PREDICTION OF THE LONG-TERM RESISTANCE OF POLYMER COMPOSITES*

R. D. Maksimov

UDC 539.376: 678.067

The present communication is based chiefly on the results of investigations carried out in recent years at the Institute of the Mechanics of Polymers, Academy of Sciences of the Latvian SSR; their principal object was the study of the prerequisites for accelerated tests of polymer composites, and on their basis the devising of methods of predicting the resistance of these materials in different states of simple and complex stresses under conditions of long-term static loading. The objects of the investigations were modern structural plastics reinforced by unbroken fibers such as glass, organic, carbon, and boron plastics, and also different variants of the so-called hybrid composites. The degree to which inelastic deformations of these composites manifest themselves under long-term loading can be judged from the data presented in Table 1 where it is shown by how many times full compliance in creep of the material exceeds its instantaneous compliance. The results were obtained in long-term tests of unidirectional reinforced composites carried out in recent years with three types of loading: tension in the direction of the fibers, transverse tension, and longitudinal shear. It can be seen that after tests lasting three years the compliance of organic, glass, carbon, and boron plastics in the transverse direction and in shear exceeds the instantaneous elastic compliance by a factor of more than two (or even three). With hybrid composites the time effect may be considerable even in the direction of the reinforcement. For instance, when in organic plastic apart of the organic fibers are replaced by high-modulus (boron and carbon) fibers, the effect is that compliance in creep in the course of one year under conditions of tension in the direction of the fibers may be almost three times as large as the instantaneous compliance. Here, together with the viscoelasticity of the components, a substantial contribution is also made by the accumulation of damage.

TABLE 1. Ratio of Full Compliance in Creep of Unidirectional Composites to the Compliance in Instantaneous Loading

Type of composite material	$\frac{I_{1111}(t)}{I_{1111}(0)}$	$\frac{I_{2222}(t)}{I_{2222}(0)}$	$\frac{I_{1212}(t)}{I_{1212}(0)}$	Duration of creep t and stress level relative to short-term strength R
Two-component:				
organic plastic (μ_o=0,5)	1,6	2,6	2,4	
glass plastic (μ_g=0,5)	1,06	2,3	2,5	t=3 yr
carbon plastic (μ_c=0,5)	1,03	2,1	2,3	$\sigma=(0,1-0,3)R$
boron plastic (μ_b=0,5)	1,02	3,3	—	
Hybrid:				
organic boron plastic (μ_o=0,3; μ_b=0,1)	2,8	—	—	t=1yr; σ=0,7R
organic carbon plastic (μ_o=0,3; μ_c=0,1)	2,1	—	—	t=1yr; σ=0,6R
organic glass plastic (μ_o=0,3; μ_g=0,2)	1,4	—	—	t=1yr; σ=0,6R
Type of state of stress	σ_{11}	σ_{22}	σ_{12}	

Note. Axis 1 corresponds to the direction of the reinforcement; μ_o, μ_g, μ_c, μ_b are the volume content of organic, glass, carbon, and boron fibers, respectively, in the composite.

*Presented at the Fifth All-Union Conference on the Mechanics of Polymer and Composite Materials (Riga, October, 1983).

Institute of the Mechanics of Polymers, Academy of Sciences of the Latvian SSR, Riga. Translated from Mekhanika Kompozitnykh Materialov, No. 3, pp. 514-527, May-June, 1984. Original article submitted December 23, 1983.

0191-5665/84/2003-0376$08.50

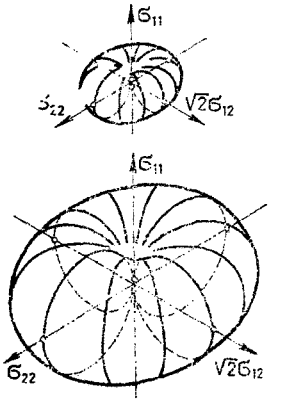

Fig. 1. Isochronous strain quadrics of unidirectional organic plastic with volume content of fibers 0.6 in instantaneous loading (top) and after creep for three years (bottom).

More significant is the time-dependent change of the strain quadrics of unidirectional composite in the state of plane stress; it is known that unidirectional layers in disoriented laminated composites operate under such conditions. The isochronous strain quadrics of organic plastic plotted by a method worked out in [1] are shown in Fig. 1 in the stress space σ_{11}, σ_{22}, σ_{12} for the case of instantaneous loading and creep for three years. The radius vectors of the surface are a function of the invariants of the strain tensor and of the compliance tensor of the material. The σ_{11} axis corresponds to the direction of the fibers. It can be seen that even a slight deviation from the direction of the reinforcement leads to a substantial difference of the surfaces; the mean value of the radius vector of the surface after 3 years of deformation is 2.4 times larger than the mean radius vector of the strain quadric in instantaneous loading. The isochronous strain quadrics of glass, carbon, and boron plastic have the same aspect. Yet the averaged values of the radius vectors of these same quadrics of boron plastic differ even more – by a factor of 3.4. All this shows that the inelastic strain of polymer fiber composites manifests itself substantially and that the development of methods of accelerated testing is very topical.

The basic ideas that later formed the physical basis for the development of methods of predicting the relaxational properties of polymers were contained in [2-4] and expressed by the widely known equation of Aleksandrov–Lazurkin–Gurevich expressing the correlation between the relaxation time, temperature, and stress. An analogous correlation is also established from the relations obtained in [5] by statistical probability analysis of the micromechanisms of viscoelastic strain of polymers. As a result of the detailed investigation of the temperature dependence of the viscoelastic functions of various polymers [6-8], the method of reduced variables (or viscoelastic corresponding states) was devised which makes it possible to divide the influence of the two basic variables (temperature and time) into the manifestation of the viscoelastic properties of polymers.

Later (late sixties and early seventies) systematic study of the dependence of the speed of the relaxation processes on various factors affecting polymer materials under conditions of their creep made it possible to establish that, together with the temperature – time analogy, there may also exist stress–time [9], vibration–time [10], and moisture–time [11] analogies; also substantial and shown were possibilities of utilizing the method of analogies for taking into account the effect of hydrostatic pressure [12, 13] and of disperse fillers [14] on the viscoelastic properties of polymers. All this made it possible to formulate the principle of multiparameter prediction of creep of polymer materials [15, 16]. A natural extension of this work were investigations of the thermoviscoelastic properties of modern structural fibrous composites and the discovery of the prerequisites for devising methods of predicting their long-term resistance. It is known that in the manifold manifestations of the inelastic resistance of fiber-reinforced composites, the inelastic properties of the polymer matrices make a substantial contribution. The viscoelastic behavior of such matrices has a considerable effect on the deformability and failure of polymer composites exposed to the long-term action of mechanical loads and environmental factors. A number of authors confirmed the possibility of maintaining the temperature–time analogy on the sample of various fibrous composites. For instance, in [17-20] it was shown that the analogy is maintained for various glass plastics, in [21] in the study of the relaxation properties of carbon plastic, in [22, 23] the maintenance of the analogy for high-strength organic plastic was revealed. Here the

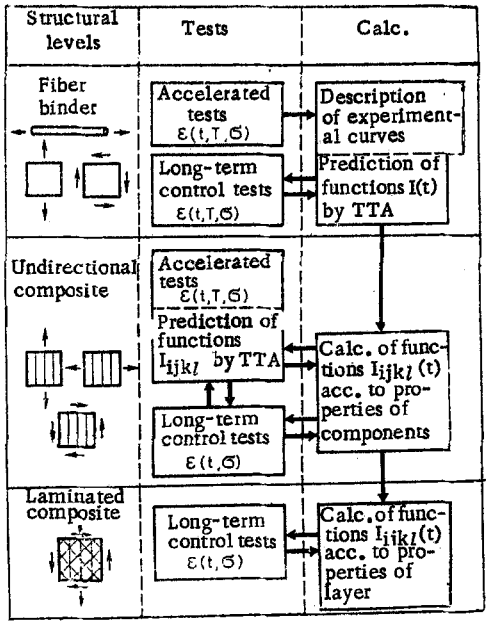

Fig. 2. Diagram of the stagewise investigation of the possibilities of predicting long-term creep of polymer composites.

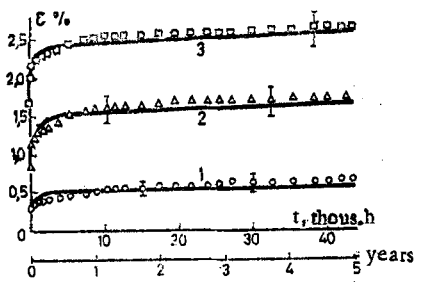

Fig. 3. Long-term creep of organic fibers for σ = 330 (1); 1000 (2); 1650 MPa (3). Dots: control experiments; lines: prediction according to accelerated (to 5 h) thermal tests.

composite is regarded as quasihomogeneous anisotropic material, and therefore the data of such a prediction characterize the actually tested material only, and strictly speaking, they do not make it possible to utilize the principal advantage of fibrous composites, i.e., the possibility of optimizing the structure of the reinforcement of the material in connection with actual structures with specified service life and operating conditions. More promising seems the approach based on using the results of accelerated tests in the complex and predicting the viscoelastic function of the structural elements of the composite, on the one hand, and subsequently applying the structural theories on the other hand [24, 25]. The possibilities of such an approach were investigated on four types of composite: glass, organic, carbon, and boron plastics. Let us briefly consider the principal results.

Figure 2 shows a diagram of the main stages of the investigations. The structural organization of the composite is subdivided into the following levels: fiber and binder, unidirectionally reinforced material, and finally, disoriented composite. For the first two levels, accelerated thermal tests and prediction of the viscoelastic functions were carried out; the data of the prediction were used for calculating the functions of the composite with specified arrangement of the reinforcement, which in their turn were checked with different kinds of state of stress by long-term tests (up to 3-5 years).

Here there is no need to dwell at length and in detail on the prediction of the viscoelastic properties of the reinforcing fibers. It is known that glass, carbon, and boron fibers may be regarded as elastic. The possibilities of predicting the creep of organic fibers were investigated in [26], and they are illustrated here in Fig. 3 from which it follows that, firstly, such fibers reveal considerable creep, and secondly, the curves of

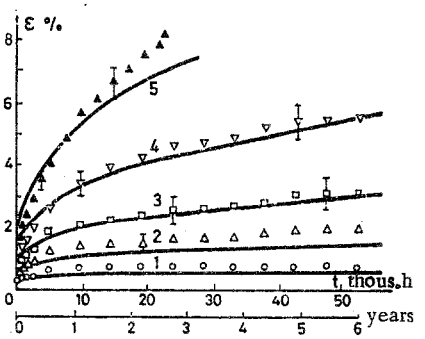

Fig. 4

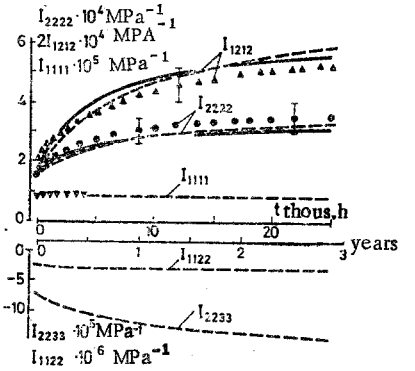

Fig. 5

Fig. 4. Long-term creep of the epoxy binder ÉDT-10 in tension for σ = 6.8 (1); 13.6 (2); 20.4 (3); 27.2 (4); 34 MPa (5). Dots: control experiments; lines: prediction according to accelerated (to 5 h) thermal tests.

Fig. 5. Curves of the viscoelastic compliance in creep of unidirectionally reinforced carbon plastic. Dots: mean experimental data; lines: calculation using the results of long-term tests of the binder (——) and the results of predicting the viscoelastic compliance of the binder on the basis of temperature–time analogy (---).

their long-term creep can be perfectly satisfactorily predicted from the results of accelerated thermal tests on the basis of the revealed maintenance of the temperature–time analogy (TTA).

The investigation of the possibilities of accelerated relaxation processes in different thermosetting binders was dealt with by many authors. Maksimov et al. [27-30] carried out an extensive program of studying creep of polyester binder with different (including complex) kinds of states of stress under the effect of temperature–moisture factors of the environment; it was established that the temperature–moisture–time analogy had been maintained, and a method was worked out for using it for the purpose of multiparameter prediction of creep. The possibilities of accelerated determination of the rheological characteristics of epoxy binder were studied in [26, 31]; it was revealed that the temperature–time analogy had been maintained with complex state of stress in the range of physically linear and nonlinear viscoelastic resistance under conditions of both active and passive loading; it was shown that in a wide range of stresses the function of temperature displacement a_T is practically independent of the type of state of stress, and this in turn makes it possible to reduce considerably the number of rapid tests. The possibilities of predicting the physically nonlinear creep of epoxy binder revealed in [31] are confirmed in Fig. 4 where, on the example of the binder ÉDT-10 widely used in the production of reinforced plastics, the experimental data of long-term (up to 6 years) control creep tests in tension are compared with the results of prediction according to accelerated tests in the temperature range from 20 to 60°C.

Thus, having available the data of the prediction of the functions and parameters of long-term viscoelastic resistance of the reinforcing fibers and of the binder, we can calculate the components of the tensor of viscoelastic compliance of unidirectional reinforced composite. The calculation procedure was dealt with in detail in [32] where, with the aid of the so-called method of sections, the problem was reduced to the elastic problem by applying Laplace transforms to the initial systems of equations;* the originals of the sought functions of viscoelasticity of a composite were found by numerical inversion of the Laplace transform. Long-term (up to 3 years) control creep tests were carried out with specimens of unidirectionally reinforced glass, organic, carbon, and boron plastics. As an example Fig. 5 presents the curves of the independent components of the tensor of viscoelastic compliance in creep of unidirectionally reinforced carbon plastic; the results of control creep tests of tubular specimens of the composite are compared with the theoretical curves obtained by the use of the data of long-term tests of specimens of binder, and also of the data of accelerated thermal tests. In [32] an analogous comparison was also carried out for glass, organic, and boron plastic. When gen-

*The possibilities of the method of sections for predicting elastic characteristics were preliminarily verified in detail on two-component [33, 34] and multifibered (hybrid) composites [35-37].

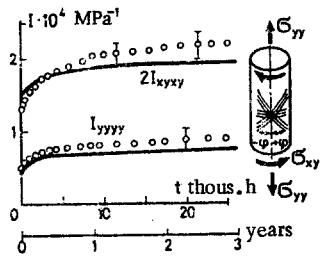

Fig. 6

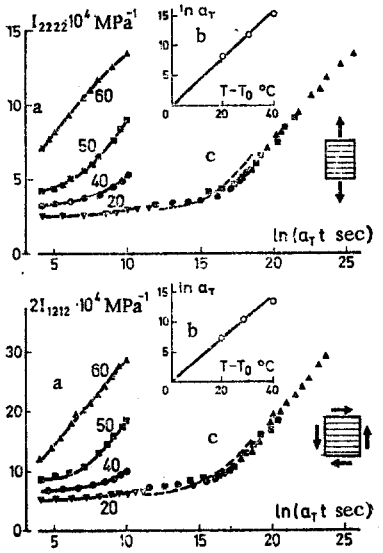

Fig. 7

Fig. 6. Curves of viscoelastic compliance in creep pipes of organic plastic with helical-tangential reinforcement under conditions of longitudinal tension and torsion. Dots: mean experimental data; lines: calculation using the results of the prediction of the viscoelastic functions of unidirectionally reinforced layers.

Fig. 7. Compliance curves in creep of unidirectionally reinforced pipes of organic plastic under conditions of transverse tension (I_{2222}) and longitudinal shear (I_{1212}): a) initial curves at 20, 40, 50 and 60°C; b) function of thermal shear; c) generalized compliance curve reduced to T_0 = 20°C. Dashed line: 3-year-long control tests.

eralizing the results of these investigations, we may conclude that the predicted and control functions of creep of the above unidirectional composites differ (with rare exceptions) within the limits of the confidence intervals of the mean experimental curves; yet it is very important that the results of the calculations of the creep functions of the composites using the data of accelerated tests and long-term tests of the binder differ insignificantly. The conclusion is correct at least for the verified range of values of volume contents of fibers in the composite (0.4-0.6).

The above-said applies to unidirectionally reinforced material, and it the basis for going over to composites with more complex reinforcement arrangements. The possibilities of such a transition were verified on the example of laminated disoriented materials. The calculation schema of such a stack uses the usually adopted assumptions that the deformations of the layers in the plane of reinforcement are equal and that the stresses acting in the direction perpendicular to the plane of the reinforcement are equal. The characteristics of the regularity of deformation of individual unidirectional layers were predicted by the method examined above. The results can be judged from Fig. 6 where the dots indicate the data of three-year creep tests in tension and torsion of pipes of organic plastic with helical-tangential reinforcement. The lines indicate the theoretical curves using accelerated thermal tests of the components of the material. An analogous result was also obtained with pipes of carbon and glass plastic. On the whole we found perfectly acceptable agreement between prediction and long-term tests.

The above-explained variant of predicting the viscoelastic properties of reinforced plastics is applicable on the assumption that the properties of the fibers and of the binder in the composite are additive. Errors of the method may become enlarged in consequence of the manifestation of effects of physicomechanic interaction of the fibers and binder in the curing of the composite and the consequent changes of the properties of the components. Therefore the study of the thermoviscoelastic properties of specimens of unidirectionally reinforced plastics was distinguished in Fig. 2 as a separate stage of the experimental investigation. The results of such tests may be used for predicting the viscoelastic behavior of composites with more complex reinforcing arrangements, and also for additional checks of the predictions according to data of accelerated tests of the fibers and the binder. For this purpose we carried out short-term (up to 5 h) creep tests at different temperature

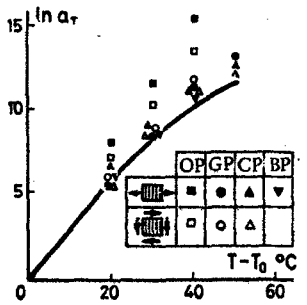

Fig. 8

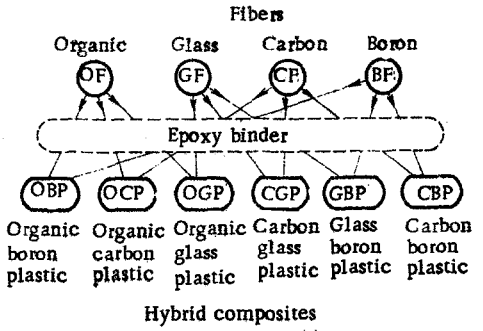

Fig. 9

Fig. 8. Values of the function of thermal shear for unidirectionally reinforced organic plastic (OP), glass plastic (GP), carbon plastic (CP), and boron plastic (BP) from creep tests with transverse tension and longitudinal shear. The line indicates the function ln a_T for the binder.

Fig. 9. Diagram of the variants of the investigated hybrid composites.

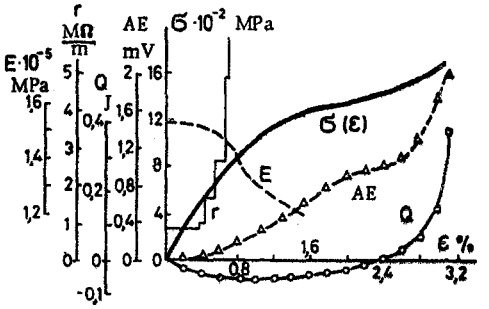

Fig. 10. Averaged stress–strain diagram $\sigma(\varepsilon)$ of organic boron plastic in the direction of the reinforcing fibers and curves of the effects accompanying deformation of the composite: r) change of the electrical resistance of the specimen; AE) total acoustic emission; Q) heat flux; E) change of the modulus of elasticity of the composite in the direction of tension.

levels with specially made thin-walled, unidirectionally reinforced (by circular winding) tubular specimens of organic, glass, carbon, and boron plastic. All the specimens were made on the basis of the same type of binder, viz., ÉDT-10, with a reinforcement coefficient equal to 0.5. The tests were carried out with transverse tension and longitudinal shear. The obtained data made it possible to verify directly on the unidirectional composite whether the temperature–time analogy had been maintained. As an example Fig. 7 shows the compliance curves of organic plastic in transverse tension $I_{2222}(\ln t, T)$ and longitudinal shear $I_{1212}(\ln t, T)$. An analysis carried out with the use of the algorithm from [38] showed that within the limits of the permissible scatter, the initial curves at different temperature levels differ only by the time scale, i.e., $I(\ln t, T) = I(\ln t + \ln a_T) = I[\ln (a_T t)] = I(\ln t')$, where a_T is the function of the thermal shear.

An analogous analysis was also carried out for glass, carbon, and boron plastic. The values of the function of thermal shear that were found are presented in Fig. 8; the same figure also shows the function ln a_T found in tests of specimens of cured binder ÉDT-10 [26]. It can be seen from the figure that the values of the function ln a_T, which is a quantitative measure of the thermal acceleration of relaxation processes, for three types of composites (glass, carbon, and boron plastic) in the investigated temperature range, firstly, are practically independent of the kind of state of stress, and secondly, that they differ little from ln a_T for the binder. This cannot be extended to apply to organic plastic because there we found that the curves ln a_T for the plastic and for the binder deviated increasingly from each other with increasing temperature.

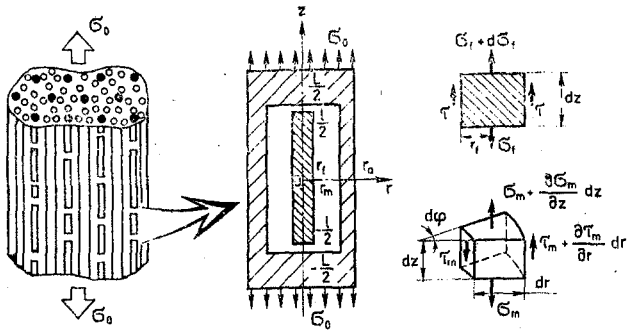

Fig. 11. Calculation schema of a hybrid composite.

All that has been explained above concerns the case when inelastic deformation of the composite is due chiefly to the viscoelastic properties; it was possible to neglect the contribution of other mechanisms (ductility, accumulation of damage). Yet accumulation of damage may cause a substantial change of the effective characteristics of deformability of polymer composites. This is particularly distinct in hybrid composites containing brittle high-modulus fibers and fibers with great compliance. Great interest in devising structures made of such composites is due, as is well known, to the additional possibilities of deliberately controlling the properties of the material. The study of these problems was the object of a cycle of works carried out in order to investigate a number of such materials whose variants are illustrated in Fig. 9. Each variant comprised two types of fibers with different ratio of their volume content. The bulk of the work was carried out with unidirectionally reinforced composites with statistically homogeneous mixture of both types of fiber throught the bulk of the composite.

Here are some preliminary remarks on the characteristics of elasticity and short-term strength of hybrid composites. The authors of [35-37] investigated the possibilities of predicting the characteristics of elasticity of such composites from the properties of the components in dependence on the type of reinforcing fibers and the ratio of their volume content. It was shown that calculation by the method of sections with subsequent averaging of the elastic properties of two repeating structural elements containing different types of fibers makes it possible to predict the elastic properties of such multifiber materials with an accuracy that is acceptable for practical applications. The authors discovered and correctly predicted cases of change of the modulus of elasticity of unidirectional composites longitudinally and transversely caused by the difference in anisotropy of the fibers; e.g., in organic glass plastic and carbon glass plastic with decreasing content of organic and carbon fibers, respectively, the modulus of elasticity of the composite in the longitudinal direction decreases, and in the transverse direction it substantially increases.

The strength properties of these materials were studied by Maksimov et al. [39] who determined experimentally the dependence of the strength on the type and volume ratio of different fibers with different ways of quasistatic simple loading (tension and compression in the direction of the fibers, the same in the transverse direction, longitudinal shear, and two types of combined loading). It was established that a change in the ratio of volume content in a hybrid composite of two types of fiber leads in most cases to a relatively monotonic change of strength. At that, the ambiguity of the change in strength with different types of loading is clearly revealed; e.g., with decreasing content of organic fibers in organic boron plastic and organic carbon plastic the strength in compression in the direction of the fibers increases, whereas in tension it conversely substantially decreases. Very effective in increasing the strength of organic plastic in compression is the partial replacement of organic fibers by high-modulus ones. For instance, if half (by volume) of the organic fibers are replaced by boron fibers, the strength of the plastic becomes four times as great as the strength of the initial organic plastic. The same effect (only on a lesser scale) is also found in the case of organic carbon plastic and organic glass plastic. An analysis of the experimental data in [39] leads to the conclusion that it is possible to describe the strength of the tested hybrid composites in a state of plane stress by the tensor-polynomial criterion [40] with retaining the terms up to second power inclusively; the results of the calculation made it possible to reveal and describe the dependences of the components of the tensors of the strength surface on the ratio of different types of fibers contained in the hybrid composite; the results of the analysis may be used for purposes of prediction (interpolation of the calculations) of the strength within the investigated ranges of volume content of fibers.

Let us now turn to the question of the deformation of such composites when they are subjected to tension in the direction of the reinforcement. The stress–strain diagrams obtained from the tests provide grounds for

stating that, with the exception of organic glass plastic, all the variants of hybrid materials contained in Fig. 9 have an intermediate range of ratios of contents of two types of fibers within which the stress–strain diagrams have a considerably nonlinear shape which is unlike the shape of the diagrams of the initial two-component composites. The cause of the nonlinearity can be grasped on the basis of obvious considerations: when a composite reinforced by brittle fibers in combination with fibers with great compliance is subjected to tensile load, intense accumulation of disperse damage of the brittle fibers may take place already at an early stage of deformation. This is confirmed by a number of effects observed in the deformation of the material. Figure 10 shows the averaged stress–strain diagram of organic boron plastic and the curves of the effects accompanying deformation of the material, viz., the curve of change of electrical resistance of the composite whose intense increase indicates that the current-conducting boron fibers are being destroyed; curves of acoustic emission and heat release; the curve of the irreversible change of the modulus of elasticity.

The results of diagnosing the accumulation of damage, explained in detail in [41-43], form the basis for assuming, in solving the problem, that the stresses are redistributed upon destruction of the brittle fibers in a hybrid composite [44], and they are also the basis for working out a structural model of deformation of the hybrid composite taking the effect of fragmentation of the fibers into account [45]. In the calculation schema of the material (Fig. 11) it was accepted that the failing brittle fibers operate in a quasihomogeneous anisotropic matrix consisting of a polymer binder reinforced by compliant fibers. Another peculiarity of this problem distinguishing it from the known solutions for two-component composites consists in the necessity of taking the resistance of the matrix to tension into account. Thus, in the equilibrium equations of a fiber of length dz and the elementary volume of the matrix and composite, presented below, it is assumed that the brittle fiber absorbs the tensile load, and the matrix absorbs the tensile load and the shearing forces in the vicinity of the ends of the fractured fibers:

$$\frac{d\sigma_f}{dz}+\frac{2\tau}{r_f}=0;\quad \frac{\partial\sigma_m}{\partial z}+\frac{1}{r}\frac{\partial}{\partial r}(r\tau_m)=0;$$

$$\sigma_f r_f^2+2\int_{r_f}^{r_m}\sigma_m(z,r)\,r\,dr+\sigma_a(r_a^2-r_m^2)=\sigma_0 r_a^2\ ,$$

where

$$\tau=\tau_m(z,r_f).$$

The equation of the stress curve in the ruptured fiber, obtained from the solution of the system of initial equations with the corresponding boundary conditions, is then introduced into the expression for the damage to the fibers P_f determined by reducing the stresses absorbed by the fiber and the distribution function $\varphi(l)$ of the pieces of fibers according to lengths

$$\sigma_f(z)=\sigma_0\frac{E_f}{E}\left(1-\frac{\operatorname{ch}\eta z}{\operatorname{ch}\eta\frac{l}{2}}\right),$$

where

$$z\in\left[-\frac{l}{2};\frac{l}{2}\right];\quad \eta=\frac{2\sqrt{G_m}}{r_f\sqrt{(E_m-E_f)\ln\mu_f+E_m\left(\frac{1}{\mu_f}-1\right)}}$$

$$P_f=\frac{\int_0^L\varphi(l)\int_{-\frac{l}{2}}^{\frac{l}{2}}\left[1-\frac{\sigma_f(z)}{\sigma_{f0}^f}\right]dz\,dl}{\int_0^L\varphi(l)\,l\,dl}.$$

The distribution of the pieces of fibers in the strain function of the composite was obtained on the assumption of Weibull distribution of the strength of the fibers and the assumption that the fibers fragment only at the places of maximum stresses:

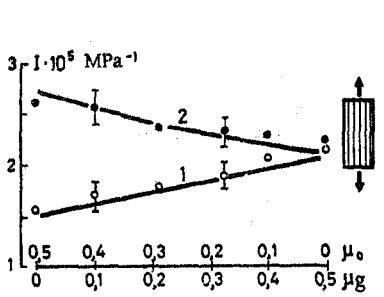

Fig. 12

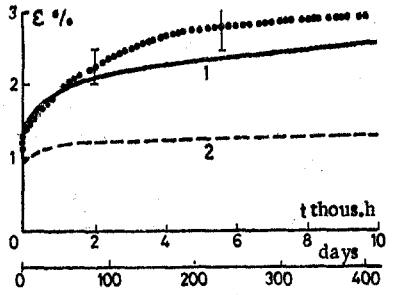

Fig. 13

Fig. 12. Isochronic curves of compliance of unidirectional organic glass plastic in dependence on the content of organic μ_o and glass μ_g fibers for instantaneous loading (1) and after creep for 10,000 h (2). Dots: experiment; lines: calculation according to the elastic characteristics of the components (1) and using the functions of viscoelastic compliance of the organic fibers and of the binder found in accelerated thermal tests (2).

Fig. 13. Long-term creep of unidirectional organic boron plastic (μ_o = 0.31, μ_b = 0.09) in tension in the direction of the reinforcement for σ = 750 MPa (0.73 of short-term strength). Dots: experiment; lines: prediction: 1) with viscoelastic properties of the organic fibers and of the binder and also the fragmentation of the boron fibers taken into account; 2) with viscoelastic properties of the organic fibers and of the binder taken into account on the assumption that there is no damage.

$$N_i(\varepsilon)=\sum_{j=0}^{i} b_{ij}\exp\left(-rc_j\varepsilon^{\beta}\right);\quad i=0,1,2,\ldots,n;\quad b_{00}=N_0(0);$$

$$b_{ii}=N_i(0)-\sum_{k=0}^{i-1} b_{ik};\quad i\geqslant 1;$$

$$b_{ij}=\frac{2b_{i-1,j}c_{i-1}}{c_i-c_j};\quad i>j;\quad c_j=2^{-i}\left[1-\frac{1}{\operatorname{ch}\left(\eta l_0 2^{-i-1}\right)}\right]^{\beta};\quad r=l_0\alpha E_f^{\beta}.$$

And finally, the dependences presented below correspond to the explicit expression of the change of the modulus of elasticity in consequence of the fragmentation of fibers upon loading of the composite, and also the function of damage to the material characterized by the relative change of the modulus of elasticity:

$$E(\varepsilon)=E_f\mu_f\left[1-\frac{2}{\eta l_0 N_0(0)}\sum_{i=1}^{n}\operatorname{th}\frac{\eta l_0}{2^{i+1}}\sum_{j=0}^{i} b_{ij}\exp\left(-rc_j\varepsilon^{\beta}\right)\right]+E_m(1-\mu_f);$$

$$P(\varepsilon)=1-\frac{E(\varepsilon)}{E_0}=\frac{E_f\mu_f}{E_f\mu_f+E_m(1-\mu_f)}\frac{2}{\eta l_0 N_0(0)}\sum_{i=1}^{n}\operatorname{th}\frac{\eta l_0}{2^{i+1}}\sum_{j=0}^{i} b_{ij}\exp\left(-rc_j\varepsilon^{\beta}\right).$$

The possibilities of using the model for predicting the stress–strain diagrams of hybrid composites were confirmed in [43, 45, 46] by a comparison with results of short-term quasistatic tests.

Let us now turn to the question of the effect of the time factor. It follows from Table 1 that for hybrid unidirectional composites the time factor may be substantial even with loading in the direction of the reinforcement. The results of diagnosing the accumulation of damage in the composites shown in Fig. 9 made it possible to reveal the fundamental difference between the mechanisms of inelastic deformation of these materials. For instance, long-term creep of organic glass plastic is due predominantly to the viscoelastic properties of the organic fibers and of the binder. The closeness of the values of elasticity and maximum deformations of the investigated glass and organic fibers is the reason why with stresses up to 0.7 of the ultimate strength, the damage observed by indirect methods (e.g., according to acoustic emission) do not cause any substantial changes

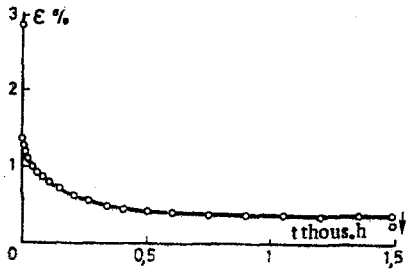

Fig. 14. Reverse creep of unidirectional organic boron plastic after preliminary creep for 10,000 h in tension in the direction of the reinforcement for σ = 750 MPa and subsequent complete unloading.

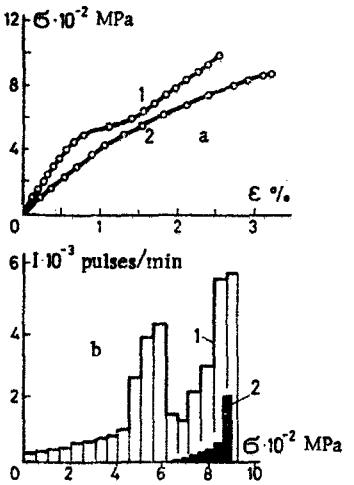

Fig. 15

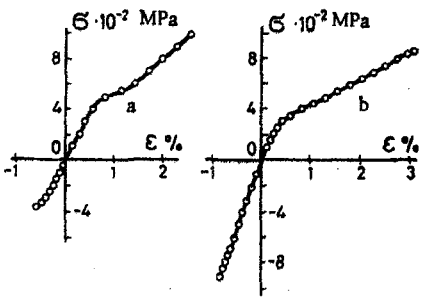

Fig. 16

Fig. 15. Stress–strain diagrams (a) and histograms of the intensity of acoustic emission (b) of the initial specimens of organic boron plastic (1) and specimens after preliminary creep for 10,000 h with σ = 750 MPa, subsequent complete unloading, and recovery for 1500 h (2).

Fig. 16. Stress–strain diagrams of unidirectional hybrid composites in tension and compression in the direction of the fibers: a) organic boron plastic (μ_o = 0.31, μ_b = 0.09); b) glass boron plastic (μ_g = 0.29, μ_b = 0.16).

of the averaged (effective) values of the modulus of elasticity and the time-dependent function of compliance of the composite in the direction of the fibers. This is confirmed by an analysis of the results of long-term (one year) creep tests of specimens of organic glass plastic with different ratio of the content of organic and glass fibers. The obtained isochronic curves of compliance are shown in Fig. 12 from which it can be seen that the instantaneous compliance of the composite increases with increasing content of glass fibers in it because the modulus of elasticity of the organic fibers is somewhat larger than the modulus of elasticity of glass fibers [37]. However, the manifestation of creep of organic fibers has the effect that from 10,000 h onwards the full compliance of the organic plastic is higher than the compliance of glass plastic. Partial replacement of organic fibers by glass fibers suppresses the creep effect of the material. In Fig. 12 we also show the results of perfectly satisfactory prediction of the long-term creep of these composites. The predicted compliance curve was obtained by calculation according to the properties of the components on the assumption that glass fibers resist elastically, and that the binder and organic fibers resist viscoelastically; in the calculations we used the functions of viscoelastic compliance of the organic fibers and of the binder found in [26] from accelerated thermal tests.

In distinction to organic glass plastic, creep of hybrid composites containing high-modulus (boron, carbon) fibers may to a large extent depend on the scattered fragmentation of these fibers. The method of predicting long-term deformation of such materials was worked out by Kochetkov and Maksimov [47]. Here we wil will confine ourselves to the example of predicting the creep of organic boron plastic in tension in the direction of the fibers taking the effect of fragmentation of the boron fibers into account (Fig. 13). Curve 1 was calculated by a program devised in [47] with a view to the viscoelastic resistance of the matrix in tension and shear, and also to the statistics and the time dependence of the strength of the boron fibers; the viscoelastic functions of the anisotropic (reinforced by organic fibers) matrix were determined according to short-term thermal tests by the above-explained method of predicting the viscoelastic properties of two-component composites. For the sake of comparison we also present curve 2 which was calculated according to the known rule of mixtures for a viscoelastic matrix and elastic boron fibers on the assumption that there is no accumulation of damage. From a comparison of curves 1 and 2 it can be seen that the effect of damage accumulation in long-term creep is considerable, and that on the whole it is predicted satisfactorily.

It should be noted that after unloading of specimens damaged in the process of long-term creep we find very intense reverse creep (Fig. 14). The magnitude of the residual deformation after long-term recovery as a rule does not exceed 10% of the value of full deformation attained at the instant of unloading. From this, however, it does not follow that the mechanical properties of the material are restored. A lucid confirmation of this is Fig. 15 in which stress–strain diagrams are compared with the histograms of the observed acoustic emission of the initial specimens (not subjected to preliminary loading) of the same organic boron plastic and specimens after preliminary long-term creep shown in Figs. 13 and 14, subsequent complete unloading, and recovery. The shape of the stress–strain diagram changed and the intensity of the acoustic emission decreased substantially.

The investigation of creep of hybrid composites that was carried out has, after all, to be complemented by tests with other kinds of state of stress. For instance, even in unidimensional loading, the resistance of these materials is largely dependent on the sign of the stress; this can be clearly seen from the stress–strain diagrams in tension and compression in the direction of the reinforcement of organic boron plastic and glass boron plastic shown in Fig. 16.

In conclusion the following must be pointed out. To define more accurately the range of applicability of the examined variant of predicting the viscoelastic properties of fiber-reinforced composites entails the necessity of studying further and more thoroughly the physicochemical interaction of the fibers and the binder. Important are not only the facts of interaction thereby discovered; it is indispensable to evaluate the consequent quantitative change of the characteristics of the mechanical properties of the components of the composite used in structural models. It is also very important to improve the methods of diagnosing damage to the material in structures directly in the process of their operation, and to use these data, not only for evaluating the state of the material at the instant of inspection, but also for improving the accuracy of the prediction of the specified life of the structure. And finally, the question remains topical: to develop further the methods of prediction for conditions approaching operating conditions. In this respect much was done in taking into account the actual operation of the material under conditions of complex state of stress; questions of the aging of material and of the additional effect of various factors, including extremal and environmental ones, have been investigated to a lesser extent.

LITERATURE CITED

1. A. F. Kreger and A. F. Zilauts, "A variant of constructing numerical characteristics of the degree of anisotropy of the deformability of physically linear materials," Mekh. Polim., No. 6, 1013-1019 (1978).
2. A. P. Aleksandrov, "Frost resistance of high-molecular compounds," in: Transactions of the First and Second Conferences on High-Molecular Compounds [in Russian], Moscow (1945), pp. 49-59.
3. A. P. Aleksandrov and Yu. S. Lazurkin, "The study of polymers. I. Highly elastic deformation of polymers. II. The dynamic method of investigating elastic polymers," Zh. Tekh. Fiz., 9, No. 14, 1249-1266 (1939).
4. G. I. Gurevich, "The law of deformation of solids and liquids," Zh. Tekh. Fiz., 17, No. 2, 1491-1502 (1947).
5. A. K. Malmeister, "Statistical interpretation of rheological equations," Mekh. Polim., No. 2, 197-213 (1966).
6. M. Vil'yams, R. Landel, and Dzh. Ferri, "The temperature dependence of relaxation processes in amorphous polymers and other vitrifying liquids," Prob. Sov. Fiz., Fiz. Polim., 8, No. 12, 20-33 (1956).

7. J. D. Ferry, Viscoelastic Properties of Polymers, Wiley (1970).
8. A. Tobol'skii, Properties and Structure of Polymers [in Russian], Moscow (1964).
9. Yu. S. Urzhumtsev and R. D. Maksimov, "The stress–time analogy with nonlinear viscoelasticity," Mekh. Polim., No. 2, 379-381 (1968).
10. Yu. S. Urzhumtsev and R. D. Maksimov, "On vibration-time analogy," Mekh. Polim., No. 5, 793-798 (1968).
11. R. D. Maksimov, V. P. Mochalov, and Yu. S. Urzhumtsev, "Moisture–time analogy," Mekh. Polim., No. 5, 780-786 (1972).
12. S. B. Ainbinder, K. I. Alksne, É. L. Tyunina, and M. G. Laka, Properties of Polymers at High Pressures [in Russian], Moscow (1973).
13. O. E. Ol'khovik, A. Ya. Gol'dman, and É. S. Grigoryan, "Temperature–time analogy in volumetric creep of some tough polymers," Mekh. Polim., No. 5, 930-934 (1974).
14. Yu. S. Lipatov, V. F. Babich, and N. I. Korzhuk, "The question of the existence of the superposition of frequency–concentration of the filler in filled polymers," Vysokomolekulyarnye Soed., Ser. A, 14, No. 7, 1629-1635 (1974).
15. Yu. S. Urzhumtsev and R. D. Maksimov, "Multiparameter prediction of the creep of polymer materials. Communication 1," Mekh. Polim., No. 3, 420-428 (1970).
16. Yu. S. Urzhumtsev and R. D. Maksimov, "Multiparameter prediction of the creep of polymer materials. Communication 2," Mekh. Polim., No. 3, 416-420 (1971).
17. V. V. Kovriga, E. S. Osipova, I. I. Farberova, and K. Ya. Artanova, "Temperature–time superposition applied to the relaxation properties of glass-fiber reinforced plastic and its binder," Mekh. Polim., No. 2, 360-363 (1972).
18. Yu. S. Urzhumtsev and R. D. Maksimov, Prediction of the Deformability of Polymer Materials [in Russian], Riga (1975).
19. R. Sheiperi, "The viscoelastic behavior of composite materials," in: Composite Materials, Vol. 2, The Mechanics of Composite Materials [in Russian], Moscow (1978), pp. 102-195.
20. V. S. Ekel'chik, S. N. Kostritskii, and M. Z. Tsirkin, "Investigation of the temperature–time dependence of the strength and deformability of glass-fiber reinforced plastics in the transverse direction," in: First All-Union Conference on Composite Polymer Materials and Their Application in the Economy [in Russian]. Abstracts of Papers, Vol. 2, Tashkent (1980), p. 51.
21. W. J. Griffith, D. H. Morris, and H. F. Brinson, "Accelerated characterization of graphite/epoxy composites," in: Advances in Composite Materials. Proceedings of the Third International Conference on Composite Materials, Vol. 1, Paris (1980), pp. 461-471.
22. H. T. Hahn and T. T. Chiao, "Long-term behavior of composite materials," in: Advances in Composite Materials. Proceedings of the Third International Conference on Composite Materials, Vol. 1, Paris (1980), pp. 584-596.
23. E. A. Sokolov and R. D. Maksimov, "Predicting long-term creep of organic-fiber reinforced plastic," Probl. Prochn., No. 9, 45-48 (1982).
24. R. D. Maksimov, "Prediction of the mechanical resistance to static loads of composite polymer materials," in: Fifth All-Union Congress on Theoretical and Applied Mechanics [in Russian], Annotated Papers, Alma-Ata (1981), p. 245.
25. R. D. Maksimov, "Prediction of the mechanical resistance of composite material from the results of rapid tests," in: Fourth All-Union Conference on the Mechanics of Polymer and Composite Materials [in Russian], Annotated Papers, Riga (1980), p. 56.
26. R. D. Maksimov and É. Z. Plume, "Prediction of the creep of unidirectionally reinforced plastic with thermorheologically simple structural components," Mekh. Kompozitn. Mater., No. 6, 1081-1089 (1982).
27. R. D. Maksimov, E. A. Sokolov, and V. P. Mochalov, "The effect of temperature and moisture on the creep of polymer materials. 1. Unidimensional tension under steady-state temperature–moisture conditions," Mekh. Polim., No. 3, 393-399 (1975).
28. R. D. Maksimov, E. A. Sokolov, and V. P. Mochalov, "The effect of temperature and moisture on the creep of polymer materials. 2. Unidimensional tension under nonsteady-state temperature-moisture conditions," Mekh. Polim., No. 6, 976-982 (1975).
29. R. D. Maksimov, V. P. Mochalov, and E. A. Sokolov, "The effect of temperature and moisture on the creep of polymer materials. 3. Shear and simultaneous shear and tension," Mekh. Polim., No. 4, 627-632 (1976).
30. R. D. Maksimov, V. P. Mochalov, and E. A. Sokolov, "The effect of temperature and moisture on the creep of polymer materials. 4. Prediction according to results of rapid tests," Mekh. Polim., No. 6, 982-987 (1976).

31. A. A. Malmeister and Yu. O. Yanson, "Prediction of the relaxational properties of the epoxy binder ÉDT-10 in a state of complex stress," Mekh. Kompozitn. Mater., No. 5, 889-894 (1983).
32. R. D. Maksimov and É. Z. Plume, "Creep of unidirectionally reinforced polymer composites," Mekh. Kompozitn. Mater., No. 2, 215-223 (1984).
33. R. D. Maksimov, É. Z. Plume, and E. A. Sokolov, "The elasticity of high-strength organic fibers and organic-fiber reinforced plastics," Mekh. Kompozitn. Mater., No. 2, 211-220 (1980).
34. R. D. Maksimov, É. Z. Plume, E. A. Sokolov, and V. M. Ponomarev, "Determination of the elastic characteristics of anisotropic fibers in composite material reinforced by them," in: Methods and Means of Diagnosing the Load-Bearing Capacity of Products Made of Composites [in Russian], Riga (1983), pp. 144-150.
35. R. D. Maksimov and É. Z. Plume, "The elasticity of hybrid composite material based on organic and boron fibers," Mekh. Kompozitn. Mater., No. 3, 399-403 (1980).
36. É. Z. Plume and R. D. Maksimov, "Algorithm for determining the elastic characteristics of hybrid multifiber composite material," Algoritmy Programmy, No. 3, 55 (1980).
37. R. D. Maksimov, É. Z. Plume, and V. M. Ponomarev, "Elastic characteristics of unidirectionally reinforced hybrid composites," Mekh. Kompozitn. Mater., No. 1, 13-19 (1983).
38. É. Z. Plume, "Algorithm for checking the observation of the temperature-time analogy in the temperature–time dependences of the strain and strength properties of polymers," Algoritmy i Programmy, No. 2, 34 (1978).
39. R. D. Maksimov, É. Z. Plume, and V. M. Ponomarev, "Strength properties of unidirectional hybrid composites," Mekh. Kompozitn. Mater., No. 1, 35-41 (1984).
40. A. K. Malmeister, "The geometry of the theory of strength," Mekh. Polim., No. 4, 519-534 (1966).
41. R. D. Maksimov and V. M. Ponomarev, "Prerequisites of the complex diagnosing of the accumulation of damage in the deformation of a hybrid composite," in: Methods and Means of Diagnosing the Load-Bearing Capacity of Products Made of Composites [in Russian], Riga (1983), pp. 150-155.
42. R. D. Maksimov and V. M. Ponomarev, "Diagnosing the damage to a hybrid composite under the effect of mechanical loads," Mekh. Kompozitn. Mater., No. 1, 123-128 (1982).
43. R. D. Maksimov, V. A. Kochetkov, and V. M. Ponomarev, "Acoustic emission and the kinetics of accumulation of damage in tension of a hybrid composite," in: Methods and Means of Diagnosing the Load-Bearing Capacity of Products Made of Composites [in Russian], Riga (1983), pp. 137-143.
44. V. A. Kochetkov and R. D. Maksimov, "Stress redistribution upon rupture of brittle fibers in multifiber composite," Mekh. Kompozitn. Mater., No. 6, 1014-1028 (1980).
45. R. D. Maksimov and V. A. Kochetkov, "Description of the deformation of a hybrid composite with the effect of fiber fragmentation taken into account," Mekh. Kompozitn. Mater., No. 2, 233-238 (1982).
46. R.Maksimov, "Grundlagen des Deformationsverhaltens von Mischverbunden," in: Verstärkte Plaste-82. Vorträge, Berlin (1982), pp. 82-89.
47. V. A. Kochetkov and R. D. Maksimov, "Prediction of the creep of a unidirectional hybrid composite with the effect of fiber fragmentation taken into account," Mekh. Kompozitn. Mater., No. 5, 895-905 (1983).