RESIDUAL STRENGTH OF WOUND COMPOSITE PRESSURE VESSELS SUBJECTED TO FIRE EXPOSURE

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Keywords: hydrogen storage, damage modeling, wound composite, fire

Abstract

The present study aims at determining the influence of an exposure to a fire on the mechanical strength of hyperbaric storage vessels. Assessment of residual strength needs to know the way damage evolves in the material. A damage model dedicated to wound composite is validated by comparing with experimental data the simulations of samples first subjected to fire exposure and then submitted to three-point bending. This comparison allows relating the properties of the char part of the sample to a given damage configuration. Then, a preliminary simulation of hydrogen tanks subjected to fire allows assessing the residual strength of the storage.

1. Introduction

Nowadays, hydrogen is seen as an alternative source of energy in order to reduce greenhouse effects and dependence on fossil resources. But the use of hydrogen on a wide scale needs to overcome a large number of technological bottlenecks. For example, it is necessary to master the reliability of on-board storage of gaseous hydrogen at high pressure. The objectives of the European project FireComp are, first, to improve the knowledge about the damage mechanisms and the subsequent loss of strength of composite in fire conditions, and, secondly, to model the thermo-mechanical behavior of those storages.

The FireComp project brings together partners from diverse expertise: a gaseous compressed hydrogen technology integrator as a coordinator (AIR LIQUIDE), a pressure vessel supplier (HEX), a leading actor in international Standards, Codes and Regulations development (HSL), experts in industrial risks (INERIS), experts in thermal radiation and mechanical behaviour of the composite (CNRS (Pprime & LEMTA), LMS Samtech), experts in thermal degradation and combustion of composites, numerical simulation (CNRS, Edinburgh University and LMS Samtech) and an expert in European R&D collaborative project management (ALMAcg). This communication provides preliminary results obtained in the framework of the project.

Different types of pressure vessels already exist. Type IV vessels (made of a polymeric liner for tightness, metallic bosses for the connectivity and a wound carbon/epoxy composite shell which ensures the mechanical strength) are one of the most promising technologies, but the design of these tanks needs tools to simulate their behaviour under different in-service (normal or accidental) conditions, for example an exposure to a fire. Whereas the final objective of the project is to simulate the effects of simultaneous mechanical (inner pressure) and thermal (fire) loadings, this preliminary study considers both loadings successively: composite is first subjected to fire and then to a mechanical load.

In a first step, damage phenomena due to thermal aggression on composite carbon/epoxy structures must be studied. For that purpose, the relationship between thermal parameters and residual mechanical properties are analyzed in composite samples: thermal attacks are led by means of a cone calorimeter (ISO 5660 [1]) on composite samples. The damaged samples are then cut into parallelepipedic beams, which are mechanically tested under three-point bending.

In a second step, these mechanical three-point bending tests are modeled in a Finite Element analysis. A fixed directions damage model for composite materials is used to predict the different failure modes of the tested samples (fiber fracture, fiber – matrix interface cracking and delamination) as well as damage variables evolution. Thanks to these simulations, an explicit relationship between the applied density of energy and the mechanical damage level in the thermally affected zone can be drawn. From this result, the behaviour of wound composite hyperbaric storage vessels is simulated in both configurations (with and without thermal aggression) and the loss of mechanical strength is estimated by comparing the burst pressure of the tank.

In order to validate the global approach, the experimental tests and simulations have been performed on a reference composite material, whose mechanical properties have been studied in previous works [2].

2. Relationship between fire exposure and residual mechanical strength: experimental study on composite samples

In order to characterize the combustion properties of the composite material, tests of fire exposure under cone calorimeter (ISO 5660 standard [1]) have been performed on square unidirectional samples (100mm x 100 mm x 10 mm), Figure 1. The fibre volume ratio is about 60%. Different conditions of thermal flux (ranging from 15 kW/m^2 to 60 kW/m^2), exposure time, energy density have been chosen, in order to determine the key factor governing the loss of mechanical strength. It is showed in particular that the beginning of the thermal degradation is driven by the intensity of the incident flux. The more important it is, the earlier the inflammation is and the quicker the degradation is [3].

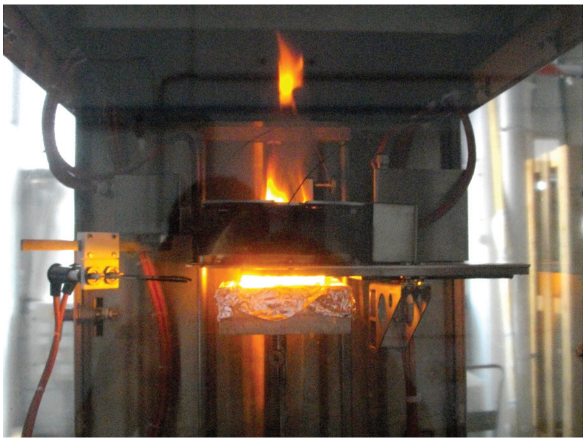

Figure 1: cone calorimeter test

In a second experimental part, the square samples first subjected to fire are cut (in the fibre direction) into beams (100 mm x 20 mm x 10 mm) that are then submitted to three-point bending (Figure 2, char is located in the bottom of the sample). The curves applied load vs. vertical displacement allow determining the flexural stiffness E_f and to relate it to the fire exposure conditions [4]. Note in Figure 2 that the main damage mode samples undergo is delamination (see steps on the right-hand side of the sample, and cracks in the center).

It is observed that the flexural stiffness is inversely proportional to the thermal energy density brought to the sample: Figure 3 exhibits a linear trend relating the normalized flexural modulus and the energy density. This latter parameter is the main driving force for the mechanical degradation, provided inflammation is observed.

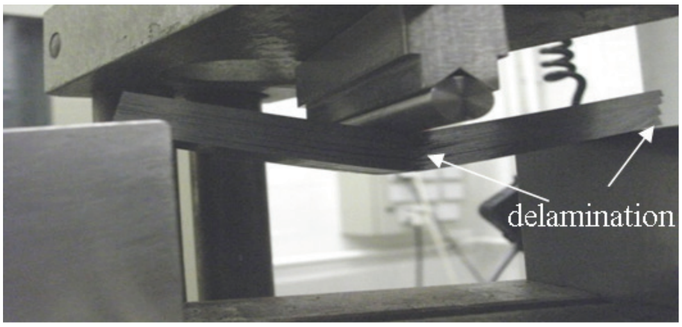

Figure 2: mechanical three-point bending test

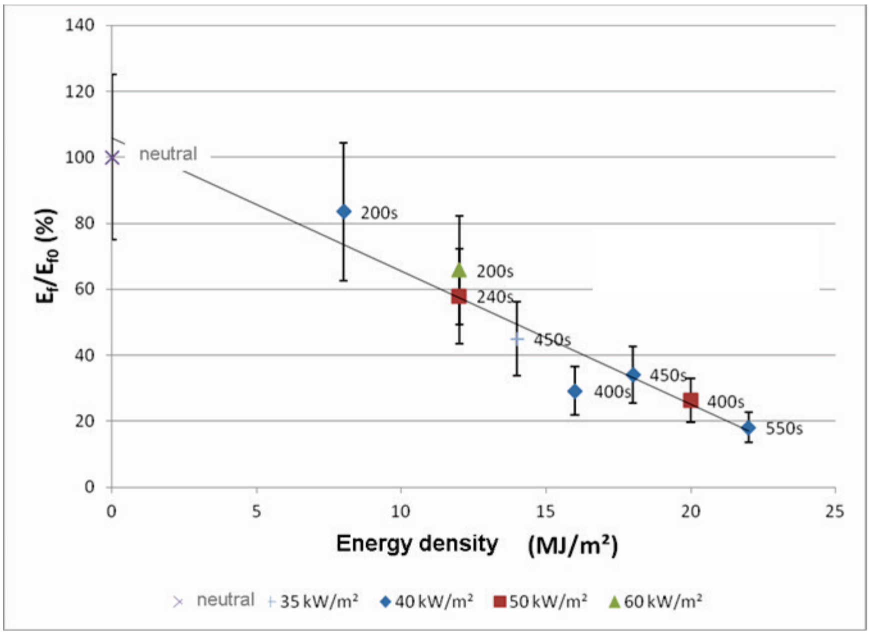

Figure 3: Normalized flexural modulus vs. energy density (E_{f0} is the flexural modulus of the virgin material; for each thermal flux value, the exposure time is given)

3. Damage modeling for composite material – simulation of three-point bending

The previous part proved that the fire exposure leads to a rigidity drop of the composite stiffness. In order to assess the residual strength of complex storage vessels subjected to fire, it is necessary to develop a damage model capable of simulating the damage evolution and the stiffness drop caused by the presence of char on structures first subjected to fire. Mouritz et al. [5-7] proposed some modeling approaches but dedicated to beam-like structures. A damage model has been developed in a three dimensional framework for more complex structures as wound tanks [8]. The next subsection sums up the basic principles of this damage model.

3.1. A damage model for composite

The following degradation mechanisms are accounted for:
- Fibre fracture (brittle)
- Fibre / matrix interface cracking (brittle)
- Fibre matrix debonding, matrix microcracking (progressive degradation).
- Delamination mode I – II, III (characterized by an off-plane loss of rigidity).

Two additional phenomena can be observed on tensile tests performed on samples made of [±45°] sequence, namely matrix viscosity and permanent shear strain.
The model is built in the framework of the Continuum Damage Mechanics using the concepts and tools of Irreversible Processes Thermodynamics. To build the model, the damage fixed directions concept [9] has been exploited. Any damage state (anisotropic by nature) is decomposed, at the meso – scale (*i.e.*, at the ply scale), in a set of couples $\left(\rho_i, \bar{\bar{N}}_i\right)$, whose number is to be defined. The fixed directional tensors $\bar{N}_i$ are defined as $\bar{N}_i = \bar{n}_i \otimes \bar{n}_i$, where $\bar{n}_i$ is the normal to the fracture surface and it is related to the aforementioned damage modes. These directions are chosen according to material anisotropy directions:

- $\bar{N}_0$ related to fibre direction and fibre fracture,
- $\bar{N}_{90}$ related to transverse direction and associated to fibre – matrix interfaces fracture,
- $\bar{\bar{N}}_{HP}$ related to the direction normal to the ply plane and associated to delamination phenomena (Mode I).
- $\bar{\bar{N}}_{i-j\,{}^{p}/_{n}}$ (*i* and *j* take the values 0, 90 and HP) related to shear directions (+45° (p) and -45° (n)) with respect to *i* direction. These directional tensors are associated to so-called diffuse damage (that is to say, matrix micro – cracking, fibre – matrix debonding, delamination (mode III) in 0° - 90° directions and delamination mode II in 0°/90° – HP directions) related to shear loadings.

The effects of damage are represented by the scalar variable ρ_i associated to the corresponding damage system. The permanent strain due to relative sliding of crossed plies is dealt with in the same manner: a scalar internal variable γ_i is associated to the in-plane shear directions (±45° with respect to the fibre direction). The sum of these sliding contributions constitutes the global residual strain tensor $\bar{\bar{\Psi}}$. The viscous behaviour is captured by a set of scalar variables $\{z_{i-j}\}$, also associated to the in-plane and out-of-plane shear directions. The residual shear strain and the matrix viscosity are related to $\bar{\bar{N}}_{i-j\,{}^{p}/_{n}}$ directions.

The tensorial functions representation theory [10] is used to build the thermodynamic potential (strain energy per unit volume) from invariants involving the aforementioned directional tensors. At the ply scale, three parts can be distinguished: an elastic contribution $w_{Elastic}$, the damage one w_{Damage} and the viscous one $w_{viscous}$.

$$\begin{aligned} & w\left(\bar{\bar{E}}, \bar{\bar{N}}_0, \bar{\bar{N}}_{90}, \bar{\bar{N}}_{HP}, \left\{\bar{\bar{N}}_{i-j\,{}^{p}/_{n}}\right\}, \left\{z_{i-j}\right\}, \left\{\rho_i\right\}\right) \\ & \quad = w_{elastic}\left(\bar{\bar{E}}, \bar{\bar{N}}_0\right) + w_{damage}\left(\bar{\bar{E}}, \bar{\bar{N}}_0, \bar{\bar{N}}_{90}, \bar{\bar{N}}_{HP}, \left\{\bar{\bar{N}}_{i-j\,{}^{p}/_{n}}\right\}, \left\{\rho_i\right\}\right) \\ & \quad + w_{viscous}\left(\bar{\bar{E}}, \left\{\bar{\bar{N}}_{i-j\,{}^{p}/_{n}}\right\}, \left\{z_{i-j}\right\}\right) \end{aligned} \qquad (1)$$

where $\overline{\overline{E}}$ is the elastic strain tensor, related to the total strain $\overline{\overline{\varepsilon}}$ by $\overline{\overline{E}} = \overline{\overline{\varepsilon}} - \overline{\overline{\Psi}}$.

According to the Thermodynamics of Irreversible Processes, the elastic stress $\overline{\overline{\sigma}}$ and the thermodynamic forces associated to damage F_{ρ_i}, residual strain F_{γ_i} and viscosity $F_{z_{i-j}}$ are obtained by deriving w with respect to $\overline{\overline{E}}$, ρ_i,, γ_i and z_{i-j} respectively (Equations 3):

$$\overline{\overline{\sigma}} = \frac{\partial w}{\partial \overline{\overline{E}}} \ , \ F_{\rho_i} = -\frac{\partial w}{\partial \rho_i} \ , \ F_{\gamma_i} = -\frac{\partial w}{\partial \gamma_i} \ , \ F_{z_{i-j}} = -\frac{\partial w}{\partial z_{i-j}} \qquad (3)$$

The evolution of the damage and residual strain variables is found to follow the normality rule with respect to the elastic domain. Concerning the viscosity evolution, the variable rate is chosen proportional to deviation from the equilibrium.

3.2. Simulation of the three-point bending test of a non exposed sample

The simulation is performed by the means of the commercial software Abaqus. The Finite Element model reproduces accurately the experimental set-up shown in Figure 2 (Figure 4). The sample is modelled with 3D elements C3D20, whereas the supports are non deformable solids. The boundary conditions avoid any rigid body motions. The damage model parameters are identified from tests performed in [2].

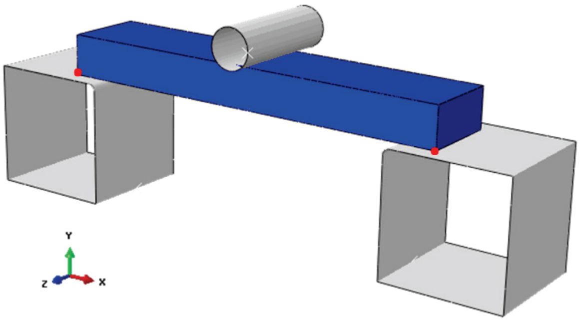

Figure 4: Finite Element model of the three-point bending test

Figure 5 exhibits the damage pattern given by the damage model. The simulation is found to accurately predict the progressive delamination in the sample length and depth. Note, as it can be corroborated by Figure 2, a high damage density in the centre of the sample, as well as the emerging cracks on both sides. This simulation emphasizes the capability of modelling genuine out-of-plane damage modes, whereas classical models (for example, Hashin [10]) are limited to in-plane fracture.

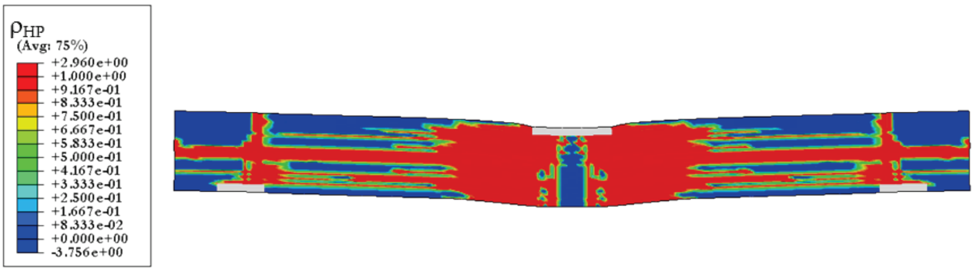

Figure 5: simulation of delamination damage density ρ_{HP}

3.3. Simulation of the three-point bending test of a sample first exposed to fire

In order to relate the fire exposure conditions and the mechanical damage undergone by the material, simulations of three-point bending tests have been performed on samples containing an initial non-zero damage field. As it can be observed on sample first subjected to fire (Figure 6, left), the exposure conditions under cone calorimeter lead to a quasi uniform thickness of char, whose value can be related to the applied energy density [4]. Given these observations, a uniform initial damage field is imposed to the sample (Figure 6, right): the char is modelled by a fully damaged model (that is to say, the damage variables related to delamination, matrix cracking and fibre breakage are equal to 1). The three-point bending test is then simulated and this damage configuration allows retrieving the linear trend between the normalized flexural modulus and the energy density (Figure 7).

Figure 6: Micrography of the composite sample subjected to fire (top), initial conditions for simulation: uniform damage field (bottom, red = full damage, blue = undamaged material)

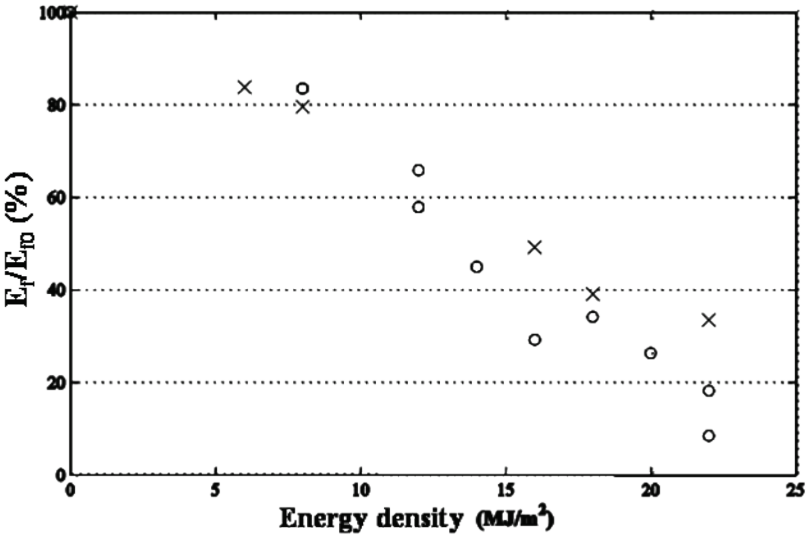

Figure 7: Normalized flexural modulus vs. fire energy density - comparison experiment (o) / simulation (x)

4. Simulation of residual strength of hydrogen tanks subjected to fire

The same approach has been used to model the burst pressure of a hydrogen tank subjected to fire. The thickness of the composite shell in the cylindrical part is 11mm. It is composed of alternations helical / circumferential plies. The outer layers of the cylinder are fully damaged (this damage is assumed to stand for the char due to fire exposure) as it can be seen in Figure 8. Different values for char thickness ranging from 0 to 6.7mm have been tested: for a given char thickness, inner pressure increase is simulated up to burst. Burst pressure is drawn as a function of the char thickness (Figure 9): a sharp drop of the simulated burst pressure can be observed. In the case of a virgin material, internal stresses due to fibre breakage of inner layers (when loading is close to burst pressure) are transferred to outer layers but in the case of an initially damaged tank, these outer layers cannot withstand these stresses.

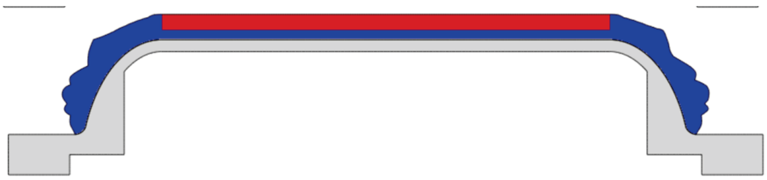

Figure 8: tank geometry (red = fully damaged composite, blue = undamaged composite, grey = liner + metallic bosses)

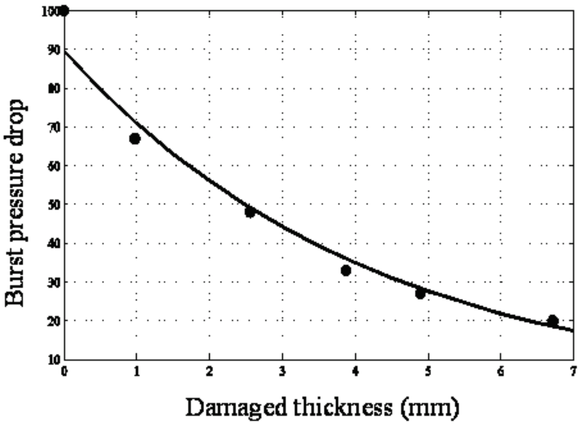

Figure 9: burst pressure drop vs. fully damaged thickness

5. Conclusion

The preliminary study allows one relating the fire exposure conditions to the mechanical damage. However no coupling between thermal and mechanical mechanisms is considered: the fire exposure and the mechanical loading are successive, whereas actual tanks undergo them simultaneously. The next step will investigate the influence of a mechanical load on the thermal degradation: samples submitted to creep will be exposed to a cone calorimeter, in order to be representative of the tank subjected to internal pressure and fire.

Acknowledgments

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant agreement n° 325329.

This work pertains to the French Government program “Investissements d’Avenir” (LABEX INTERACTIFS, reference ANR-11-LABX-0017-01).

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