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Toward a Digital Twin of Hydrogen Pressure Vessels Enabled by Distributed Fiber Optic Sensors

Christos Karapanagiotis, Marcus Schukar, Mathias Breithaupt, Konstantin Hicke
Bundesanstalt für Materialforschung und-prüfung, Berlin, Germany
konstantin.hicke@bam.de

Summary:
We present a digital replica of a hydrogen pressure vessel enabled by distributed fiber optic sensors (DFOS). This digital replica dynamically displays and updates the vessel's structural condition by calculating strain residuals defined as the difference between the measured DFOS strain and the expected strain based on pressure data. As an example, we show the ability of the DFOS to detect and localize damage caused by drilling six holes into the vessel's body. This digital replica represents a foundational step toward a fully integrated digital twin for predictive maintenance and remaining lifetime prognosis.

Keywords: fiber optic sensors, structural health monitoring, predictive maintenance, hydrogen, digital twins

Introduction

The demand for composite overwrapped pressure vessels (COPVs) for hydrogen storage is expected to rise significantly in the future, driven by the ongoing energy transition toward sustainable sources. Therefore, an efficient and cost-effective solution to ensure safety and long-term sustainability is of high importance. Currently, COPVs are operated under strict regulations, including regular and time-consuming inspections to assess their structural integrity [1]. The need of these regular inspections could be partially eliminated by using DFOS for continuous and real-time monitoring. So far, DFOS have been used for COPV monitoring only under stable pressure conditions [2,3].

In this paper, we present, to the best of our knowledge, for the first time a digital replica of a hydrogen pressure vessel that dynamically updates the structural condition by analyzing real-time DFOS and pressure data. We show that digital twins based on data streams from DFOS could facilitate predictive maintenance and remaining lifetime prognosis.

Results

Fig. 1a shows a section of the tested COPV with surface-applied optical fibers, along with damage caused by drilling six holes into the composite structure. The optical fibers were wrapped circumferentially around the COPV with a relatively fixed wrapping angle, ensuring that the distance between two consecutive windings was approximately 20 mm. Because these fibers are generally sensitive to both strain and temperature, additional strain-free optical fibers were used to compensate the temperature effect. To render these fibers strain-free, they were placed inside capillary tubes glued along the vessel's horizontal direction. Two of these capillary tubes are visible in Fig. 1a.

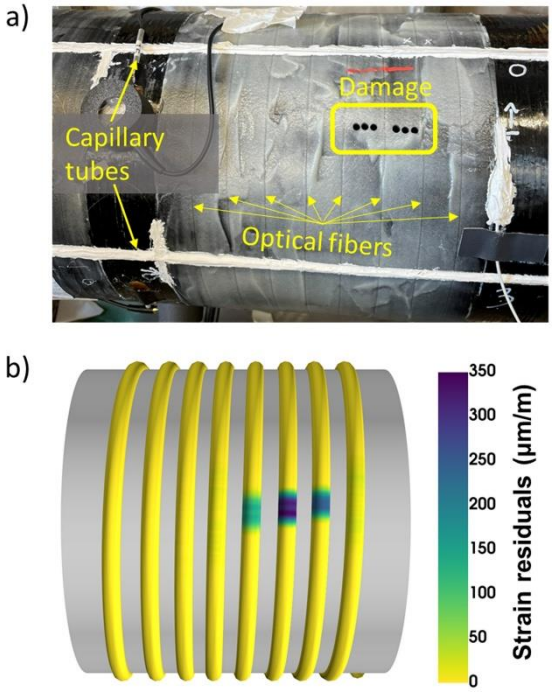

Fig. 1. A composite overwrapped pressure vessel (COPV) with damage caused by drilling six holes, monitored using distributed fiber optic sensors (a), and a 3D visualization of the calculated strain residuals.

Fig. 1b shows a 3D visualization of the DFOS results after drilling six holes of a depth and diameter of 8 mm and 4 mm, respectively. DFOS measurements were conducting using the commercial interrogator LUNA ODiSI 6100 (Luna Innovations Inc., Roanoke, VA, USA). Further details about the sensing technique can be found in [4]. We observe that DFOS are able to detect, localize and quantify the damage in terms of strain residuals. The strain residuals result from the difference between the measured strain and the expected one under normal (undamaged) conditions. The expected strain arises from a simple regression model that outputs strain based on pressure data [5].

Results from previous experiments show that DFOS are also capable of providing early indications of damage through strain residuals, even a few thousand of pressure cycles before failure [2]. These results, combined with the real-time sensing capabilities, can clearly open the way for the development of digital twins, such as the one shown in Fig. 2.

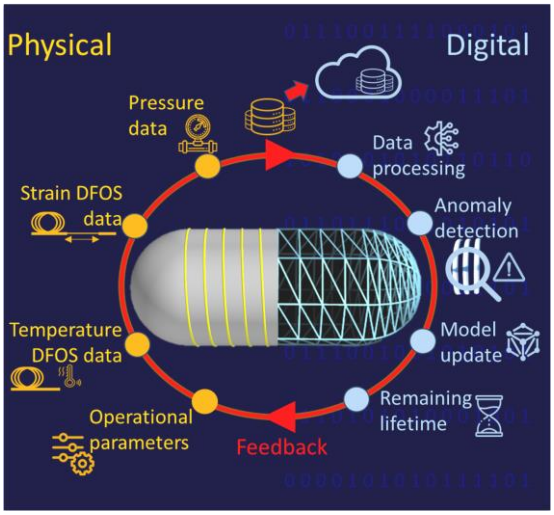

Fig. 2. The concept of a digital twin enabled by distributed fiber optic sensors (DFOS). DFOS and pressure data are sent in real-time from the physical to the digital domain. In the digital domain, the data are processed, anomalies are detected, remaining lifetime is predicted, and commands are sent back to the physical object.

The physical object is the real COPV instrumented with DFOS. The DFOS data along with pressure data are sent to a cloud. The digital replica is updated in real-time using the data stream from the physical object. In the digital domain, the data are processed and anomalies, like the one shown in Fig. 1b are detected. Then feedback is sent to the physical domain to determine whether to continue or terminate the operation.

While our system is able to detect early signs of damage in COPVs, it is currently unable to reliably assess the severity of the detected damage. Future work will focus on developing machine learning methods to classify damage severity and estimate the COPV remaining service lifetime. The estimation of the remaining lifetime is expected to reduce maintenance costs, enable more timely inspections, enhance the sustainability of the technology, and yield positive economic impacts overall. To achieve this, we will make use data from previous experimental campaigns as well as data to be collected from planned future experiments. However, we need to mention that due to the time-consuming and expensive nature of such experiments, simulations and probabilistic machine learning algorithms that can generalize well even with limited data should be employed.

Conclusions

We have reported to the best of our knowledge for the first time on a digital replica of a hydrogen pressure vessel enabled by DFOS data. Up to now, the digital replica allows for anomaly detection based on DFOS and pressure data. In the future, we will also include data from other COPVs that have already been tested and in combination with probabilistic machine learning, we will incorporate remaining lifetime prognosis.

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