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SHORT-TERM CREEP AND STRENGTH OF FIBROUS POLYPROPYLENE STRUCTURES

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The short-term creep and strength of fibrous polypropylene structures are investigated. On the basis of these characteristics, we develop the models of linear and nonlinear viscoelastic deformation of materials, specify the fields of their applicability, and study criteria used for the evaluation of the static strength and durability of these composites.

Keywords: short-term creep, static strength, durability, fibrous structures, models of viscoelastic deformation of materials, equations of state.

Introduction. Fibrous structures and frames produced according to the technologies used in the textile industry are now more and more extensively applied in various fields of the national economy, namely, in machine building, light industry, transport, civil engineering, materials science (for the development of new composite materials), production of consumer goods, etc. Elements of machine parts and mechanisms produced by using these structures decrease the consumption of materials and the amount energy required for manufacturing the products, improve their functional parameters, increase their reliability and service life, and decrease the cost of production.

As source materials for the major part textile structures, it is customary to use polyamide (capron and anid), polyester (lavsan), and staple threads. A thread is a linear combination of fibers (filaments) in the form of a continuous strand whose properties are typical of textile materials, including high tensile strength and flexibility. It may consist of a single fiber or of a family of continuous or discontinuous fibers. To avoid the possibility of sliding of the fibers and form a functional thread, the fibers are twisted or woven.

The mechanical properties of threads depend on the properties of fibers or monofibers and the structure of the thread. The serviceability of the thread is determined by the packing density of the fibers, their geometric dimensions, the length of the segment of a fiber between the points of linking, its mobility, and the orientation of fibers about the axis of the thread. The structure of the thread plays the principal role in the mechanism of transformation of the properties of fibers into the properties of the thread.

The structure of threads and its influence on the mechanical characteristics of the materials for different types of thermal and force loading were especially comprehensively investigated in [1–7]. Thus, it was indicated that, for each thread (depending on its design), it is possible to choose the optimal thickness of filaments allowing one to get a substantial improvement of the initial moduli of longitudinal elasticity and shear, ultimate strength, ultimate fracture strain, wear resistance, fatigue strength under multicycle loading, etc.

Numerous models were proposed for the prediction of the stress–strain diagrams of twisted threads according to their structure and the mechanical properties of constituents [7]. However, only for systems formed by continuous fibers, it is possible to attain satisfactory agreement between the numerical results and the experimental data. For threads made of short of mixed fibers consisting of two or more types of filaments, the numerical analysis is possible only under the assumptions of small strains and the validity of Hooke's law.

Numerous experimental data [1, 2, 4, 6, 7] show that the influence of strain rate on the mechanical properties of the major part of textile structures is significant. Hence, in the development of the mathematical models aimed at

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the description of the processes of deformation in fibrous systems, it is necessary to take into account the existing rheological effects.

The aim of the present work is to study the regularities of short-term creep and strength of LIPOLA/A-10 polypropylene thread and use these regularities to deduce the effective equations of state of hereditary type. To solve the posed problem, we use the models of linear and nonlinear theory of viscoelasticity and determine the fields of their applicability.

The LIPOLA/A-10 thread consists of 148 continuous filaments. Its thickness is equal to 11 tex. The analyzed structure is an untwisted thread. The density of polypropylene is equal to 993.6 kg/m^3. Threads of this sort are produced in the Ukraine and mainly used for stitching the products and manufacturing the ropes and packing means.

1. Experimental Procedure and Results. To study the reaction of fibrous structures at room temperature, we performed the experimental investigation of their mechanical behavior according to the standard specifications [8]. In the static tests of specimens in an Instron-1126 testing machine, the strains were measured by analyzing the displacements of the crosspiece of the machine. To improve the results of measurements of the effective instantaneous modulus of longitudinal elasticity E_0, ultimate strength σ_u and the corresponding ultimate strain ε_u, and the approximate instantaneous tensile stress–strain diagram of the thread, the tests were performed on five specimens and then the accumulated results were averaged. Note that the instantaneous stress–stain diagram was reconstructed from the series of isochronous creep curves. The data of tensile tests enable us to plot only the curve of "rapid deformation" practically independent of the strain rate and sufficiently close to the instantaneous diagram.

The analysis of the experimental instantaneous stress–strain diagram enables us to conclude that, at room temperature and low strains (up to 5%), the investigated threads have linear tensile stress–strain diagrams and, hence, can be regarded as a linear viscoelastic material. The effective instantaneous longitudinal modulus of elasticity E_0 is set equal to 6208.2 MPa. The tensile strength and the corresponding ultimate strain are equal to $\sigma_u = 629.7$ MPa and $\varepsilon_u = 21.07\%$, respectively.

To study the long-term characteristics of the composition, we also performed the uniaxial creep tests of the specimens for a constant level of the acting stresses. The displacements of the reference points of the specimens in the process of deformation were measured for a gauge length of 100 ± 10 mm with the help of a KM-8 cathetometer with a scale factor of 0.01 mm.

The tests were performed for 10 constant values of stresses $\sigma_k = p\sigma_u$, where $p = 0.16$, 0.23, 0.30, 0.37, 0.40, 0.51, 0.58, 0.65, 0.70, and 0.77. The obtained time dependences of the total strain $\varepsilon(t, \sigma_k)$ for different fixed levels of stresses σ_k are presented in Fig. 1. As approximating functions used to describe the experimental values, we took functions of the form $\varepsilon = ab^t t^d$, where a, b, and d are parameters of the creep curve.

As follows from Fig. 1, two segments (of unstable and steady-state creep) are typical of the presented curves. The absence of the third stage with accelerated creep enables us to ignore the presence of defects in the material in deducing the equations of state.

According to the experimental data obtained for each level of acting stresses σ_k, we also plotted the compliance functions $J_k(t)$ given by the formula

$$J_k(t) = \frac{\varepsilon(t, \sigma_k)}{\sigma_k}. \quad (1)$$

2. Determination of the Region of Linearity of Viscoelastic Strains for a Thread. For the description of the processes of deformation of fibrous structures, we use the approaches of linear and nonlinear theory of viscoelasticity [9, 10]. The determination of the region of linearity of viscoelastic strains is an urgent problem for the choice of the equations of state and description of the rheological behavior of materials.

In the one-dimensional case, the equation of state of the linear theory of viscoelasticity for the case of low strains takes the form

$$\varepsilon(t) = \frac{\sigma(t)}{E_0} + \frac{1}{E_0}\int_0^t K_1(t-\tau)\,\sigma(\tau)\,d\tau, \quad (2)$$

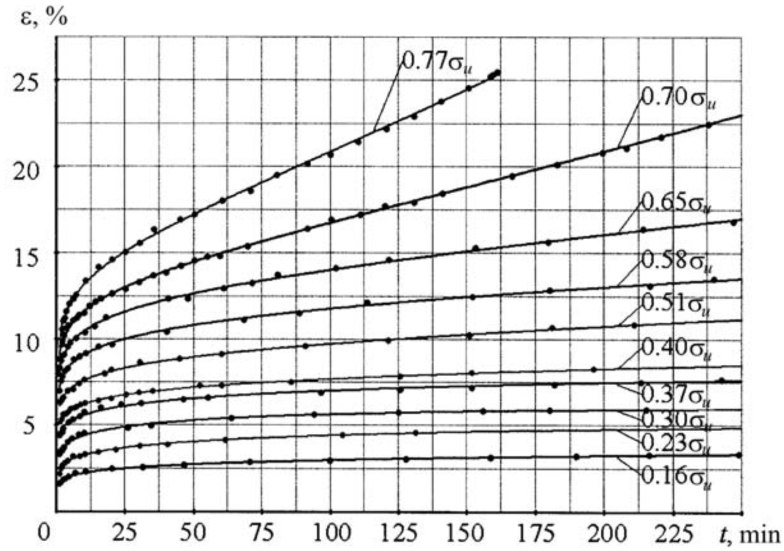

Fig. 1. Primary short-term creep curves for the LIPOLA/A-10 thread. (Experimental values of strains are marked by the dark symbols.)

where σ is a level of stresses, $\varepsilon = \varepsilon^e + \varepsilon^c$ is the total strain including the elastic and creep components, E_0 is the instantaneous modulus of elasticity, and $K_1(t)$ is the creep kernel or the function of influence.

Let us now analyze the creep of a thread subjected to the instantaneous action of tensile stresses

$$\sigma(t) = \sigma_k h(t), \qquad k = 1, 2, \ldots, n, \tag{3}$$

where $h(t)$ is the Heaviside function and $\sigma_k = \text{const}$.

Under the action of constant stresses σ_k, relation (2) reduces to the following determining equation of creep for a linearly viscoelastic material:

$$\varepsilon(t, \sigma_k) = \frac{\sigma_k}{E_0} h(t)\left[1 + \int_0^t K_1(\tau)d\tau\right]. \tag{4}$$

As the necessary condition of linearity of viscoelastic strains, we can use the invariance of the compliance function under the action of the stresses σ_k. In this case, the condition of linearity takes the form

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

However, in view of the statistical nature of the mechanical properties of materials, the experimental compliance curves plotted for each level of stresses σ_k are separated according to representation (5). In this case, we can speak about their coincidence with the compliance function only with a certain error and probability.

Following [11, 12], any material is treated as a linear viscoelastic material with an error $2\delta = 10\%$ if all experimental compliance curves lie in the interval bounded by the values $\pm\delta$ relative to its sample mean.

The sample mean of the compliance function $\bar{J}(t_j)$ for small sizes of the samples ($n < 50$) most often encountered in practice is given by the formula [13]

$$\bar{J}(t_j) = \frac{1}{n}\sum_{k=1}^{n} J_k(t_j), \qquad j = 1, 2, \ldots, m, \tag{6}$$

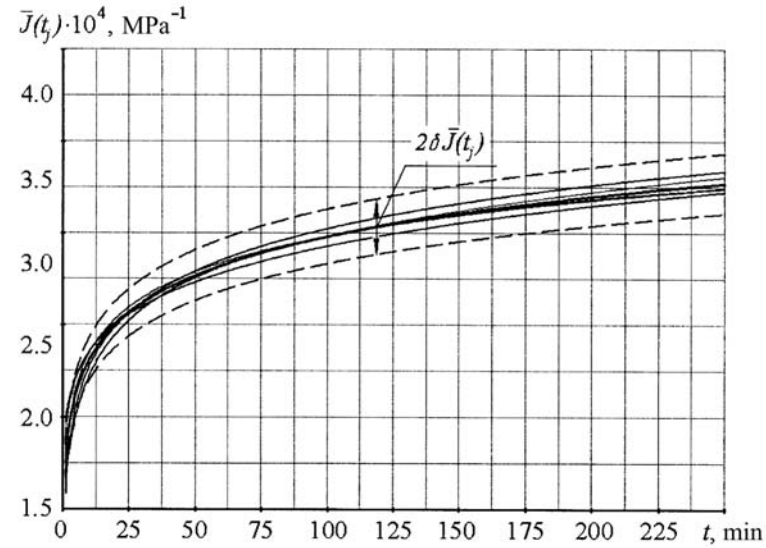

Fig. 2. Plots of the compliance functions for a thread, their mean-square values, and confidence limits.

where $J_k(t_j)$ is the experimental value of the compliance function at time t_j under the action of the stress σ_k, n is the number of compliance curves, and m is the number of reference points in each compliance curve. Then the true value of the compliance function at time t_j is given by the formula $J(t_j) = \bar{J}(t_j)$.

In Fig. 2, we present the plots of compliance functions for the LIPOLA/A-10 thread for the values of stresses characterized by the linear behavior of strains. The results of approximation of the experimental data of $J_k(t)$ are presented in the form of thin solid lines. On the basis of these approximations, we compute the mean-square values of the compliance function $\bar{J}(t_j)$ depicted in Fig. 2 as the thick line. The dotted lines mark bounds of the range corresponding to the maximum values of the error δ for the values of $\bar{J}(t_j)$.

The analysis of the stress–strain diagram shows that, for stresses lower than 0.4$, the investigated fibrous structure behaves as a linear viscoelastic material. Similar results for the region of linearity were obtained on the basis of isochronous creep curves in [12].

3. Explicit Form of the Determining Equations of the Linear Theory of Viscoelasticity. Equation (2) yields the following inverse relation for stresses:

$$\sigma(t) = E_0\varepsilon(t) - E_0\int_0^t R_1(t-\tau)\varepsilon(\tau)\,d\tau, \tag{7}$$

where $R_1(t)$ is the relaxation kernel of the material characterizing the degree of forgetting of the preceding histories of deformation.

The specify the explicit form of the determining relations (2) and (7), it is necessary to choose the type of hereditary kernels and determine their parameters. The indicated kernels must be [9, 10] positive monotonic functions summable in the interval [0, ∞).

The creep $K_1(t)$ and relaxation $R_1(t)$ kernels are chosen in the form of Rzhanitsin fractional-exponential kernels [9, 10] whose efficiency was demonstrated in analyzing the strain of various materials. Assume that

$$R_1(t) = A_1 e^{-\beta_1 t} t^{\alpha_1 - 1}, \qquad K_1(t) = \frac{e^{-\beta_1 t}}{t}\sum_{n=1}^{\infty}\frac{[A_1\Gamma(\alpha_1)]^n t^{\alpha_1 n}}{\Gamma(\alpha_1 n)}, \tag{8}$$

where $\Gamma(\alpha_1)$ is the Euler gamma-function, A_1, α_1, and β_1 are the unknown characteristics of the material.

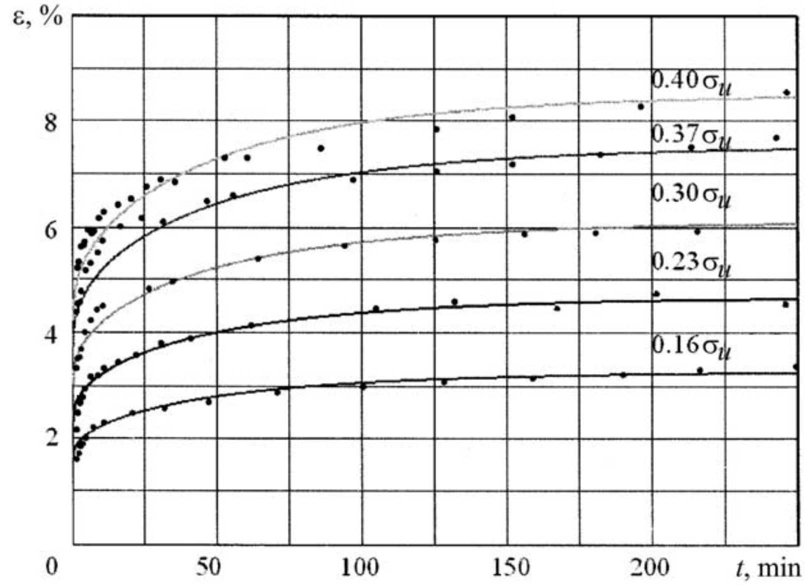

Fig. 3. Comparison of the experimental (symbols) and numerical (lines) values of creep strains computed according to the linear model of viscoelasticity.

Here, we do not dwell upon the detailed presentation of the procedures of evaluation of the parameters of singular kernels and refer the reader, e.g., to [14, 15]. Thus, in particular, the required characteristics can be found by approximating the compliance curve plotted on a logarithmic coordinate system by a linear function with regard for the coefficient of its linear shift relative to the reference curve [14]. As a result, we get

$$A_1 = 0.04696, \qquad \alpha_1 = 0.35, \qquad \beta_1 = 0.01665.$$

The efficiency of these equations can be demonstrated by describing the process of creep of a polypropylene thread under the action of constant tensile stresses σ_k that do not exceed $0.4\sigma_u$ as shown in Fig. 3.

The predicted values of creep strains $\varepsilon(t, \sigma_k)$ were found according to relations (2) by using the presented values of the parameters of the Rzhanitsin kernels. To find the definite integrals of the functions with weak singularities, we use the computational procedure from [16] eliminating these singularities.

As follows from Fig. 3, in the entire analyzed range of acting stresses, we get good agreement of the numerical results with the experimental data, both in the initial stages of viscoelastic deformation and in the steady-state regions under significant strains whose values can be as high as 8.5%.

4. Evaluation of the Parameters of the Equations of State of the Nonlinear Theory of Viscoelasticity for the Investigated Thread. As already indicated, for stresses higher than $0.4\sigma_u$, the investigated structure is characterized by the appearance of nonlinear effects, which can be described by the models of the nonlinear theory of viscoelasticity [9, 10].

The equations of state of the nonlinear theory of viscoelasticity have the form of different integrodifferential equations [8, 9, 17, 18].

We now consider the possibility of prediction of the processes of creep for the indicated stress range within the framework of the cubic theory of viscoelasticity. The equation of state of this theory has the form [10, 18]:

$$\varepsilon(t) = \frac{1}{E_0}\left[\sigma(t) + \int_0^t K_1(t-\tau)\sigma(\tau)\,d\tau\right] + h\int_0^t K_3(t-\tau)\sigma^3(\tau)\,d\tau, \tag{9}$$

where the functions of influence $K_1(t)$ and $K_3(t)$ are given by the formulas

$$K_i(t) = \frac{e^{-\beta_i t}}{t} \sum_{n=1}^{\infty} \frac{[A_i \Gamma(\alpha_i)]^n t^{\alpha_i n}}{\Gamma(\alpha_i n)}, \qquad i = 1,\ 3. \tag{10}$$

As indicated in [10, 14], the series in relation (10) converges uniformly in t for any finite time interval. For large values of t, the kernels $K_i(t)$ admit the following asymptotic representation:

$$K_i(t) \approx \frac{1}{\alpha_i} [A_i \Gamma(\alpha_i)]^{\alpha_i^{-1}} e^{([A_i \Gamma(\alpha_i)]^{\alpha_i^{-1}} - \beta_i)t}. \tag{11}$$

Relation (11) yields that the following two cases are possible for sufficiently large t:

$$\text{(i)} \qquad \text{if} \qquad \frac{\beta_i^{\alpha_i}}{A_i \Gamma(\alpha_i)} > 1, \qquad \text{then} \qquad K_i(t) \to 0; \tag{12}$$

$$\text{(ii)} \qquad \text{if} \qquad \frac{\beta_i^{\alpha_i}}{A_i \Gamma(\alpha_i)} < 1, \qquad \text{then} \qquad K_i(t) \to \infty. \tag{13}$$

In the first case, the creep strain rate at constant stress approaches zero, which corresponds to the case of limited creep and the level of strains approaches a constant value. In the second case, the strain rate tends to infinity. This means that the process of creep is unlimited and, beginning with a certain value of t, the creep rate remains constant and the corresponding part of the creep curve turns into a straight line. Hence, relation (9) can describe both limited and unlimited creep and both parts of the creep curves taken together depending on the chosen parameters of the kernels.

As follows from Fig. 1, if the level of acting constant stresses σ_k lies within the range $[0.4\sigma_u;\ 0.77\sigma_u]$, then the creep strain rate first decreases to a certain level and then approaches a nonzero value.

In this case, the problem of specifying the explicit form of the determining equations is reduced to the evaluation of eight parameters A_i, α_i, β_i, E_0, and h of the two functions of influence from the family of creep curves.

Equation (9) for the constructed compliance curves with $\sigma = \sigma_k H(t)$ takes the form

$$\frac{\varepsilon(t)}{\sigma_k} = \frac{1}{E_0}\left[1 + \int_0^t K_1(t-\tau)\, d\tau\right] + h\sigma_k^2 \int_0^t K_3(t-\tau)\, d\tau. \tag{14}$$

We first consider the compliance curves lying inside a narrow band for $0 \le \sigma_k \le 0.4\sigma_u$. For these curves, relation (14) has the form of a linear equation

$$\frac{\varepsilon^l(t)}{\sigma_k^l} = \frac{1}{E_0}\left[1 + \int_0^t K_1(t-\tau)\, d\tau\right], \tag{15}$$

where ε^l and σ_k^l are, respectively, the strains and stresses in the linear region. The parameters of this model have already been determined by the matching method in Section 3. Knowing E_0 and $K_1(t)$, we now represent the equation of creep (9) in the nonlinear region $(\sigma > 0.4\sigma_u)$ in the form

$$E_0 \frac{\varepsilon(t)}{\sigma_k} = 1 + \int_0^t K_1(\tau)\, d\tau + hE_0\sigma_k^2 \int_0^t K_3(\tau)\, d\tau \tag{16}$$

or

$$E_0 \frac{\varepsilon(t)}{\sigma_k} - \left[1 + \int_0^t K_1(\tau)\, d\tau\right] = hE_0\sigma_k^2 \int_0^t K_3(\tau)\, d\tau. \tag{17}$$

Denote the expression on the left-hand side of the last equation by $I(t)$, i.e.,

$$I(t) = E_0 \frac{\varepsilon(t)}{\sigma_k} - \left[1 + \int_0^t K_1(\tau)\, d\tau\right]. \tag{18}$$

Note that the function $I(t)$ can be regarded as known because $\varepsilon(t)/\sigma_k$ are measured quantities from the experimental compliance curve and the remaining parameters have already been found in the previous section. Hence, relation (17) admits the following representation:

$$I(t) = hE_0\sigma_k^2 \int_0^t K_3(\tau)\, d\tau. \tag{19}$$

By using representation (18), we now plot the function $y = I(t)$ on the logarithmic coordinates. To find the constant h and the parameters A_3, α_3, and β_3, we use a series of plots of the functions $y_i = \int_0^t K_3(\tau)\, d\tau$ also constructed on the logarithmic coordinates for various values of the parameters of the kernel. By matching the experimental plot $y = I(t)$ with the "theoretical" curves (in particular, by their relative horizontal shifts), we choose in the presented family a plot that coincides with the required function. The shifts of the plots along the abscissa correspond to transformations of the time scale:

$$\log(t_m) - \log(t_e) \equiv \log(k) \qquad \text{or} \qquad t_m = kt_e. \tag{20}$$

The parameters of the established similar "theoretical" curve are assigned to the "experimental" kernel $K_3(t)$ in relation (19). Then the value of the parameter h is given by the formula

$$h = \frac{I(t_e)}{E_0\sigma_k^2 \int_0^{t_e} K_3(\tau)\, d\tau}. \tag{21}$$

As a result, we get $A_3 = 0.025$, $\alpha_3 = 0.3$, $h = 5.8 \cdot 10^{-10}$ MPa^{-3}, and $\beta_3 = -0.008$. Thus, all parameters of the equation of state (9) are determined. The other approaches to the evaluation of the parameters of the equations of state of the theory of viscoelasticity are discussed in [9–12, 15, 19, 20].

In Fig. 4, we present the predicted dependences of the total strain ε on time t computed by using the determining relations of the cubic theory of viscoelasticity for various fixed levels of stresses σ_k. It is worth noting that, in this case, the agreement between the numerical results and the experimental data is not so good, although the principal trends of the process of deformation are reflected by the equations of state. The predicted distributions of strains for the linear regions of deformation are not presented here because they almost completely coincide with the results obtained by using simpler determining relations (see Fig. 3). The correlation between the numerical results and the experimental data can be made somewhat better if we also take into account the instantaneous plastic strains readily determined from Fig. 4. It seems likely that, for a more exact description of these deformation processes, it is necessary to take into account the final strains, which leads to certain difficulties in deducing the explicit form of the equations of state.

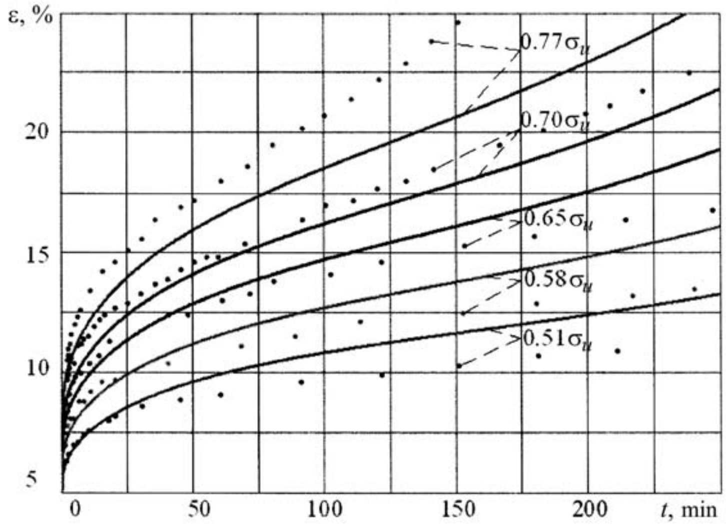

Fig. 4. Comparison of the experimental data (symbols) with the numerical results obtained by using the nonlinear model of viscoelasticity (lines).

5. Simplified Relation for the Description of Steady-State Creep for the Polypropylene Thread. The analysis of the experimental data presented in Fig. 1 shows that the initial period of the diagrams (characterized by the decrease in the creep rate with time) does not exceed 10–15 min after which the process is stabilized. In the case of steady-state creep, the strain rate depends on the level of stresses and weakly depends on the prehistory of deformation. For the analyzed fibrous structures, the creep curves do not contain the third section characterized by accelerated creep. This facilitates the procedure of prediction of fractures of the composites. Moreover, for the levels of strains higher than 10% (see, e.g., Fig. 3), it is also necessary to take into account the instantaneous plastic strains ignored in Sections 3 and 4.

Therefore, in analyzing the case of steady-state creep [21, 22], it is possible restrict ourselves to simpler equations of state. It is assumed [21, 22] that the total strain can be represented in the form $\varepsilon = \varepsilon_0 + \varepsilon^c$, where ε_0 is the instantaneous strain including the elastic and plastic components. Furthermore, the creep strains accumulated in the first part of the are is also included in the instantaneous strains ε_0, as shown in Fig. 5.

Thus, the level of strains in the steady-state mode is given by the formula

$$\varepsilon(t) = \varepsilon_0(\sigma) + v(\sigma)t, \tag{22}$$

where $v(\sigma)$ is the creep strain rate depending only on the level of stresses.

In this case, we have

$$\varepsilon_0(\sigma) = (-4.753 + 0.2905\sigma)10^{-3} \qquad \text{and} \qquad v(\sigma) = (29.0894 - 0.0511\sigma)^{-1.7428}\ \text{min}^{-1}.$$

The established approximate expressions for strains almost completely coincide with the distributions of strains for the steady-state sections of the creep curves. By using these formulas, one can fairly exactly predict the fractures of fibrous structures if the curves of long-term strength of the investigated materials are available.

6. Strength Analysis of the Polypropylene Thread in the Presence of Creep. As a rule, the processes of creep in which significant levels of strains leading to the violation of the structural integrity of products are accumulated for relatively short periods of time are regarded as the processes of short-term creep of materials. From the viewpoint of a designer, the maximum admissible level of strains for metals varies within the range 1–2% and rarely approaches 5% [21]. The indicated (short) periods of time vary from about 2–3 s to about 20 min. For textile products, the indicated strain range is not indicated explicitly but, in our opinion, can be somewhat broader.

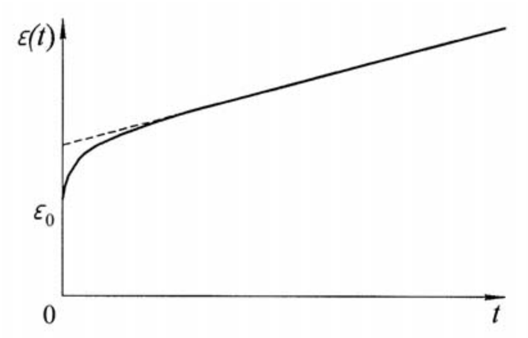

Fig. 5

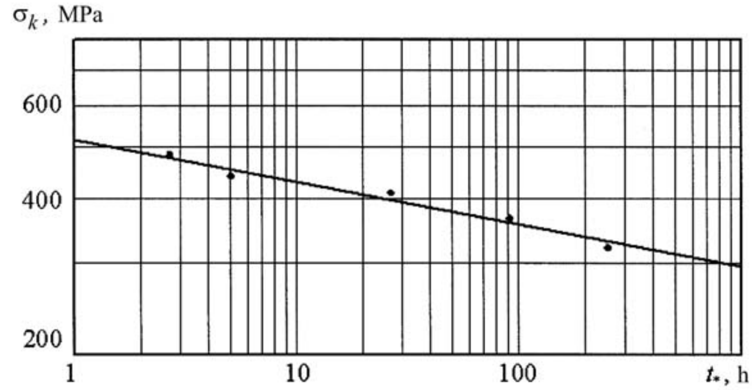

Fig. 6

Fig. 5. Computational scheme for choosing the parameters of the simplified model.
Fig. 6. Long-term strength diagram for the polypropylene thread.

The presented numerical results for strains used to describe the process of creep of a thread were accumulated for a period of 250 min. The creep tests were carried out for the chosen fixed levels of stresses up to the complete fracture of the specimens. The plot of the dependence of the time t_* to fracture of the investigated structure on the level of acting stresses σ_k is shown in Fig. 6 (on the logarithmic coordinates).

It is easy to see that, for the analyzed stress range, all experimental data lie, in fact, in the same straight line. Hence, the long-term strength diagram of the thread is described by the equation

$$\log \sigma_k = \frac{1}{m} \log t_* + \log n, \tag{23}$$

where $m = 0.08116$ and $n = 517.07472$ MPa. Further, by taking the antilogarithms of both sides of this equation, we obtain

$$t_* = 10^{m \log(\sigma_k / n)}. \tag{24}$$

This formula enables us to find the time to fracture of an element of the thread in the presence of creep (in hours).

CONCLUSIONS

1. The data of the experimental investigation of the mechanical behavior of LOPOLA/A-10 untwisted polypropylene threads enable us to conclude that indicated thread possesses a linear tensile stress–strain diagram and, for low strains (up to 5%), can be regarded as a linear viscoelastic material. Under the action of tensile forces, these structures are characterized by the formation creep strains, which can be found by using the models of mechanics of hereditary media.

2. The analysis of the experimental data enables us to establish the regularities of short- and long-term deformation of fibrous structures. It is shown that, under stresses lower than $0.4\sigma_u$, the processes of inelastic deformation can be computed within the framework of the linear viscoelastic model. Under stresses higher than $0.4\sigma_u$, we observe the appearance of nonlinear creep effects, which can be described by using more complicated models of the nonlinear theory of hereditary media.

3. The equations of state of the linear and nonlinear theories of viscoelasticity presented in the explicit form enable us to give a fairly efficient description of the active processes of deformation of the investigated polymeric fibrous structures. The proposed approximate diagrams of long-term strength of a thread enable one to predict the strength of threads in fairly broad ranges of stresses and strains.

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