

CREEP OF TEXTILE-REINFORCED COMPOSITE UNDER STATIC AND CYCLIC LOADS

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The paper considers the creep of a textile-reinforced thermoplastic composite with a glass filler under the action of a combined short-term cyclic and long-term static tensile loads at room temperature. The investigations were carried out on glass-fabric-reinforced polypropylene specimens, which were made by autoclave molding. The creep of the composite was experimentally investigated under a cyclic load at different amplitudes. The creep kernel has been calculated from experimental data according to the Boltzmann superposition principle. Other creep models of materials have been analyzed based on data from a review. The laws governing the short-term creep of polypropylene under the action of a static load have been determined. A behavioral model of the composite under investigation under the considered conditions is proposed. Numerical calculations have been made with the aid of the proposed model using experimental results taken from other works, and a good agreement between them has been established. The peculiarities of the creep of textile-reinforced polypropylene under the considered conditions have been determined. The range of application of the model has been determined.

Keywords: composite, glass fiber, creep, static and cyclic loads.

Introduction. At the present time, composites are widely used in aircraft manufacture, in particular in aircraft flight control systems (control surfaces, flaps, trimmers, fasteners, beams and different tie rods [1, 2]), which are in a complex stress-strain state during operation. When developing models of their behavior, rheological aspects, such as creep, must be taken into account.

The study of the creep of structures under the action of a load is an important matter on account of the loss of load-carrying ability, which can result in their failure under operating conditions with time or in the loss of functionality. This process is acted upon by the following factors: the type and level of load, temperature, irradiation, humidity, etc [3–5]. The elements of the flight control system are under different conditions: the tie rods and fasteners are in the airtight area at room temperature or close to it. The control surfaces and boosters are installed outside under the conditions close to the environmental conditions. The use of thermoplastic composites in the aircraft structure is greatly increasing [2, 6]. The low-temperature creep of these materials is usually not observed [4]. However, the thermoplastic materials and composites contained in them have a high creep and ductility not only at elevated temperatures, but also at room temperature [7]. That is the creep of the elements that are in the airtight area of the aircraft and in the control surfaces during take-off and landing is possible. The functioning of any control system involves a sequence of signals of different duration and amplitude in an arbitrary sequence. In terms of strength and creep, this can be interpreted, with respect to the structure, as a sequence of static loads of different duration and amplitude in an arbitrary sequence. Additionally, transient processes as cyclic loading between regimes occur in systems. That is the load on an element of the control system will be an arbitrary sequence of static loads with a short-term cyclic load in the intervals between them. The creep of composites has been studied under different types of cyclic load [3, 8], whereas creep under static load is less explored [5, 9].

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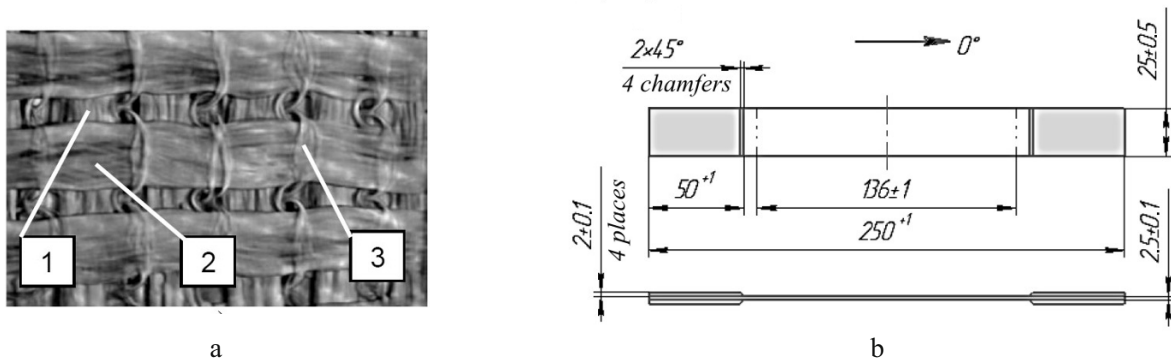


Fig. 1. Twintex material [12] (a) and tensile specimen (b): (1, 2) weft and warp fibers, and (3) stitching.

The aim of the work is the experimental-theoretical study of the creep of textile-reinforced thermoplastic composites with a glass filler.

Material and Research Procedure. The research was carried out on a polypropylene composite based on stitched glass fabric [10]. The basic modification of this material is available for order under the name of Twintex, which is a stitched bidirectional glass fabric with polypropylene fibers (Fig. 1a).

The multilayer preform of the material, developed by the Technical University of Dresden [11], has several layers of an equally oriented fabric, which are sewn together. The volume content of fibers is 51.6%. Blanks in the form of 300×300 mm plates were pressed together at 210°C. Strip-type specimens for tensile tests according to the ISO 527-4 standard were cut from obtained plates by water jet machining. Twintex patches were pasted onto specimens with an epoxy adhesive. The constants were determined in accordance with the DIN EN ISO 527 and DIN EN ISO 14129 standards on an Instron 8801 testing machine. 250×25×2.5 mm specimens with patches were used for tensile tests (Fig. 1b). The shear characteristics were determined on specimens of similar size, but with ±45° reinforcement. The absolute strain was measured with a mechanical extensometer with a gage length of 50 mm. The mechanical characteristics of the material under investigation [11] are: Young's modulus in the direction of warp fibers $E_1 = 23$ GPa, of weft fibers $E_2 = 22.5$ GPa; ultimate strength in the direction of warp fibers $\sigma_{u1} = 433$ MPa, of weft fibers $\sigma_{u2} = 484$ MPa; Poisson's ratio in the sheet plane $\nu_{13} = 0.13$. These characteristics were used in numerical calculations.

In aircraft manufacture, the strength margin of 1.5–2 is generally accepted [13]. In this range, stresses of different duration may arise in a different sequence. Taking into account that the approximate aircraft landing duration is 0.5 h, when, e.g., the flaps are permanently acted upon by static loads, which are proportional to their extension angle, we can assume static load exposure time with a reserve of 0.5–2 h. Thus, it is expedient to carry out the research using several levels of static load of the above duration. Based on the mean frequency and duration of transient processes in the case of changing the position of the control surface when handling the aircraft, we take the frequency of cyclic load as 5 Hz, its duration as 4 s, and cycle asymmetry as $R = 0.1$. Therefore, to study the creep of a plastic, it is expedient to use a step load with its successive increase and a load of broken character of different duration in a range of 0.5–2 h. Three series of identical specimens (6 pcs.) were tested on an Instron 8801 machine as follows:

Variant No. 1. One specimen of the first series (3 pcs.) was tested under a cyclic sinusoidal load with the maximum cycle stress $\sigma_{max} = 200$ MPa (cycle asymmetry $R = 0.1$, frequency $f = 5$ Hz) to failure; the second specimen and others were tested similarly, but with a maximum cycle stress of 160 and 145 MPa, respectively.

Variant No. 2. One specimen of the second series (2 pcs.) was kept under the load $\sigma_1 = 55$ MPa for 2 h, then it was tested under a cyclic sinusoidal load with the mean cycle stress $\sigma_{m1} = 55$ MPa ($R = 0.1$, $f = 5$ Hz) for 4 s (20 cycles). The described processes correspond to the first load step. The second to sixth load steps were carried out similarly, but with the following stresses: $\sigma_2 = 66$ MPa, $\sigma_{m2} = 66$ MPa, $\sigma_3 = 80$ MPa, $\sigma_{m3} = 80$ MPa, $\sigma_4 = 88$ MPa, $\sigma_{m4} = 88$ MPa, $\sigma_5 = 99$ MPa, $\sigma_{m5} = 99$ MPa, $\sigma_6 = 110$ MPa, and $\sigma_{m6} = 110$ MPa. Another specimen was tested similarly, but with a time under load of 1 h in each step.

Variant No. 3. The specimen of the third series was kept under the load $\sigma_1 = 50$ MPa for 5 min, then under the load $\sigma_2 = 100$ MPa for 5 min, and then similarly at $\sigma_3 = 50$ MPa, $\sigma_4 = 200$ MPa, and $\sigma_5 = 150$ MPa.

Methods of Taking into Account Creep. The main methods among the methods of taking into account the creep of material under different types of load are the stress method and the temperature method [4]. On the whole, these methods are combined into the so-called principle of superposition. In this work, we employed the stress superposition principle for polymers, viz the Boltzmann superposition principle [14], in which a strain kernel $\Phi(t)$, found from experimental data, which is a function of time t , is used. It is the creep value per unit stress applied at a given instant of time. The creep deformation function of plastic $\varepsilon(t)$ is found in the general case from the formula [14]:

$$\varepsilon(t) = \sum_{i=0}^j \Phi(t - \tau_i) \Delta\sigma(\tau_i), \quad (1)$$

where τ is the stress change time, $\Delta\sigma(\tau)$ is stress increment at the instant τ . That is for each new stress step, a new summand with the zero time of the kernel at the instant of jump is added.

In [9], a similar principle of taking into account the creep of material is employed, the laws governing the short-term creep and strength of a LIPOLA/A-10 polypropylene multifilament are studied, and effective hereditary equations of state are developed. The problem stated in [9] was solved with the aid of linear and nonlinear viscoelasticity theory models, and their applications were determined. Based on experimental results, compliance functions $J(t)$ were constructed for each stress, which show a good result and the possibility to form a compliance function with a small error of using the linear viscoelasticity theory. The equation of state of the linear viscoelasticity theory for small strains in the one-dimensional case is given by

$$\varepsilon(t) = \frac{\sigma(t)}{E_0} + \frac{1}{E_0} \int_0^t \Phi(t - \tau) \sigma(\tau) d\tau. \quad (2)$$

The Rzhantsyn small exponential function [15], with the aid of which obtained experimental results are described, was used as a creep kernel. Taking into account the high linearity of the creep curve, a simplified description of the creep of polypropylene by a linear dependence is proposed. Analogous procedures for a hereditarily elastic body are successively used for metals too [16]. According to the data presented in [17], the approaches proposed in [9, 16] can also be used in testing laminated plastics: composites, in particular glass-reinforced plastics.

Another approach to solving the problem can be the use of rheological models of material [4, 16], which can describe only the uniaxial stress state of unit volume. However, they allow one to conventionally break down the material into elementary components and to characterize the behavior of each component separately and the behavior of the material as a sum of the behaviors of the components, or to break down the complex behavior into a sum of simpler elementary behaviors. For a composite, it is possible to define separately the characteristics of fiber and matrix, to use the Zener model [4] for describing their behavior and to obtain a homogenizing model of reinforced composite [5, 18]. In this work, the Boltzmann superposition principle and the Maxwell rheological model are combined.

Research Results. An experimental study of the creep of a composite under cyclic load at different amplitudes has been carried out (variant of testing No. 1, Fig. 2).

As can be seen, the deformation curves are similar, though they were constructed at different amplitudes of strains, caused by corresponding load amplitudes. Using the obtained data, the creep kernel has been calculated, according to the Boltzmann superposition principle, by approximating the time dependence of mean strain under cyclic load at a constant amplitude with the mean cycle stress $\sigma_m = 72$ MPa (curve 2 in Fig. 2) by the logarithmic function $f(t)$:

$$f(t) = a \ln t, \quad (3)$$

where a is a function constant.

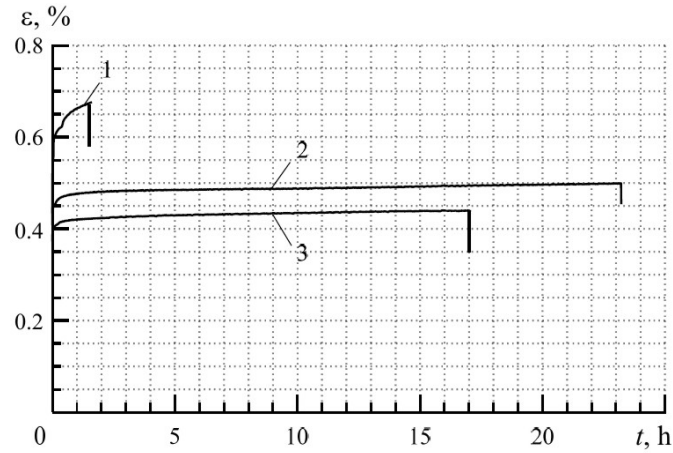


Fig. 2. Time dependence of mean strain under cyclic load with constant amplitude and mean cycle stress: (1) $\sigma_{m1} = 110$ MPa, (2) $\sigma_{m2} = 72$ MPa, and (3) $\sigma_{m3} = 65$ MPa.

The we find the creep kernel from the formula

$$\Phi(t) = \frac{f(t)}{\sigma_m}. \quad (4)$$

The creep kernel was used in constructing calculated curves for variants of testing Nos. 2 and 3.

A test with 20 load cycles and with a duration of steps of 1 and 2 h according to variant No. 2 has been performed. It was calculated according to the Boltzmann superposition principle [14]. Previously, we found the creep kernel from experimental data according to variant No. 1. Experimental and calculation results are shown in Fig. 3.

It can be seen that the calculated data give a good fit to the experimental data at one load level, but poorly describe the transition from one load level to another, which is accompanied by a cyclic load (vertical lines in Fig. 3). An increase in the slope angle of the graph in each step with increasing load is visually observed, but only at the beginning of step for calculated data. Note that in the steady-state creep zone there is a good agreement between the experimental and calculation results: the fragments of the graphs in Fig. 3 are parallel. That is as the load increases, the creep intensity increases, but only slightly for experimental data. When the material is kept under load in a step for 1 h, its behavior does not change. On the whole, for the transition region between load steps, it is expedient to use a different approach.

Based on the results of investigations of polypropylene filaments [9], one can trace the following characteristic features of polypropylene creep and use them further for a polypropylene composite:

1. The maximum strain intensity is observed in the first 15–20 min of tests; then the time dependence of creep under constant load is linear.
2. At loads of up to 35% of the ultimate strength of the material, creep is hardly noticeable on the linear portion.
3. At loads of over 60–65% of the ultimate strength of the material, an intensive creep is observed in the linear region, which is explained by nonlinear creep laws.
4. The compliance function $J(t)$, which is invariant to acting stresses σ_k ($k = 1, 2, \dots, n$), can be applied to the creep process.

These features are also typical of the deformation of Twintex composite: the first two of them are clearly visible, and the third feature holds true. Thus, the compliance function [9] can be used for a polypropylene composite:

$$J(t) = \frac{\varepsilon(t, \sigma_1)}{\sigma_1} = \frac{\varepsilon(t, \sigma_2)}{\sigma_2} = \frac{\varepsilon(t, \sigma_n)}{\sigma_n}. \quad (5)$$

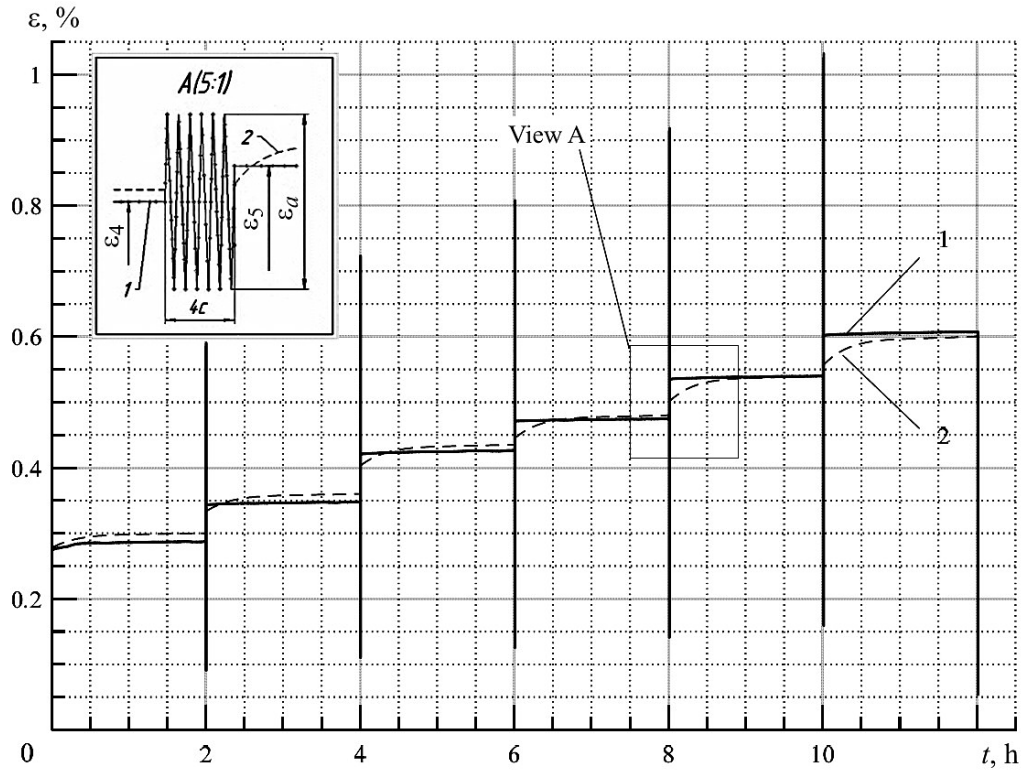


Fig. 3. Dependence of the strain ε on the time t under step load with a load exposure time in a step of 2 h: (1) experiment, (2) calculated curve according to the Boltzmann superposition principle, ε_4 , ε_5 are strain under load exposure in the 4th and 5th steps, respectively, and ε_a is amplitude strain under cyclic load.

An analogy between the creep kernel $\Phi(t)$ and the compliance function $J(t)$ is observed, which express the reduced creep function, which is independent of acting stresses. Accordingly, having one of these functions, one can find the desired creep function. It was decided to assume this possibility as a basis and to use a combination of the Boltzmann superposition principle and the Maxwell rheological model.

Thus, a creep model can be proposed, which is similar to the Boltzmann superposition principle (1) but does not contain the time shift τ_i on transition from step to step:

$$\varepsilon(t) = \sum_{i=0}^j \Phi(t) \Delta\sigma(\tau_i). \quad (6)$$

Using this model, the creep function value is determined from the strain kernel for each instant of time under the given load by adding a new component to the sum of the preceding components. For ease of calculations, formula (6) can be replaced by an equivalent one:

$$\varepsilon(t) = \sigma(t) \left(\Phi(t) + \frac{1}{E} \right). \quad (7)$$

In formula (7), a component from Hooke's law was added to additionally take into account instantaneous strains besides creep. The advantages of this approach are the possibility to make calculations in real time and ease of its implementation.

Using this approach, we have calculated the creep of a polypropylene filament under a step load using data presented in [9] since the peculiarities of its deformation were taken as a basis of the developed model (6) (Fig. 4). In

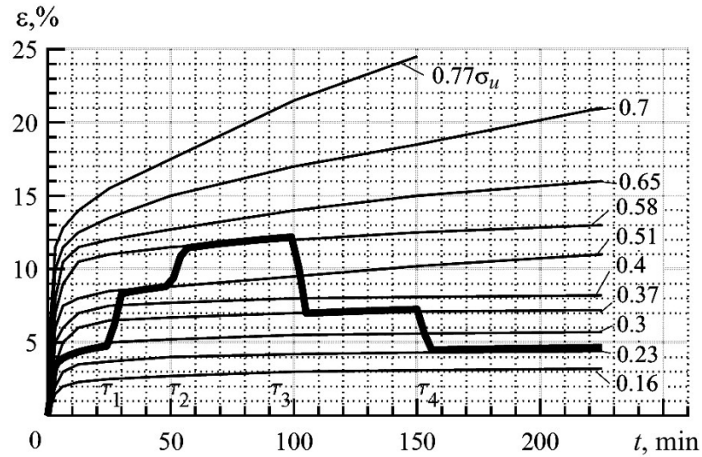


Fig. 4. Calculated (heavy line) and experimental (thin lines) time dependence of a polypropylene filament under different permanent loads (τ_1 – τ_4 are instants of load change).

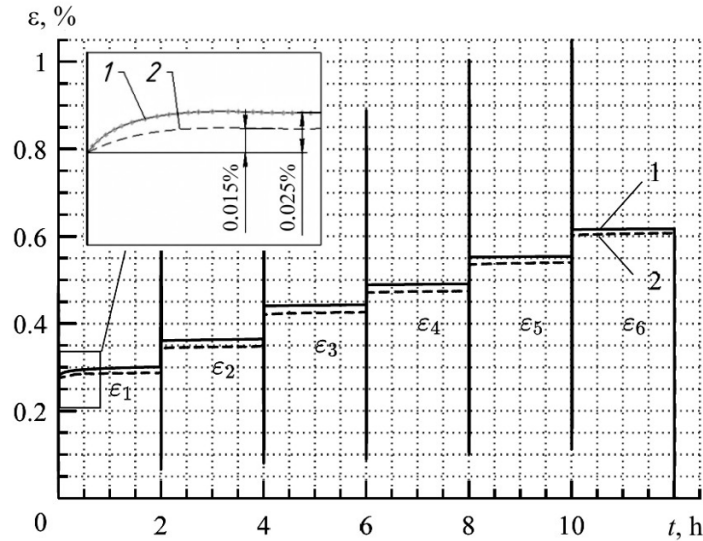


Fig. 5. Experimental (1) and model (2) time dependence of strain for the Twintex material under step stress with constant amplitude and a load exposure time in a step of 2 h (strains in the 1st–6th steps: $\varepsilon_1 = 0.3\%$, $\varepsilon_2 = 0.35\%$, $\varepsilon_3 = 0.45\%$, $\varepsilon_4 = 0.5\%$, $\varepsilon_5 = 0.55\%$, and $\varepsilon_6 = 0.62\%$, respectively).

[9], the above filament was tested under different long-term permanent load. The stress was applied in the following order: 0.3 , 0.51 , 0.65 , 0.37 , and $0.23\sigma_u$ for 0.5 , 0.4 , 0.8 , 0.8 , and 1.2 h, respectively (σ_u is the ultimate strength). The calculation results are shown by a heavy line in Fig. 4. The following constants were adopted for the polypropylene filament: $k = 5 \cdot 10^{-4} \text{ MPa}^{-1} \cdot \text{s}^{-1}$, $E = 230 \text{ MPa}$, where

$$k = \frac{a}{\sigma_m} = \frac{\Phi(t)}{\ln t}. \quad (8)$$

From Fig. 4 it is seen that the calculated curve agrees fairly well with the experimental curves [9]. However, under a load of $0.65\sigma_u$, it coincides with the experimental $0.58\sigma_u$ curve, which is accounted for by nonlinear creep effects under loads of over 60–65%. On the whole, all the above conclusions regarding the study of the creep of polypropylene filaments are confirmed [9]. This indicates the chosen assumptions to be correct for developing a creep model.

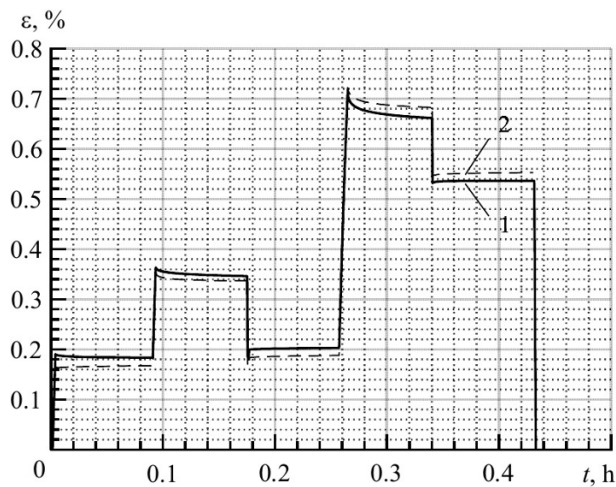


Fig. 6. Experimental (1) and model (2) time dependence of strain for the Twintex material under step stress with constant amplitude.

The developed model (6), (7) was used in all three load variants under consideration. The results of numerical calculation are shown in Figs. 5 and 6.

In test according to variant No. 1, the theoretical curves coincide with the experimental ones (Fig. 2). From Fig. 2 it is seen that two stages are typical of creep: primary creep (significant strain within a short time interval) and secondary creep (slow linear monotonic deformation).

From Figs. 2, 5, and 6 it is seen that the proposed model describes fairly well both long-term cyclic and static loads and their combination in different variants with different sequence of loads. The transition between steps is well described regardless of increase or decrease in stresses, indicating a logarithmic time dependence of strain under permanent load in the first two creep phases of the plastic and the possibility of using the proposed approach.

It should be noted that one standard specimen, which was tested under a cyclic load at a constant amplitude and a constant mean value of stresses and frequency, was taken as a basis in all calculations (creep kernel, k , E). However, the proposed model developed on its basis describes well not only similar cyclic loads, but also static cases. This allows us to state that the same mechanism, which is quantitatively described by the proposed model, taking into account mean stresses and strains, is the basis of the deformation of thermoplastic composite under the considered conditions.

CONCLUSIONS

1. Under the long-term load of a plastic and under loads lower than half of the ultimate strength of the material, its behavior corresponds to the linear viscoelastic model. The time dependence of strain is a natural logarithmic dependence but can be described both by power functions and power exponential functions.

2. Based on the Boltzmann superposition principle, a behavioral model of textile-reinforced thermoplastic composite has been developed using the Maxwell rheological model. The advantages of this model are the possibility to make calculations in real time and the ease of its implementation.

3. Based on calculations, it can be stated that the creep of thermoplastic composite under different types of load and load conditions is of common nature, which is quantitatively described by the proposed behavioral model of textile-reinforced thermoplastic composite taking into account the mean stress and strains.

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