

STRESS-CONSTRAINED SHAPE AND FIBRE ORIENTATION OPTIMIZATION FOR LIGHTWEIGHT HYDROGEN PRESSURE VESSELS

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Abstract

High-pressure hydrogen storage vessels are critical components of modern hydrogen-based energy systems, designed to store gaseous hydrogen for direct supply to fuel cells. Typically, these systems utilize Type IV vessels, which consist of a polymeric liner overwrapped with composite materials. Because hydrogen must be compressed to extreme pressures—often reaching up to 70 MPa—a substantial volume of composite material is required to safely bear the structural loads. Consequently, optimizing the design of these vessels is essential to reduce both weight and manufacturing costs.

This study presents a shape optimization framework to identify optimal vessel geometries that minimize material consumption without compromising structural safety margins. A parametric level-set method based on the velocity field level-set (VFLS) is employed to solve a stress-constrained volume minimization problem. To enforce mechanical limits, the maximum fibre stress failure criterion is utilized as the primary constraint alongside a p-norm aggregation. An Ersatz material model is used to interpolate the mechanical properties across the domain.

A major challenge in this optimization process is the inherent coupling between the macroscopic geometric shape and the microscopic orientation of the anisotropic composite materials. To address this, two distinct orientation strategies are evaluated and compared. First, an approach using the maximum absolute first principal stress direction is used. Second, a gradient-based technique, inspired by Discrete Material Optimization (DMO), to iteratively determine the optimal fibre alignment. In this approach, fibre orientation is formulated as a sub-problem where several candidate orientations are evaluated for a fixed shape. A key advantage of this method is that the orientation field does not need to fully converge; instead, a candidate orientation is assigned as soon as it becomes dominant. To this end, various dominance criteria have been proposed and compared.

Computational simulations indicate that the proposed methodology is highly effective, demonstrating a composite volume fraction reduction of 40% to 50%

relative to a standard cylindrical baseline design domain. The study concludes by comparing the computational efficiency of the distinct orientation algorithms, validating the optimized geometries against high-fidelity FEM simulations, and discussing the implications of these theoretical fibre trajectories for practical manufacturability.