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ANALYTICAL PREDICTION OF BEHAVIOUR OF DAMAGED COMPOSITE TUBULAR STRUCTURES UNDER QUASI-STATIC PRESSURE

ANALITIČKO PREDVIĐANJE PONAŠANJA OŠTEĆENIH KOMPOZITNIH CEVNIH KONSTRUKCIJA PRI KVAZISTATIČKOM OPTEREĆENJU

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Keywords
- tubular structure
- multilayer composite
- viscoelastic
- damage
- pressure loading

Abstract

The aim of this paper is to develop analytical model of viscoelastic behaviour 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 such as pure internal pressure, tension and finally internal pressure with end effect. The suggested analytical model provides an exact solution for stresses and strains for pipes and on the cylindrical section of vessel submitted to mechanical static loading. Some analytical results are compared with experimental testing from previous works, a good correlation is observed. Based to these results, the future paper is devoted to take into account the viscoelasticity coupled to damage behaviour under fatigue pressure loading, comparing experimental results obtained on prototypes of tubular structure. In order to predict the time remaining before failure of multilayered cylindrical structures, the forthcoming paper is devoted to take into account the viscoelasticity coupled to damage behaviour under cyclic loading of pressure, comparing experimental results obtained on prototypes of cylindrical structure.

Ključne reči
- cevne konstrukcije
- višeslojni kompoziti
- viskoelastičnost
- oštećenja
- pritisno opterećenje

Izvod

Cilj ovog rada je bio razvoj analitičkog modela viskoelastičnog ponašanja oštećenih višeslojnih cevnih konstrukcija sa dugim vlaknima. Razvijeni model je upotrebljen za simulaciju viskoelastičnog odgovora cilindrične kompozitne konstrukcija u različitim uslovima opterećenja, poput unutrašnjeg pritiska, zatezanja i kranjeg unutrašnjeg pritiska. Predloženi analitički model obezbeđuje precizno rešenje za napone i deformacije u cevima i u cilindričnom preseku posude opterećene statičkim silama. Neki analitički rezultati su upoređeni sa ekpserimentalnim ispitivanjima iz ranijih radova, i ustanovljena je dobra korelacija. Na osnovu ovih rezultata, budući radovi će uzeti u obzir viskoelastičnost u kombinaciji sa ponašanjem oštećenih konstrukcija izloženih zamoru i pritisku, poređenjem eksperimentalnih rezultata dobijenih ispitivanjem prototipova cevnih konstrukcija. Kako bi se predvidelo vreme presotalo do otkaza višeslojnih cilindričnih konstrukcija, sledeći rad će biti fokusiran na viskoelastičnost u kombinaciji sa oštećenjima usled cikličnog pritisnog opterećenja, uz poređenje eksperimentalno dobijenih rezultata na prototipovima cilindričnih konstrukcija.

INTRODUCTION

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. The literature shows that two theoretical approaches are used to predict the composite structures behaviour; the classical theory of laminates and the so-called theory of elasticity. The first theory assumes that the composite laminates are in a state of plane stress and provides no stress in the direction of thickness. The second shows that the stress developed through radial thickness have a large influence on the choice of stacking sequences /1/. The present work which focuses on the development of a design tool of composite tubular structures under pressure deals 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 multi-layer, /2-4/. 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, elasticity coupled to damage, viscoelasticity coupled to damage and nonlinear elasticity or incremental plasticity and finally viscoelasticity–viscoplasticity coupled to damage. Based on three-dimensional anisotropy elasticity, an exact solution for stress and deformation of the multilayered composites pipes under internal pressure has been presented by Xia et al. /5/. The research of Hocine et al. /1/ focused primarily on the analysis of tubular structures in composite coated on metal liners for storing hydrogen under high pressure, by taking into account purely elastic laws of composite materials. The study of Ghouaoula et al. /6/ deals with the development of elastic-damage behaviour model of a type III hydrogen storage composite vessel. The model is based on a meso-macro approach, which defines the response of the whole structure taking into account the damage behaviour of the composite. Onur /7/ presented a general hygrothermal stress elastic analysis, which is developed in the multi-layered thin or thick composite cylinders for the axially symmetric case under uniform or parabolic temperature distributions. Walker et al. /8/ presented an original in-depth analysis of the problem and then a new technique for determining the elastic optimal design of anisotropic fibre-reinforced laminated pressure vessels. Bouhafs et al. /9/ developed a probabilistic elastic analysis of the mechanical response of thick composite pipes under internal pressure. The second physical phenomena could be taken into account in developing a dimensioning tool in which elasticity is coupled with damage. Design of pipe and pressure vessels, which are subjected to various natures of loading, must prevent damage mechanisms occurrence /10/. Various phenomena have to be mentioned when the damage of a composite is discussed: the transverse cracking of resin, debonding between the fibers and resin, delamination between layers, and fiber breakage. In fact, during the service life of a composite, different damages are going to happen successively and eventually to compete until the final rupture of the material /11/. Lafarie-Frenot et al. /11, 12/ studied the cracking of resin in carbon/epoxy composites and quantified the effects of loading amplitude, stacking sequence, and the width of specimens on the development of cracks. They showed that the final density of cracks is strongly associated with the stacking sequence and loading. Perreux /13, 14/ studied the effect of frequency on the life and damage of filament-wound pipes with $[\pm 55]_n$ laminates under biaxial loading, but this method may be easily generalized to another stacking of type $[\pm\theta]_n$. It is shown that the frequency effect is mainly due to the interaction of creep and fatigue, and the damage development is strongly dependent on the stress ratio. A meso-macro modelling is proposed by Boubakar et al. /15/ of a polymer matrix reinforced with long fibres. Where the behaviour of a layer is expressed through elasticity coupled to damage and plasticity.

This work aims to propose and validate an analytical 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 viscoelastic behaviour of a damaged multilayer tubular structure. In order to predict the time remaining before failure multilayered cylindrical structures, the forthcoming paper is devoted to take into account the viscoelasticity coupled to damage behaviour under cyclic loading of pressure, comparing experimental results obtained on prototypes of cylindrical structure.

MATHEMATICAL FORMULATION

The considered material is a thin layer polymer reinforced with long glass fibres (see Fig. 1a). The general stress-strain relationship for each k-th constituent is given by:

$$\begin{aligned} & S_{11}^c = \frac{1}{E_z}, \quad S_{12}^c = S_{13}^c = \frac{-\nu_{xy}}{E_z} \\ & S_{22}^c = S_{33}^c \frac{1}{E_y}, \quad S_{23}^c = \frac{-\nu_{xy}}{E_y} \\ & S_{44}^c = S_{55}^c = S_{66}^c = \frac{1}{G_{xy}} \\ & E_y = E_z, \quad \nu_{xy} = \nu_{xz} \end{aligned} \tag{1}$$

In the particular case of axisymmetric loading, the local equilibrium equation for a k-th constituent takes the present form:

$$\frac{d\sigma_r^{(k)}}{dr} + \frac{\sigma_r^{(k)} - \sigma_\theta^{(k)}}{r} = 0 \tag{2}$$

with the radius r of the multilayer tubular varying in the interval $r_0 \le r \le r_n$ (see Fig. 1a). The corresponding strain-displacement relationships are:

$$\begin{cases} \varepsilon_r^{(k)} = \dfrac{dU_r^{(k)}}{dr}, \quad \varepsilon_\theta^{(k)} = \dfrac{U_r^{(k)}}{r}, \quad \varepsilon_z^{(k)} = \dfrac{dU_z^{(k)}}{dz} = \varepsilon_0 \\ \gamma_{z\theta}^{(k)} = \dfrac{dU_\theta^{(k)}}{dz} = \gamma_{0r}, \quad \gamma_{zr}^{(k)} = 0, \quad \gamma_{\theta r}^{(k)} = \dfrac{dU_\theta^{(k)}}{dr} - \dfrac{U_\theta^{(k)}}{r} \end{cases} \tag{3}$$

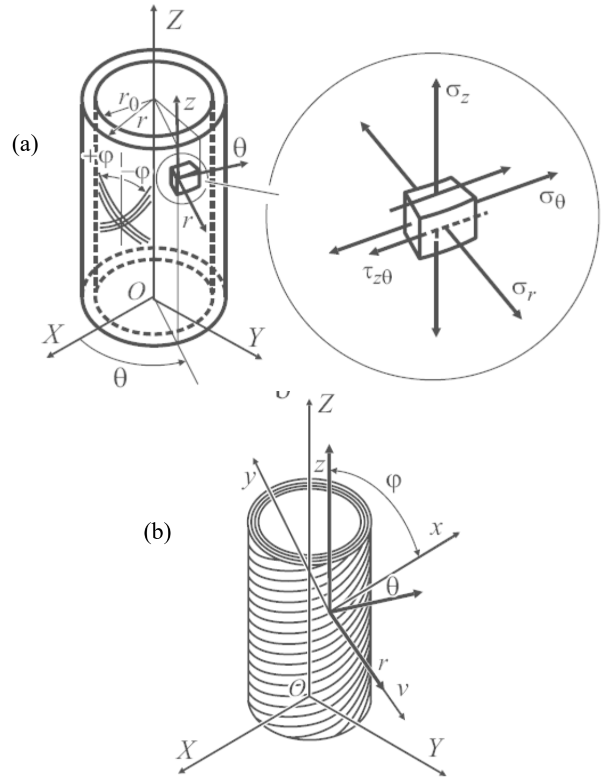

Figure 1. Composite cylindrical and the stress state in it /16/ (a) and local coordinate systems (b).

The composite is anisotropic and the description of its behaviour requires consideration of the orientation angle θ of its fibers. The composite material considered is composed of an organic resin reinforced with long fibers. With respect to the local cylindrical coordinates system (see Fig. 1b).

The composite material considered here is composed of an organic resin reinforced with long fibers. With respect to the local cylindrical coordinate system (Fig. 1b), the 4th-order compliance tensor of composite S^c is reduced to the form:

$$\begin{cases} D_{II}=1-s_{66}\left[s_{66}+\dfrac{D_I}{(1-D_I)^{1/2}}\times(s_{11}\times s_{22})^{1/2}\right]^{-1} \\ D_{III}=1-s_{44}\left[s_{44}+\dfrac{D_I}{(1-D_I)^{1/2}}\times s_{22}\right] \end{cases} \quad (4)$$

with:

$$S_{11}^c=\frac{1}{E_z},\quad S_{12}^c=S_{13}^c=\frac{-\nu_{xy}}{E_z}$$
$$S_{22}^c=S_{33}^c\frac{1}{E_y},\quad S_{23}^c=\frac{-\nu_{xy}}{E_y} \quad (5)$$
$$S_{44}^c=S_{55}^c=S_{66}^c=\frac{1}{G_{xy}}$$
$$E_y=E_z,\quad \nu_{xy}=\nu_{xz}$$

Damaged elastic behaviour

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 modulus E_2 and shear modulus G_{12} and G_{23}. The damage is introduced by adding the damage contribution tensor H to the compliance tensor of composite S^c. Then, the damaged compliance tensor S^c of a layer takes the form:

$$H=\begin{bmatrix} 0&0&0&0&0&0\\ 0&H_{22}&0&0&0&0\\ 0&0&0&0&0&0\\ 0&0&0&H_{44}&0&0\\ 0&0&0&0&0&0\\ 0&0&0&0&0&H_{66} \end{bmatrix} \quad (6)$$

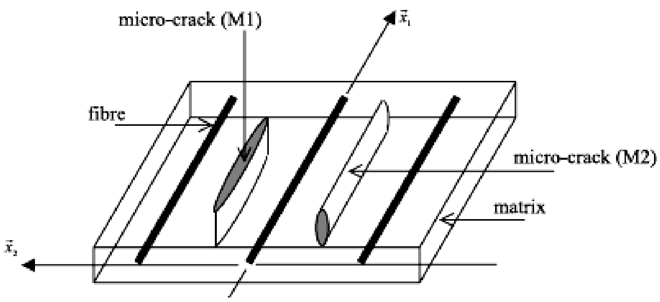

Figure 2. Micro-cracks orientation in the matrix.

The experimental analysis shows that the damage is due to the micro-cracking of polymer matrix in fibers direction x_1, perpendicularly to the transverse direction x_2 (Fig. 2).

These three variables of damage can also be expressed in terms of flexibilities:

$$\begin{cases} D_I=1-\dfrac{s_{22}}{s_{22}-H_{22}} \\ D_{II}=1-\dfrac{S_{66}}{s_{66}-H_{66}} \\ D_{III}=1-\dfrac{s_{44}}{s_{44}-H_{44}} \end{cases} \quad (7)$$

where three parameters of damage D_I, D_{II} and D_{III} characterize the lower transverse modulus E_2 and shear modulus G_{12} and G_{23}, respectively. According to /7/ and relations D_I, D_{II} and D_{III} allows to obtain:

$$\begin{cases} D_{II}=1-s_{66}\left[s_{66}+\dfrac{D_I}{(1-D_I)^{1/2}}\times(s_{11}\times s_{22})^{1/2}\right]^{-1} \\ D_{III}=1-s_{44}\left[s_{44}+\dfrac{D_I}{(1-D_I)^{1/2}}\times s_{22}\right] \end{cases}$$

Viscoelastic behaviour

The epoxy matrices have viscoelastic behaviour:

$$C_R=S_R^{-1}\begin{bmatrix} 0&0&0&0&0&0\\ 0&\beta_{22}S_{22}&\beta_{23}S_{23}&0&0&0\\ 0&0&\beta_{33}S_{33}&0&0&0\\ 0&0&0&\beta_{44}S_{44}&0&0\\ 0&0&0&0&\beta_{55}S_{55}&0\\ 0&0&0&0&0&\beta_{66}S_{66} \end{bmatrix} \quad (8)$$

It is possible to write additional evolution equations:

$$\dot{\varepsilon}^{ve}=\textstyle\sum_i \dot{\xi}_i \quad (9)$$

$$\dot{\xi}_i=-\frac{\partial \overset{*}{\varphi}_{ve}}{\partial \sigma}=-\frac{1}{\tau_i}(\xi_i-\mu_i S_R:\sigma) \quad (10)$$

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

$$\tau_i=10^{n(t)} \quad (11)$$

where:

$$\begin{cases} n(i)=n_c-n_i+(i-1)\Delta \\ \Delta=\dfrac{2n_0}{n_b-1} \end{cases} \quad (12)$$

and the weighting:

$$\begin{cases} \mu_i=+a\left[n(i)-(n_c-n_0)\right] \text{ for } n(i)\in\left[(n_c-n_0),n_c\right] \\ \mu_i=+a\left[n(i)-(n_c-n_0)\right] \text{ for } n(i)\in\left[n_c,(n_c+n_0)\right] \end{cases} \quad (13)$$

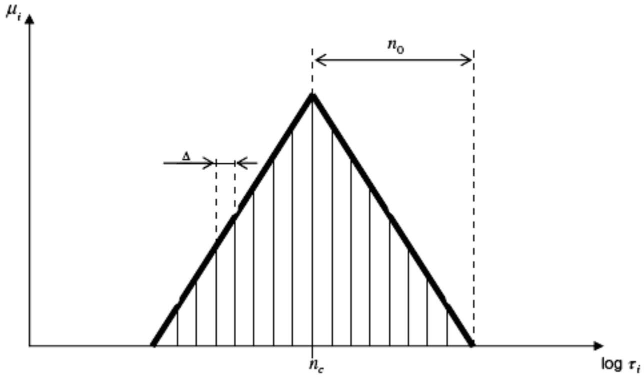

Figure 3. Spectrum of relaxation time.

The normalization of the spectrum gives:

$$\sum_{i=1}^{n_b} \mu_i = 1 \qquad (14)$$

We then obtain the expression of slope:

$$a = \frac{2}{n_0 (n_b - 1)} . \qquad (15)$$

The viscoelastic model is completely defined by the knowledge of n_0, n_c, β_{22}, β_{66}, and β_{22}.

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 the system Eq. (3), /1, 7/:

$$\frac{d^2 U_r^{(k)}}{dr^2} + \frac{1}{r}\frac{dU_r^{(k)}}{dr} - \frac{N_1^{(k)}}{r^2} U_r^{(k)} = \left[N_2^{(k)} \varepsilon_0 + N_3^{(k)} \Delta T \right] \frac{1}{r} + N_4^{(k)} \gamma_0 \qquad (16)$$

where

$$N_1^{(k)} = \frac{C_{22}^{(k)}}{C_{33}^{k}},\ N_2^{(k)} = \frac{C_{12}^{(k)} - C_{13}^{(k)}}{C_{33}^{k}},\ N_4^{(k)} = \frac{C_{26}^{(k)} - C_{36}^{(k)}}{C_{33}^{k}}$$
$$\alpha_2^{(k)} = \frac{N_2^{(k)}}{1 - N_1^{(k)}},\ \alpha_4^{(k)} = \frac{N_4^{(k)}}{4 - N_1^{(k)}} \qquad (17)$$

The solution of Eq.(14) depends on the value:

$$\beta^{(k)} = \sqrt{N_1^{(k)}}$$

sFor $\beta^{(k)} = 1$:

$$U_r^{(k)} = D^{(k)} r + E^{(k)} / r + r \ln r(r) N_2^{(k)} \varepsilon_0 + \alpha_4^{(k)} \gamma_0 r^2 \qquad (18)$$

For $\beta^{(k)} = 2$

$$U_r^{(k)} = D^{(k)} r^{\beta^{(k)}} + E^{(k)} r^{-\beta^{(k)}} + \alpha_2^{(k)} \varepsilon_0 r + \frac{N_4^{(k)}}{2} \gamma_0 r^2 \ln r \qquad (19)$$

For $\beta^{(k)} \neq 1$ (or 2):

$$U_r^{(k)} = D^{(k)} r^{\beta^{(k)}} + E^{(k)} r^{-\beta^{(k)}} + \alpha_2^{(k)} \varepsilon_0 + \alpha_4^{(k)} \gamma_0 r^2 . \qquad (20)$$

$D^{(k)}$, $E^{(k)}$, 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. Assume that there is no slip at the interfaces and that there is continuity of stresses and displacements. These boundary conditions to determine the constants of integration introduced later, /1/. The following Table 1 shows the mechanical properties of glass/epoxy. In order to validate the analytical results obtained compared with previous experimental works, /13/, a single sequence [±55]$_6$ 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 solutions are obtained by using the MATLAB software.

Table 1. Mech. properties of composite mater. Glass/Epoxy /11/.

G/E	E_x [GPa]	E_y [GPa]	E_z [GPa]	v_{xy}	v_{yz}
	55	21	21	0.27	0.495
	v_{xz}	G_{xy} [GPa]	G_{yz} [GPa]	G_{xz} [GPa]	
	0.27	8.2677	9	9	

RESULTS AND DISCUSSION

Figures 4 and 5 show the variation of the hoop stress in function of the axial and hoop strain direction for two types of loading: pure internal pressure (Fig. 4) and internal pressure with end effect (Fig. 5). The results of the developed model are compared with experimental analysis, led by Perreux et al. /13/. From the two figures, there is a good agreement between our current results and those of the experimental for both types of loading. Compared to the results already obtained, /7/, the consideration of viscosity matrix epoxy in the model, reduced the lead between the sizing tool and experimental results.

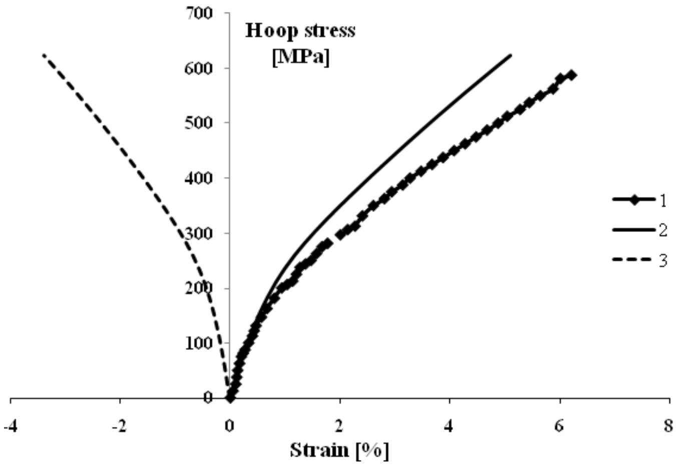

Figure 4. Experimental /13/ (1) and analytical (2, 3) hoop stresses σ_θ as functions of hoop ε_θ (1, 2) and axial ε_z (3) strains in pure internal pressure composite tube made of a [±55]$_3$ glass/epoxy.

Both figures show a nonlinear pace from the beginning of loading and this is due to the viscoelastic model. We can also remark a loss of rigidity in the stress-strain curve for the analytical and experimental results. The progressive loading of the multilayer tubular structure allowed of having a progressive damage within the composite material. This remark is characterized by loss of rigidity of the stress-strain appearance. The structure piping response under pure internal pressure is in perfect accordance with the evolution of strain (Fig. 4), it records a narrowing axial strain and swelling circumferential strain. The evolution of the axial and hoop strains according to the hoop stress in Fig. 5 is characteristic of the applied load, it means an internal pressure with closed end effect.

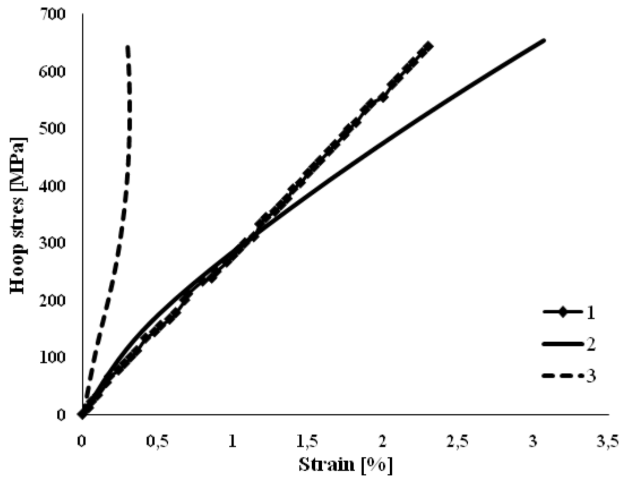

Figure 5. Experimental /13/ (1) and analytical (2, 3) hoop stresses σ_θ as functions of hoop ε_θ (1, 2) and axial ε_z (3) strains in internal pressure with bottom effect composite tube of $[\pm 55]_3$ glass/epoxy.

SUMMARY AND CONCLUSIONS

The aim of this paper is to develop analytical model of viscoelastic behaviour coupled to damage of multilayer tubular structures in long fibers. This tool predicts the mechanical response of cylindrical composite structure under different types of loading such as pure internal pressure, tension and finally internal pressure with end effect. The obtained results are compared with respect to experiments previous results, where good agreement is reported. Shapes of the stress-strain curves is used to record nonlinear characteristic from the beginning of loading, taken into account the viscoelastic behaviour of the composite. In addition, we note a loss of rigidity in the analytical and experimental gaits, due to the progressive damage of composite material. To reduce the acceptable deviation between the model- and experimental results, taking into account the visco-plastic behaviour of the damaged multilayered cylindrical composite is important. Thus, the tubular structures design model is validated based on the results obtained. The forthcoming paper is focused on the life prediction in composite structures, which is an important tool in the conception of composite structure. In order to predict the time remaining before failure of tubular structures under cyclic loading of pressure, the future paper is devoted to take into account the viscoelasticity coupled to damage behaviour under fatigue pressure loading, comparing experimental results obtained on prototypes of tubular structure.

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NOMENCLATURE

Latin symbols

C	The matrix of rigidity.
D_I	Parameter of damage.
E_x	Young's modulus [MPa].
E_y	Young's modulus [MPa].
$\boldsymbol{E}_z$	Young's modulus [MPa].
G_{xy}	Shear modulus [MPa].
G_{xx}	Shear modulus [MPa].
G_{yz}	Shear modulus [MPa].
H	The correction matrix.
R^d	Function hardening.
$R_{int}^{(k)}$	Inner radius of the layer k (mm).
$R_{ext}^{(k)}$	Outer radius of the layer k (mm).
S^c	The flexibility of the composite matrix.
Ur	Radial displacement (mm).
X	Longitudinal direction.
Y	Motor force.
Y_c	The damage threshold.
e_k	Layer thickness k (mm).
f^d	Charge function.
r	Radius (mm).
ν_{xy}	Poisson coefficient.
ν_{xx}	Poisson coefficient.
ν_{yz}	Poisson coefficient.

Greek Symbols

θ	Circumferential direction.
α	Coefficient director.
φ	Winding angle (°).
ψ	Freedom energy density.
$\dot{\sigma}$	Stress vector in the coordinate system (r, z, θ).
$\dot{\varepsilon}$	Deformation vector in the coordinate system (r, z, θ).
$\dot{\lambda}^d$	Lagrangian multiplier.
γ_0	Twist per unit of length (1/mm).
ε_0	Axial strain.
$\varepsilon^{\varepsilon}$	Elastic strain
ε^{ve}	Viscoelastic strain
τ_i	Relaxation time
μ_i	The weights

Subscripts

r	Radial direction.
z	Axial direction.
θ	Circumferential direction.
x	Longitudinal and transverse fiber direction.
Y	Transverse fiber direction

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