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Numerical study of influence of temperature and matrix cracking on type IV hydrogen high pressure storage vessel behavior

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ABSTRACT

Type IV hydrogen high pressure storage vessels are subjected to severe thermo-mechanical loading due to fast filling. In this study a thermo-mechanical model of this kind of tank is developed, taking into account wind angle and thickness variation in domes, thermal dependencies of mechanical and thermal material properties and damage. Influence of damage and temperature on tank behavior is analyzed with isothermal calculations at different temperatures (−40 °C, 25 °C and 85 °C) before performing a simulation of filling which leads to spatial and temporal temperature gradients in the structure. Influence of this complex thermal loading on the mechanical response of the tank is also studied.

1. Introduction

The development of hydrogen energy still faces some problems like storage. Some barriers must be overcome before industrial commercialization because of tanks specifications. Researches on constitutive materials have to be done in order to make them lighter, cheaper, and safer without compromising performance (refueling time, capacity). Hydrogen can be stored in different forms: gas (high pressure), liquid (cryogenic), metal hydrides, chemical hydrogen storage, etc. [1,2].

Type IV high pressure storage vessels are made of composite wound around a polymer liner. In order to meet industry's specifications, such as volumetric hydrogen density, internal pressure of this kind of tank has to be increased up to 700 bars. Designing a tank which can support such a pressure is not a problem, however, if it must be carried, the mass must be reduced. This optimization should be performed without decrease of the durability of the tank during its service life; this is also a crucial scientific challenge. Moreover, the hydrogen tank filling must be done in a relatively short time similar to that of a petrol tank filling. To reduce the time at the pump for the user, fast filling is considered. But fast filling leads to thermo-mechanical stresses due to the pressure increase and thermo-mechanical effects (Joule–Thomson effect [3,4], transformation of hydrogen kinetic energy into internal energy, compression of hydrogen at the bottom of tank). This stage generates severe thermo-mechanical loadings [5,6] and the control of this load and of its consequences is necessary to ensure the safety of the tank.

Nowadays, finite element models have shown their ability to predict failure under pressure with a fairly high degree of reliability. To determine the failure, either simple and efficient failure criteria [7] or models taken into account kinetics of damage are used: for example, filament wound composite structure simulation with winding angle variations versus the longitudinal and thickness directions was compared with water pressuring test [8,9]. Some studies have been performed on burst failure load of composite pressure vessels [10–12]. Other studies are made on the thermal behavior of high pressure hydrogen storage vessel. These studies are done in order to better understand thermal distribution during filling [13,14] and to model this phenomenon [15–17]. Tank behavior is complex and many studies can be found on thermal behavior or on mechanical behavior. But during fast filling, these two phenomena are coupled causing additional difficulties of studies. Few studies have been performed on the coupled thermo-mechanical behavior of high pressure tanks, particularly on the effect of fast filling. Hu et al. use an axisymmetric thermo-mechanical model accounting for the decomposition of resin and for the loss of mechanical properties in order to predict the behavior of pressured tanks subjected to localized flame impingements [18]. In addition, the expansion of embedded sensors in high pressure tanks [19–21] will allow a better analysis of phenomena inside tanks and thus facilitate the development of models, including their validations.

The influence of thermo-mechanical couplings on the structure behavior is not well known. But, they can significantly reduce the durability of the tank [22]. One can think that this effect is second order since the burst is essentially driven by fibers strength. However, temperature gradients induce excessive stresses, material properties also change with temperature creating a new distribution of maximum stresses in the ply, and nothing proves that for

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a given architecture, temperature does not change the mode of failure (cylindrical part or dome part), for example by changing the state of stress in domes. Although these phenomena are complex, they must be considered in the design, especially for weight optimization. The aim of this article is to quantify with numerical tool the influence of temperature and matrix damage on tank behavior. In this study, a thermo-mechanical behavior model is developed for type IV high pressure storage vessel. We focus particularly on the behavior of the composite, which ensure the stiffness of the structure. The developed behavior law is anisotropic, thermo-dependent and takes into account transverse damage; it is presented in Section 2. This model must be sufficiently accurate, while generating reasonable time calculations in order to perform parametric study. Geometry of the structure is modeled as fine as possible, taking into account the thickness and the fiber angle variations in domes and exact stacking sequence in cylindrical part. Temperature and damage influence of tank behavior is investigated by comparison of different simulations in Sections 3 and 4. The aim is to compare the different effects and identify their influence on field stress. It permits also to estimate the burst of tank in particular environments (very low or very high temperature), which are important results for designer. In Section 5, simulation of filling process is then performed in order to quantify and analyze the influence of the rise of temperature on the mechanical behavior of such a structure.

2. Design, geometry and finite element modeling

The tank modeled in this study is a type IV hydrogen storage vessel, made of metal bases ensuring the connection of the tank, a polyurethane liner to seal the tank and a composite shell whose role is to ensure the strength of the structure. This tank is a two liters tank based on CAQ and CEA data. Its elliptical bases are made in 316L stainless steel. A carbon/epoxy composite is wound around a polymer liner (polyurethane) made by rotational molding. The bases are present in the mold during the rotational molding of polyurethane allowing the connection between the two parts. One can see the design of the liner and bases in Fig. 1.

The manufacturing technique requires a fiber angle of 90° at the end of the layers in the domes. Thus, the angle of the fibers varies in a layer from the value in the cylindrical part to 90°. This angle variation leads to an increase in the thickness of the domes, making the geometry of the structure complex. In order to model the tank as accurately as possible, an axisymmetric model was implemented, taking into account these angle and thickness variations. These variations are determined by the following equations using the module ABAQUS Wound Composite Modeler:

$$\theta(r) = \sin^{-1}\left(\frac{R_0}{r}\right) \pm \delta \cdot \left(\frac{r - R_0}{R_{tl} - R_0}\right)^4 \qquad (1)$$

$$e(r) = \frac{e_{tl} \cdot \cos(\theta_{tl})}{\cos(\theta_r)} \cdot \frac{R_{tl}}{r + 2.b \cdot \left(\frac{R_{tl} - r}{R_{tl} - R_0}\right)^4} \qquad (2)$$

where R_0 is the radius at the end of the layer, and R_{tl}, e_{tl} and θ_{tl} are respectively the inner radius of the layer, the thickness of the layer and the angle of the fibers at the cylindrical portion. b Is the band-width. δ Is the difference between the angle in degrees of the fibers in the cylindrical portion θ_r and the winding angle is calculated by the first term of Eq. (1). The geometry of the model, representing a quarter of the tank, is shown in Fig. 2 in which it can be seen the fibers angle variations in the layers.

Fig. 3 shows the boundary conditions applied to the model regardless of the type of simulation performed. An internal pressure is applied on all internal sides of the tank (bases and liners). This pressure can be time dependent in order to be applied simultaneously to a thermal loading. To block all movements of rigid body, displacements along the y direction are imposed to be zero at the end of one steel base. Depending on the type of study, thermal boundary conditions are added:

- Temperature imposed throughout the tank in order to know its influence on the tank behavior.
- Heat transfer coefficient and gas temperature imposed to know the behavior of the tank in case of a fast filling.

These boundary conditions will be detailed in each configuration studied in the following paragraphs.

3. Materials behavior

In this section, the mechanical and thermal behavior laws are detailed. For this model, to be the more predictive as possible, the used behavior laws must take into account many phenomena while keeping a certain degree of simplicity in order to be implemented in a complex model. Three different materials are used in this vessel: steel, polyurethane and carbon/epoxy composite.

For tanks applications, thermal dependencies of steel are negligible because of low temperature amplitude and the mechanical behavior of polyurethane does not have a significant influence in the global structure due to the low stiffness of polyurethane compared to composite or steel one. Thus, for steel and polyurethane materials, classical elasto-plastic behaviors at ambient temperature have been used. The tabulated data have been entered in the model.

For the composite material, thermal and elasto-plactic-damage behavior laws have been obtained by performing different characterization tests. In order to be as close as possible to the vessel, tests have been performed on curved specimens made by filament winding (Fig. 4).

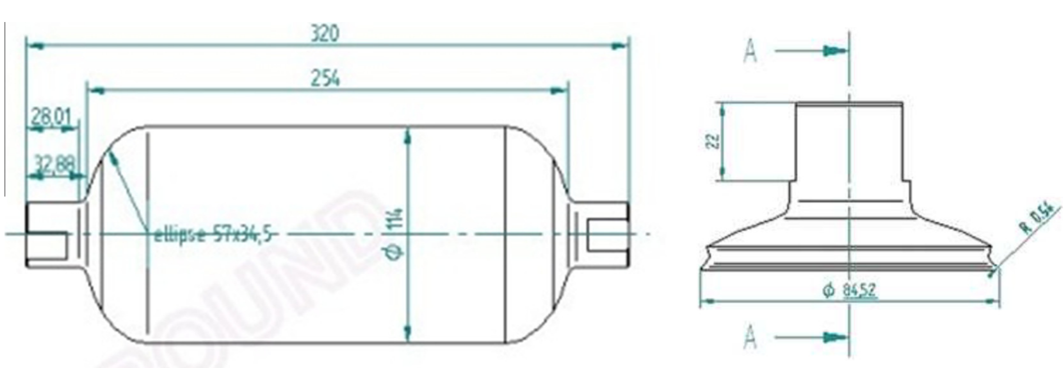

Fig. 1. Liner and bases design (in mm) [23].