EFFECT OF REINFORCING STRUCTURES ON THE CRITICAL DEFORMABILITY AND STRENGTH OF SHELLS MADE OF ORIENTED GLASS-PLASTIC COMPOSITES UNDER AN INTERNAL EXPLOSIVE LOAD

A. G. Ivanov, M. A. Syrunin,
and A. G. Fedorenko

UDC 624.074.4:678.067

Fiber-wound glass-plastic composites have been shown to be promising materials for use as load-bearing elements of large shell structures, localizing an accidental single explosive release of energy [1-5]. The use of these composites substantially enhances the reliability of the system by preventing catastrophic elastic failures as a result of the strong scale effects of an energetic nature that can occur in homogeneous materials [6]. The critical strain (at the failure threshold) and the upper value of the specific explosive load (ratio of the mass of the explosive charge to the mass of the shell), which the structure can reliably localize, can serve as critical parameters for comparison of the deformability and strength of shells [1-5]. One of the main problems that arise during the design of high-strength shells from the indicated materials and protective structures based on them is that of determining the optimum reinforcement scheme as a function of the load realized. It has been determined experimentally that among cylindrical shells under an internal radially symmetric explosion a shell made of oriented glass-plastic composite with alternating double spiral and annular layers have the highest specific load capacity [3]. All types of fiber-wound glass-plastic composites display elastic behavior up to failure and have elastic constants that are independent of the strain rate [1, 3, 5]. In a complex layered packet, however, the load-bearing layers with different orientations of fibers linked into one whole by a polymer matrix are subject to different local stresses and strains because of different rigidities under tension in a given direction. When the critical stresses and strains in the fibers with the highest loads are exceeded the fibers may break, causing weakening or failure of the entire layer. At the same time a more effective application of one-time systems requires full use of the reserves of the strength of the material, i.e., the structure must function at the failure threshold. For fiber-wound composites it is important to know how fully the strength of the load-bearing fibers is realized at the layer level and what limiting characteristics of the components and of the material as a whole determine the strength of the structure.

Our aim was to make an experimental study of the effect of the reinforcement structure on the critical strain of open-ended cylindrical glass-plastic composite shells under an internal radially symmetric load and under the conditions when they are broken in the first stage of tension. The tests were done on cylindrical glass-plastic composite shells made by wrapping ribbons of roving, based on epoxy-impregnated VM-1 fiber, on a technological mandrel.

We studied three types of shells with inside radius R = 150 mm, length 4R, relative wall thickness δ/R = 4.8-7%, and the following reinforcement schemes: type 1 – annular winding of layers; type 2 – alternating spiral ($\varphi = \pm 45°$) and annular ($\varphi = 90°$) layers with a 1:1 thickness ratio; type 3 – alternation of spiral ($\varphi = \pm 65°$) and annular ($\varphi = 90°$) layers with 1:1 thickness ratio.

In the tests with shells of type 1 and 2 in order to suppress the mechanism of bending failure during vibrations and to exploit the load-bearing capacity more fully [2, 4] a steel (type 20) shell, with inside radius R_1 = 147.5 mm and relative thickness δ_1/R_1 = 1.35%, was inserted into the glass-plastic shell with a minimal gap (no more than 0.5 mm). The prepared samples were measured and weighed, and the average density ρ of the glass-plastic composite was found.

The shell was subjected to one internal explosive load, produced by a spherical charge of TG 5/5 explosive of mass m at the geometric center of the shell. The experimental setup and method of recording were described in detail in [1-5]. In the experiments the displacement of

---

Arzamas. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, No. 4, pp. 130-135, July-August, 1992. Original article submitted June 14, 1991.

 0021-8944/92/3304-0594$12.50

TABLE 1

Type of shell	Expt. No.	δ_1/δ, %	δ/R, %	ρ, kg/m^3	m, g	$\xi\cdot10^3$	ε_y, %	t_y, μsec	v_m, m/sec	$\dot{\varepsilon}$, 1/sec	State of shell
1 (90°)	1	21,7	6,16	2057	300,2	15,55	2,2	62	82,5	518	Broke in 3rd period of oscillations in the compressive phase
	2	21,7	6,16	2057	409,3	21,2	3,0	75	90	565	Broke in 1st period of oscillations in the compressive phase
	3	23,5	5,94	1897	484	25,2	3,4	79	109	682	The same
	4*	24,5	5,87	2077	766,7	39,4	4,4	7,5	120	753	Broke in the tensile phase
	5*	24,7	5,46	2032	925	48,5	4,9	55	178	1123	The same
2 (±45; 90°)	1	22,2	6,02	1945	276,7	14,05	2,75	100	66	414	Did not break
	2	23,2	5,99	1933	296,6	16,0	3,15	95	81	510	The same
	3	21,3	5,96	1940	334,5	18,9	3,9	95	88	555	Did not break (damage to the plastic between the fibers)
	4	19,6	7,03	1920	432	22,7	5,0	110	105	653	Broke in 1st period of oscillations in the compressive phase
	5*	21,8	6,45	2008	573	28,6	5,2	80	134	840	Broke in the tensile phase (Figs. 1c and 2c)

the outer surface of the shell at the central section with the largest load was determined in a time $\Delta R(t)$ by high-speed photography. From the results of the measurements to within 10% we found the maximum circumferential strain ε_y and the corresponding time t_y taken to reach it (measured from the beginning of the wall displacement), and the maximum radial displacement rate v_m, which makes it possible to calculate the maximum strain rate $\dot{\varepsilon} = v_m/R_L$ ($R_L = R + \delta$). The quantity chosen as the characteristic of the specific explosive load was $\xi = m/M$ [1-5], where M is the mass of a one-layer (glass-plastic) or two-layer (steel-reinforced glass-plastic) shells. The main results of the experiments are given in Tables 1 and 2. Typical photochronograms and the shape of the shells after the tests are illustrated in Figs. 1 and 2.

TABLE 2

Type of shell	Expt. No.	δ/R, %	ρ, kg/m^3	m, g	$\xi\cdot10^3$	v_m, m/sec	$\dot{\varepsilon}$, 1/sec	ε_y, %	t_y, μsec	T_y, μsec	State of shell after test
2 (±45; 90°)	1	5,95	1953	169	16,9	72	453	2,75		245	Did not break, damage occurred
	2	5,85	1870	169	17,6	82	515	2,7	80	235	Did not break
	3	5,64	2025	168,5	17,8	65	410	2,6	80	215	Did not break, damage occurred
	4	4,8	2120	169	19,3	80	509	3,1	70	235	The same
	5	6,52	1925	209	20,0	76	475	3,3	85	235	Broke in 6th period of oscillations in the compressive phase (Figs. 1a and 2a)
	6	5,77	2030	205	21,25	78	490	3,2	80	—	Broke in 1st period of oscillations in the compressive phase
	7*	6,7	1940	303	28,6	110	686	4,7	75	—	Broke in the tensile phase
3 (±65; 90°)	1	6,2	1948	164,5	15,6	62	388	1,6	67	190	Did not break, damage occurred
	2	6,72	2013	206	17,4	76	474	1,9	65	195	The same
	3	6,21	1935	208	19,9	80	502	2,15	73	195	Broke in 3rd period of oscillations in the compressive phase
	4	6,39	2107	264	22,3	85	522	2,2	75	205	The same
	5	6,59	2023	466	40	134	838	3,9	70	—	Broke in 1st period of oscillations in the compressive phase (Figs. 1b and 2b)
	6*	625	1930	483	48,3	158	991	5,2	75	—	Broke in the tensile phase

Note. T_y is the period of the fundamental tone of radial oscillations.

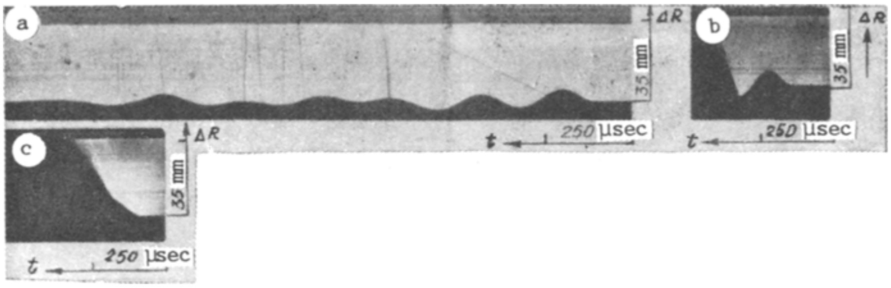

Fig. 1

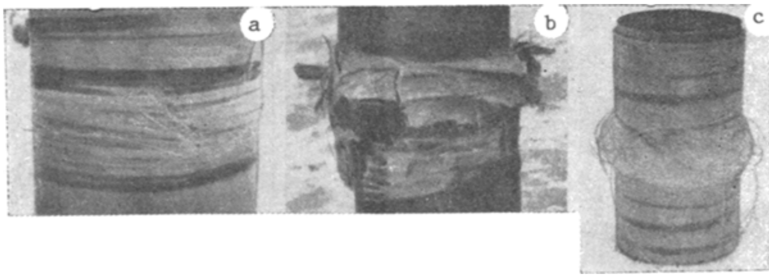

Fig. 2

From the experiments we found that the critical (breaking) circumferential strain in the first stage of tension of glass-plastic shells (with and without a steel insert) is $\varepsilon_y^* = 4.8 \pm 0.4\%$ (the average value from the experiments, labeled with an asterisk in Tables 1 and 2) and is independent of the winding angle of the spiral layers.

For example, for shells made by combined winding (types 2 and 3) this strain is $\varepsilon_y^* = 4.7\text{-}5.2\%$ (experiments 6 and 7, Table 2), which is in satisfactory agreement with the data of [4] for shells of similar structure with $\varphi = \pm 35°$ and half the fiber content in the circumferential layers, where $\varepsilon_y^* = 4.7\%$ (variation coefficient 11.5%). Comparing these strains with the critical value for shells with a ring structure ($\varepsilon_y^* = 4.4\text{-}4.9\%$), we see that all the values agree to within the error of measurement with the critical breaking strain when the elementary glass fiber is under static tension, $\varepsilon_b = 4.8$ [7].

All of the structures considered had annular layers, which (judging from the comparison with ε_b of the fiber) determine the critical circumferential strain of the glass-plastic combined structure. Critical stresses (strains) in the layers cause them to break and this results in the catastrophic destruction of the entire layered packet (shifts and partial tears of the spiral layers) and loss of load-bearing capacity by the shell (Figs. 1c and 2c).

When a shell breaks in the initial phase of high-rate tension the layered packet of the composite completely exhausts the strength reserve becuase of a rupture of the load-bearing matrix in the layers under highest load. In this case the critical circumferential strain ε_y^*, by analogy with [1] for glass-fiber composites based on glass cloth, is determined by the breaking stress of the load-bearing glass fibers.

Single-layer shells of glass-plastic combined structures (without steel) failed after one or several radial oscillations in the central section with an initial strain $\hat{\varepsilon}_y \approx 2\text{-}3\%$ (Table 2), which is substantially below the critical value for the given materials under dynamic tension (see above). This happened because the radial axisymmetric modes lost stability and flexural modes of the parametric resonance type developed, when the flexural modes with a frequency equal or close to the frequency of axisymmetric modes are excited most, as in [1, 8]. Just as in [3, 5], local bulges, cracks, and breaks form after one or several periods of radial expansion-compression (Figs. 1a, b and 2a, b).

When shells fail during flexural oscillations the critical strain $\hat{\varepsilon}_y$ depends on the angle φ of the spiral layers. The critical strain $\hat{\varepsilon}_y \leqslant 3.3\%$ for a combined structure with $\varphi \pm 45°$ and $\hat{\varepsilon}_y \leqslant 2.15\%$ for $\varphi = \pm 65°$ (see Table 2). Failure during the development of flexural modes is determined by factors that affect the stability of the oscillations, such as the reverse of elastic energy of the radial oscillations, possible load asymmetry, variation of the elastic modulus and density of the material, deviation of the diameter and the relative wall thickness (δ/R) of the shell, etc. [1, 8]. When a steel reinforcing layer is used [2, 4] the strain in shells may rise almost to the critical values for the material. The reserves of load-bearing capacity (with respect to both ε_y and ξ) of such samples, therefore, are not the same for different φ, i.e., $\hat{\varepsilon}_y$ cannot be taken as a criterion for comparison of the dynamic strength of composite shells, with different winding angles and reinforcement structures, when they fail as a result of loss of stability by the radial oscillations. The parameter ξ, which characterizes the specific load, may serve as the main criterion for this comparison, just as it was used in [1-5, 8]. Although the rigidity in the annular direction is greater in samples with $\varphi = \pm 65°$ than in those with $\varphi = \pm 45°$ (they have a large reserve of strength in regard to the critical circumferential tensile strain), their load-bearing capacity with respect to ξ is roughly the same when a bending mechanism of failure operates, while the ratio of the critical strains are inversely proportional to the rigidity.

A steel shell makes it possible to increase the resistance of a glass-plastic shell to the development of flexural oscillations and more fully to realize its reserve load-bearing capacity (comparison of the critical $\hat{\varepsilon}_y = 2.15\text{-}3.2\%$ for one-layer shells (Table 2) and $\varepsilon_y^* \approx 5\%$ for two-layer shells (Table 1)), which is consistent with the conclusions of [2]. The mechanism of loss of stability by the glass-plastic shell at chosen thickness ratios δ_1/δ, however, could not always be eliminated completely in a two-layer shell. This manifested itself most typically in type-1 samples with annular winding, for which $\varepsilon_y^* = 4.4\text{-}4.9\%$ (see Table 1). Already at $\xi \leqslant 15.55 \cdot 10^{-3}\text{-}25.5 \cdot 10^{-3}$, however, distinct meridional cracks formed in the material, as a result of bending failure [1, 3, 5, 8]. The elastic modulus is highest [$E_y \approx (4\text{-}5) \cdot 10^{10}$ Pa [3]) in the annular direction in samples of this type and so is the energy capacity. The resistance of the strained steel layer, therefore, was insufficient to damp the oscillations completely. According to [3], shells with an annular structure without a steel insert began to break during oscillations at $\xi \leqslant 16.5 \cdot 10^{-3}$ and $\hat{\varepsilon}_y \leqslant 1.9\%$; critical strains had not previously been obtained during expansion.

For a wound oriented glass-plastic composite with a combined spiral—annular reinforcement structure, the critical circumferential strain ε_y^* of dynamic tension thus does not depend (to within the error of measurement) on the angle of the spiral layers in the range studied, $\varphi = 35\text{-}65°$. Its value is $\varepsilon_y^* = 4.8 \pm 0.4\%$ and is determined by the breaking strain of the elementary fibers, which undergo the greatest tension in the annular layers under the given form of load. Just as for glass-plastic composites based on glass cloth [1], the critical strain can be a strength criterion for the material under dynamic load. This conclusion is valid for composites whose structure makes it possible to realize the ultimate strength of the load-bearing fibers under tension. If the structure and the form of the load allow critical shear or breaking stresses to exist before the tensile stresses in the fibers reach the breaking value, the strength and deformation characteristics of the load-bearing matrix are not utilized fully. For example, in [3] such an effect was observed for shells made by spiral winding with $\varphi = \pm 30°$ (without winding of annular layers).

Besides being the load-bearing element in glass-plastic composite [1], glass fiber also determines the critical dynamic elastic (deformation) characteristics of the composite, regardless of the angle of the reinforcement of the less loaded layers, but on the condition that there are layers with fibers oriented in the direction of the leading components of the tensile stresses. This does not rule out the possibility of a situation when, because of distinctive features of the dynamic reaction of a specific shell structure, the critical strain in the first phase of tension in that shell may be substantially below ε_y^* and may result in the specific strength of the shell, depending on the structure.

LITERATURE CITED

1. A. G. Ivanov and V. I. Tsypkin, "Strain and failure of glass-plastic composite shells under extreme pulsed loads," Mekh. Kompozit. Mater., No. 3 (1987).
2. V. I. Tsypkin, V. N. Rusak, A. G. Ivanov, et al., "Strain and failure of two-layered metal-plastic shells under an internal pulsed load," Mekh. Kompozit. Mater., No. 5 (1987).
3. M. A. Syrunin, A. G. Fedorenko, and A. T. Shitov, "Strength of cylindrical shells of glass-plastic composites with various structures under an explosive load," Fiz. Goreniya Vzryva, No. 4 (1989).
4. O. S. Vorontsova, M. A. Syrunin, A. G. Fedorenko, et al., "Experimental study of the variation coefficients of the strength characteristics of glass-plastic composite cylindrical shells under an internal pulsed load," Mekh. Kompozit. Mater., No. 4 (1987).
5. A. G. Fedorenko, V. I. Tsypkin, M. A. Syrunin, et al., "Behavior of composite shells with a highly elastic binder under an internal pulsed load," Mekh. Kompozit. Mater., No. 2 (1988).

6. A. G. Ivanov and V. N. Mineev, "On scale effects during failure," Fiz. Goreniya Vzryva, No. 5 (1979).
7. V. I. Al'perin, N. V. Korol'kov, A. V. Motavkin, et al., Structural Glass-Plastic Composites [in Russian], Khimiya, Moscow (1979).
8. A. G. Fedorenko, V. I. Tsypkin, and A. G. Ivanov, "Strain and failure of cylindrical glass-plastic composite shells of various scales under an internal pulsed load," Mekh. Kompozit. Mater., No. 4 (1986).

PHYSICOMECHANICAL NATURE OF THE EFFECT OF MATERIAL STRENGTHENING FOR WHISKERS AND THIN FILAMENTS

V. Z. Vasil'ev and S. Yu. Kaptelin

UDC 620.10

Numerous experiments by researchers at home and abroad have established the fact of a marked increase in the material strength of whiskers and thin filaments with a reduction in the characteristic size of them, i.e., the diameter or cross-sectional area. Existing hypotheses about the nature of this phenomenon are generally of a phenomenological character and they do not provide an explanation at the microlevel.

Concepts are advanced in this work which in the opinion of the authors make it possible to give a physicomechanical explanation of the strengthening effect.

1. The first researcher to establish reliably a connection between the material strength of a fine filament and its cross-sectional size was apparently Griffith [1]. Tests for breaking glass rods with diameters of 10-100 μm showed that the material strength of specimens achieved is significantly above the normal technical strength for a given material. Confirmation and further development of the results in [1] was obtained in tests on crystals of antimony, silicon, salt columns, and quartz filaments [2-5].

Subsequently experiments spread to metal whiskers and fine metal filaments. The results of tests by Herring and Holt with tin crystals are well-known. Experiments were carried out in [6-8] with copper and iron whiskers. For metals it was normally shown that with small test specimen diameters (about 1 μm) the material strength increases appraoching the theoretical strength. By theoretical strength σ_t we understand the limiting value of ultimate breaking resistance for material with an "ideal" structure.

A considerable amount of data has been accumulated recently in tests on crystals consisting of a structural base of various ceramics, and cemented and gypsum stones. These results are particularly reflected in [9-11].

By comparing and analyzing the numerous experimental results for different materials independent of the chemical nature and method of preparation it is possible to conclude that there is a clear connection between material strength and the cross-sectional size of a test whisker or a thin fiber.

2. Many researchers have attempted to explain the material strengthening effect described above for specimens of small size. In [1] an effect of a denser surface layer on the strength of thin filaments was suggested. However, subsequent tests [12] and particularly in [5] disproved this hypothesis. It was shown that even if some oriented layer on the surface of glass or quartz exists, its effect on the strength properties of specimens is hardly perceptible. Nonetheless, other concepts have been advanced in one form or another using the effect of a surface layer of a test specimen on material strength. For example, Ienckel-Münster [13] considered that forces of surface tension fulfill a specific strengthening role. He suggested an equation for describing the relationship between breaking, perimeter, and specimen cross section:

$$\sigma_f = a + bK/F.$$

Here σ_f is material ultimate breaking strength; K, F are specimen perimeter and cross-sectional area; a, b are constants determined from an experiment.

St. Petersburg. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, No. 4, pp. 135-141, July-August, 1992. Original article submitted June 20, 1990; revision submitted May 8, 1991.

 0021-8944/92/3304-0598$12.50