Robotic End-of-Line Testing for Hydrogen Pressure Vessels Using a Strain-Based SHM System

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ABSTRACT

High safety factors lead to increased material input and costs for Composite Overwrapped Pressure Vessels (COPV) in hydrogen mobility. Reducing safety factors in the form of material can improve profitability, but reliability must be maintained. Currently, there is no automated end-of-line testing that can help quickly and reliably check the structural integrity and enhance testing scalability for COPVs. Our novel approach to COPV quality assurance uses robotically applied test loads to inspect the structural condition of each COPV. It captures the structural response using a strain-based SHM system. The design of the sensor layout for this application faces two central challenges: selecting an efficient combination of measuring points, damage indicators, and appropriate test loads and ensuring the system is functional as an onboard SHM system. In the context of this conference contribution, we explain the mentioned quality assurance approach in more detail. Additionally, the first results in the design of the sensor layout, which measures the structural state of COPV in robotic testing and onboard operation, are presented.

INTRODUCTION

Manufacturing costs must be reduced significantly to make hydrogen-powered road, water, or air vehicles attractive and competitive and achieve the necessary economies of scale for broad market penetration. One cost driver here is material costs [1]. Specific and cost-intensive materials in fuel cell vehicles include fiber composites, which comprise the supporting structure of most current pressure vessels for gaseous hydrogen. In the mobility sector, type IV vessels, i.e., the design with load-bearing outer layers made of carbon fiber-reinforced plastic (CFRP) and an inner vessel made of a thermoplastic, the so-called ”liner,” have proven successful. Today’s Type IV pressure vessels are designed with safety factors over 2.0 concerning operating pressure. Reducing the current safety factors by reducing the CFRP layers used in Type IV pressure vessels is an essential ”adjusting screw” for the widespread use of fuel cell vehicles. Safety factors can

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only be reduced if uncertainties in the design and manufacturing phases are reduced.

If the aim is to achieve this reduction in the long term and establish it in the type approval, quality assurance (QA) in the manufacturing process and structural monitoring in operation will become even more important than before. The QA in the manufacturing process ensures that each pressure vessel meets the required standards in terms of structural integrity. Furthermore, the particular product condition and the SHM system can calibrate for continued operation monitoring. Calibration and measurement of individual structures at the entry-into-service are key in implementing Digital Twins to evaluate individual product lives. In order to achieve all these mentioned tasks even at targeted high volumes, we are investigating robotic, automated end-off-line testing, which will be presented in this paper.

The text is structured as follows: We begin with a brief overview of hydrogen pressure vessel testing and derive the approach for our measurement procedures. Subsequently, the development of the test bed is introduced, and the first results from comparing different measurement approaches are presented. Finally, a summary with an outlook on future work follows.

TESTING OF HYDROGEN PRESSURE VESSELS

So far, the QA of pressure vessels for gaseous hydrogen has essentially been carried out in two steps: In the first step, the finished winded vessels are filled with water and pressurized to test them for leaks, while in the second step, a visual inspection is carried out. Visual inspection involves looking for and identifying possible damage or irregularities on the container surface. There is potential for improvement in both the first and second steps. Above all, visual inspection is associated with a specific variability due to the human factor and with a significant expenditure of time. Given the issues of process improvement and cost reduction, this gives rise to the need to initiate a development that enables a reliable statement regarding the structural integrity of each pressure vessel in a fast and automated form.

In end-of-line testing, the use of SHM is sparsely documented. In this section, leak testing predominates. Concerning structural integrity, these are one-off or sample measurements in the sense of a manually performed inspection. Therefore, non-destructive testing (NDT) methods are usually considered here [2, 3]. However, for monitoring structures in their operational phase, there are already many different SHM approaches [4]. Next, vibration-based, ultrasonic-based, or acoustic emission, also strain-based approaches, have already been investigated, usually using fiber optic sensors [5–9]. In prior research unrelated to COPVs, strain-based SHM techniques were employed, utilizing a concept known as Structural Damage Indicators (SDIs) [10]. These SDIs rely on baselines or zero references, such as the strain measured at the neutral axis of a beam or the direction of zero strain trajectories [11, 12].

However, when dealing with a COPV, the existing SDIs cannot be directly applied due to the dominant load case of internal pressure, which does not result in a neutral axis or a zero strain direction. We, therefore, address the research question: Can the use of external loads positively influence the monitoring of hydrogen pressure vessels using a strain-based SHM system?

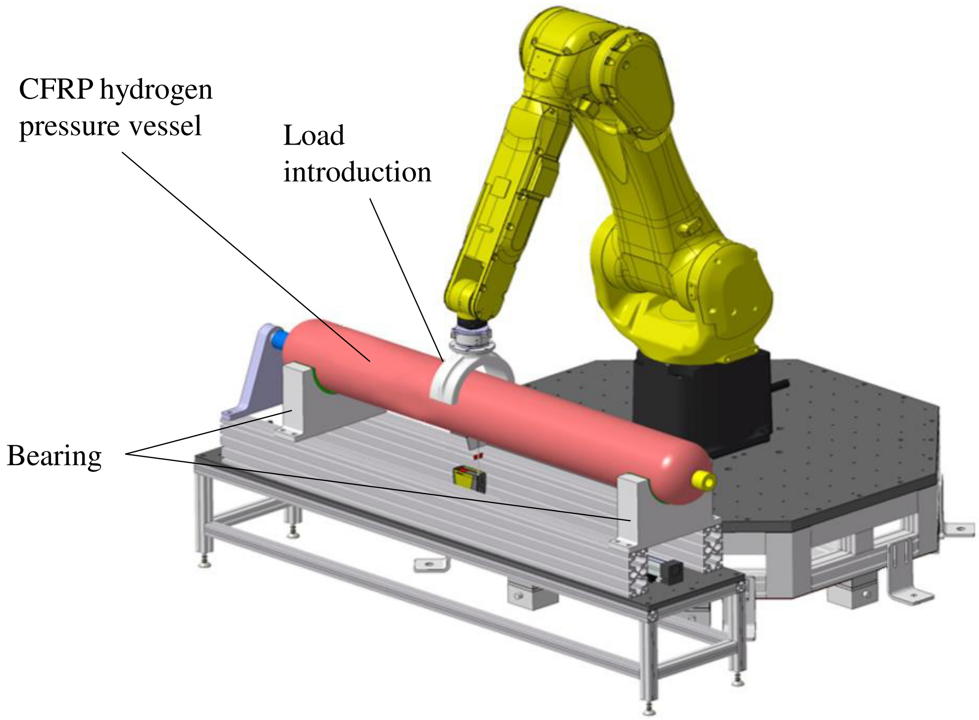

Figure 1. Current design of the robotic test bed for structural end-of-line testing of COPV (Image provided by Battenberg Robotic GmbH).

DEVELOPMENT OF THE TEST-BED

Based on the need mentioned above, we are pursuing the goal of developing a demonstrator for a robotic testing rig suitable for series production, which will become part of QA and, thus, the manufacturing process for mobile pressure vessels. Standardized and automated testing will ensure that safety requirements regarding structural integrity are met, even when applying reduced safety factors.

The currently designed test setup looks as follows; see Figure 1. The hydrogen tank is bedded on a test bed with adjustable bearing points. Loads, for example, according to a three-point bend or cantilever, are introduced through the robotic arm at arbitrary points via a semi-circular load introduction tool. In this design, the robot performs the load application, which limits the loads that can be applied to $\mathrm{F} < 10\mathrm{kN}$. If higher loads need to be applied, the test bed must perform the load application using a hydraulic load application. The test bed should be instrumented so optical measurement systems can record the deformation behavior during the load application process.

In addition to the instrumentation of the test bed, the tank requires a suitable strain-based SHM system. Fiber optic sensors and electrical strain gauges are available for strain-based measurement. Fiber optic systems offer the possibility of capturing several distributed measuring points. However, a disadvantage is the high cost, especially on the side of the evaluation unit. For this reason, we pursue an approach with discrete measuring points through applied strain gauges [13]. The strain gauge measuring points must be arranged in a suitable sensor layout on the tank. This sensor layout must meet the following requirements:

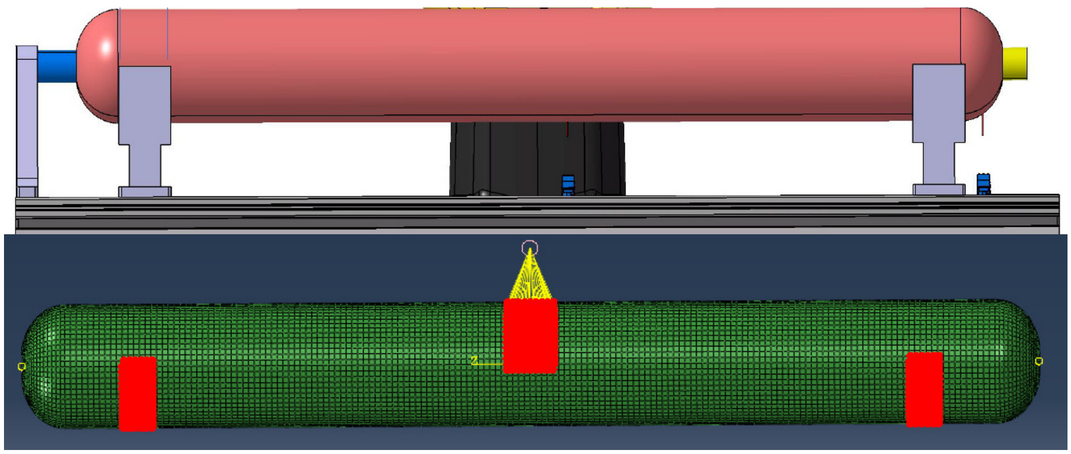

Figure 2. Transfer of the test bed (top) into the modeling of the tank structure with 2D shell elements under 3-point bending (bottom).

- Cost efficient, so wide economic use is possible
- Performing QA measurements in end-of-line testing at external loads (or internal pressure)
- Performing SHM measurements in operation at an internal pressure

COMPARISON OF MEASUREMENT APPROACHES

To develop the sensor layout, we must determine which measurement principles and SDIs we will use to perform measurements [10]. We compare different measurement approaches based on simulated data to identify suitable SDIs in Table I. We conceptually test the approaches in simulations on a tank shell elements model under internal pressure and 3-point bending; see Figure 2.

SDIs that use a zero reference within the structure are particularly sensitive [10]. Therefore, we first look at SDIs with a zero reference, such as a zero-strain trajectory or neutral axis [11, 12, 14]. A zero-strain trajectory could not be established for the considered load cases in the presented structure. The second SDI, the neutral axis, is usually used in beam-like structures under bending load. Thus, it is unsuitable for internal pressure since no compression regions can be formed. However, tracing back the structure on the test bed to a beam-like structure reveals a significant change, as shown in Figure 3. In this case, the neutral axis's displacement or the neutral fiber's strain can be potential damage indicators. The individual sensitivity to damage, a potential combination of the methods, and the practicability of both variants need to be further investigated. In principle, however, it can be assumed that when using the neutral axis as SDI, the tank must be re-positioned by rotating it around the longitudinal axis during the test process.

Since no zero references can be found for the load case internal pressure, general strain values $(\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{12}, ...)$, respectively the Δ-values from their undamaged states $(\Delta\varepsilon_{11}, \Delta\varepsilon_{22}, \Delta\varepsilon_{12}, ...)$ can be considered. Especially in the initial measurement of the tank in the context of a QA, using non-zero references is difficult. Deviations from the

TABLE I. OVERVIEW OF DIFFERENT SDIS ON THE HYDROGEN TANK

	SDI	Internal pressure (Preliminary operating phase)	External Loads, e.g. 3-point bending (Exclusively QA)
Zero reference	Zero-strain-trajectory [12]	non-existent	non-existent
	Neutral Axis [11, 14]	non-existent	Load-independent tensile-pressure change
Absolute values	Absolute strain	Δ-values small, potentially not measurable	Δ-values small, potentially not measurable
	Symmetries	circumferential & axial, unless constrained by boundary conditions	axial, for symmetrical bearing and load application

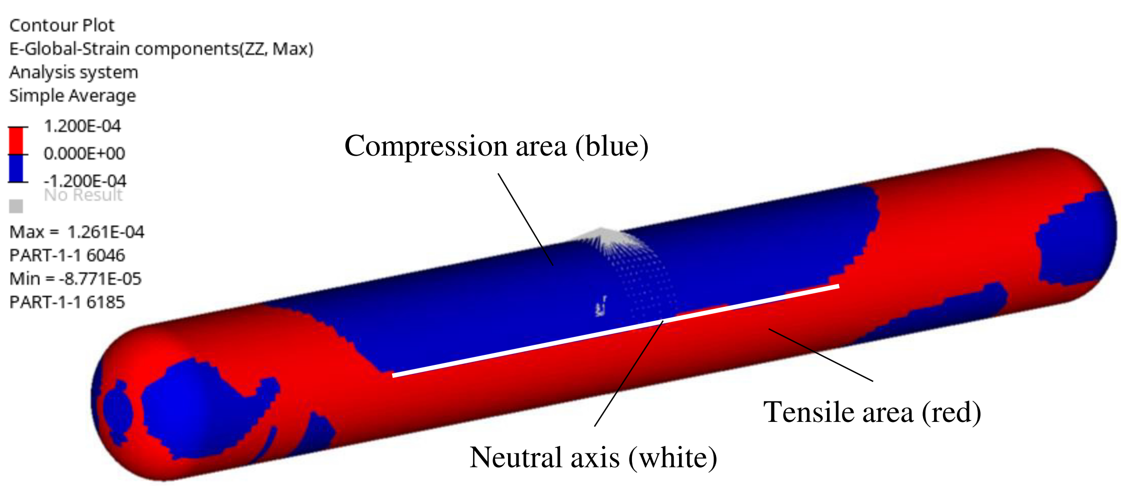

Figure 3. Formation of a neutral axis under three-point bending, by artificially creating a tension (red) and a compression (blue) area.

expected value cannot be unambiguously attributed to unique influences, e.g., force, local damage, global material properties). One physical constraint that can facilitate the use of absolute strain values is the longitudinal and rotational symmetries in the tank structure. If the load is applied symmetrically under symmetrical boundary conditions, the strain distribution in the undisturbed state will also have to be symmetrical. Otherwise, deviation from symmetry can be an SDI for this structure. Symmetries or deviations from perfectly symmetrical behavior can also be used at internal pressure, i.e., in the operating phase.

Based on the previous investigations, switching to external loads in the QA step is a reasonable approach that needs further investigation in the following steps. Once the structure is calibrated, deviations, even from non-zero reference, may be easier to correlate with damage or fatigue. In the discussion so far, particular attention has been paid to detecting local deviation, for example, damage. In principle, damages are the exception and not the rule when testing end-of-line pressure vessels. Therefore, in addition to detecting local properties, global properties, for example, the structure's stiffness (EA, EI), are also of interest.

CONCLUSION AND OUTLOOK

This paper presents the concept and current results of developing an automated end-of-line testing for hydrogen pressure vessels using a strain-based SHM system. With the help of the system, the applied sensor system can be used in QA to check the structural integrity and store the "as-is" state in a digital product file, which can be a central starting point for the Digital Twin of the structure.

Upcoming work is to merge the presented measurement approaches into a fixed sensor layout and to validate the system using appropriate pre- and full-scale tests. Long-term goals are to extend the measurement approach to other structural components to establish SHM throughout the product life cycle (PLC) to take advantage of all the benefits, see Figure 4.

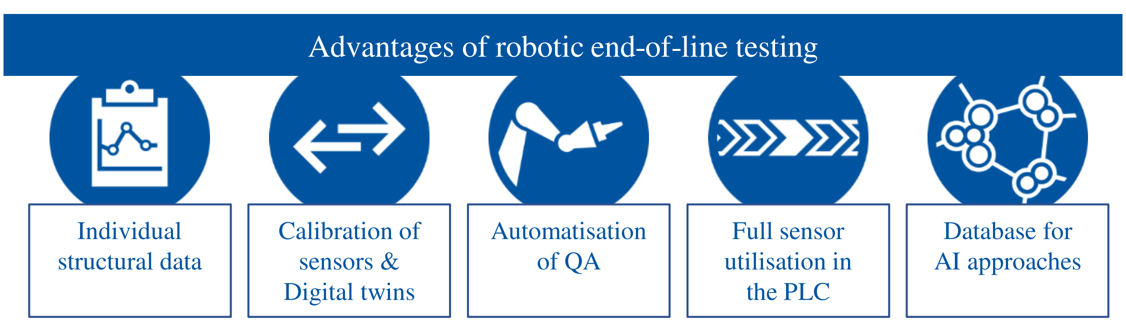

Figure 4. Overview of potential applications and advantages of a robotically executed end-of-line inspection for structural components.

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