Journal of Applied Mechanics and Technical Physics, Vol. 36, No. 3, 1995

DYNAMIC STRENGTH IN ORIENTED FIBER GLASS COMPOSITE SHELLS

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UDC 624.074.4:678

Differences in chemical compositions and mechanical properties of fibers and different schemes of layer reinforcement of composite shells pose the problem of their optimal choice to ensure high specific strength under dynamic loading (such as for protective constructions of a single action) [1–3].

The purpose of this paper is to study the dynamic response and the carrying capacity under the internal explosive loading of oriented fiberglass shells reinforced with roving strips based on VM-1, VMP, R and X fibers by the same scheme [VM-1, VMP are widely used fibers, R, and X are experimental fibers of special composition (developments by VNIISPV in Kryukov, Moscow region)]. Here, similar results obtained for Plexiglas shells based on SVM fibers are presented for comparison.

For comparing the calculated estimates of the resistance of the tested fibers to pulse action, the criterion $\hat{v} = c\hat{\varepsilon}$ suggested in [1] was used instead of the specific strength σ_p/ρ, where $\hat{v}$ is the limiting expansion rate of an annular element, c is the sound velocity in the fiber, and $\hat{\varepsilon}$ is the limiting stress strain. Previously the criterion was checked by comparing different load-carrying fibers in axisymmetric constructions made of composite materials, and for the explosive action the following proportion was established: $\hat{v} \sim \hat{\xi}$ ($\hat{\xi} = m/M$ is the ratio of the charge mass m of the explosive causing the initial stage of fracture on explosion to the shell mass M with internal radius R and length $4R$) [1, 4].

Some comparable data on mechanical properties, specific strength, and calculated values of $\hat{v}$ for the above fibers are listed in Table 1. In terms of the parameter $\hat{v}$, the VMP and VM-1 glass fibers R and X are slightly worse by factors of 1.3 and 1.4, respectively. Plexiglas fiber surpasses glass fibers in specific strength by a factor of more than 1.4.

The test objects were cylindrical shells fabricated by combined winding of strips impregnated with an epoxy binder with the intercalation of double spiral layers ($\varphi = \pm 45°$) and circumferential ones ($\varphi = 90°$) with a thickness ratio 1 : 1. The shells used in the experiments were composed of fiberglass and Plexiglas materials with internal radius $R = 150$ mm, length $4R$, and relative wall thickness $\delta/R = 4.18$–6% (fiberglass shells based on X fibers had $\delta/R = 2.45$–2.7 and Plexiglas shells had $\delta/R = 8.2$–8.6%). Fiberglass and Plexiglas shells were reinforced with roving strips and fiber bundles, respectively:

Type 1: VM-1 fiberglass, roving RVMN 10-1260-80 TU 6-11-370-75;
Type 2: VMP fiberglass, roving RVMPN 10-1200-78 (a pilot batch);
Type 3: R fiberglass, roving PPH 10-1400-78 (a pilot batch);
Type 4: X fiberglass, roving PXH 9-925-78 (a pilot batch);
Type 5: SVM Plexiglas (fiber), SVM fiber bundle 3-300-58,8 × 17-1000 TU 6-06-112-84.

An epoxy binder (brand EDT-10, SST 3-4750-80) was used for all types of specimens.

Dynamic loading of a shell open from the end faces was made by explosion at the geometric center of a spherical explosive charge of mass m made of trotyl-hexogen alloy (TH 50/50) [1–4]. The quantity $\xi = m/M$ was taken as the provisional characteristic of the specific explosive load on the shell, hence for fiberglass $\varepsilon_y \sim \xi$ [1–3, 6]. The methods of high-speed photorecording and strain measurement were used in experiments wherein the maximal annular shell strain ε_y, the frequency of the fundamental radial vibrations f, and the maximum velocity of the radial displacement V_m, which permits evaluation of the maximum strain velocity

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Research Institute of Experimental Physics, Arzamas-16 607200. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 36, No. 3, pp. 141–145, May–June, 1995. Original article submitted January 12, 1994; revision submitted May 19, 1994.

TABLE 1

Characteristics	Brand of fiber				
	VM-1	VMP	R	X	SVM
ρ, kg/m^3	2580	2490	3060	3900	1450
Fiber diameter, μm	10	10	10.8	9.3	30
σ_p, MPa	4200	4400	3780	3880	3700
Young's modules $E_{\text{в}}$, GPa	95	94.75	99.3	100.9	125
$\hat{\varepsilon}$, %	4.4 (4.8)*	4.6 (5.4)*	3.8	3.85	2.96
c, m/sec	6070	6170	5696	5087	9285
$\hat{v}$, m/sec	267	284	216	196	275
$(\sigma_p/\rho)\cdot 10^{-6}$, N·m/kg	1.63	1.77	1.24	0.99	2.55

Note: 1) The ultimate tensile strain of fibers is obtained from the ratio $\hat{\varepsilon} = \sigma_p/E_{\text{в}}$; 2) * Values are taken from [5].

TABLE 2

Type of specimen	δ/R, %	ρ, kg/m^3	m, g	$\xi\cdot 10^{-3}$	V_m, m/sec	$\dot{\varepsilon}$, 1/sec	ε_y, %	f, kHz	State of shell
1	5.95	1953	169	16.9	72	453	2.75	4.2	Unfractured
	4.8	2120	169	19.3	80	509	3.1	4.25	» »
	6.5	1925	209	20.0	76	475	3.3	4.25	Fractured
	6.7	1940	303	28.6	110	686	4.7	—	»
2	5.0	2000	136	15.8	73.5	468	2.7	4.35	Unfractured
	5.8	1990	173	18.5	75	474	3.3	4.3	» »
	5.8	1990	204.5	22.0	84	530	3.6	—	Fractured
	5.0	2000	206	24.0	85	541	3.7	4.65	»
3	4.7	2350	136	14.5	62	395	2.4	4.35	Unfractured
	5.0	2347	169.5	17.6	74	469	3.1	—	Fractured
4	2.45	2950	64.7	10.9	47.5	309	1.8	3.95	Unfractured
	2.52	2936	83.8	13.95	62	463	2.45	4.1	Fractured
	2.73	2925	211.7	34.7	105	681	3.1	—	»
5	8.26	1350	135	14.8	64	393	1.8	5.0	Unfractured
	8.22	1305	170	18.6	68	417	2.4	5.25	» »
	8.6	1300	206	20.7	80	556	2.6	—	Fractured
	8.2	1350	206	22.6	118	725	2.5	—	»

$\dot{\varepsilon} = V_m/R$, were determined by measurements. The error in determining the mentioned quantities did not exceed 10%.

Two sets of experiments were performed. They enabled us to test: a) free cylindrical shells of all types; b) free cylindrical fiberglass shells into which steel shells (steel 20) were fitted with a gap not greater than 0.2 mm, which had internal diameter $2R_1 = 295$ mm, relative thickness $\delta_1/R_1 = 1.35\%$, and length $4R$, with shell thickness ratio $\delta_1/\delta = 0.2$–0.3. The most representative results of the first set of experiments are presented in Table 2.

Analysis of these results reveal that:

1. The VM-1 and VMP fiberglass shells have the highest specific carrying capacity and those based on R and X fibers rank below in that indicator by 25 and 45%, respectively. Shells based on SVM Plexiglas have specific carrying capacity that closely matches that based on high-strength fiberglass. A similar strength distribution has been expected using the calculated criterion $\hat{v}$ determined by physicomechanical parameters of fibers.

TABLE 3

Type of specimen	Brand of fiber	ρ, kg/m^3	$\nu_в$	$E_x \cdot 10^{-10}$	$E_y \cdot 10^{-10}$	μ_{xy}	μ_{yx}	f'	f
				Pa				kHz	
1	VM-1	1995	0.57	1.63	3.48	0.196	0.418	4.3	4.23
2	VMP	1995	0.57	1.71	3.72	0.195	0.425	4.47	4.43
3	R	2350	0.61	1.93	4.18	0.193	0.418	4.36	4.35
4	X	2935	0.64	2.08	4.44	0.192	0.412	4.08	4.0
5	SVM	1350	0.545	2.19	4.39	0.197	0.395	5.65	5.15

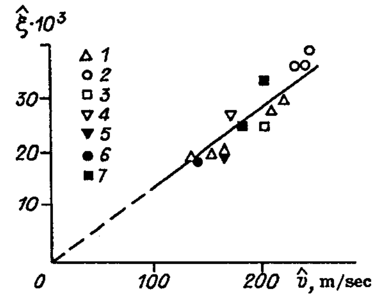

Fig. 1. The dependence $\hat{\xi}(\hat{v})$. Fiberglass shells: 1) data of the present work (see Table 1); 2) VMP, $\varphi = 90°$, $\varphi = \pm 60$ and 90° complies with ratio of thicknesses 1 : 1, $\varphi = \pm 60$ and 90° — 1 : 2 [2]; 3) VM-1, $\varphi = \pm 45$ and 90° — 2 : 1 [7]; 4) fiberglass fabric TS - 8/3 - T [6]; two-layer (fiberglass–steel) shells: 5) fiberglass fabric TS - 8/3 - T [12]; 6) VM-1, $\varphi = \pm 35$ and 90° — 2:1 [16]; 7) VM-1, $\varphi = 90°$, $\varphi = \pm 45$ and 90° — 1:1 [17]

2. The mechanism of failure in VM, VMP, R, and X fiberglass shells behaving plastically until fracture is similar to that found previously [7] and caused by the loss of dynamic stability of the axisymmetric radial vibrations in the central zone of a shell with maximum strain of the first expansion $\hat{\varepsilon}_y \approx 3.1$–$3.3\%$. In this case the maximum strain is less than the limiting value for the material used in [8]. This effect is most distinct for shells made of X fibers and possessing halved relative thickness, which qualitatively corresponds to data in [9]. This failure machanism in Plexiglas shells is not observed owing to the sharp increase of the internal friction in the material under deformation, close to failure strains $\hat{\varepsilon}_y \approx 2.5$–$2.6\%$ (similarly to [1, 10, 11]).

3. The elastic properties of all types of materials differ by no more than 30%, as shown in Table 3. Based on initial data on the physicomechanical characteristics of fibers (Table 1) with Poisson coefficient $\mu_в = 0.2$, the epoxy resin ($E_m = 3 \cdot 10^9$ Pa, $\mu_m = 0.4$, $\rho_m = 1230$ kg/m^3 [12]) and on the winding structure (three zones with the angles +45, −45 и 90° and the relative thickness 0.25, 0.25 and 0.5) by the method in [2], Table 3 gives the elastic constants of shell materials E_y, E_x, μ_{xy}, μ_{yx} calculated from their true densities ρ, the estimate of the fiber content $\nu_в$, and the calculated frequencies f' of the fundamental mode of the radial vibrations, which correspond to the experiment within the limits of experimental error of less than 5%. Consequently, the stability of the elastic constants is confirmed for the tested materials over the studied covered range of strain rates ($\dot{\varepsilon}_y \leqslant 700$ 1/sec).

4. It has been confirmed that a steel shell enables one to increase the specific strength $\hat{\xi}$ (a two-layer shell relative to a single-layer glass-plastic one) and to use more fully the deformability reserves and the strength of a composite [1]. In the experiments with well-known fracture the following limiting strains of shell

radial expansion on failure in the first motion phase are obtained: $\hat{\varepsilon}_y = 3.3\%$ (X fibers), $\hat{\varepsilon}_y = 3.7\%$ (R fibers), $\hat{\varepsilon}_y = 4.55$–$4.8\%$ (VMP fibers), $\hat{\varepsilon}_y = 4.7$–$5.2\%$ (VM-1 fibers; the result agrees with [8, 10, 11]). Notice that a similar value of $\hat{\varepsilon}_y$ for VM-1 fibers is obtained in [14] at a rate $\dot{\varepsilon}_y \sim 10^5$ 1/sec peculiar to a spalling loading. For shells based on Plexiglas fibers $\hat{\varepsilon}_y = 2.5$–$2.6\%$, which is slightly below that in [1] (as well as in [4, 10, 15]).

The magnitudes of $\hat{\varepsilon}_y$ obtained for all materials are close to the limiting strains in fibers upon static stretching (Table 1).

5. If the criterion $\hat{v} = c_y\hat{\varepsilon}_y$* is calculated for a material rather than a fiber, the relation $\hat{\xi} \sim \hat{v}$ may be confirmed experimentally [1, 4] when the shell failure is attained by fracturing the material in the first expansion phase (see Fig. 1, which shows similar estimates of the criterion $\hat{v}$ and the magnitudes of $\hat{\xi}$ corresponding to $\hat{\varepsilon}_y$ for a variety of composite shells tested previously [2, 6, 7, 12, 16, 17], involving two-layer shells). All the experimental data are seen to fall virtually on a dependence close to the linear one.

Therefore, with knowledge of the limiting strain $\hat{\varepsilon}_y$ and the the criterion $\hat{v}$ of the material (also determined by the strain), one can evaluate (using the curve in the figure, with an error less than 10–15%) the limiting carrying capacity $\hat{\xi}$ of cylindrical shells that fail in the first expansion phase on explosive loading. In this case, the central-symmetric explosion occurs in air and the carrying capacity is determined independently of the composite type and its reinforcement scheme (involving a two-layer shell composed of plastic and elastic materials in the inner and outer layers, respectively).

Thus, the limiting strain of the load-carrying element of composite-fibers in dynamic stretching, together with the elasto-mass characteristics of the composite, can serve as a governing criterion for the specific strength of shell constructions under pulse loading.

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*For a shell, $c_y \approx \sqrt{E_y/\rho(1-\mu_{xy}\mu_{yx})}$; for a two-layer steel fiberflass shell, c_y is estimated according to [11]; the quantity $\hat{\varepsilon}_y$ is determined in the dynamic (explosive) experiment.

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