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Optimisation of 700 bar type IV hydrogen pressure vessel considering composite damage and dome multi-sequencing

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ABSTRACT

This study investigated with the optimisation of the composite stacking sequence of hydrogen pressure vessels manufactured by filament winding. It is a response to the need to develop cost-effective hydrogen energy carriers to permit greater use of hydrogen technology for transport and thus satisfy current environmental requirements. Within the framework of the OSIRHYS IV project, a comparison of the optimal solutions is presented. This comparison focuses on different optimisation strategies and methods including multi-sequence dome lay-up characteristics and composite damage. Optimisation results are compared and discussed with the aim of identifying optimal design rules to meet industrial needs. Finally, prospective work is presented.

Introduction

Hydrogen storage remains a key issue for the high-scale deployment of fuel cell applications. The gaseous hydrogen storage at high pressure with type IV vessels is currently the best technology. However, to reach commercial deployment, this technology needs research and development to cut costs and improve the performance, reliability and durability of current high pressure vessels. The composite shell withstands high mechanical stresses due to internal pressure. The massive use of carbon fibre accounts for 50–70% of the final cost of the vessel [1,2]. Therefore, the composite structure needs to be optimised to significant reduce the cost of hydrogen devices.

There have been various studies [3–16] on pressure vessel optimisation, but most of them generally focus on different parts or aspects of the pressure vessel: the optimised dome shape, optimisation of the lay-up in the domes or in the cylindrical section, global optimisation limited to a single helical layer, etc. Thus, dome-shape optimisations [7,9,10,14] (topological optimisations) aim to improve stress redistribution in

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the domes of vessels by integrating a mechanical criterion (minimisation of strain energy) into the optimisation process. However, in these studies the influence of the polar bosses was not considered. Yet, given their geometrical shape, these polar bosses modify the redistribution of mechanical stresses and therefore of fibres. This can lead to different solicitation modes and therefore different damage modes for the composite envelope in the domes, thus generating different types of vessel bursting: bursting in the domes or in the cylindrical shell. Vessel design improvements in this regard may consist in modifying the shape of the polar bosses to reduce the concentrations of local stresses and/or adding helical layers with different winding angles to locally reinforce the domes at the polar bosses. In addition, considering several helical layers would well expand optimisation research [6].

Based on the thin-layer hypothesis, the vessel's cylindrical shell [5,12] can be optimised analytically. These optimisations naturally result in optimal dual-layer laminates to absorb axial and radial stresses. In this case, however, the lack of data from the dome parts can result in solutions where winding is impossible in practice, where the domes are not entirely covered with composite, highly detrimental in terms of resistance to vessel rupture.

Since the mechanical behaviour (in particular vessel burst pressure and burst type) of a pressure vessel depends on the geometry, the design and reinforcements of the domes as well as the cylindrical section, an optimisation procedure must consider both parts. This is also a requirement to ensure the feasibility of the winding process. Considering damage to the composite in an optimisation process is an advancement [3,4,11] but should be generalised to multilayer vessels. Considering uncertain parameters [15] and the probabilistic lessons gleaned from the OSIRHYS IV project would make it possible to converge towards robust optimised solutions within a long-term perspective.

This article presents the different optimisation methods established and developed with the objective of running a global optimisation campaign considering (i) the mutual influences of the domes and the cylindrical part of the vessel on the overall behaviour of the vessel, (ii) the impact of composite damage on optimisation, including (iii) multilayer composite structuring. It was decided to limit this study to a single topology, material and winding process. Furthermore, direct and indirect optimisation methods were used and compared to identify competitive methods in relation to industrial requirements. Indirect methods are based on metamodels, the main set-up methods of which are listed as followed:

- design of experiments (DOE), polynomial regression [17–21];
- kriging methods [22–28];
- artificial neural networks [29,30];
- radial basis [31–36];
- polynomial chaos [37–40].

The preliminary results are presented and compared to those obtained by the usual optimisation methods. The influence of damage on the optimal solutions obtained is discussed. Finally, prospective work is presented.

Optimisation specifications

The use of an automated optimisation technique simultaneously taking into account numerous laminate parameters such as: different winding angles, thicknesses, slippage tendencies, lay-up and ply numbers, with a composite damage model currently does not exist for this kind of structure.

Ideally, overall optimisation, requires considering a number of different aspects:

- A multi-sequencing dome lay-up model is needed to take into account changes in the dome characteristics in relation to the design parameters.
- A composite damage model must be used to accurately predict burst pressure and type.
- Fatigue behaviour of the vessel.
- A probabilistic approach must be used to assess the influence of material property variability.
- A thermo-mechanical analysis must be investigated to meet safety standards for extreme temperatures.

Unfortunately, working simultaneously with all these different aspects is too difficult. Consequently, the optimisation process used in this study will focus only on dome and cylindrical section multi-sequencing and composite damage for burst calculations.

Constraints and optimisation criterion

Due to the significant proportion of carbon fibre in the final cost of the pressure vessel [2], the optimisation process will focus on the reduction of the mass of the pressure vessel (optimisation criterion) because this will reduce both direct costs (amount of carbon fibre) and manufacturing time. To meet safety standards, two main optimisation constraints are imposed:

- The burst type. Two burst types can occur when the vessel is abnormally loaded under pressure: a safe type (inner expulsion of the metallic bases) and an unsafe type (outer expulsion of the metallic bases). In this study, the safe type is required.
- The burst pressure. A minimum burst pressure is generally required by the specifications.

Depending on the composite structure, both vessel burst types can appear, as illustrated in Fig. 1. Vessel bursting will be determined by the divergence of the axial displacements measured between the two ends of the polar bosses. The burst pressure provides information on the overall mechanical performance of the vessel but not on its burst type, this why a criterion on displacements is introduced: when axial prior to radial displacement divergence is detected, burst in the dome areas occurs. This is considered as an unsafe burst type. Otherwise, safe burst type is considered.

Design parameters

The classical design parameters of this kind of problem are:

- winding angles;
- the number of layers;