Development of film- and- fabric composite materials durability assessing methodology under time-dependent influences of temperature and solar radiation

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Abstract. In this paper, we present the design of stress-strain state calculation and film-and-fabric composite materials durability under stresses and solar radiation. We have constructed a two-dimensional finite-state-element computer model of the deforming process of the low-level cell of film-and-fabric-based composite material for the evaluation of its durability which takes into account non-linear viscoelasticity, temperature variations, ageing of the material, the process of upbuilding of microdamage and photodegradation. Qualitative research of operational factors influence (UV, temperature) on film-and-fabric composite materials durability was conducted.

1. Introduction

Nowadays pneumatic and canvass structures made of film-and-fabric composite materials are widely used. With the advent of new polymeric materials the diversity and application area of such structures increase. Advantages of film-and-fabric composite materials structures are low investment costs, low material consumption, mobility and quick installation.

Film-and-fabric composite materials is a composite with fabric reinforcing foundation of high-strength synthetic yarns and film coating of elastomers or thermoplastics, protecting the reinforcing foundation from weather conditions and giving material air permeability.

Analyzing the application of mobile structures it turns out that unlike traditional structures, the greatest efficiency of their use is determined by not so much maximal as economically proved optimal service life. For that matter the problem of film-and-fabric composite materials creating not only with maximal, but also with preset durability under certain conditions of operation arises. Currently, one of the most important issues is fabric composite durability evaluation considering the aging of material under weather conditions, temperature and UV irradiation.

To assess the long-term strength of the given material we need to know the stress-strain state of each composite component on a scale of fabric unit cell [2]. Obviously, because of the small size of film-and-fabric composite materials material cross section (0.8-3 mm) solving this problem with methods and means of full-scale strain measurement or other empirical methods only is not possible. Clearly, creating optimal structures, therefore optimal property performance requires development of film-and-fabric composite materials structurally-simulated model adequately imitating real
material [1,4,5]. Creating such models is possible using numerical methods only, focused on modern computers with advanced visual system. The term structurally-simulated model means finite element model of composite unit cell, where physical, mechanical and geometrical parameters of structural components vary.

2. Structure defining (physical) relations for film-and-fabric composite materials component considering static, kinematic and structural parameters of the material with ultraviolet radiation

When choosing a structure defining relations we take into account the well-known experimental facts concerning polymeric materials. First, the film-and-fabric composite materials matrix is assumed to be isotropic. Defining relations for the aging viscoelastic material are taken as:

\[
\varepsilon = S\sigma + \int_0^t H(t, \sigma, \omega, W, T, v, \ldots) dt, \tag{1}
\]

here \(\omega, W\) – some parameters of the deformation process, \(v\) – vector of structural parameters (specific volume of various types of modifying additives, regulating mechanical and operational characteristics of the film-and-fabric composite materials matrix – plasticisers, fillers, stabilizers, etc.)

To determine the model of all possible kinds of parameters, consider the following. First, we use damage parameter \(\omega\) which describes the accumulation of material defects like microcracks, micropores. For \(\omega\) we take up the kinetic equation:

\[
\frac{d\omega}{dt} = \Omega(\sigma, \omega, T, h, \ldots, \ldots, \ldots) \tag{2}
\]

Further, affected by external non-bearing aggressive action, UV radiation in particular, phase transformation and polymer matrix mechanical properties changes occur which is called material degradation (UV affection causes photodestruction). As a result of the secondary reactions the process develops inside the material on some layer of height \(h\), and it comes from the surface side exposed to radiation. Microcracks appear on the surface and increase in size, which leading to \(h\) layer height increasing. In this regard, we introduce the scalar parameter \(W\), which we call parameter of photodegradation, considering it proportional to the exposure intensity \(\gamma\). For it, we take evolutionary equation as a constitutive relation:

\[
\frac{dW}{dt} = U(\sigma, \omega, T, h, \ldots, \ldots, \ldots) \tag{3}
\]

Fick's law is not used due to the fact that as we stop radiation process photodegradation also stops. For simplicity we assume that the radiation surface is flat, the penetration of photodegradation inside the material will be describe by equation similar to (3):

\[
\frac{dh}{dt} = R(\sigma, \omega, T, h, \ldots, \ldots, \ldots) \tag{4}
\]

Material stiffness characteristics, included in matrix \(D=S^{-1}\), at a first approximation can be assumed as time-related \(t\) due to aging of structural parameters and material, accumulation of microdamages, temperature, photodegradation parameter:

\[
D = D(\omega, W, T, v, t). \tag{5}
\]

Material strength condition will be described by the following equation:

\[
f(\sigma, \varepsilon, \omega, W, g, T) = 1, \tag{6}
\]

here \(g\) – structural parameters including, strength limit or microcrack’s typical length in particular.

In this paper, to conduct the qualitative analysis of the given composite behavior, task was formulated simpler. First, the strength of the matrix was investigated, because its destruction causes destructions of the fabric due to UV access to foundation. Secondly, it was assumed that film-and-fabric composite materials element is flat and deformed. Thirdly, strains and displacements were minor.
3. Development of finite element analysis method of representative film-and-fabric composite materials cell deformation process

Film-and-fabric material regular structure allows to allocate as a representative element for modeling material only one cell (Figure 1) formed by two adjacent pairs of warp yarns (1 and 2) and weft (4 and 5). Layers between matrix and yarns are also introduced in this model (2, 3, 6, 7).

Geometry of the basis is totally determined by two components - the upper and lower contours changing according to cosine law. Sectional shape of the weft in presented structural cell is an ellipse. Light protecting coating which is applied directly to the matrix (10), also presented as separate fields (8 and 9) in composite cell structure.

Space wise problem discretisation is carried out by finite elements method, consisting of 6-noded triangular elements with quadratic approximation of displacement [3]. Following boundary conditions were taken for the cell. Surface of the element \(y=a\) is irradiated with ultraviolet. On the left end when \(x=0\) there are no displacements along the axis \(x\). At the point with coordinates \((0,0)\) there is no any displacement along the axis \(y\). The upper and lower bounders \((y=0\) and \(y=a)\) are neither loaded nor fixed. Right end \(x=b\) is given displacement \(u_x = \Delta\). In time, stress relaxation occurs, but as a result of irradiation and microdamages at some point strength can be broken. This value we will call durability further in the paper.

Total strain vector \(\varepsilon\) considering viscoelastic properties of phases of microdamades accumulation process is written as (further the vectors are in curly braces and matrices in square):

\[
\{\varepsilon\} = \{\varepsilon\} + \{\varepsilon^c\} + \{\varepsilon^\omega\},
\]

where \(\{\varepsilon\}\) is the vector of the elastic of deformation, \(\{\varepsilon^c\}\) is creep strain vector, \(\{\varepsilon^\omega\}\) is vector of deformations arising from scattered damage accumulation. Elastic law in numerical calculations was taken as linear:

\[
\{\sigma\} = [D]\{\varepsilon\}.
\]

For creep strain \(\{\varepsilon^c\}\), according to Kachanov’s hypothesis the following constitutive relation was accepted:

\[
\varepsilon^c = \int_0^t H(t-\tau,\sigma(\tau)]\sigma(\tau) d\tau
\]

To provide flat strain state, further it was assumed that matrices \(D\) and \(H\) are proportional:
\[ H = \lambda(t - \tau, \sigma_i) D^{-1} \] 

In numerical experiments, the function \( \lambda \) was taken as generalization of Abel’s kernel:

\[ \lambda(t - \tau, \sigma_i) = \frac{C(\sigma_i)}{(t - \tau)^{\alpha(\sigma_i)}}, \quad C \geq 0, \quad 0 < \alpha < 1; \]

Creeping parameters approximated as follows:

\[
\begin{align*}
C &= (c_0 + c_1 \sigma_i)^2 \\
\alpha &= 1 - \frac{1}{\sqrt{1 + (\alpha_0 + \alpha_1 \sigma_i)^2}}
\end{align*}
\]

Figure 2. Damage parameter distribution \( \omega \) in film-and-fabric composite materials cell at a time \( t^*/3 \).

Figure 3. Damage parameter distribution \( \omega \) in film-and-fabric composite materials cell before destruction.

Figure 4. Photodegradation distribution level in film-and-fabric composite materials cell at a time \( t^*/3 \).

Figure 5. Photodegradation distribution level in film-and-fabric composite materials cell before fracture.

Based on PVC film coating full-scale analysis we get the following matrix creep parameters \( c_0 = 0.096 \) (\( \sqrt{\sigma} \)^{-1}, \( c_i = 0.026 \) (MPa \( \sqrt{\sigma} \)^{-1}, \( \alpha_0 = 9.15 \), \( \alpha_i = 2.402 \).

Figure 2 shows the damage parameter distribution \( \omega \) in film-and-fabric composite materials cell at time \( t^*/3 \), and figure 3 – shows the state before material destruction. Figure 4 shows photodegradation distribution level at a time \( t^*/3 \), and figure 5 – shows the state before fracture.
4. Solutions under unsteady temperature variations

This section describes the results of a qualitative research of influence patterns of temperature variations on durability of film-and-fabric materials. A year round temperature variation formula can be approximated as follows:

\[ T = T_0 + \Delta T \cdot \sin(\omega t). \]  

(13)

Consequently (see 13), the temperature variation diagram is represented in fig 6.

Durability prediction calculations were based on the linear addition of damageability principle which states that damage occurs under the following conditions [6]:

\[ \int_0^t \frac{d\tau}{t^*(T)} = 1. \]  

(14)

Considering that durability \( t^* \) is determined numerically, thus, (14) was substituted for an approximate ratio:

\[ \sum_i \Delta t_i / t_i^* = 1 \]  

(15)

\[ \text{Figure 6. Time Temperature changes law.} \]  

\[ \text{Figure 7. Jump function temperature approximation.} \]

Suppose \( \Delta t \) is the time step estimated, for instance, as three months of spring, three months of summer, three months of autumn and three months of winter. Thus, temperature variations occur four times a year. Consequently, \( T \) is approximated by a step function as is shown on fig. 7.

Therefore, the problem can be written as follows (15):

\[ N_{\text{years}} \cdot \left( \frac{\Delta t}{t_{\text{spring}}} + \frac{\Delta t}{t_{\text{summer}}} + \frac{\Delta t}{t_{\text{autumn}}} + \frac{\Delta t}{t_{\text{winter}}} \right) = 1, \]  

(16)

where \( N_{\text{years}} \) is the unknown number of years which determines the durability of the composite material in question given a specific temperature variation \( \Delta T \).

The formation of defining correlations should be based on the known experimental facts referred to polymeric materials, due to the fact that mechanical properties that constitute creep flow ratio (19), will depend on the temperature \( T \). Let us introduce as an example, the following function \( f_1 \), that determines the law of pattern change of mechanical properties of creep flow depending on the temperature:

\[ f_1 = (f_0 \cdot (\arctg[(T - T^{*\prime})/\theta_1] + \frac{\pi}{2})) + \frac{\pi}{2} \cdot (\arctg[(T - T^{*\prime})/\theta_1] + \frac{\pi}{2}), \]  

(17)
here, the constants $f_0, \theta_1$ determine the nature of changes in creep flow parameters depending on the temperature. Mechanical properties of the creep flow, included in the ratio (12), as shown in figure 8, are equated as follows:

\[ c_0 = c_{01} \cdot f_1(T), \quad c_1 = c_{11} \cdot f_1(T), \quad \alpha_0 = \alpha_{01} \cdot f_1(T), \quad \alpha_t = \alpha_{t1} \cdot f_1(T). \]  

(18)

Here, $c_{01}, c_{11}, \alpha_{01}, \alpha_{t1}$ are the mechanical parameters that correspond to the average operating temperature $T^{**}$. Figure 8 illustrates the variation of $c_0$ with $T$.

\[ f_2 = (f_0 \cdot (-Arctg[(T - T^{**}) - \frac{1}{f_0} \cdot \frac{\pi}{\theta_2}] \cdot \frac{\pi}{2}) + \frac{\pi}{2})^2 \]  

(19)

Here, $f_0, \theta_2$ are the parameters that determine the nature of elasticity coefficient variations depending on the temperature. Parameter $E_{00}$ shall be equated as follows:

\[ E_{00} = \bar{E}_{\infty} \cdot f_2(T), \]  

(20)

where $\bar{E}_{\infty}$ is the Young's modulus, which corresponds to the average operating temperature $T^{**}$. Figure 9 illustrates the variations of $E_{\infty}$ with $T$.

The mechanical property $C_B$ for the damage parameter $\omega$, shall be similarly (19) represented as follows:

\[ C_B = C_{B0} \cdot f_3(T), \]  

(21)

where $C_{B0}$ is the parameter which corresponds to the average operating temperature $T^{**}$.

The sake of intensification, UV-radiation $\gamma$ shall be similarly represented as follows:

\[ \gamma = \gamma_0 \cdot f_4(T). \]  

(22)

Next, we carried out numerical experiments. For the sake of simplicity, we assumed that $f_3 = f_1, \quad f_4 = f_2$. The calculations were made on the assumption of smallness of deformity in accordance with the developed model. $T^{**} = 283^\circ K$ was taken as the average equivalent temperature on the Kelvin temperature scale.

Figures 10 - 11 represent the diagrams of dependence of durability $t^*$ on temperature variations $\Delta T$ with different positions of the right-side abutting end.
5. Results and discussion

Conducting numerical experiments we studied the effect of geometrical parameters on the durability of fabric composite cells. Numerical experiments revealed some expected and unexpected results. The following principles were obtained. As it was predicted the higher the film-and-fabric composite materials thickness (under constant reinforcing foundation and weft flattening) the higher $t^*$ durability. This can be determined by the increasing of matrix thickness above and below the weft. As step of weaving also increases the longevity increases too. The bigger the shift of the right-side abutting end, the lower the durability, exceedingly at that.

Due to modifiers mechanical properties of the matrix and light shielding layer can be changed, for example, it can influence matrix sensitivity and the light shielding layer to photodegradation. It is possible to vary the coefficients $E_0, c_0, c_1, c_0, c_1, \alpha_0, \alpha_1$, characterizing the viscosity and stiffness of the matrix and light shielding layer in the formula (19), and the modulus of elasticity and Poisson's ratio of the warp and weft. Therefore further durability was investigated by means of varying the mechanical characteristics of film-and-fabric composite materials structural components. Other cases of different sensitivity to photodegradation and light shielding layer matrix were studied.

Studies showed that stiffness reduction of the surface layer or matrix increases the durability. But increasing the warp or weft stiffness causes a slight decrease in durability.

We also revealed the following qualitative regularities of temperature-dependent $\Delta T$ changes in durability $t^*$. Temperature variations result in slight changes in elasticity properties and creep flow parameters; an increase of $\Delta T$ results in a decrease of durability $t^*$. However, with sufficiently high $\theta_1$ and $\theta_2$, durability starts to increase from a certain value of $\Delta T$, as is shown in figure 11. This is attributable to the fact that with higher parameters of $\theta_1, \theta_2$ and larger $\Delta T$, a material starts to soften so fast that damages in material accumulate slower. Thus, our numerical experiments led to scope for structure optimization and this type of composites durability increase.

Acknowledgments

The reported study was supported by RFBR research projects No. 15-08-06018.

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