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A probabilistic damage behavior law for composite material dedicated to composite pressure vessel

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ABSTRACT

This paper written in the framework of OSIRHYS IV project which aim is to clarify uncertainties and approximations of high pressure vessel composite design and calculation. The project, headed by CEA, mainly consists in the comparison between experimental results on type IV hydrogen high pressure storage vessel and numerical results. This paper presents a composite damage behavior law whose specificity is to take into account the variability of some material parameters. A model of wound notched structures is realized and compared with experimental results in order to verify the capability of this law to model the behavior of the composite used in OSIRHYS IV type IV hydrogen storage vessel.

Introduction

Among the various techniques of hydrogen storage [1–8], the most advanced technology for hydrogen on-board storage is high pressure gaseous hydrogen storage (700 bar). Cost reduction is an imperative step for widespread deployment of hydrogen energy. Design optimization with numerical simulation is a mean which could significantly reduce tank cost thanks to conception cost reduction (tests number decrease) and manufacture cost reduction (carbon fiber weight decrease). Consequently, it is imperative to assess the difference between experimental and numerical results and if necessary, to reduce the gap between these results.

The purpose of the OSIRHYS IV project is to clarify uncertainties and approximations of high pressure vessel composite design and calculation. The project is dedicated to all conception and simulation chain. It aims at improving material and process (filament winding) characterization and at establishing a strong and shared database between all project partners. The goal of OSIRHYS IV project is to develop and validate models and methods for composite high pressure design and optimization with behavior uncertainties knowledge.

One of the challenges to be faced in tank modeling is to know the uncertainty calculations. Indeed, there may be a significant dispersion of the tank burst behavior experimental results [9]. A prediction of this dispersion could be really interesting for manufacturers in order to reduce their safety margin with respect to standards [10]. In fact, it can often be seen manufacturers who, in addition to the safety factor required by the standard, add an extra margin to account for dispersion.

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The idea presented in the paper is to take the variability into account in the calculations. The implementation of probabilistic variables on the critical parameters of the model can provide interesting results for design. This approach to the problem was performed on the composite material where a significant number of variability sources can be observed due to the complexity of the manufacturing process.

A thermo-mechanical and damage behavior law incorporating fiber strength variability and fiber volume fraction variability is developed based on [11]. Validation tests on specimens and wound notched semi-structures are presented to validate this behavior law before full tank burst behavior simulations [12].

Thermo-mechanical behavior laws

The mechanical behavior law detailed in this section is based on the work presented in Ref. [11] where a coupled anisotropic thermo-mechanical behavior law is presented. In this work, only matrix cracking is taken into account. The non-linear shear behavior is not modeled because of the low shear stress values reached in a high pressure tank. In addition to the initial damage variable d_m (Eq. (1)) relative to matrix cracking, another damage variable d_f (Eq. (2)) is added to model fiber breakage.

Triangular law used in Ref. [3] is replaced by exponential law in order to be smoother and so to improve numerical convergence.

$$d_m = \begin{cases} 0 & \text{if } \varepsilon_{22} < \varepsilon_{22R}(T) \\ 1 - exp\left(\frac{\left(\varepsilon_{22R}^2(T) - \varepsilon_{22}^2\right)}{\alpha_m(T)}\right) & \text{else} \end{cases} \quad (1)$$

$$d_f = \begin{cases} 0 & \text{if } \varepsilon_{11} < \varepsilon_{11R} \\ 1 - exp\left(\frac{\left(\varepsilon_{11R}^2 - \varepsilon_{11}^2\right)}{\alpha_f(T)}\right) & \text{else} \end{cases} \quad (2)$$

where $\varepsilon_{11R}(T)$ and $\varepsilon_{22R}(T)$ are strains threshold for damage initiation, $\alpha_f(T)$ and $\alpha_m(T)$ are parameters governing damage evolution.

Once a damage initiation criterion is satisfied, material stiffness coefficient is degraded (Fig. 1). The damage variable associated with the failure mode vary from 0 (undamaged state for the mode corresponding to this damage variable) to 1 (fully damage state for the mode corresponding to this damage variable).

The variability of the material taken into account in this study is mainly related to the dispersion of the fibers properties. Indeed, two random variables are introduced into the model to account for the dispersion of fiber breakage observed by Armines during a test campaign on dry fiber [13,14] and for the variability of fiber volume fraction. The two probabilistic variables are ε_{11R} and FVR. The corresponding probabilistic laws have been characterized experimentally and follow a Weibull distribution for fiber breakage ε_{11R} and a normal distribution for the fiber volume fraction FVR.

One can see in Fig. 2 that the normal distribution of fiber volume fraction depends on the size of studied area. The dispersion is greater for smaller areas (these areas may therefore correspond to areas without fiber or with a high density of fiber). When the size increases, the variability of the fiber volume ratio decreases and the distribution representing the fiber volume ratio does not vary for areas superior to $0.5 \times 0.5\ mm^2$.

In the model, composite damage initiation in fiber direction is the only phenomenon affected by the variability of the fiber breakage. Indeed, the fiber breakage strain is equal to the ultimate strain of the composite in the fiber direction. Composite damage initiation in fiber direction will therefore follow the probability distribution of the fiber breakage strain.

The composite elastic matrix can be written as the matrix in Eq. (3)

$$C = \begin{bmatrix} (1-d_f)C_{11}(T, FVR) & (1-d_f)(1-d_m)C_{12}(T) & (1-d_f)C_{13}(T) & 0 & 0 & 0 \\ (1-d_f)(1-d_m)C_{12}(T) & (1-d_m)C_{22}(T) & (1-d_m)C_{23}(T) & 0 & 0 & 0 \\ (1-d_f)C_{13}(T) & (1-d_m)C_{23}(T) & C_{33}(T) & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44}(T) & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55}(T) & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66}(T) \end{bmatrix} \quad (3)$$

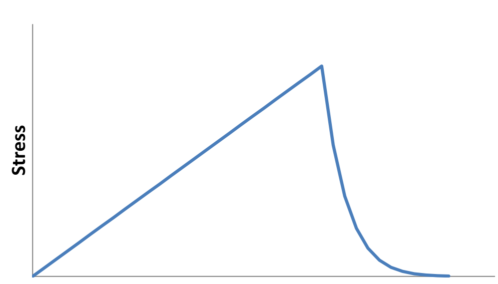

Fig. 1 – Stress – Strain curves obtained with exponential damage evolution (Eq. (1) and Eq. (2)).

Where $C_{ij}(T)$ are the elastic stiffness coefficients, T is the temperature, d_m and d_f are the damage variables defined in Eq. (1) and Eq. (2).

Each layer of a wound structure is made of intertwining of fiber yarn with $-\theta$ and $+\theta$ angles. Thus, the behavior of a layer C_{ply} has been determined by a homogenization process applied o stiffness matrix (Eq. (4))

$$C_{ply}(T, d_m, d_f, VFR) = \frac{C_\theta(T, d_m, d_f, FVR) + C_{-\theta}(T, d_m, d_f, FVR)}{2} \quad (4)$$

where C_θ and $C_{-\theta}$ are the stiffness matrix of an elementary ply C rotated by an angle θ and $-\theta$.