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Deterministic Analysis for Creep Behavior of Damaged Composite Tubular Structure

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Abstract

The aim of this paper is to study the effect of creep loading on damaged multilayered composite cylindrical structure, taking into account various damage rates by developing analytical model. The developed model is used to simulate the elasto-visco-plastic response of damage cylindrical composite structure under different types of loading such as tension and internal pressure with end effect. This model makes it possible to estimate the service life of the multilayed damaged structures subjected to a creep loading. The results obtained make and show that the presence of the damage within the multilayer structures causes a clear increase of the circumferential stress which is the only responsible of the ruin, where some results are compared with experimental testing from previous works and a good correlation is obtained.

Introduction

The use of fiber-reinforced polymeric composites materials has become a current practice in gas transport and storage cylindrical structures due to their lightweight, relative low cost and mainly their high strength over metallic materials, although these composites structures performances may decay significantly over time. This is mainly due to the viscoelastic nature of the matrix, damage accumulation and propagation within the matrix and fiber breaking. One serious consequence, as a result of static fatigue (creep failure), is a premature failure which is usually catastrophic [1].

The static fatigue or creep failure is the tendency of materials to deform when subjected to long-term stress, particularly when exposed to heat, causing damage which may progress to failure in composite pressure vessels type III or IV and pipelines reinforced by composite system, in order to predict a failure pressure [2–4].

Most researchers conducted deterministic studies to analyze the composites cylindrical structures behavior under various loads. However, some of them used statistical models to describe the failure process, but neglect the randomness in mechanical properties, winding angle, loading and geometrical parameters. Different research works focus on the development of a reliability design tool of composites tubular structures under creep and fatigue loading with the physical, mechanical properties of materials, based on the theory of elasticity, which is relevant tool for such structure design. Before performing a structure optimization, a stress and strain analysis is required in order to get a reliable and economical design of the composite multilayer [5–7].

The first step in obtaining a dimensioning tool of composite structure is to start with short-term loading and to identify the different physical phenomena observed in this case, such as elasticity and viscoelasticity coupled to damage and incremental plasticity and finally all phenomena coupled to damage. The research of Hocine [8, 9] et al. focused primarily on the analysis of tubular structures in composite coated on metal liners for storing hydrogen

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under high pressure, by taking into account purely elastic laws of composite materials and elasto-plastic for metallic liner. Perreux et al. [10, 11] studied the effect of frequency on the life and damage of filament-wound pipes with $[\pm 55]_n$ laminates under biaxial loading. It was shown that the frequency effect was mainly due to the interaction of creep and fatigue, and the damage development was strongly dependent on the stress ratio. At the experimental level, Chermant et al. [12] deals with the creep mechanism for ceramic composites tested at low stresses and low temperatures. This work was dedicated to the prediction of deterministic creep behavior with or without damage. Ghouaoula et al. [13] developed analytical model of viscoelastic behavior for damaged multilayer tubular structures in long fibers. The developed model is used to simulate the viscoelastic response of cylindrical composite structure under different types of loading.

The present work aims to propose and validate a deterministic model tool dedicated to the designing of a pressure piping and vessel where the viscous nature of the matrix is taken into account in the model, which allows us to model the elasto-visco-plastic behavior of a damaged multilayered tubular structure under creep loading. Some results were compared with experimental results obtained by Treasurer et al. [14].

Mathematical Formulation

The considered material is a thin layer polymer reinforced with long glass fibers. The general stress–strain relationship for each kth constituent is given by:

$$\begin{Bmatrix} \sigma_z \\ \sigma_\theta \\ \sigma_r \\ \tau_{\theta r} \\ \tau_{zr} \\ \tau_{z\theta} \end{Bmatrix}^{(k)} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & C_{16} \\ C_{12} & C_{22} & C_{23} & 0 & 0 & C_{26} \\ C_{13} & C_{23} & C_{33} & 0 & 0 & C_{36} \\ 0 & 0 & 0 & C_{44} & C_{45} & 0 \\ 0 & 0 & 0 & C_{45} & C_{55} & 0 \\ C_{16} & C_{26} & C_{36} & 0 & 0 & C_{66} \end{pmatrix}^{(k)} \begin{Bmatrix} \varepsilon_z \\ \varepsilon_\theta \\ \varepsilon_r \\ \gamma_{\theta r} \\ \gamma_{zr} \\ \gamma_{z\theta} \end{Bmatrix}^{(k)} \quad \text{(Eq 1)}$$

where r, θ, z represent a cylindrical coordinate system. In the particular case of axisymmetric loading, the local balance equations becomes in each k- component:

$$\frac{\mathrm{d}\sigma_r^{(k)}}{\mathrm{d}r} + \frac{\sigma_r^{(k)} - \sigma_\theta^{(k)}}{r} = 0 \quad \text{(Eq 2)}$$

When the strain–displacement relationships are:

$$\begin{cases} \varepsilon_r^{(k)} = \dfrac{\mathrm{d}U_r^{(k)}}{\mathrm{d}r}, \ \varepsilon_\theta^{(k)} = \dfrac{U_r^{(k)}}{r}, \ \varepsilon_z^{(k)} = \dfrac{\mathrm{d}U_z^{(k)}}{\mathrm{d}z} = \varepsilon_0 \\ \gamma_{zr}^{(k)} = 0, \ \gamma_{\theta r}^{(k)} = \dfrac{\mathrm{d}U_\theta^{(k)}}{\mathrm{d}r} - \dfrac{U_\theta^{(k)}}{r}, \ \gamma_{z\theta}^{(k)} = \dfrac{\mathrm{d}U_\theta^{(k)}}{\mathrm{d}z} = \gamma_0 r \end{cases} \quad \text{(Eq 3)}$$

The composite material considered is composed of an organic resin reinforced with long fibers, with respect to the local cylindrical coordinates system (see Fig. 1).

Damaged Elastic Behavior

The damage considered in this work is related to the cracking of resin in the direction parallel to fibers. This type of cracking is assumed to change the compliance tensor. In this context, three damage parameters D_{I}, D_{II} and D_{III} are defined, and they characterize the lower transverse

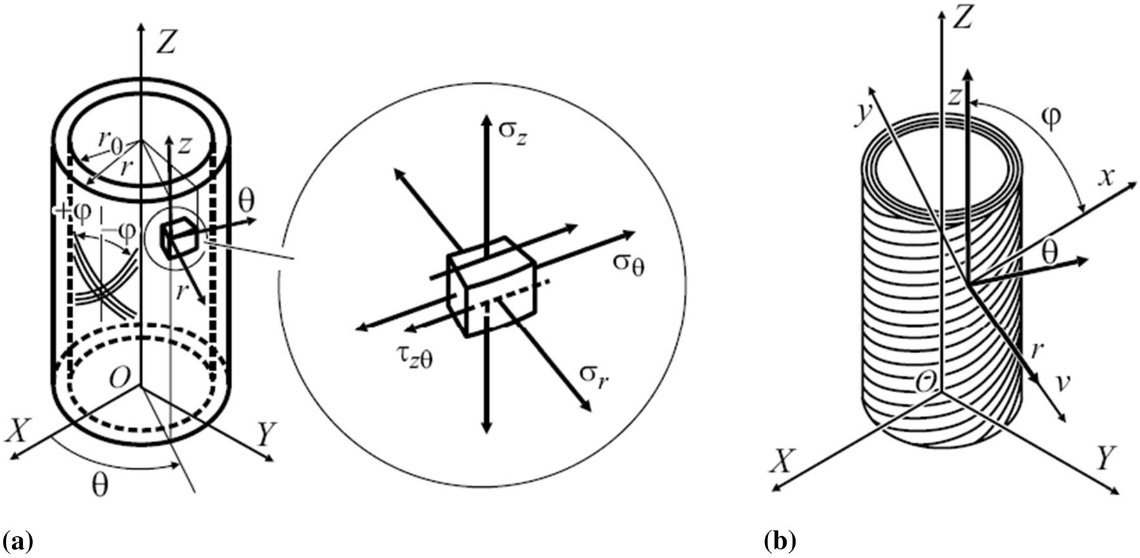

Fig. 1 Composite cylindrical and the stress state and local coordinate systems

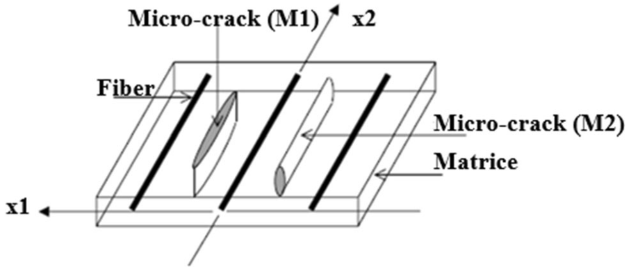

Fig. 2 Micro-cracks orientation in the matrix

modulus E_2 and shear modulus G_{12} et G_{23}. The damage is introduced by adding the damage contribution tensor H to the compliance tensor of composite S^c, where H is defined by:

$$H = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & H_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & H_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & H_{66} \end{pmatrix} \qquad \text{(Eq 4)}$$

The experimental analysis shows that the damage is due to the microcracking of the polymer matrix in the fibers direction x_1, perpendicularly to the transverse direction x_2 (see Fig. 2). The three variables of damage can also be expressed in terms of flexibilities:

$$D_I = 1 - \frac{S_{22}}{S_{22} + H_{22}}; D_{II} = 1 - \frac{S_{66}}{S_{66} + H_{66}}; D_{III} = 1 - \frac{S_{44}}{S_{44} + H_{55}} \qquad \text{(Eq 5)}$$

Viscoelastic Behavior

The epoxy matrix have a viscoelastic behavior, where the compliance tensor is defined by:

$$C_R = S_R^{-1} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \beta_{22}S_{22} & \beta_{23}S_{23} & 0 & 0 & 0 \\ 0 & 0 & \beta_{33}S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \beta_{44}S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \beta_{55}S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & \beta_{66}S_{66} \end{bmatrix} \qquad \text{(Eq 6)}$$

With: $\beta_{22} = \beta_{33}$, $\beta_{55} = \beta_{66}$, $\beta_{44}S_{44} = 2(\beta_{22}S_{22} - \beta_{23}S_{23})$.

It is possible to write additional evolution equations as:

$$\begin{cases} \dot{\varepsilon}^{\text{ve}} = \sum_i \dot{\xi}_i; \\ \dot{\xi}_i = -\frac{\partial \varphi^*_{\text{ve}}}{\partial \sigma} = -\frac{1}{\tau_i}(\xi_i - \mu_i S_R : \sigma) \end{cases} \qquad \text{(Eq 7)}$$

The shape of the distribution of relaxation times is selected triangular rather than Gaussian (Fig. 3). Noting the number x of relaxation time, Δ the interval between time and pitch triangle, we obtain:

$$\begin{cases} \tau_i = 10^{n(t)} \\ n(i) = n_c - n_i + (i-1)\Delta \\ \Delta = \frac{2n_0}{n_b - 1} \end{cases} \qquad \text{(Eq 8)}$$

and the weighting:

$$\begin{cases} \mu_i = +a[n(i) - (n_c - n_0)] \, \text{pour} \, n(i) \in [(n_c - n_0), n_c] \\ \mu_i = +a[n(i) - (n_c - n_0)] \, \text{pour} \, n(i) \in [, n_c, (n_c + n_0)] \end{cases} \qquad \text{(Eq 9)}$$

The normalization of the spectrum gives:

$$\sum_{i=1}^{n_b} \mu_i = 1 \qquad \text{(Eq 10)}$$

We then obtain the expression of slope:

$$a = \frac{2}{n_0(n_b - 1)} \qquad \text{(Eq 11)}$$

The viscoelastic model is completely defined by the knowledge of c_n, c_0, β_{22}, β_{66} and β_{23}.

Irreversible Behavior

For this present paper, we have chosen the irreversible or plastic strain, which is related to the increase in volume of the material due to voids created by microcracking. This damage plasticity creates an additional strain in the transverse direction, and its amplitude is directly linked to the density of microcracking. A linear relation between DI and this plastic strain is proposed:

$$\dot{X} = \delta \dot{D}_I = \delta \dot{\varepsilon}^{vp} \qquad \text{(Eq 12)}$$

A viscoplastic shear strain due to delayed friction phenomenon is also considered in the model. The dissipation potential has the following form:

$$\frac{K}{\eta + 1} \sqrt{(\tilde{\sigma} - X) : M : (\tilde{\sigma} - X)} - Z_c^{\eta + 1} \qquad \text{(Eq 13)}$$

Procedure Resolution

Differential equations that travel should check the circumferential and radial displacements multilayer composite tubular structures in order to meet the equilibrium of both internal and external efforts on each layer (k) are expressed by Eq 14 [1, 2]:

$$\left\{ \frac{\mathrm{d}^2 U_r^{(k)}}{\mathrm{d}r^2} + \frac{1}{r}\frac{\mathrm{d}U_r^{(k)}}{\mathrm{d}r} - \frac{N_1^{(k)}}{r^2} U_r^{(k)} = \left[N_2^{(k)} \varepsilon_0 + N_3^{(k)} \Delta T\right] \frac{1}{r} + N_4^{(k)} \gamma_0 \right. \qquad \text{(Eq 14)}$$

Table 1 Material properties [14]

Parameter	Value	Parameter	Value
E_x (MPa)	138,000	α (MPa)	0.11
E_y (MPa)	9200	P	0.99
NU_{xy}	0.34	δ_1 (MPa)	8921
G_{xy}	5350	δ_2 (MPa)	3453
N_c (s)	3.313	γ	157
N_0 (s)	4.989	δ_3 (MPa)	0.003
β_{22}	0.13	K	2.57e−11
β_{22}	0.38	δ (MPa)	3.93
Y_c (MPa)	0.0645	H	7366
Y_i (MPa)	0.046	…	…

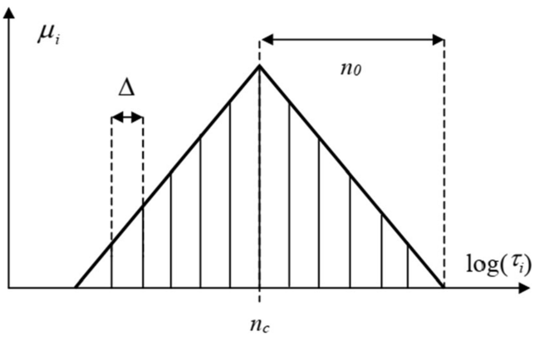

Fig. 3 Spectrum of relaxation time

where the parameters are $N_2^{(k)}$, $N_3^{(k)}$, $N_5^{(k)}$, $\alpha_2^{(k)}$ and $\alpha_4^{(k)}$ are given by [4]. If $\beta^{(k)} \neq 1$ *and* $\beta^{(k)} \neq 2$ the solution of (15) takes the form:

$$U_r^{(k)} = D^{(k)} r^{\beta^{(k)}} + E^{(k)} r^{-\beta^{(k)}} + \left(\alpha_2^{(k)} \varepsilon_0\right) r + \alpha_4^{(k)} \gamma_0 r^2. \tag{Eq 15}$$

$D^{(k)}$, $E^{(k)}$, γ_0 and ε_0 are the constants of integration. The boundary conditions are on the one hand the continuity and conservation of volume, and secondly those imposed by the loading.

In order to validate the analytical results obtained compared with previous experimental works [14], a single sequence [± 45°] is selected in this paper, where the order of angle of each laminate is interior until the external one. The internal radius of the multilayered cylindrical structure is of 33 mm, where the thickness of each composite layer is of 0.27 mm. The material parameters are given in Table 1, where the tubular structure is subjected, first to tensile loading in the same conditions that Treasurer [14] works, namely a tensile force of 50 MPa and finally to internal pressure loading about 15 MPa. The solutions are obtained by using the MATLAB software.

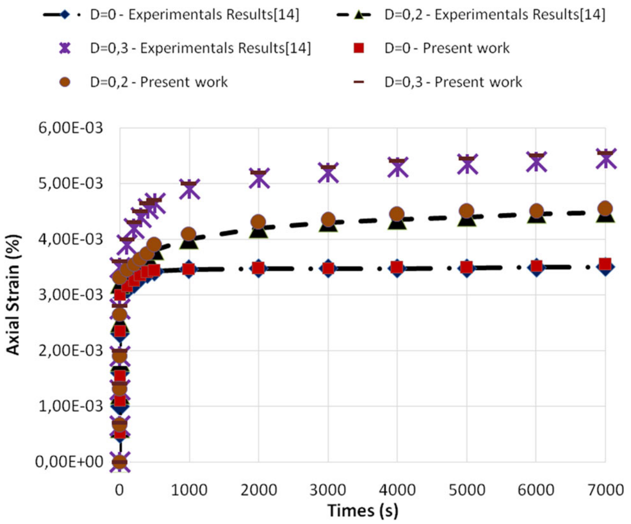

Fig. 4 Comparison of analytical model with experimental results for [± 45°] under creep tests at 50 MPa of traction loading

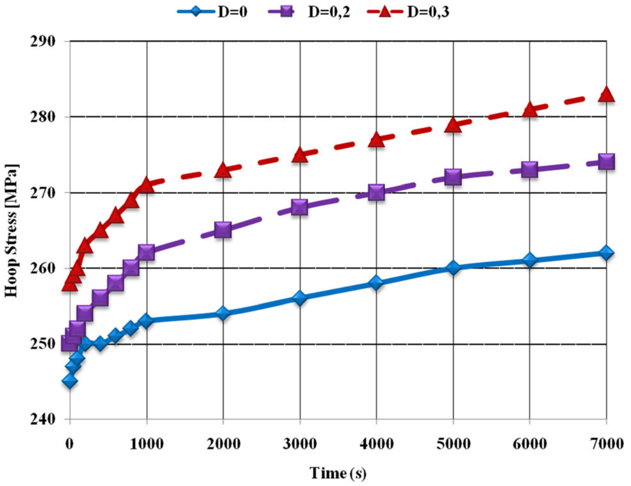

Fig. 5 Hoop stress variation of multilayered pipe for [± 45°] sequence under creep tests at 15 MPa of internal pressure loading

Results and Discussion

Creep Traction Loading

Figure 4 gives a comparison of the analytical viscoelastic modeling and experimental tests of a [± 45°] lay-up at three different damage levels DI = 0, DI = 0.20, and DI = 0.30—for the same load.

A typical strain–time graph of creep is shown in figure below, where the load is kept constant for a just nearly 02 h period of time. As seen on the graph, the creep strain increases rapidly in the early minutes after loading and then flattens to an asymptote called the creep limit of the material. The curve of creep loading is different for the value of damage level. Overall, the analytical model provides correct results for the evolution of damage and irreversible deformations with almost negligible differences between model and experiment by a good prediction of viscoelastic and viscoplastic behavior in the presence of damage. During the creep tests shown in Fig. 4, the results of the axial strain at the end of the tensile loading show a progression of damage during the test, with different levels of damage depending on the damage parameters.

Internal Pressure Loading

In this second part of results and discussions, we try to model the creep behavior of a cylindrical multilayered structure under internal pressure, for a stacking sequence Seq 1 = $[\pm 45°]_4$. The choice of the 45° angle is justified by the availability of material creep parameters, which are provided by Treasurer and all [14]. Fig. 5 illustrates the variation of the hoop stress in the short time. Three damage rates ($D = 0$, $D = 0.2$ and $D = 0.3$) are taken into consideration to value the influence of the damage on the creep behavior of cylindrical multilayered structure. The paces show that the presence of the damage in analytical model with viscoelastic and viscoplastic equations causes an increase in circumferential stress. This increase takes a value close to 5% for a rate variation 20% damage. These results obtained make it possible to estimate the service life of the multilayer structures in the presence of damage, subjected to a quasi-loading static during the running time.

Conclusion

This paper has been the subject to study the effect of creep loading on damaged multilayered composite cylindrical structure, taking into account three damage rates $D = 0$, $D = 0.2$ and $D = 0.3$, in order to value the influence of the damage on the creep behavior of cylindrical multilayered structure.

The developed model is used to simulate the elasto-visco-plastic response of damage cylindrical composite structure under different types of loading such as tensile and internal pressure. The results obtained make and show that the presence of the damage within the multilayer structures causes a clear increase in the axial strain for tensile loading and hoop stress for internal pressure loading which is the only responsible of the ruin. The analytical results were validated by experimental results, published by of Treasurer [14], where a good correlation is obtained. Overall, this model makes it possible to estimate the service life of the multilayer structures in the presence of damage subjected to a quasi-loading with the wide variety of behaviors observed for cylindrical composite structure.

The forthcoming paper is devoted to couple the present deterministic validated model with the Monte Carlo method and to get reliability model, which can predict the time remaining before failure multilayered cylindrical structures and identify the influence of the main parameters as materials and geometrical properties. In further works, a number of changes can be made to improve the model. Adding a dissipation potential to include time-dependent damage would increase the accuracy of the creep simulations, and would also permit modeling fatigue damage evolution. A relation between the time-dependent damage and the viscoelastic parameters would further improve the accuracy of the model.

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