EXPERIMENTAL INVESTIGATION OF THE DYNAMIC BEHAVIOR OF TUBULAR SAMPLES OF COMPOSITE FIBER MATERIALS AT THE LIMIT OF CARRYING CAPACITY

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The range of applications of composite fiber materials (CFMs) is increasing. Together with the traditional applications (structural elements and joints operating under static and quasistatic loads), CFMs are increasingly being used for fabrication of structural elements which are subjected to high-intensity dynamic loads. A strong impulsive load creates in the structural material a stress–strain state (SSS) that is characterized by a high degree of variability in time. As a result, in order to classify the process it is necessary to introduce the norm of the strain-rate tensor. In experimental work it is convenient to employ the analog of the integral norm – the average rate of strain on a monotonic section of the time dependence $\varepsilon = \varepsilon(t)$ – and then to take this quantity as the characteristic strain rate for the given experiment.

In many works (see, for example [1, 2]) it is pointed out that the elastic and strength properties of some types of CFMs depend on the characteristic strain rate with $\dot{\varepsilon} \sim 10^2$ sec^{-1}. A study of this dependence and the dynamical behavior of different CFMs at the limit of the carrying capacity could help to reduce the amount of material needed in parts operating under conditions of a high-intensity dynamic load. For a number of reasons, however, in particular, due to the fact that the effect of dynamic pressure on a sample must be measured as a function of time, it is difficult to obtain numerical values characterizing the properties of CFMs at high rates of strain ($\dot{\varepsilon} \sim 10^3$ sec^{-1}). In this connection, it is of interest to develop experimental methods for studying the behavior of CFMs at the limit of their carrying capacity – such as the methods presented in [3-8].

1. Experiments on internal impulsive loading were performed on circular cylindrical shells, fabricated by winding in rings materials of two types: epoxy glass based on VM fiberglass and ÉDT-10 epoxy complexing agent and organic plastic based on SVM organic fiber and ÉDT-10 complexing agent.

The results of static tests of ring-shaped samples with the help of rigid half-disks by the method of [9] showed that the modulus of elasticity and the strength of glass epoxy in the circumferential direction are $E_g = 65.0 \pm 5$ GPa and $\sigma_g = 1.54$ GPa and for organic plastic $E_{or} = 116.0 \pm 5$ GPa and $\sigma_{or} = 2.01$ GPa. The density of the glass epoxy is equal to 2.03 g/cm^3 and the density of organic plastic is equal to 1.32 g/cm^3.

A schematic diagram of the arrangement of the experiments is presented in Fig. 1. An impulsive load was produced by detonating at the geometric center of the tubular sample 6 a spherical explosive charge 8 consisting of an alloy of trotyl with hexagen TG50/50. The explosive was initiated at its center with the help of a small electric detonator 9. The explosive with the detonator was secured on a paper tube 10, which was inserted into a centering insert 12, and the insert together with four pins 5 were, in turn, welded into the base 14. The tubular samples tested had an inner diameter of 100 mm. The length of the sample (250-300 mm) was chosen so that the free ends did not affect the character of the stress–strain state at the center of the sample when the deformation process was recorded. The thickness h of the walls of the samples ranged from 1.7 to 5 mm.

The main condition dictating this experimental arrangement was the requirement that the ends of the sample should be left free as much as possible. This was achieved by securing the upper flange 2 with the nuts 1 and 3 so that the sample could freely expand in the radial direction and at the same time it could not move as a rigid body. The sample was centered

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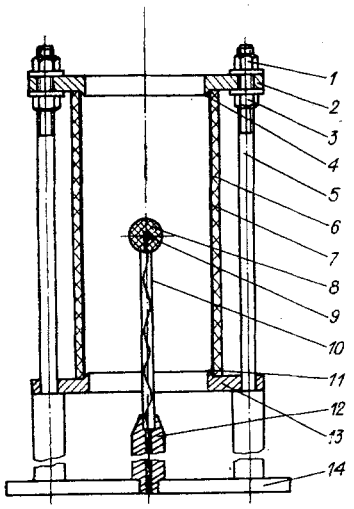

Fig. 1

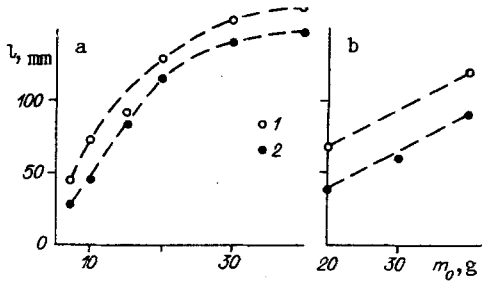

Fig. 2

by special 3 mm high triangular projections 4 and 11 on the flanges 2 and 13. Copper foil 7 (M1 brand), 0.1 mm thick, was glued in one or several layers on the inside of the samples. During the experiments, the circumferential deformation in the central section and in sections displaced frlom the central section of the sample were recorded. The deformation process was recorded with the help of strain gauge, resistors, similar to those described in [10, 11], glued on the outer surface of the sample.

Table 1 gives the experimental results for impulsive loading of samples with 5 mm thick walls. All samples were loaded only once. Here m_1 is the mass of a 1 cm length of the sample (including the foil), m_0 is the mass of the explosive, ε_{max} is the maximum circumferential deformation, t_{max} is the time at which maximum deformation is reached, ε_{av} is the average rate of strain, and ℓ is the size of the annular failure zone. The characteristic test results are presented in Figs. 2-4. Figure 2 shows the dependence of the size ℓ of the failure zone of the sample versus the mass of the explosive: h = 2.5 (a) and 5 mm (b); the points 1 and 2 are for epoxy glass and organic plastic. Figure 3 shows an exterior view of the samples with h = 5 mm after the tests (epoxy glass on the left and organic plastic on the right; the mass of the explosive is equal to 20 (a) and 40 g (b)).

Figure 4 shows the typical experimental dependences $\varepsilon = \varepsilon(t)$ for h = 5 mm: a – organic plastic 5; b – organic plastic 8, 6 – lines 1, 4; epoxy glass 5, 6, 4 – lines 2, 3, and 5.

2. First, it is of interest to examine the results obtained, some of which are presented in [12-14], from the viewpoint of the conclusions drawn in [8]. If reduction of carrying capacity of the sample is understood to mean the appearance of global defects (from formation of through cracks up to separation into parts), then the epoxy glass and organic plastic samples have approximately the same carrying capacity. At the same time, the following fact merits attention. In a series of experiments on samples with 5 mm thick walls, as the mass of the explosive increases from sample to sample from 10 to 40 g, the failure of the epoxy glass samples for the smaller explosives is caused by dynamic instability of radial axisymmetric vibrations and a rapid buildup of the flexural forms (which was also noted in [5, 8]) while in the case of large explosives failure occurs because the tensile strength is reached in the fiber glass. Instability of the axisymmetric motion was recorded on oscillograms (lines 2 and 5 in Fig. 4b) and from the residual deformation of the copper foil. Effects which would indicate instability of axisymmetric motion of the sample were not found in any experiment of a similar series on organic plastic samples with different wall thickness. Failure of organic plastic samples occurred during the first phase of the motion of the walls of the sample from the center (Fig. 4a) and was characterized by the presence of a continuous annular failure zone. If in this phase the sample did not fail and maintained its carrying capacity, then it later underwent rapidly decaying vibrations, in which the half-period decreased together with the half-swing of the vibrations (line 4 in Fig. 4b). Radial vibrations, as also noted in [8], decay much more rapidly in the organic plastic shell, but it would be incorrect to explain this effect by cracking of the complexing agent at the start of the vibrations, since the same cracking also occurs in shells made of epoxy glass, but does not lead to such rapid decay of vibrations. Here the difference between the dissipative

TABLE 1

Sample material	Sample number	m_1, g	m_0, g	ε_{max}, %	t_{max}, μsec	$\dot{\varepsilon}_{av}$, sec^{-1}	l, mm	Exterior view of sample after the experiment
Organic plastic (SVM + ÉDT-10)	1	23,8	40	4,37	9	4850	90	Failed with formation of an annular failure zone
	2	— —	20	3,84	17	2260	35	Failed with formation of an annular failure zone
	3	— —	10	1,42	20	710	—	Remained whole, foil pressed on the interior surface of the sample
	4	— —	30	4,62	13	3550	60...85	Failed with formation of asymmetric annular failure zone
	5	29,3	20	3,58	19	1880	35	Held together by the foil, which is squeezed out through the failure zone
	6	— —	10	1,16	21	550	—	Remained whole, the foil contains a small axial crimp
	7	— —	30	—	—	—	—	Incomplete detonation of explosive. The foil at the center of the sample separated and is bent inward with an axial crimp
	8	— —	40	4,56	11	4140	65	Failed with formation of an annular failure zone
Epoxy glass (VM + ÉDT-10	1	34,1	10	—	—	—	—	Divided into two parts by a circular crack and several axial cracks, the edges of the foil are bent inwards
	2	— —	20	—	—	—	60	Held together by the foil, which is strongly bent inward. Seven axial cracks can be seen
	3	— —	40	4,25	20	2120	120	Failed with formation of an annular failure zone
	4	39,6	10	1,77	29	610	—	Remained whole. Two diametrically opposite through axial cracks, about 20 mm long, at the center
	5	— —	20	3,58	26	1370	65	Same picture as observed in sample No. 2 (epoxy glass). Differs by the presence of five instead of seven axial cracks
	6	— —	40	4,45	22	2020	120	Failed with formation of an annular failure zone

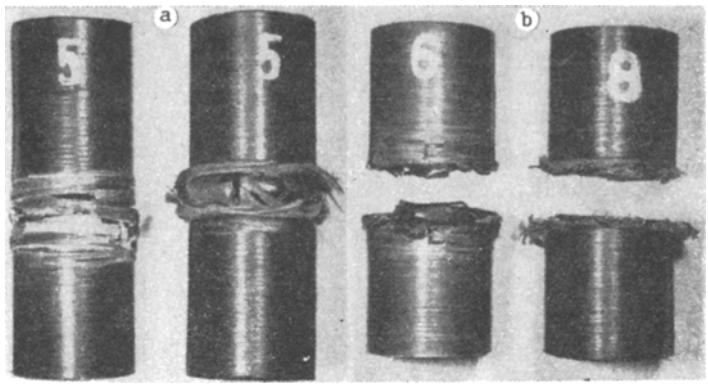

Fig. 3

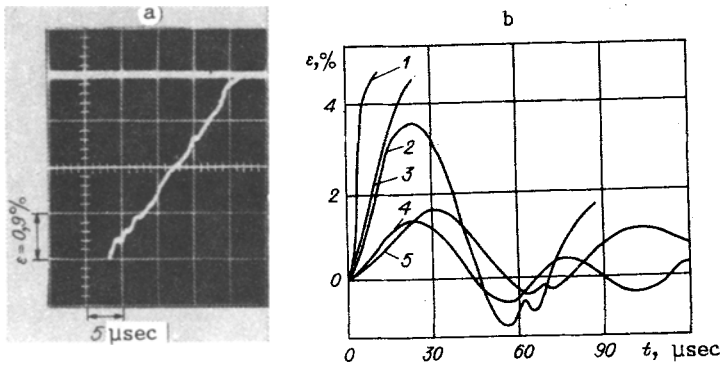

Fig. 4. The picture in Fig. 4a is inverted.

properties of the strong filler as well as the fact that Poisson's ratio $\nu_{\alpha\beta}$ (α is the meridional coordinate and β is the circumferential coordinate) in the unidirected organic plastic is 1.5 times higher than the corresponding value for the unidirected plexiglass [15], is evidently manifested. The quantity $\nu_{\alpha\beta}$ characterizes the coupling of the radial and axial motions in a cylindrical shell. The larger $\nu_{\alpha\beta}$, the more energy of radial vibrations transforms into axial motion and "leaks out" from the most highly loaded zone of the sample. This, combined with the dissipative properties of SVM, leads to much faster decay of vibrations in the central section of the organic plastic samples.

3. As noted above, in order to find the numerical values characterizing the dynamical values of the modulus of elasticity and the strength of the material under study, it is necessary to record as a function of time the pressure acting on the sample. When the dynamical stressed state in the sample is produced by a highly intense short-duration (impulsive) load, however, the estimated values of the elastic and strength characteristics of the sample material can be obtained by using approximate equations of motion and energy balance.

After the pressure pulse is over, before the first maximum of the strain is reached, the radial motion of the walls of the sample is described approximately by the equation [13]

$$Eh_g\varepsilon(t) + (h_g\rho_g + h_c\rho_c)R\ddot{\varepsilon}(t) = 0,$$

where h_g, ρ_g and h_c, ρ_c are the thickness and density of the epoxy glass and copper; R is the inner radius of the sample. Now, choosing the smooth section on the rising interval of the oscillogram $\varepsilon = \varepsilon(t)$, we fix the point t corresponding to the center of this section. The second derivative $\ddot{\varepsilon}(t)$ is approximately replaced by the relation $\ddot{\varepsilon}(t) \approx [\varepsilon(t - \tau) - 2\varepsilon(t) + \varepsilon(t + \tau)]/\tau^2$, and after substitution into the equation of motion the value of E is calculated. These calculations were performed for the oscillograms from five experiments, in which the quantities h_g, h_c, and the mass of the explosive were different, and in addition, in the calculations for each experiment, the value of τ was varied. As a result, the average value of E_{dyn}, with a spread of up to 20%, was found to be 5% smaller than the static value. This

result, just as the results of [3-5, 8], does not permit talking about the existence of a dependence of the modulus of elasticity of epoxy glass on the strain rate. The value of the absolute error is not discussed, since the calculations were approximate.

In order to estimate the dynamic strength of epoxy glass and organic plastic, we shall use an approximate equation of energy balance. The detonation products (DP) of the spherical explosive charge, initiated at the geometric center of a tubular sample, produce in the shell an axisymmetric stress–strain state which varies along the axis. In a time interval comparable to the period of characteristic vibrations of the ring, the process of transfer of elastic energy along the axis, because of the specific nature of the properties of CFMs, has virtually no effect on the proportionality of the stress–strain state to the form of the dependence of the magnitude of the pressure pulse on the axial coordinate [6]. A ring-shaped element of the shell obtains an impulse (momentum) that is approximately equal to the impulse of the force exerted on the element of the shell by the pressure of the DP. The kinetic energy of the ring-shaped element of the shell (which the element acquires as a result of the work performed by the DP) is practically completely transformed in the element, which does not collapse on stretching, into potential energy of deformation. Thus, at the boundary of the failure zone of the sample, when failure appeared at the stretching phase, we have in the linear approximation

$$\Delta V \frac{\sigma\varepsilon}{2} = \frac{\Delta m v_0^2}{2} = \frac{(\Delta m v_0)^2}{2\Delta m} = \frac{(i\Delta S)^2}{2\Delta m}.$$

From the equality of the two extreme quantities, after elementary transformations we obtain

$$\frac{N}{c} = \frac{i}{1 + h/2R}, \tag{3.1}$$

where ΔV, Δm, and ΔS are the volume, mass, and area of an elementary ring; R is the inner radius of the sample; h is the thickness of the packet; c is the velocity of the sound in an acoustically similar material, whose density is equal to the general density of the sample including the inner metallic layer; and, the elastic properties are determined by the modulus of elasticity of the sample material. Then, if i is the specific impulse corresponding to the boundary of the failure zone, then N is the maximum dynamic force for the given sample. In the point-explosion approximation [16], we obtain for the specific impulse i

$$i = \frac{2m_0 D}{27\pi R^2 [1 + (l/2R)^2]^2} \sqrt{1 + \frac{\rho_1 R^3}{\rho_0 r_0^3}\left[1 + \left(\frac{l}{2R}\right)^2\right]^{3/2}}. \tag{3.2}$$

Here r_0 and m_0 are the radius and mass of the explosive charge; D is the detonation velocity in the charge; ρ_1 and ρ_0 are the density of air and the explosive; and l is the size (along the axis) of the failure zone, formed in the sample during the first phase of the motion of the sample walls away from the center. Substituting for l the results of a series of experiments on samples with h = 2.5 mm (Fig. 2a) and the data in Table 1 for samples with h = 5 mm with m_0 = 40 and 20 g (taking l = 0 for the epoxy glass sample) in Eq. (3.2) and then in Eq. (3.1), we find the values of the specific impulse, applied at the boundary of the failure zone and the maximum dynamic forces for shells made of epoxy glass N_g and organic plastic N_{or}. Due to the approximate character of the quantities obtained, we can draw only qualitative conclusions. We note that at the boundary of the failure zone i decreases by about 10% as the mass of the explosive increases. For organic plastic samples i is approximately 15 times grater than the corresponding value for the epoxy glass samples. To within 20% N_{or}/N_g = 1.8, which is somewhat higher than the indirect estimate of the ratio of the maximum dynamical forces of organic plastic and epoxy glass, which can be found from the data in [8], where an approximate estimate of the ratio of the dynamic elastic moduli of SVM and glass fibers (~1.4) and the values of the maximum strains ε_g = 5.4% and ε_{or} = 4%, are presented. The difference is explained by the fact that the estimates in [8] refer to the strong base and can be applied to the composite material only if a correction for its concentration is made.

4. An external examination of the epoxy glass samples with h = 5 mm, which have lost their carrying capacity as a result of an increase in the flexural forms of motion, shows that the cracks develop from the outer surface of the sample. Taking into consideration the regular arrangement of the meridional cracks over the circumference, this allows us to assert that the number of cracks is equal to the number of the flexural form (number of waves) of the motion. From the results presented in Table 1 and Fig. 4b it follows that the number of

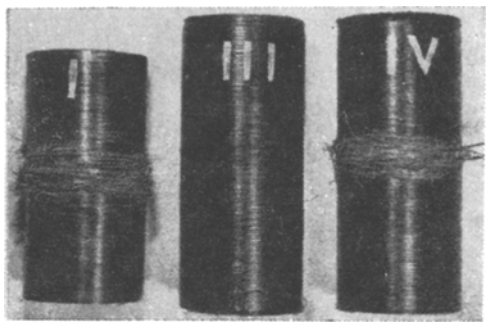

Fig. 5

cracks formed depends on the maximum velocity of the walls of the sample toward the center and thus, in turn, is affected by the elastic energy stored on stretching and the overall density of the material of the sample.

Comparing the experimental results for samples with h = 5 mm, made of different materials, shows that there are significant differences in the character of the deformation and collapse of shells made of epoxy glass and organic plastic. Under loading with a 10 g explosive charge, the organic plastic samples remain whole, while the epoxy glass samples lose their carrying capacity. On the other hand, under loading with a 20 g explosive charge, the glass plastic samples remained whole under tension and failed owing to the increase in flexural motion. The organic plastic samples, however, failed under tension, and the stress level was only slightly higher than the limiting value for this material (due to the presence of the foil, sample 5 also remained whole).

5. According to the literature (see, for example, [1, 2]), combined CFMs (CCFMs) are used in practice. A small addition of stronger but more expensive fibers to the main strong fill is used in order to obtain a reasonable ratio between the strength and cost of the CCFM obtained. Aside from strength, however, there also exists an entire series of factors, noted, for example, in [1, 8, 12-14] and in the present paper, that affect the carrying capacity of structures made of CFMs. In particular, one can see by comparing epoxy glass and organic plastic that each of these materials has its own advantages when used in structures intended for use under conditions in which a highly intense impulsive load can arise. For epoxy glass these advantages are its higher density and degree of deformation in the direction of the strong base and in the case of organic plastic these are the presence of dissipative properties and higher tensile strength.

In [14] recommendations for choosing an efficient concentration of fibers of different types in CCFMs are made on the basis of an approximate analysis of the dynamics of deformation of the most highly loaded part of the sample, taking into consideration a number of factors which affect the carrying capacity under impulsive loading. In order to check these recommendations experimentally a series of tubular samples made of epoxy glass with h = 2.1 mm, organic plastic with h = 1.7 mm, and two types of CCFMs with relative volume content of SVM fibers $\gamma = 0.67$ and $\rho = 1.55$ g/cm^3 for type I with h = 2.8 mm and $\gamma = 0.25$, $\rho = 1.87$ g/cm^3, and h = 1.7 mm for type II, was prepared. By systematically increasing the mass of the explosive from experiment to experiment, it was found that a 7.5 g charge gives, under a single loading, a picture similar to that shown in Fig. 3a in samples made of epoxy glass as well as organic plastic. Since the maximum stresses under an impulsive load are inversely proportional to the thickness of the sample and are proportional to the distributed impulse of the pressure (which is proportional to the mass of the explosive [16]), a 10 g explosive is equivalent for CCFM of the type I with h = 2.8 mm.

Figure 5 shows samples of CCFMs subjected to a single load of DP from explosives of mass 10 and 15 g (type I, samples III and IV) and 7.5 g (type II, sample I). The type II CCFM sample withstood the stretch phase with partial failure of the SVM fibers (an abrupt decrease of the strain rate is seen in the oscillogram), but it lost carrying capacity due to build up of flexural motion because of the higher stored elastic energy. The type I CCFM samples, however, had no global defects. An equivalent picture obtains in the presence of one or two layers of copper foil. A ring-shaped sample was cut from the type I CCFM sample which was exposed to the DP of the 10 g explosive. This sample was tested for residual strength, which was equal to 0.58 GPa, which is 14% higher than for epoxy glass with the same volume concentration of glass fibers as the type I CCFM.

TABLE 2

$\xi \cdot 10^2$	Epoxy glass		Organic plastic		Type of CCFM	
	h, mm		h, mm		I	II
	5	2,1–2,5	5	1,7–2,5	$\gamma = 0{,}67$	$\gamma = 0{,}25$
10—11				●	⊗	
9—10			●			
8—9	●					
7—8				⊗	⊙	□
6—7	□	●				
5—6		□			○	⊗
4—5			○			
3—4	△	⊙				
2—3	○					

Note. Samples after the experiment: ○) whole, no visible consequences of the tests; ⊙) separate fibers are broken; ⊗) many breaks in fibers; △) through breaks and cracks (without separation into parts); □) failure due to flexure; ●) failure under tension.

Thus, in terms of the absolute mass of the explosive charge, the carrying capacity of CCFM samples with $\gamma = 0.67$ is at least 1.5 times higher than for samples of the starting materials, and if the method of comparison employed in [3-8] (ratio of the mass of the explosive producing the damage to the mass of the sample) is used, then the carrying capacity is almost two times higher. In Table 2 the results of all experiments are summarized and classified according to the parameter $\xi = m_0/M$, where m_0 is the mass of the explosive used in the experiment and M is the mass of a part of the sample of length 2R including the mass of the copper foil).

Our investigation shows that CCFM for structures operating under extreme conditions can be obtained by taking into consideration the dynamics of deformation and failure at the limit of the carrying capacity of materials which are reinforced with different types of fibers and by combining the advantages of each type of fiber.

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