

Design, Process Monitoring, and Test of a Filament-Wound Pressure Vessel

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To advance the development of lighter composite high-pressure vessels for hydrogen storage in aerospace applications, a probabilistic design approach should be employed. This enables the accounting of the expected manufacturing uncertainties rather than using conservative safety factors, particularly within the critical dome region. Such a methodology involves the quantification of these uncertainties during the winding process and probabilistic calculations of their influence on structural performance. Subsequently, the results can be reintegrated into the design optimization. In the process of experimental validation of the described approach, a 700-bar, 61-liter pressure vessel is studied with the aim to investigate the load distribution and failure behavior of the dome. In this region, the sensitivity to manufacturing uncertainties and the optimization potential are highest. This work describes the design process, pre-test analysis, and the data gained from sensor-supported manufacturing and testing of the vessel prototype.

The composite laminate is based on a layer-by-layer angle optimization method that minimizes fiber failure while maintaining a windable geometry¹. The employed approach is extended through a multi-fidelity method employing a computationally efficient shell model for optimization iterations and an axisymmetric solid finite element model for a high-fidelity correction of the stress and strain state. The main advantages of the latter model are an improved representation of the laminate-boss interaction and the improved applicability to thick-walled structures. Prior to testing, probabilistic simulations are conducted to assess the possible mechanical influences of manufacturing deviations reported in existing literature.

During production of this vessel, the winding process is monitored to characterize the as-manufactured fiber angle, polar opening radius, fiber volume content, and thickness buildup on the dome for each layer. The results of these measurements are compared to the predictions of the winding simulation of the design. Optical strain sensors are integrated, enabling continuous strain measurements along the tank contour and circumference during pressurization. The sensor layout on the outer and inner surfaces and the application method are described. Finally, the experimental strain data and ultimate failure from a burst test of the vessel are compared to the initial simulations.

¹ L. Jacobsen, S. Freund: "Automated Structural Design Optimization of Composite High-Pressure Vessels Considering Manufacturing Constraints", DLRK 2025, Augsburg