

Towards predictive maintenance of hydrogen pressure vessels based on multi-sensor data fusion and digital twin modelling

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Abstract. Hydrogen pressure vessels are among the most essential components for reliable hydrogen technology. Under current regulations, a mostly conservative strategy is employed, restricting the usage time of hydrogen pressure vessels without providing information on the real remaining lifetime. During the service life, pressure vessels are inspected periodically. However, no established method can provide continuous monitoring or information on the remaining safe service life of the vessel.

In this paper, we propose a sensor network for structural health monitoring (SHM) of hydrogen pressure vessels where data from all sensors are collected and centrally evaluated. Specifically, we integrate three different SHM sensing technologies namely ultrasonic guided waves (GW), acoustic emission (AE) testing, and distributed fiber optic sensors (DFOS). This integrated approach offers significantly more information and could therefore enable a transition from costly and time-consuming periodic inspections to more efficient and modern predictive maintenance strategies, including artificial intelligence (AI)-based evaluation. This does not only have a positive effect on the operational costs but enhances safety through early identification of critical conditions in the overall system in real time.

We demonstrate an experimental set-up of a lifetime test where a Type IV composite overwrapped pressure vessel (COPV) is investigated under cyclic loading instrumented with AE, DFOS, and GW methods. We acquired data from the sensor network until the pressure vessel failed due to material degradation. The data collected using the three different SHM sensor technologies is evaluated using data fusion, and AI. In the future, we aim to integrate the measurement setup into a hydrogen refueling station with the data stream implemented into a digital signal processing chain and a digital twin.

Keywords: Structural health monitoring, fiber optic sensors, ultrasonic guided wave, acoustic emission testing, hydrogen, composite pressure vessels, digital twin, predictive maintenance

1. Introduction

In recent years, hydrogen has attracted a lot of interest as a clean energy carrier and potential alternative to fossil fuels. Hydrogen is usually stored in Type IV composite overwrapped pressure vessels (COPVs). These pressure vessels that are made of a plastic liner overwrapped by carbon fiber-reinforced polymer offer high capacity and lightweight design [1]. To ensure safety, the COPVs are characterized by a predefined service lifetime and need to undergo regular inspections [2]. Non-destructive evaluation (NDE) methods, such as x-ray tomography, thermography and ultrasonic imaging are suitable for regular inspections, but they cannot be used for continuous condition monitoring and usually require the object under inspection to be out of service. In contrast to NDE, structural health monitoring (SHM) techniques allow real-time condition monitoring [3]. Therefore, the SHM of COPVs is expected to reduce maintenance costs, extend the specified service life, and enhance safety.

In this paper, we make use of a SHM sensor network consisting of distributed fiber optic sensors (DFOS), ultrasonic guided waves (GW), and acoustic emission (AE) sensors. Although all these SHM methods have already been employed separately in condition monitoring of Type IV COPVs [4-6], in this paper we apply these methods simultaneously. This approach provides three channels of information for assessing the pressure vessel's structural integrity and can facilitate predictive maintenance. We note that so far, no established method that can predict the remaining useful lifetime has been demonstrated.

2. Installation of the Structural Health Monitoring Sensors

For our investigations, we made use of a Type IV COPV manufactured by NPROXX (Heerlen, Netherlands) as can be seen in Fig. 1. Since it is a Type IV COPV, it consists of a plastic liner and overwrapped carbon fiber reinforced polymers. The vessel's outer diameter and total length was 228 mm and 1510 mm, respectively.



Fig. 1. Photograph of the experimental setup. The COPV is carried via tension belts inside the test rig (PN020) equipped with a hybrid sensor network consisting of AT, DFOS and GW sensors.

2.1 Distributed Fiber Optic Sensors

Unlike pointwise sensors that measure only at specified positions, distributed fiber optic sensors (DFOS) measure without gaps along the entire length of an optical fiber. In this paper we make use of a distributed fiber optic sensing technology based on swept wavelength interferometry and specifically the commercial device LUNA OBR 4600 (Luna Innovations, Inc., USA). In short, this method enables temperature or strain measurements

with high spatial resolution in millimeter range. Strain and temperature changes are calculated by cross-correlating Rayleigh backscatter profiles from actual and reference measurements in the frequency domain. Further details about this fiber-optic sensing technique can be found in [7].

A polyimide (PI)-coated single-mode optical fiber (SM1500 (6.4/125)P, Fibercore), with a length of approximately 60 m was employed as the sensing fiber. The fiber consists of a core, cladding, and coating, with diameters of 6.4 μm , 125.0 μm , and 156.0 μm , respectively. This specific fiber variant is characterized by a higher germanium doping and expanded numerical aperture in comparison to a standard acrylate-coated fiber. These characteristics result in enhanced backscattered amplitude, which in turn contributes towards a higher strain accuracy [8].

To ensure robustness and protect the optical fiber during monitoring the optical fiber wrapping process took place as follows: First, the pre-strained optical fiber was wrapped in a circumferential direction around the vessel's cylindrical part as shown in Fig. 2. The fiber placement at the dome area is slightly more complex. The optical fiber was glued with an epoxy resin-based adhesive. After the curing of the adhesive, a layer of silicone was applied to protect the optical fiber from potential mechanical damage. As can be seen in Fig. 2, on the vessel's cylindrical part there are three sections where no optical fibers are placed. This was done intentionally to ensure safe handling by a crane during the vessel's placement into the pressure machine.

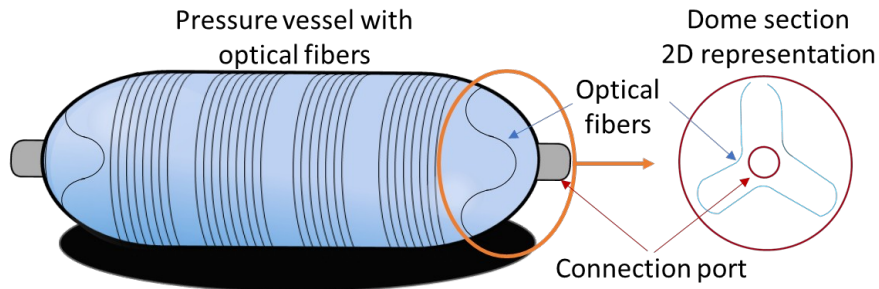


Fig. 2. Schematic illustration of the COPV with hoop layers of surface-applied optical fiber wrapped around the cylindrical part. In the dome areas, optical fibers are positioned as depicted on the right.

2.2 Ultrasonic Guided Waves

For monitoring and assessing the condition of Type IV COPV with GWs, a sensor network comprising piezoelectric wafers (PZT) was applied to the pressure vessel's cylindrical surface. The sensor network consisted of three rings, each equipped with five PZTs. The PZTs were placed at approximately 72-degree intervals around the circumference with a distance of 610 mm between the single rings so that the total length of the COPV is covered, as shown in Fig. 3. The PZTs used in the setup were DuraAct patch transducers (P 876K025) with a 10 mm circular ceramic embedded in a ductile polymer from PI Ceramics (Lederhose, Germany). The total of fifteen PZTs were bonded to the COPV's surface with a thin layer of two-component epoxy adhesive and then connected to a VantageTM 64 LF system from Verasonics (Kirkland, USA).

Being an active measuring method, the data acquisition methodology involves a sequential operation where a single PZT is operated as an actuator while the remaining PZTs serve as sensors. This role alternates until each PZT has served as an actuator. This results in an entire dataset of 105 different actuator-sensor combinations. Based on previous experiments on wave propagation characteristics within the pressure vessel, a five-cycled and von Hann-filtered sine wave for two different excitation frequencies ($f_1=130$ kHz and $f_2=220$ kHz) were used to excite the GWs [9].

2.3 Acoustic Emission Testing

Acoustic emission (AE) testing is a mature and common method to identify defects in materials by detecting acoustic signals. The elastic energy released from a defect or imperfection within a pressure vessel that undergoes loading generates acoustic waves detectable by AE sensors. These sensors are piezoelectric and convert the acoustic waves recorded by the sensors into electrical signals. The conventional analysis of AE data allows for evaluating waveform signals or the features extracted from these signals (e.g., amplitude).

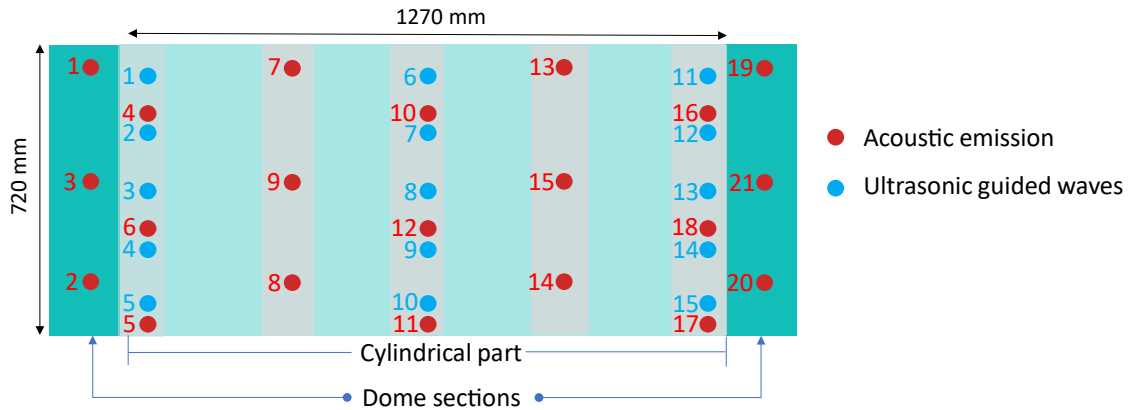


Fig. 3. Schematic 2D illustration of the COPV with the positions of the guided wave (GW) sensors and acoustic emission (AE) sensors marked in blue and red, respectively.

3. Results and Discussion

Once the SHM sensors were installed, the COPV was placed into a hydraulic internal pressure machine (PN020, Maximator GmbH) for load cycle testing (Fig. 1). This testing involves periodic changes in internal pressure between a predetermined lower and upper pressure level. Initially the lower and upper pressure level was set to 0 bar and 800 bar respectively, while the ambient temperature was set to 50 °C. To accelerate material failure, after 22000 load cycles the ambient temperature and the maximum pressure level were increased to 65 °C and 900 bar, respectively. Finally, the pressure vessel failed after 60000 load cycles. Fig. 4 shows an internal view of the damaged vessel. The damage occurred mostly in the plastic liner, which let the liquid penetrate through the composite material and leave the vessel.



Fig. 4. Internal view of the damaged pressure vessel.

Fig. 5 shows a 2D representation of the blind dome area of the COPV with the surface-applied optical fibers. We observe that at the bottom left area close to the vessel's cylindrical section, the strain is significantly increased. This measurement was conducted once the leakage occurred and shows that DFOS managed to detect and precisely locate the damage. The observed slight relaxation, depicted in deep purple, is due to both the structural deformation caused by high strain in neighboring positions (depicted in yellow) and the complex geometry and wrapping angles of the optical fibers within the dome area.

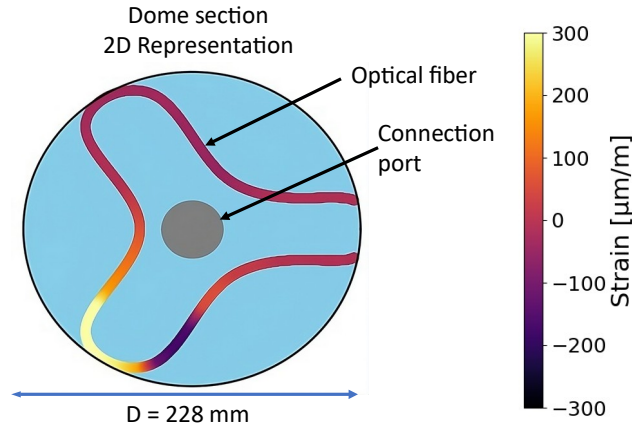


Fig. 5. Distributed fiber optic sensors detect and localize damage precisely at the position where it occurred. The colors indicate the measured strain in the fiber.

The condition of the COPV was monitored using GWs at predefined pressure levels. At each pressure level the fifteen surface-mounted PZTs were used for recording 105 time series for each excitation frequency corresponding to 105 sensor-actuator pairs. As an example, the recorded time series for path 1-2, pressure level 50 bar, and 220 kHz excitation frequency are shown in Fig. 6a. These GW signals were then analyzed using an unsupervised deep learning model called TimesNet [10] where the first measurement was used for training and the rest of the measurements were used for model evaluation. The reconstruction error of the model was used as the anomaly score and is displayed in Fig. 6c where the colors again indicate the chronological order of the experiments exactly like Fig. 6a. Both the raw data and the anomaly scores clearly demonstrate the gradual changes occurring during the cyclic loading of the COPV which reveal that GWs are well suited for continuous monitoring of the COPV since they are clearly sensitive to material aging. Fig 6b shows the localization results based on reconstruction algorithm for probabilistic inspection of damage (RAPID) [11] used together with the anomaly scores calculated by the TimesNet model. The red areas highlight the regions with the highest anomaly scores after applying the localization method. The red region close to sensors 1, 4, and 5 overlaps the position of the actual damage located between sensors 1 and 5. These results clearly demonstrate the capability of GWs for continuous monitoring of COPVs.

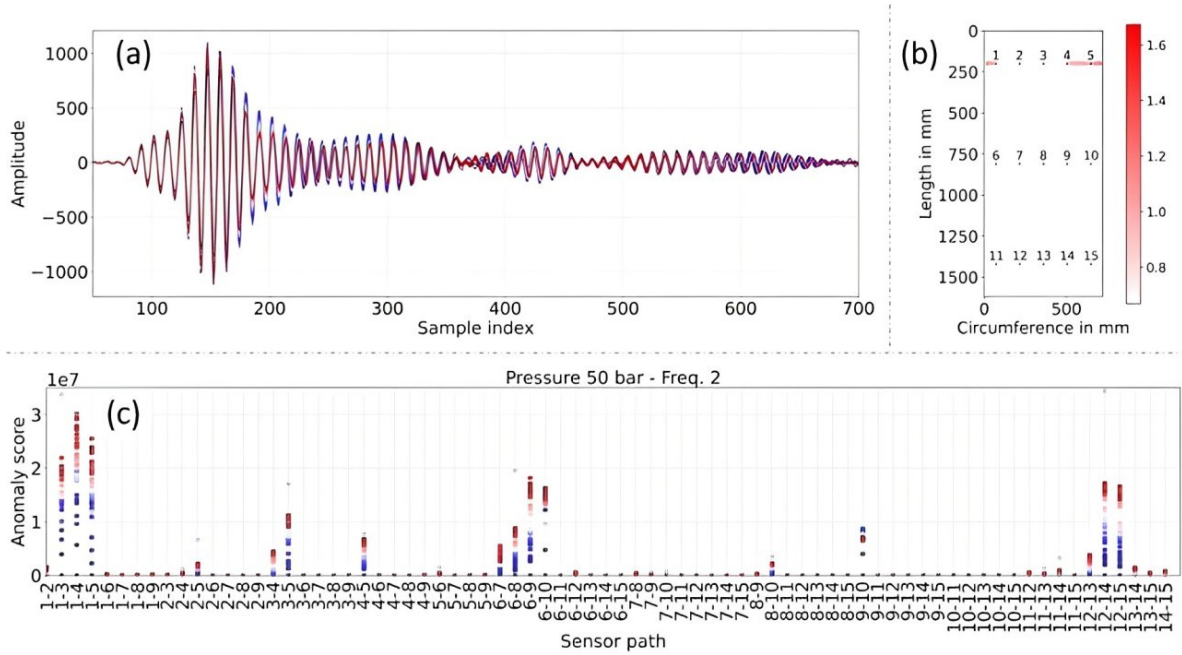


Fig. 6. GWs offer a robust methodology for assessing the aging process and localizing possible defects. Figure (a) shows the recorded signals for path 1-2 at pressure level 50 bar and for an excitation frequency of 220 kHz. The colors go from blue to red which correspond to the measurements starting from the beginning up until the failure of the COPV. Figure (b) shows the localization results based on the RAPID method and the calculated anomaly scores using the TimesNet model. The highlighted region corresponds to the position of the damage located between sensors 1 and 5. Figure (c) shows the anomaly scores calculated for all 105 sensor paths using the TimesNet model.

Fig. 7. shows the accumulated AE energy recorded from all the ring sections (as depicted in Fig. 3) during the last 900 load cycles. In general, we observe that the channels that are located at the blind dome area, where the vessel failed show a higher AE energy than those sensors placed at the other sections of the vessel. Furthermore, we observe that 300 cycles (60 min) before the vessel's failure, a progressive increase in energy is observed which indicates an upcoming failure.

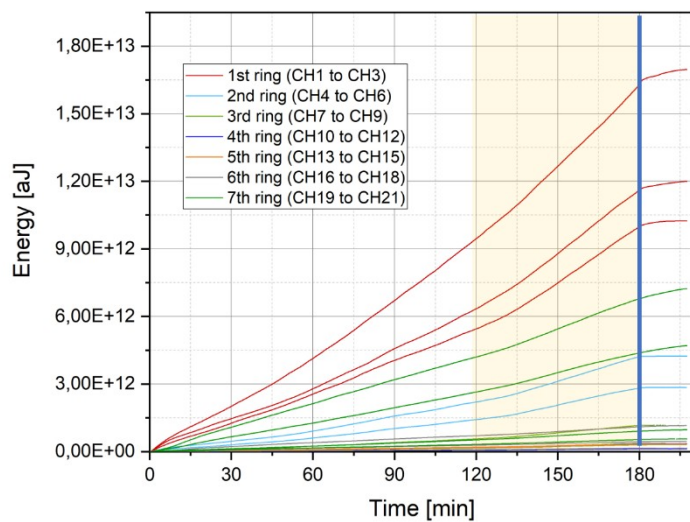


Fig. 7. Accumulated AE energy for the different ring sections (see Fig. 3): progressive energy increase for the last 300 cycles (yellow frame) especially in the dome section (1st ring) indicating upcoming failure. The failure occurred at 180 min (blue vertical line).

Our results are very promising for further studies considering that all the applied SHM methods provided useful information for assessing the pressure vessel's structural integrity. In the future, we plan to conduct more lifetime tests and collect data to train a machine learning model using data fusion. A data stream resulting from the three SHM methods will be implemented into a digital signal processing chain and will end up into a digital twin, as shown in Fig. 8. The digital twin will be a digital model of the real pressure vessel depicting its current condition, structural integrity, and operational parameters. Such a quality infrastructure will allow predictive maintenance by analyzing real-time data, warning for potential issues, and estimating remaining service life.

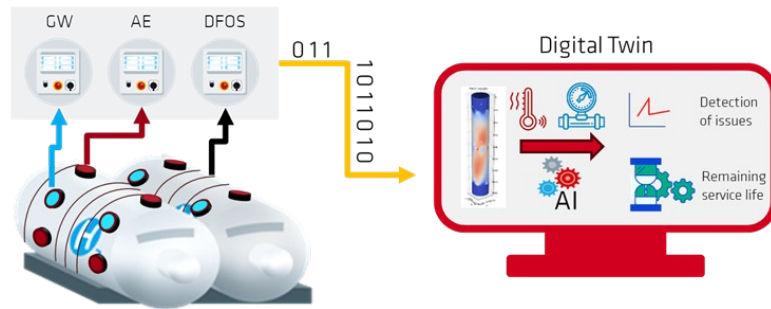


Fig. 8. Digital twin implementation for structural integrity assessment, and remaining service life estimation of the pressure vessel

4. Conclusions

In this paper, we demonstrated a SHM sensing network for monitoring COPV consisting of DFOS, GWs and AE. The results showed that the combination of all these SHM methods allows damage detection and localization and has the ability to provide early warning signals. The implementation of the proposed digital twin aims to digitalize the quality infrastructure to ensure safety while mitigating maintenance costs. Our work in Structural Health Monitoring (SHM) of COPVs for hydrogen storage is anticipated to contribute to the ongoing efforts in the energy transition towards a greener and more sustainable future.

Acknowledgments

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