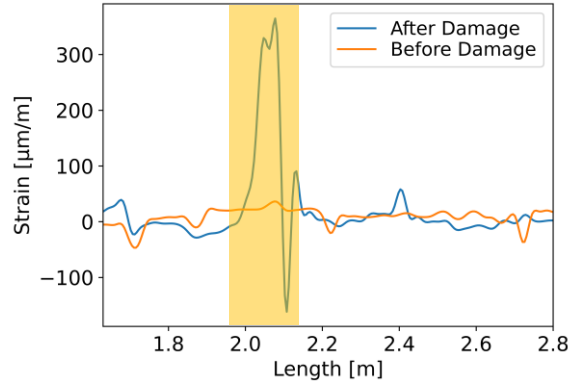


Fig. 7. Strain profile of the dome section before and after the damage. The yellow frame contains the damaged section and corresponds to the frame in Fig.4

To open the way for predictive maintenance using surface-applied optical fibers, damage precursors need to be detected. To this end, a machine learning-assisted data analysis could play a significant role. We note that in the last few years machine learning has been used in many SHM methods to detect early signs of damages [15]. In the field of DFOS, machine learning could also be used to analyze time series data for each sensing position. For example, from Fig. 5b we derive that the pressure sensitivity increases over time, which is attributed to the vessel’s aging. Even though such an increase in pressure sensitivity is expected during normal operation conditions, in some cases it could also indicate damage, as shown in [14]. Furthermore, more features including statistical parameters from the time series data could be extracted to improve the machine learning model [16]. As we have already mentioned in [14], machine learning could also be used to enhance the DFOS signal processing in terms of strain accuracy and provide solutions towards temperature and strain discrimination [17].

To develop robust machine learning models for predictive maintenance more experiments are required. However, the high cost of the lifetime tests of composite pressure vessels limits the number of data that can be collected. This necessitates the training of probabilistic machine learning models that are interpretable and can be effectively trained using small datasets.

4. Conclusions

In this paper we used surface mounted DFOS to monitor a Type IV COPV. The results showed that DFOS can successfully detect and localize damages even in cases where small-scale damages occur. These results can open the way for a cost-effective method to monitor COPVs for hydrogen storage which contributes to a sustainable energy transition.

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