STRENGTH OF ANISOTROPIC GLASS-REINFORCED PLASTICS WITH A COMPLEX STRESSED STATE AND HIGH LOADING RATE

V. A. Kopnov and V. A. Kolotilov

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The strength of anisotropic composite materials of the glass, carbon, and organoplastic types with static loads has been studied quite well and they are described very satisfactorily by known phenomenological strength criteria [1, 2]. However, it is known [3] that domestic and foreign recommendations for standards with respect to static strain rate for composite specimens disagree considerably (from $\dot{\varepsilon}$ = 0.00007 to 0.00145 sec^{-1}). It has been suggested [3] in order to determine static strength and strain characteristics for reinforced plastics that the strain rate is selected within the limits $\dot{\varepsilon}$ = 0.0008... 0.0025 sec^{-1} or a rate of increase in stress of about $\dot{\sigma}$ = 2500 $MN/m^2 \cdot min$.

With strain rates of ~10^{-6} sec^{-1} or less we are talking about stress rupture strength of composites, which has also been studied to a certain extent [4, 5].

The strength of these materials with high loading rates (e.g., in the strain range $\dot{\varepsilon}$ = 1-10^6 sec^{-1}) has not been studied sufficiently either theoretically or experimentally. In addition, with an increase in loading rate there is more development of dynamic strength effects, and with very high rates (when wave processes are excited in the material) qualitatively new phenomena are revealed (spalling, etc.).

In the present work consideration is given to the strength of some glass-reinforced plastics in the "prewave" loading rate range whose main feature compared with static strength is an increase in material strength characteristics (and the whole deformation diagram) with an increase in loading or strain rate, observed with simple strengths (tension, compression, shear) and with a complex stressed state. It is noted that this strength feature is inherent for the majority of structural materials.

In order to estimate the strength of structural elements made of anisotropic composite materials (CM) with high-speed loading it is necessary to set out the corresponding strength criteria. In these criteria simultaneously there should be consideration of: a) the complex stressed state factor; b) features of the mechanical properties of the material (anisotropy, etc.); c) the effect of high loading rate on material strength. Apparently, the first possible variants of these criteria were considered by Gol'denblat and Kopnov [6]. In essence they consist of the following.

If we consider what has been said above about an increase in strength characteristics for high-speed loading, then the connection of dynamic and static strength limits for the material may be presented as:

$$\sigma_f^{\partial} = \sigma_f^{st} + \varphi(\dot{\sigma}). \tag{1}$$

Then the strength condition with uniaxial tension or compression has the form

$$\sigma \leqslant \sigma_f^{\partial} = \sigma_f^{st} + \varphi(\dot{\sigma}) \tag{2}$$

or

$$\sigma - \varphi(\dot{\sigma}) \leqslant \sigma_f^{st},$$

where σ is active stress with dynamic loading; $\varphi(\dot{\sigma})$ is some function of average constant loading rate, and $\varphi(\dot{\sigma}_0) = 0$ ($\dot{\sigma}_0$ is statically applied loading rate); $\sigma_f{}^{st}$ is ultimate strength with static loading.

Thus, in strength condition (2), written for dynamic loading, in the right-hand part there is first the static strength limit, and in the left-hand part some "reduced" (com-

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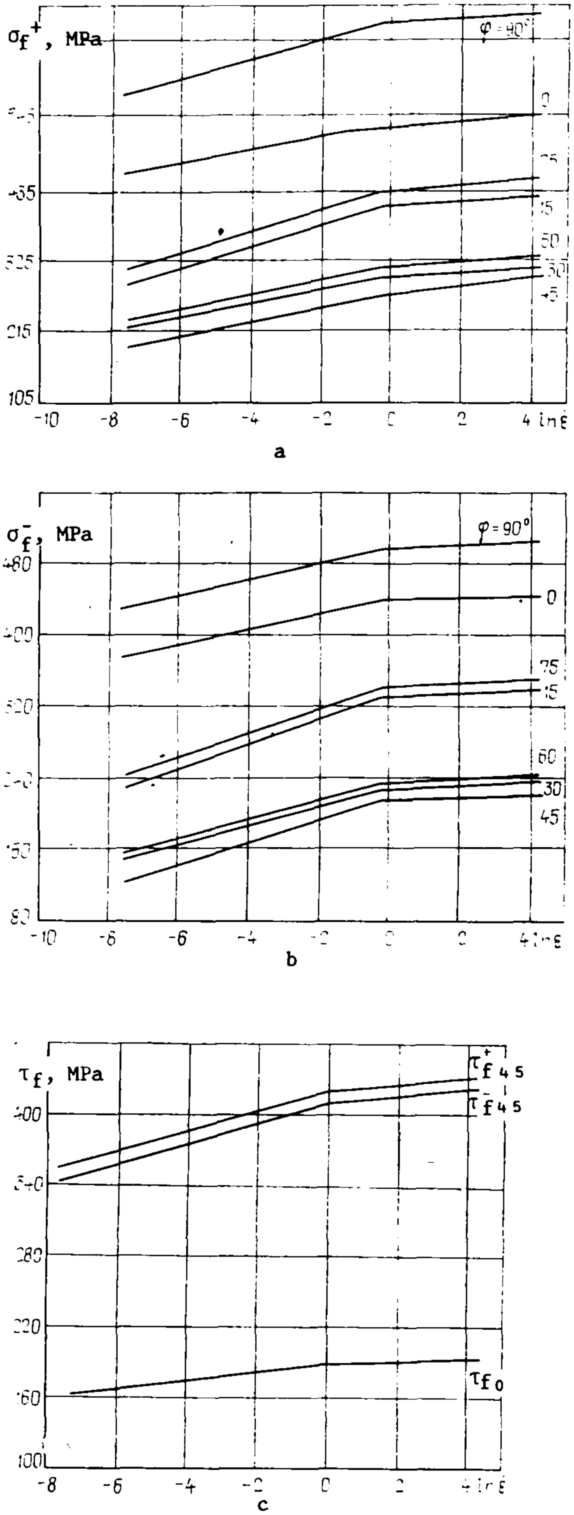

Fig. 1. Experimental dependences for the ultimate strengths of specimens made of fiber glass laminate based on TSU-8/3 fabric on strain rate with testing in tension (a), compression (b), and shear (c).

pared with the active dynamic) stress. The form of function $\varphi(\dot{\sigma})$ is established by experiment.

In the case of a complex stressed state some "static" strength criterion should be used appropriate for a given material, and these reduced stresses should be placed in it. For example, the Gol'denblat-Kopnov criterion for the strength of anisotropic materials

$$\Pi_{ik}\sigma_{ik} + (\Pi_{ikmn}\sigma_{ik}\sigma_{mn})^{0.5} = 1 \tag{3}$$

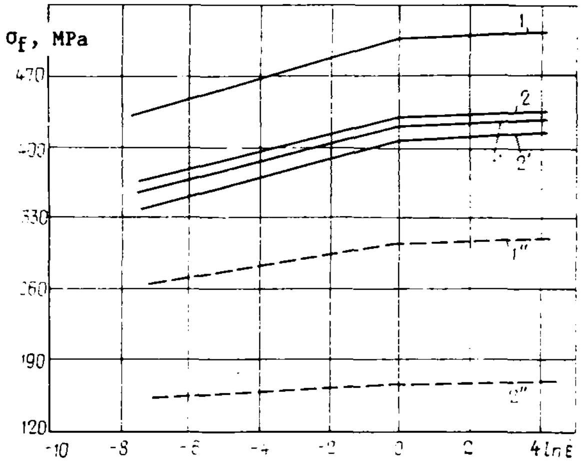

Fig. 2. Experimental dependences for the ultimate strength of specimens made of fiber glass laminates based on T-10-80 (1, 1', 1") and SMMT (2, 2', 2") cloths on strain rate with testing in compression (solid lines) and tension (broken lines): 1, 2' – $\varphi = 90°$; 1', 1", 2, 2" – $\varphi = 0°$.

(Π_{ik}, Π_{ikmn} are static strength components; σ_{ik}, σ_{mn} are stress tensor components) for the case of high-speed loading takes the form

$$\Pi_{ik}\,[\sigma_{ik}-\varphi_{ik}(\dot{\sigma}_{ik})]-\{\Pi_{ikmn}\,[\sigma_{ik}-\varphi_{ik}(\dot{\sigma}_{ik})]\ [\sigma_{mn}-\varphi_{mn}(\dot{\sigma}_{mn})]\}^{0.5}=1, \tag{4}$$

where Π_{ik}, Π_{ikmn} are as usual static strength tensor components for the material; φ_{ik}, φ_{mn} are some tensor functions of loading rate $\dot{\sigma}$.

By postulating certain connections existing between stress and strain rates, in criterion (4) instead of the function for loading rate $\varphi(\dot{\sigma})$ it is possible to introduce strain functions $f(\dot{\varepsilon})$ which are also determined by experiment. Then the Gol'denblat–Kopnov criterion is written as follows:

$$\Pi_{ik}\,[\sigma_{ik}-f_{ik}(\dot{\varepsilon}_{ik})]-\{\Pi_{ikmn}\,[\sigma_{ik}-f_{ik}(\dot{\varepsilon}_{ik})]\ [\sigma_{mn}-f_{mn}(\dot{\varepsilon}_{mn})]\}^{0.5}=1, \tag{5}$$

and i, k, m, n = 1, 2 for a plane stressed state; i, k, m, n = 1, 2, 3 for a spatially stressed state.

For the plane stressed state of an orthotropic material criterion (5) in expanded form is presented as:

$$\frac{1}{2}\left(\frac{1}{\sigma_{f1}^{+}}-\frac{1}{\sigma_{f1}^{-}}\right)[\sigma_{11}-f_{11}(\dot{\varepsilon}_{11})]+\frac{1}{2}\left(\frac{1}{\sigma_{f2}^{+}}-\frac{1}{\sigma_{f2}^{-}}\right)\times$$
$$\times[\sigma_{22}-f_{22}(\dot{\varepsilon}_{22})]+\frac{1}{2}\left\{\left(\frac{1}{\sigma_{f1}^{+}}+\frac{1}{\sigma_{f1}^{-}}\right)^{2}[\sigma_{11}-f_{11}(\dot{\varepsilon}_{11})]^{2}+\right.$$
$$+\left(\frac{1}{\sigma_{f2}^{+}}+\frac{1}{\sigma_{f2}^{-}}\right)^{2}[\sigma_{22}-f_{22}(\dot{\varepsilon}_{22})]^{2}+\left[\left(\frac{1}{\sigma_{f1}^{+}}+\frac{1}{\sigma_{f1}^{-}}\right)^{2}+\right.$$
$$\left.+\left(\frac{1}{\sigma_{f2}^{+}}+\frac{1}{\sigma_{f2}^{-}}\right)^{2}-\left(\frac{1}{\tau_{f45}^{+}}+\frac{1}{\tau_{f45}^{-}}\right)^{2}\right][\sigma_{11}-f_{11}(\dot{\varepsilon}_{11})]\times$$
$$\left.\times[\sigma_{22}-f_{22}(\dot{\varepsilon}_{22})]+\frac{4}{\tau_{f0}^{2}}[\sigma_{12}-f_{12}(\dot{\varepsilon}_{12})]^{2}\right\}^{0.5}=1, \tag{6}$$

where σ_{f1}^{+} and σ_{f1}^{-} are strength limits in tension and compression in the first warp direction of the material; σ_{f2}^{+} and σ_{f2}^{-} are the same in the second warp direction; τ_{f45}^{+} and τ_{f45}^{-} are strength limits with shear at an angle of 45° to the warp directions of the material; τ_{f0} is strength limit in shear in the main material directions.

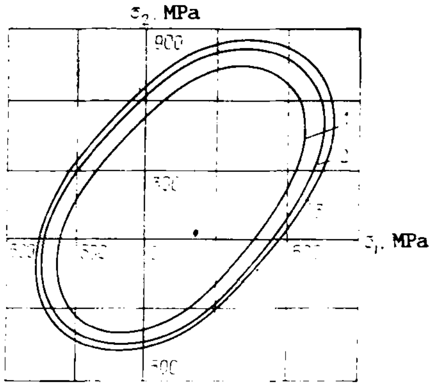

Fig. 3. Limiting curves for glass fiber laminate based on TSU-8/3 fabric with three different strain rates: 1) $\dot{\varepsilon} = 33.5 \cdot 10^{-5}\ \mathrm{sec}^{-1}$; 2) $\dot{\varepsilon} = 0.82\ \mathrm{sec}^{-1}$; 3) $\dot{\varepsilon} = 62.5\ \mathrm{sec}^{-1}$.

It should be noted that presentation of criterion (6) in terms of the strength characteristics in it is not unique, and other approaches are possible [7].

It can be seen from expression (6) that in order to construct limiting strength surfaces in the case of high-speed loading for a composite material it is necessary to establish by experiment the form of the following functions

$$\sigma_{f1}^{+}(\dot{\varepsilon}_{11}); \quad \sigma_{f1}^{-}(\dot{\varepsilon}_{11}); \quad \sigma_{f2}^{+}(\dot{\varepsilon}_{22}); \quad \sigma_{f2}^{-}(\dot{\varepsilon}_{22});$$
$$\tau_{f0}(\dot{\varepsilon}_{12}); \quad \tau_{f45}^{+}(\dot{\varepsilon}_{12}) \text{ and } \tau_{f45}^{-}(\dot{\varepsilon}_{12}),$$

and the relationship $\tau_{f45}{}^{+}(\dot{\varepsilon}_{12})$ or $\tau_{f45}{}^{-}(\dot{\varepsilon}_{12})$ may be found if one of them is known by the so-called compatibility condition [2]:

$$\frac{1}{\sigma_{f1}^{+}(\dot{\varepsilon}_{11})} - \frac{1}{\sigma_{f2}^{+}(\dot{\varepsilon}_{22})} - \frac{1}{\sigma_{f1}^{-}(\dot{\varepsilon}_{11})} + \frac{1}{\sigma_{f2}^{-}(\dot{\varepsilon}_{22})} = \frac{1}{\tau_{f45}^{+}(\dot{\varepsilon}_{12})} - \frac{1}{\tau_{f45}^{-}(\dot{\varepsilon}_{12})}. \qquad (7)$$

The form of these functions is determined by testing CM in tension, compression, and shear in the appropriate direction with different strain rates.

Experiments were carried out in an Instron-1196 machine and also in a specially designed and prepared vertical impact machine. Loading rate in the machine, determined from the movement velocity of the mobile beam, was varied within the limits 0.5...500 mm/min (0.5; 1.0; 2.0; 5.0; 10; 20; 50; 100; 200; 500). Strain rate was calculated by the well-known equation

$$\dot{\varepsilon} = V_{tr}/L_b,$$

where L_b is specimen gage length; V_{tr} is movement velocity of the mobile beam of the machine.

For tensile testing, specimens of fiber glass laminate based on fabric grades TSU-8/3, T-10-80, and epoxy phenyl binder, fabric SMMT and chlorine-containing epoxy binder were prepared in the form of flat blades (GOST 9950-71) with a gage length equal to 80 and 10 mm, a width of 16 mm, and a thickness of 4 mm. In order to study the effect of loading rate on compressive strength prismatic specimens were prepared (GOST 4651-68) 20 and 10 mm high, 15 and 8 mm wide, and 10 and 8 mm thick. Particular attention was devoted to observing parallelness of the end supporting sections and perpendicularity of the specimen longitudinal axis. Specimens for shear testing (GOST 16483.13-72) had the following dimensions: 60 × 10 × 10 mm.

Thus, in tensile testing, the strain rate in the machine $\dot{\varepsilon} = (1 \cdot 10^{-4} \ldots 0.8)\ \mathrm{sec}^{-1}$, in compression and shear it was $\dot{\varepsilon} = (4 \times 10^{-3} \ldots 0.8)\ \mathrm{sec}^{-1}$. For testing at higher strain rates a vertical impact machine was prepared providing a maximum movement rate for the falling hammer of 6-7 m/sec. In the case of tensile testing of specimens made of CM they failed with a velocity of 5 m/sec, in compression and shear at 1.2-1.3 m/sec. As a result of this the highest strain rate for specimens in tension, compression, and in shear in the impact machine was about the same (62.5 sec^{-1}).

TABLE 1. Values of Strength Constants for Glass Fiber Laminate for Determining Strength Characteristics

Material	Constants	Ultimate strengths						
		σ_{f1}^{+}, MPa	σ_{f2}^{+}, MPa	σ_{f1}^{-}, MPa	σ_{f2}^{-}, MPa	τ_{f45}^{+}, MPa	τ_{f45}^{-}, MPa	τ_{f0}, MPa
TSU-8/3	*A*	54,38	69,25	43,8	49,9	42,24	42,875	19,2
	B	1,01	1,45	0,8	0,9	1,03	1,125	0,2
	C	53,5	66,55	43,53	49,8	42,1	42,4	19,0
	D	0,22	0,245	0,125	0,2	0,6	0,6	0,1
T-10-80	*A*	31,0	—	38,2	47,5	—	—	—
	B	0,7	—	1,0	1,2	—	—	—
	C	30,8	—	47,5	47,4	—	—	—
	D	0,2	—	1,2	0,3	—	—	—
SMMT	*A*	16,0	—	38,2	36,3	—	—	—
	B	0,25	—	0,85	0,8	—	—	—
	C	15,8	—	38,1	36,3	—	—	—
	D	0,05	—	0,2	0,2	—	—	—

TABLE 2. Values of Strength Constants (MPa) with Different Angles φ for Glass Fiber Laminate Based on TSU-8/3 Fabric

Loading	Constants	φ (deg), equal to				
		15	30	45	60	75
Tension	A_i	424,0	298,0	273,4	314,1	425,0
	B_i	18,0	10,0	10,6	10,9	17,75
	C_i	410,0	298,0	273,0	311,3	440,3
	D_i	5,0	3,5	6,0	4,7	3,5
Compression	A_i	332,5	231	214,5	237,5	346,0
	B_i	13,75	11,0	10,5	11,25	14,0
	C_i	331,0	228	215	234,5	345
	D_i	2,0	1,0	1,0	1,5	1,0

Specimens of fiber glass laminate based on fabric TSU-8/3 and epoxy binder were cut from the CM sheet in the direction of the weft (0°), the warp (90°), and also at angles φ of 15, 30, 45, 60, and 75° in relation to the weft direction. It is well known, for example [2], that in testing specimens cut at different angles to the warp direction of material anisotropy, due to the effect of intersecting fibers distorted values are obtained for material ultimate strength. In the test described the authors knowingly ignored this situation since a study was made of the effect only of a single factor, i.e., strain rate $\dot{\varepsilon}$, on ultimate strength and not on the nature of alloy anisotropy.

Results of testing in tension, compression, and pure shear for specimens made of glass fiber laminate based on TSU-8/3 fabric and epoxy binder ÉP-5122 are presented in the form of lines in Fig. 1. It can be seen that a change in slope for all of the strength lines occurs approximately with the same strain rate which is within the limits $0.57 \leq \dot{\varepsilon} \leq 0.82$ sec^{-1}. In the strain rate range less than 0.6 the slope of straight lines characterizing the degree of increase in ultimate strength with an increase in $\dot{\varepsilon}$ is markedly greater than with $\dot{\varepsilon} > 0.8$ sec^{-1}. A similar picture was also observed with high-speed testing of glass fiber laminate based on T-10-80 and SMMT fabrics and binders ÉP-5122 and ÉKhDU, respectively, loaded only along the direction of the warp and weft of the glass fabric (Fig. 2). Apparently with strain rates corresponding to the change in slope of curves $\sigma_f = f(\dot{\varepsilon})$ there is a change in the failure mechanism for the CM studied, which has been particularly noted previously [8, 9].

Experimental data (Fig. 1) were approximated by linear regression equations of the following form:

$$\sigma_{fi}^{\pm} = f(\dot{\varepsilon}) = A_i - B_i \ln \dot{\varepsilon} \text{ with } \dot{\varepsilon} \leqslant 0{,}82 \text{ sec}^{-1},$$

$$\sigma_{fi}^{\pm} = f(\dot{\varepsilon}) = C_i - D_i \ln \dot{\varepsilon} \text{ with } \dot{\varepsilon} > 0{,}82 \text{ sec}^{-1},$$

where A_i, B_i, C_i, and D_i are experimental constants for the material determined using the least squares method. Numerical values for strength constants for the test glass fiber laminates for the warp directions of the materials are presented in Table 1, and for different angles φ (glass fiber laminate based on TSU-8/3 fabric) in Table 2.

It is noted that for all of the test range of strain rates values of ultimate strength for CM with shear $\tau_{f_{45}}^{-}$ were calculated by relationship (7).

Shown in Fig. 3 are limiting curves for glass fiber laminate based on TSU-8/3 fabric plotted from strength criterion (5) with three different strain rates. It can be seen that the region of safe stressed states (limits bounded by ellipses) increases with an increase in strain rate. In addition, the different form of relationship $\sigma_{fi} = f(\dot{\varepsilon})$ leads to the fact that with an increase in $\dot{\varepsilon}$ limiting ellipses not only expand, but they also deform.

A final judgement of the operating capacity for strength criteria type (4) or (5) may only be made after carrying experiments for high-speed loading of glass-reinforced plastic specimens under complex stressed state conditions.

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