Estimation of the durability of polymer composites on a fabric basis, taking into account the influence of non-force factors

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Abstract. We considered the problem of evaluating the durability of film-fabric material (FFCM). The models of phase deformation of a film-fabric composite material was developed which took into account nonlinear viscoelasticity, temperature changes, material aging, microdamage accumulation processes and photodestruction. We presented the composite under consideration as an inhomogeneous body. When choosing the structure of the defining relations, we used the experimental data obtained by the authors for the phases of FFCM. Based on the modification of the second Fick’s law, the kinetic law of propagation of the photodestruction parameter deep into the representative cell of FFCM was constructed. To conduct a qualitative analysis of the behavior of the composite material under study, we formulated the problem with some model constitutive relations and numerical experiments were performed.

1. Introduction

When designing elements of the structures and buildings made of polymer composite materials (PCM), the most important were the tasks of assessing their strength, stiffness and durability, taking into account the destruction of the material, since under real operating conditions the material of structures was subjected to the complex effects of aggressive environments, temperature, mechanical loads and other energy impacts, various combinations of which caused various mechanisms of destruction.

The aggressive media, penetrating into the volume of a structural element of FFCM, sometimes led to significant changes in its physical and mechanical characteristics, which also caused a change in the stress-strain state of structures. The researches, for example, [1-3] were devoted to improving the effectiveness of FFCM in the aggressive environments we had in service. In the work [1] we investigated the issues of improving the quality and efficiency of FFCM application for using in chemically and biologically aggressive environments by the methods of physical-and-chemical and structural modifications with small additives. In the work [2] was analyzed the effect of the content and grain size of the filler particles on the strength and durability of FFCM, technological and operational factors. We revealed dependencies that made it possible to predict the properties of PCM. In the work [3] we suggested using complex modifiers that significantly stiffen resistance of PCM to different kinds of fungi as well as improve their physical and mechanical properties.
In the works [4-6] we explored the subject of aging and PCM degradation under the influence of climatic factors and operational impacts. For example, in the work [5] we studied aging of PCM of aviation purpose, we also showed a collectively accelerating synergistic effect of climatic factors in the formation of material damage. In the work [6] we showed the test results of PCM compositions based on epoxy binders, carried out under the influence of natural climatic factors of a temperate climate. The analysis of changes in the total solar radiation and ultraviolet radiation of various ranges was carried out and the influence of the duration and intensity of irradiation on the change in the elastic-strength characteristics of polymer composites was determined. In the work [7] we submitted the data on the change in the tensile strength, elastic modulus, and elongation under tension of the materials after several cycles of a rapid temperature change. In the work [8] we studied a strain-stress state (SSS) of fiberglass plastic under conditions of climatic aging. It was revealed that the destructive stresses of fiberglass plastic were significantly reduced during the first two years of its using, what should be taken into account when choosing fiberglass plastic with the declared characteristics. Ultraviolet did not significantly affect the stress-related properties of fiberglass plastic. In the work [9] we presented an assessment of the use of the composites based on a polyalkanamide matrix under thermal cycling. We also presented the data on the change in tensile strength, elastic modulus, and elongation in tension of materials after several cycles of a rapid temperature change. Vacuum ultraviolet radiation created by the sun in the outer space could lead to degradation of thermoregulatory coatings, what would lead to a change in their optical, mechanical and chemical properties. In the work [10] we represented the researches of high-strength thermal control coatings with the radiological protection function, carried out with the aim of reducing degradation of the optical properties of coatings under the influence of aggressive factors of the outer space and protecting on-board electronic equipment from electromagnetic interference. The effect of vacuum ultraviolet radiation on polymer composites led to a mass loss, a change and a deterioration in their optical properties [11]. We revealed the effect of smoothing the surface of composites. In the work [12] we made an experimental assessment of the effect of temperature aging on the mechanical behavior, residual strength, and rigidity of PCM. It turned out that, as a result of temperature aging, the mechanical properties of the composite deteriorated, defective structures grew, matrix embrittlement and fiber breakdown occurred. In the work [13] we offered a model which described degradation of the elastic moduli of PCM upon heating to the high temperatures. Using the model, we obtained analytical dependences between the elastic moduli of textile composites and the elastic characteristics of their matrices and fibers, as well as the geometric structural parameters of composites at the high temperatures. The results showed a good correlation with experimental data for carbon and glass phenolic composites.

2. Experimental part

To determine the parameters of the behavior patterns of the phases of a composite, we carried out the experiments to identify the mechanism of aging and destruction of the film-fabric composite material (FFCM) under the operating conditions. To ensure strict regulation of the simulation of FFCM operating conditions, the tests were carried out in the laboratory conditions under influence of the artificial factors that are adequate to the full-scale energy values according to the power-producing values [14].

The experimental studies revealed a unique effect of the FFCM aging and fracture mechanism under influence of the climatic factors in a stress-strain state. The facts cited in the literature [15–18] were explained, according to which the local gaps in the materials of fencing in many types of structures from soft shells that had been in operation for a certain period of time, as a rule, did not coincide with any of the places of the greatest tensile forces found as a result of calculation.

The climatic aging and fracture mechanism of stress-strain FFCM was as follows. Due to the high degree of initial crimping of the reinforcing threads, deformability of the material in the direction of the large tensile loads was very high and could reach 10-20% (the threads straighten in this direction). Moreover, in the orthogonal direction, if the tensile load was less than in the perpendicular, the threads
of the reinforcing base were bent and created local stress zones in the polymer matrix of the composite. Additional influence of the climatic factors, mainly UV radiation of the sun, led to formation of microcracks in the above zones. Next, those microcracks grew into main through cracks, being oriented perpendicular to the direction of maximum deformation of the coating. It opened up an access of UV radiation to the less loaded threads of the reinforcing base, what led to an increase in the aging and fracture rate in the less loaded direction of the soft shell.

3. Structure of the defining (physical) relations for the FFCM components, connecting the static, kinematic and structural parameters of the material

To assess the durability of FFCM, a model of deformation of its representative cell was developed, taking into account nonlinear viscoelasticity, temperature changes, aging of the material, the processes of microdamage accumulation, and photodestruction. The considered cell was presented as an inhomogeneous body. When choosing the structure of the determining relations, the known experimental facts regarding the FFCM phases were taken into account. Based on the modification of the second Fick’s law on diffusion the kinetic law of the propagation of the photodestruction parameter deep into the representative FFCM cell was constructed. To conduct a qualitative analysis of the behavior of the studied composite material, the problem was formulated for some model defining relations.

The defining relations for the FFCM phases were constructed taking into account the viscoelastic properties of polymeric materials. For the structural components of the polymer composite, nonlinear relations of the theory of hereditary elasticity were used [19]. The theory of damage accumulation developed by Yu. N. Rabotnov [20] was used to formulate criteria relations of the delayed fracture of the material in question.

The following parameters of the FFCM aging process were introduced as the main ones. First, this was a damage parameter \( \omega \), which described the accumulation of defects in the material, such as microcracks, micropores. For it, we could use defining relations both in differential form and of a hereditary type [20-23].

In the numerical examples, the following kinetic equation is adopted:

\[
\frac{d\omega}{dt} = B(T) \cdot \eta(\omega, \sigma_i), \tag{1}
\]

where \( B(T) \) is some fugacity of temperature, \( \eta(\omega, \sigma_i) \) is a function depending on stress intensity \( \sigma_i \) and on a parameter of accumulated defects \( \omega \) in the FFCM cell.

Under influence of the climatic factors, in particular ultraviolet irradiation, there was aging of the material, which covered the tissue. After crack opening, phase transformations and changes in the mechanical properties of the fabric material began. We called that process a photodestruction of the material. We introduced a scalar parameter \( W \), which we called a photodestruction parameter. Diffusion of destruction into the thickness of the material in a certain layer of height \( h \) proceeded from the side of the surface exposed to ultraviolet radiation. Microcracks appeared on the surface, which also grew with time, which, in turn, again led to an increase in the layer thickness \( h \). The photodestruction parameter was considered changeable in proportion to the irradiation intensity \( \gamma \).

It is proposed to use the following evolution equation for the photodestruction parameter \( W_0 \) on the surface of a representative FFCM cell, subjected to irradiation:

\[
\frac{dW_0}{dt} = \gamma \cdot \zeta(T) \cdot f(\sigma_{i0}, W_0), \tag{2}
\]

where \( \zeta(T) \) is a nonlinear temperature function \( T \), and \( f(\sigma_{i0}, W_0) \) is a function of two arguments: stress intensity \( \sigma_{i0} \) and degree of photodestruction \( W_0 \) on the surface of the material.
The kinetic law of the propagation of the photodestruction parameter $W$ deep into the representative FFCM cell can be written on the basis of Fick's law in the following form:

$$\frac{\partial W}{\partial t} = \gamma \cdot \zeta (T) \left( \frac{\partial}{\partial x} (\mu \frac{\partial W}{\partial x}) + \frac{\partial}{\partial y} (\mu \frac{\partial W}{\partial y}) \right),$$ (3)

where $\mu = \mu(x, y)$ is a diffusion coefficient of photodestruction parameter $W$. We assume that, in the case of completion of irradiation, the destruction process should end, therefore the coefficient $\gamma$ is introduced in (3).

The disadvantage of the equation (3) was that it was hyperbolic, therefore, in the very first moment after the appearance of destruction on the irradiated surface this destruction instantly spread over the entire FFCM depth, (although in infinitely small values) gradually increasing with time. Since this was not natural for the material degradation process, we introduced the hypothesis that the penetration depth of photodegradation $h$ was determined by some dependence on the state parameters of the material. The irradiated surface of the representative FFCM element, was assumed to be flat, just for simplicity, therefore, the process of increasing the depth of penetration of photodestruction into the material is described by the ratio:

$$\frac{dh}{dt} = \gamma \cdot \zeta (T) \cdot g(\sigma, W_0, h).$$ (4)

Then for $W$ the boundary conditions take the following form:

$$W(\sigma, \omega, T, x, y, t) \bigg|_{y=0} = W_0(x, t)$$ (5)

$$W(\sigma, \omega, T, x, y, t) \bigg|_{y=h} = 0$$ (6)

4. Problem solving with non-stationary temperature changes

This section presents the results of the qualitative studies of the influence pattern of temperature differences on the FFCM durability. The law of a temperature difference $T$ during the year can be approximated as:

$$T = T_{cp} + \Delta T \cdot Sin(\omega t)$$ (8)

where $T_{cp}$ is an average operating temperature, $t$ is time, $\Delta T$ is a temperature difference.

The principle of linear summation of damage is taken as a basis of calculations of durability. Let us introduce as an example the following function $f_{1i}$, that determines the law of change in the mechanical characteristics of elasticity and creep of a component with the number $i$ depending on the temperature $T$:

$$f_{1i} = \left( f_{0i} \cdot \left( Arctg \left( \frac{T - T_{cp}}{\theta_i} \right) + \frac{\pi}{2} \right) / \frac{\pi}{2} \right),$$ (9)

here the constants $f_{0i}, \theta_i$ determine the nature of the change in mechanical characteristics, which are increased with a raise of the temperature.

The Figures 1, 2 show the diagrams of durability dependency on the temperature difference for various deformations $\varepsilon$ at $\theta_{11} = 0.045$, $\varepsilon_{11} = 0.045$ and at $\theta_{11} = 0.18$, $\varepsilon_{11} = 0.18$.

The following qualitative regularities of the change in durability due to temperature difference were revealed. If the temperature difference leads to small changes in the elastic characteristics and creep parameters, then with increase in $\Delta T > 0$ durability $t^*$ also decreases (Fig.1). However, at sufficiently large $\theta_{11}$ and $\varepsilon_{11}$ durability starts increasing from a certain value of $\Delta T$, as can be seen
in Fig. 2. This can be explained by the fact that at the large parameters of $\theta_{11}$ and $\psi_{11}$, and, at large $\Delta T$, the material softens so quickly that the damages in the material start being accumulated more slowly.

![Fig. 1. Durability dependency on temperature difference at $(\theta_{11} = 0.045, \psi_{11} = 0.045)$](image1)

![Fig. 2. Durability dependency on temperature difference at $(\theta_{11} = 0.18, \psi_{11} = 0.18)$](image2)

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