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Damage modeling for carbon fiber/epoxy filament wound composite tubes under radial compression

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ABSTRACT

The focus of this study is the development of a computational model with damage to predict failure of carbon fiber/epoxy filament wound composite tubes under radial compressive loading. Numerical analysis is performed via Finite Element Method (FEM) with a damage model written as a UMAT (User Material Subroutine) and linked to commercial software. The experimental analysis carried out followed ASTM D2412-11, where the specimen is parallel-loaded by two steel-based plates. Three stacking sequences have been evaluated. Both numerical and experimental results show that the presence of hoop layers at inner and outer layers plus ±75° non-geodesic layers gives maximum compressive load to the composite tube, since the reinforcement is wound closer to the loading direction. Moreover, failure modes are predominantly delaminations, which are confirmed via numerical analyses through high in-plane shear stresses levels, and via experimental analyses through stereoscopic micrographs.

1. Introduction

Cylindrical shells have numerous applications in aerospace, aeronautic and marine structures, such as in launch vehicle fuel tanks, fuselages and offshore structures. They have the ability to support high levels of axial and transverse compression loadings, where most of the structure is submitted to membrane loads, and its efficiency is derived from the lack of through-the-thickness stress gradients [1]. These structures are traditionally metallic-based, but the requirements for increasing the payload in such aeronautic and marine structures are motivating the use of polymeric composites, mainly due to their lack of corrosion and high stiffness and strength-to-weight ratios [2].

Among the composite manufacturing processes, filament winding (FW) stands out due to high precision in fiber positioning, high fiber content, good automation capability and low void content, being the most common process for manufacturing revolution and axisymmetric parts, such as pressure vessels and tubes [3]. When these structures suffer uniaxial or biaxial compression loads, the shell structure initially starts to deform stably, eventually reaching a critical point where equilibrium stops to be stable. Buckling occurs when the structure suddenly deflects unstably, losing its capacity to keep resisting the compressive loading [4].

Composite tubes may fail due to global or local buckling under compressive loadings, and they present two distinct behavior. The evolution of high radial displacements followed by global buckling and, consequently, collapse, or just a sudden collapse. The load prediction is much more difficult for composite structures than for metallic shells, beams and plates [5]. In addition, if the composite is sufficiently thick, the structure may fail due to material failure, thus avoiding buckling [6].

Damage prediction is a key aspect in the designing of composite tubular structures. Continuum Damage Mechanics (CDM) has been applied with success to model failure in composite structures. For instance, Camanho et al. [7] used CDM to predict strength and size effects in notched carbon/epoxy open-hole specimens subjected to tensile loading. Su et al. [8] developed a model using CDM for the progressive damage in open-hole specimens under compressive loading. Liu and Zheng [9] developed an energy-based stiffness degradation CDM model to predict the progressive failure of pressure vessels considering three failure modes: fiber breakage, matrix cracking and fiber/matrix interface failure.

An important parameter in the laminates is the stacking sequence, since each ply contributes to the global mechanical response. The effect of the winding sequence on the radial compressive behavior of composite tubes is significant. As shown by Melo [10], tensile strength and modulus can increase up to 20% just changing the stacking sequence in comparison to those laminates with the same ply angle throughout the laminate. The

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development of a computational model to simulate damage in filament wound composite tubes allows reducing costs and time-consuming experimental tests in the development of products.

There are many reports on the literature dealing with the compressive behavior of composite tubes under axial compression [11–13]. Faria and Guedes [14] and Guedes et al. [15] performed similar experimental ring deflection tests on glass fiber/polyester pipes focusing on long-term creep behavior. However, there are only few investigations on composite tubes under radial compression. Among them, Rafiee [16] evaluated the radial compressive behavior of FW tubes by means of experimental and theoretical approaches, and Tonatto et al. [17] performed an experimental and numerical assessment of the crushing behavior of offloading hoses.

The number of damage models has increased, but failure prediction for composite structures is still a challenge, especially for tubular structures. Therefore, the present work proposes to develop a computational model to predict damage initiation and evolution of carbon fiber/epoxy composite tubes manufactured by FW and subjected to radial compressive loading, and to compare the results to those from actual experiments.

2. Damage model

Ribeiro et al. [18] developed a damage model based on CDM, which was slightly modified for the material and geometry herein used. The model considers the composite lamina under plane stress state and damage is considered uniform throughout the laminate thickness [19].

2.1. Fiber failure modeling

A unidirectional carbon/epoxy composite laminate under tensile loading in the fiber direction (σ_{11}) is assumed linear elastic with brittle fracture. The model considers that the fiber behavior is not influenced by the damage state of the matrix. The maximum stress criterion is used to identify fiber failure:

$$\frac{\sigma_{11}}{X_t} \leqslant 1 \tag{1}$$

where X_t is the strength under tension in the fiber direction.

After failure, the damage variable in the fiber direction (d_1) is set to be "1". There is no evolution in d_1, i.e. it represents the catastrophic failure of the carbon fiber. To avoid possible localization issues, degradation of properties occurs at the end of each time step through Finite Element Method (FEM) solution. In addition, no degradation is allowed during each interaction to improve convergence. This strategy is required to control the time step in order to limit the element size between a particular step (calculation of the damage) and the following step (application of the damage). Thus, a parametric step-size sensitivity analysis in the FEM should be carried out to find best results.

The fiber behavior under compressive longitudinal load is set to be linear elastic until a specified value and, after that, non-linear elastic. The linear to non-linear elastic limit (X_{C0}) is then used in Eq. (2) to represent the compressive failure, as:

$$\frac{|\sigma_{11}|}{X_{C0}} \leqslant 1 \tag{2}$$

After $|\sigma_{11}| \geqslant X_{C0}$, the non-linear elastic stress–strain behavior is simulated using a secant modulus, as shown in Eq. (3):

$$E_{11} = \frac{X_{C0}}{|\varepsilon_{11}|}(1 - h(\varepsilon_{11})) + h(\varepsilon_{11})E_{11_0} \tag{3}$$

where $h(\varepsilon_{11})$ is obtained from the fitting of stress-strain plots for 0° specimens under compressive loading, ε_{11} is the strain in the longitudinal direction and E_{11_0} is the initial elastic modulus for 0° specimens under compression loading.

2.2. Matrix failure modeling

In a unidirectional filament wound laminate, the damage process in the matrix is essentially driven by transverse loading (σ_{22}) and shear loading (σ_{12}). A non-linear behavior in the matrix is reported due to inelastic strains and matrix damage [20], being the latter modeled using two internal damage variables, d_2 (related to σ_{22}) and d_6 (related to σ_{12}). Based on CDM, the hypothesis of effective stress links the damage variables with the stresses, and Eq. (4) gives this relationship:

$$\begin{Bmatrix} \hat{\sigma}_{11} \\ \hat{\sigma}_{22} \\ \hat{\sigma}_{12} \end{Bmatrix} = \begin{bmatrix} 1/1 - d_2 & 0 & 0 \\ 0 & 1/1 - d_2 & 0 \\ 0 & 0 & 1/1 - d_2 \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{Bmatrix} \tag{4}$$

where the $\hat{\sigma}_{ij}$ terms are the effective stress tensors.

According to Ribeiro et al. [6], the damage strain energy density can be described in function of effective stresses considering matrix phase stresses only, as shown in Eq. (5):

$$E_D = \frac{1}{2}\left[\frac{\langle\sigma_{22}^2\rangle_+}{E_{22_0}(1-d_2)} + \frac{\langle\sigma_{22}^2\rangle_-}{E_{22_0}} + \frac{|\sigma_{12}^2|}{G_{12_0(1-d_6)}}\right] \tag{5}$$

where $\langle\sigma_{22}^2\rangle_+ = \sigma_{22}^2$ if $\sigma_{22}^2 > 0$, otherwise $\langle\sigma_{22}^2\rangle_+ = 0$ if $\sigma_{22}^2 < 0$. Similarly, $\langle\sigma_{22}^2\rangle_- = -\sigma_{22}^2$ if $\sigma_{22}^2 < 0$, otherwise $\langle\sigma_{22}^2\rangle_- = 0$ if $\sigma_{22}^2 > 0$.

Ladeveze and LeDantec [21] introduced two thermodynamic forces into their model, which relates damage variables with the strain energy density (E_D), described in Eqs. (6) and (7):

$$Y_2 = \frac{\partial E_D}{\partial d_2} = \frac{\langle\sigma_{22}^2\rangle_+}{2E_{22_0}(1-d_2)^2} \tag{6}$$

$$Y_6 = \frac{\partial E_D}{\partial d_6} = \frac{\langle\sigma_{22}^2\rangle_+}{2G_{12_0}(1-d_6)^2} \tag{7}$$

Damage initiation in a composite can be identified as being the onset of damage due to stress reversals and the accumulation of inelastic strain (indication of appearance of a crack), which is assessed by carrying out cyclic quasi-static tests. The model regards that the damage process starts when the stress *vs.* strain curve is no longer linear.

Another characteristic of the present model is that it adjusts the Poisson's coefficient to take into account damage. Using CDM formulation performed by Matzenmiller et al. [22], Eq. (8) gives the stiffness tensor:

$$D = \frac{1}{K}\begin{bmatrix} (1-d_1)E_{11} & (1-d_1)(1-d_2)\nu_{21}E_{22} & 0 \\ (1-d_1)(1-d_2)\nu_{12}E_{11} & (1-d_2)E_{22} & 0 \\ 0 & 0 & K(1-d_6)G_{12} \end{bmatrix} \tag{8}$$

where $K = (1-(1-d_1)(1-d_2)\nu_{12}\nu_{21})$. To prevent material self-healing effect, the damage parameters (d_1, d_2 and d_6) are assumed the maximum calculated values along the simulation [6].

3. Computational models and experimental set-up

Computational models were developed on Abaqus™ 6.14 software platform (Fig. 1). The original dimensions of the tubes are: length (l) = 381 mm, inner radius (r) = 68 mm and lamina thickness (t_l) ≈ 0.6 mm. It is important to highlight that this thickness value is for ±φ winding plies. The composite structure was modeled by using S4R homogeneous reduced integration shell elements with three integration points per layer thickness and hourglass control (Fig. 1a). The rigid compressive plates were modeled as linear