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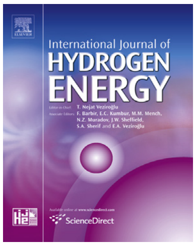

A progressive failure analysis of a 700-bar type IV hydrogen composite pressure vessel

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ABSTRACT

This study examines burst simulations of hydrogen pressure vessels manufactured by filament winding. Consideration of composite damage in an optimization process may be helpful in developing cost-effective hydrogen energy carriers and allowing greater use of hydrogen technology for transport and thus satisfy current environmental requirements. In the framework of the OSIRHYS IV project, a comparison of the bursting results of two FE models is presented and discussed. Finally, prospective work is presented.

Introduction

To encourage the dissemination of very-high-pressure hydrogen storage technology in composite vessels for mass markets in the land transport sector, it is becoming crucial to develop calculation techniques that are accessible to research and development departments and vessel manufacturers. These new tools should make it possible to reduce mass, most particularly the carbon fiber masses used and thus drastically reduce costs. These methods must not sacrifice the ability to take into account complex behaviour phenomena because the vessels are generally sized based on burst pressures, in thermomechanical fatigue and on impact. To make vessel sizing more accurate, and more generally to optimize its stacking sequence and therefore its mass, one must consider the progressive damage of materials as the load evolves. Taking damage into account in the computation procedure makes it possible to strictly identify the vessel's optimization criteria and the burst mode.

However, taking damage into consideration in an optimization process of a composite structure is delicate because of (i) the additional computing costs generated and (ii) the need for experimental trials to identify the damage parameters of the materials use. Therefore, the damage model should be chosen in relation to the future constraintes imposed by the optimization implementing the method in industrial R&D departments.

In this study, a progressive damage model, combined with an automated meshing procedure, will be used for its advantages in this context:

- ease of implementation in a commercial FE code;
- use of classical material properties;

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- low computation costs.

This meso-macro damage model is used to limit computation costs while providing enough accuracy under some hypotheses on the burst pressure of vessels. This study is indeed incorporated within the framework of an optimisation task where overall burst pressure vessel prediction is one of the main requirements. Therefore, in this work, thorough description of damage evolution is not intended.

The results of computer simulations of reference vessel bursting will be presented for two examples of FE modelling of the vessel so as to compare the quality of the results and the execution time in order to define the best model for future optimization.

The simulations results will be compared to the results of a experimental loading test where testing conditions consist in (i) embedding one of the polar boss of the vessel, loading with water the vessel in pressure and (iii) using two LVDT sensors to measure axial and radial displacements of the vessel. A description of the testing conditions can be found in Fig. 1 and the reference vessel specificities are presented in Table 1.

This research is part of the OSIRHYS IV project, joining several partners that have each developed calculation methods for sizing hydrogen storage vessels. The contribution of this article is to present and qualify an FE model taking into account progressive damage of the composite structure manufactured by filament winding, designed for a new optimization procedure developed specifically for this project [1].

Damage model

Several damage models of composite structures are available in the literature. The main damage models included herein are continuous [2–7] and progressive damage [8–17]. These models are based on the use of damage variables that drive the exhaustion of the elastic properties and the unidirectional carbon/epoxy laminate failure properties as the structure's load increases. Even though the damaged material's behaviour law is generally shared by most models (Eq. (3)), these models differ in how they define these variables. With a continuous damage model, the variables are defined by continuous evolution laws generally identified based on load/unload on samples, whereas with progressive models, the values of the failure variables can be fixed arbitrarily or based on empirical laws. The approaches to progressive damage can be improved by considering several levels for the variables during loading: these are called multilevel progressive failure models.

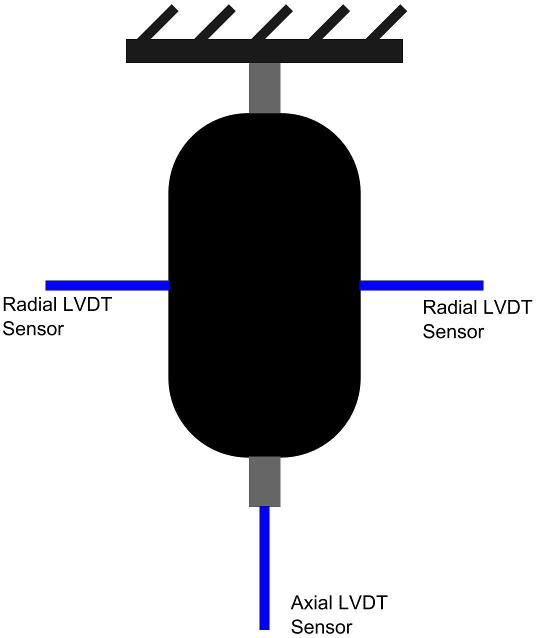

Fig. 1 – Loading test conditions. LVDT sensors are used to measure axial and radial displacements.

Table 1 – Reference vessel specificities.

Volume (L)	2L
Diameter (mm)	114
Length (mm)	317,3
Cylindrical section length (mm)	187,2
Liner	PA6
Liner thickness (mm)	4
Liner mass with polar bosses (kg)	1,649
Fibre	Toray T700S
Resin	epoxy
Volume fibre	60% à ± 2%
Composite thickness (mm)	11,1
Composite mass (kg)	1,839
Polar boss	Inox 316L
Polar boss weight (kg)	0,3
Overall pressure weight (kg)	3,488

Pressure vessel specificities

The aim of the paper is to simulate a quasistatic loading test of the pressure vessel until the dramatic failure of the vessel (burst). To perform vessel burst simulations, this study retained a single level simplified progressive failure model without taking delamination into account. Several features specific to vessels reinforce indeed the validity of this simplified model, guaranteeing good prediction of bursting:

- geometric features: presence of few singularities, revolution geometry closed under pressure;
- loading features: fibers for the most part placed in traction. The vessel is indeed designed to work mainly under traction loading considerations where fibers failure dispersion is quite limited. Aspect which will then again be reinforced by the optimisation process (improvement of the fibre orientation to increase the load capability of the vessel);
- technological features: intertwined fibers, high alternating of fiber strands, progressive variations of fiber orientations along the domes, important thickness of the lay-up. These aspects tend to limite the mechanical properties dispersion and the delamination of the plies.

All these aspects explain why the overall experimental dispersion observed on the burst pressure stays limited