Journal of Applied Mechanics and Technical Physics, Vol. 42, No. 1, pp. 169–173, 2001

DAMPING CHARACTERISTICS OF COMPOSITE STRUCTURAL MATERIALS FABRICATED BY WINDING

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UDC 624.074.4+539.3

Experiments on explosive (impulsive) loading of composite rings fabricated by winding are performed. Special loading conditions were used to excite simultaneous axisymmetric and flexural vibrations. Averaged damping characteristics of axisymmetric motion and the eigenfrequencies of axisymmetric and flexural vibrations of glass-reinforced, acrylic, and carbon-filled plastic rings were obtained from experimental results.

In contrast to metals and their alloys, composite materials possess better dissipation properties and their logarithmic decrement is one order of magnitude higher than that of metals. Existing experimental data on the damping characteristics and logarithmic decrement of composite materials [1–3] differ markedly. This is due to the fact that dissipation properties were determined by different methods for materials with different moduli of elasticity, arrangement of reinforcing fibers, volume content of the fibers, etc. In the present paper, we give experimental results on impulsive loading of glass-reinforced, acrylic, and carbon-filled plastic rings fabricated by winding fibers at nearly zero angle of reinforcement. The reinforcing fibers were VM fiberglass, SVM acrylic fiber, and carbon fabric with orthogonal weave.

In the first phase of the experiments, the rings were subjected to static tests on a tearing machine using two rigid half-disks [4]. Table 1 gives averaged results of static tests (10 specimens of each type were tested). The tested rings had inner diameter of $D = 100$ mm, cross-sectional height of 18–20 mm, and thickness of $h = 1$–2 mm. In Table 1, the following notation are used: E and ρ are the modulus of elasticity and density of the material, respectively, and $\sigma_{\max}$ and $\varepsilon_{\max}$ are the limiting stresses and strains, respectively.

The most frequently used method for measuring the viscoelastic and vibration-absorbing properties of materials is the method of free damping vibrations [1, 3], which uses, as a rule, vibrations of freely suspended or cantilevered bars. In this case, measurement results can be strongly affected by the end-fixity conditions. Manufacture of long specimens of a unidirectional composite for determining damping characteristics from damping vibrations of a cantilevered or suspended specimen involves certain technological difficulties. In the present paper, we determine the damping properties of free axisymmetric and flexural vibrations of ring specimens loaded from the inside by explosion of a high-explosive (HE) charge. This makes it possible to produce both a uniaxial uniform state and a nonuniform stress-strain state. The first of these cannot be produced in planar specimens because of the wave character of load propagation.

Figure 1 shows the experimental setup, which is almost identical to that used in [5]. Ring specimens were placed between flanges. The distance between the flanges exceeded the height of the specimen by 0.1–0.2 mm. A metallic assembly with a specimen was placed into an explosion chamber with a volume of 2 m^3. Vacuum was not produced in the chamber. Loading was performed by explosion products of a cord

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Lavrent'ev Institute of Hydrodynamics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 42, No. 1, pp. 190–195, January–February, 2001. Original article submitted February 8, 2000; revision submitted May 10, 2000.

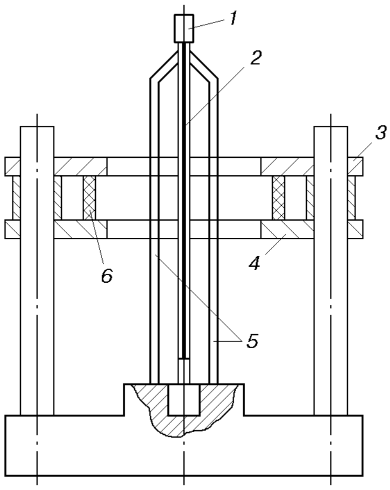

Fig. 1. Diagram of loading of a ring specimen: electric detonator (1), cord charge (2), flanges (3 and 4), detonating cords (5), and ring specimen (6).

TABLE 1

Composite material	E, GPa	$\sigma_{\max}$, GPa	$\varepsilon_{\max}$, %	ρ, g/cm^3
Glass-reinforced plastic	63.765 ± 2.256	1.511 ± 0.108	2.40 ± 0.20	2.03 ± 0.05
Acrylic plastic	113.698 ± 10.791	1.972 ± 0.098	1.74 ± 0.16	1.03 ± 0.03
Carbon-filled plastic	108.695 ± 9.320	0.765 ± 0.118	0.70 ± 0.08	1.43 ± 0.03

HE charge which was placed on the longitudinal axis of the specimen. The charge was a segment of a bare detonating cord of plasticized RDX 200 mm long and 2–4 mm in diameter. The cord segment was inserted in a rigid paper tube, which was aligned with the axis of the ring. Simultaneous axisymmetric and flexural vibrations were excited by simultaneous firing of two or three detonating cords. The firing was performed by a low-voltage small-size electric detonator using an intermediate charge of slightly pressed RDX with a mass of 0.4–0.5 g. The circumferential strain was measured by a Nichrome ring strain gauge similar to that used in static tests.

During loading, the specimen performs free damping vibrations, whose experimental frequency $f_{\rm exp}$ is determined. Figure 2 shows typical oscillograms of free damping vibrations of rings from two materials. The theoretical frequency of these vibrations $f_{\rm theor}$ is given by

$$f_{\rm theor} = \frac{1}{2\pi R}\sqrt{\frac{E}{\rho}}, \tag{1}$$

where R is the average radius of the ring.

The damping properties of a material are usually characterized by the logarithmic decrement, which is easily determined from vibration records of free vibrations. If the logarithmic decrement δ does not depend on the amplitude, it can be written in the form [3]

$$\delta = \frac{1}{k}\ln\frac{a_i}{a_{i+k}},$$

where a_i and a_{i+k} are, respectively, the vibration amplitudes at the beginning and end of an interval consisting of k cycles.

Among the factors that have a significant influence on the logarithmic decrement in the technique proposed are the friction of the edge of the ring against the flange (the mass of the specimens varied in the range 15–30 g) and the resistance of the ambient medium and explosion products. In the present study, these factors were ignored. The effect of the explosion products on the vibrations can be ignored because of the

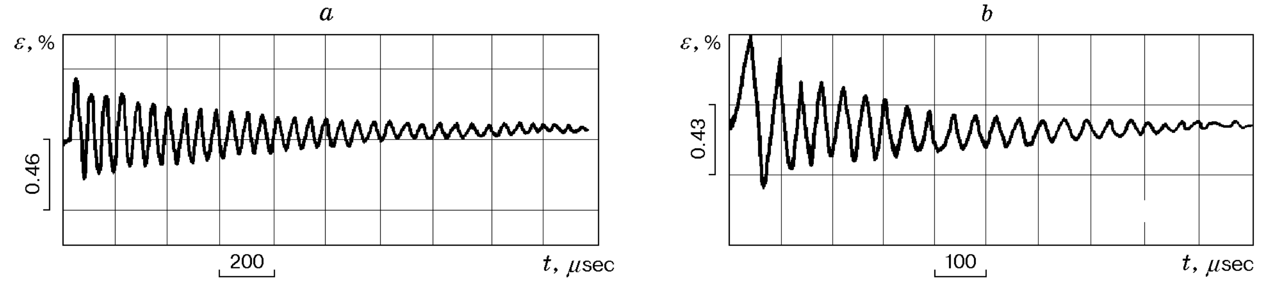

Fig. 2. Oscillograms of free damping vibrations of glass-reinforced plastic (a) and carbon-filled plastic (b) rings.

TABLE 2

Composite material	δ				δ_m
	$k = 5$	$k = 10$	$k = 15$	$k = 20$	
Glass-reinforced plastic	0.143	0.124	0.132	0.130	0.132
Acrylic plastic	0.185	0.158	0.147	0.140	0.153
Carbon-filled plastic	0.203	0.181	0.157	—	0.180

small weight of the HE specimen. In view of the presence of air in the explosion chamber, averaged damping characteristics are upper bounds of the damping characteristics of the material in vacuum.

The dependence of the logarithmic decrement δ on the vibration amplitude was checked by oscillograms, two of which are shown in Fig. 2. Table 2 lists values of the logarithmic decrement δ versus the number of periods of vibration k. The beginning of the intervals over which averaging was performed coincided with the beginning of ring vibrations.

An analysis of the data obtained shows that the logarithmic decrement depends on the interval on which it is calculated: as the interval increases, the logarithmic decrement decreases. However, one can speak of a certain average value of the logarithmic decrement δ_m and an error of this value within 10–30%.

The logarithmic decrement depends on the acting stress level. To study this dependence, we varied the thickness of the rings and the thickness of the detonating cord. The theoretical frequency $f_{\rm theor}$ was calculated by formula (1) using the moduli of elasticity obtained in the static and the experimental frequency $f_{\rm exp}$ was determined from oscillograms. Table 3 gives averaged logarithmic decrements for three types of composite rings and different levels of loading. For glass-reinforced and acrylic plastic rings, the averaged values were calculated from 20 periods of vibrations, and for carbon-filled rings, the values were averaged over 15 periods ($\varepsilon_{\max}$ is the maximum strain in the first cycle of vibrations of the ring and $\sigma_{\max} = E\varepsilon_{\max}$ is the maximum stress).

The logarithmic decrement δ versus the load intensity is shown in Fig. 3.

The experimental results lead to the following conclusions: 1) the logarithmic decrement for composites depends strongly on the load intensity (increases with load rise); 2) the experimental vibration frequencies of the rings are smaller than the theoretical values (on the average by 4, 9, and 16% for glass-reinforced plastic, carbon-filled plastic, and acrylic plastic, respectively). This may be attributed to the neglect of the added mass, the resistance of the ambient medium, and the dry friction of the specimen against the flange (all experimental frequencies are smaller than theoretical values).

Besides axisymmetric vibrations of the rings, we studied flexural modes and frequencies. The frequencies of flexural vibrations f_{nt} are given by the approximate formula [6, pp. 349–350]

$$f_{nt} = \frac{1}{2\pi}\,\frac{1}{R}\sqrt{\frac{E}{\rho}}\,\frac{h}{R}\,\frac{n(n^2-1)}{\sqrt{12}\sqrt{n^2+1}} \qquad (n = 2, 3, \ldots). \tag{2}$$

It is noteworthy that expression (2) contains the geometric parameter h/R and the mode number n. For sufficiently thin rings, relation (2) coincides with the frequency relations of [7] with accuracy up to terms of higher-order smallness.

TABLE 3

Specimen No.	f_{theor}, Hz	f_{exp}, Hz	δ	$\varepsilon_{\max}$, %	$\sigma_{\max}$, MPa
Glass-reinforced plastic					
1	17,458	15,535	0.055	0.29	182.466
2	17,496	16,686	0.061	0.36	229.554
3	17,496	17,574	0.117	0.40	255.060
4	17,496	16,914	0.102	0.39	280.566
5	17,496	17,610	0.116	0.45	287.433
6	17,496	16,925	0.110	0.52	331.578
7	17,496	16,458	0.198	0.64	417.906
8	17,496	16,241	0.162	0.69	433.602
Acrylic plastic					
1	28,920	21,764	0.123	0.31	353.160
2	28,920	21,893	0.086	0.33	375.723
3	28,821	22,152	0.168	0.38	432.621
4	29,361	26,871	0.160	0.44	500.310
5	29,347	24,045	0.160	0.55	625.878
6	29,361	26,365	0.233	0.68	774.009
Carbon-filled plastic					
1	—	—	0.093	0.24	258.984
2	26,824	23,213	0.111	0.41	437.526
3	26,824	23,217	0.150	0.56	474.804
4	26,824	23,491	0.170	0.65	706.320
5	26,990	23,381	0.265	0.72	774.990
6	26,824	24,822	0.210	0.82	863.280
7	27,000	24,242	0.330	0.84	906.444

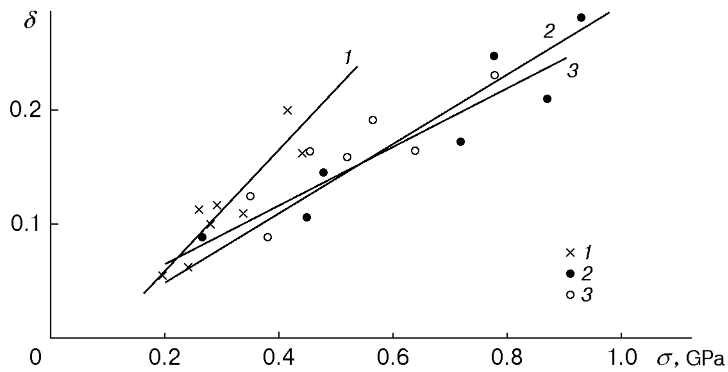

Fig. 3. Logarithmic decrement versus load for glass-reinforced plastic (1), carbon-filled plastic (2), and acrylic plastic (3).

In the experiments, simultaneous axisymmetric and flexural vibrations were excited by firing two or three detonating cords (see Fig. 1) which were equally spaced and symmetric about the center of the ring. The flexural vibrations were recorded by two foil gauges located on the ring opposite to the detonating cords. For averaging of the flexural strains, the strain gauges were connected in series.

Figure 4 shows oscillograms of ring vibrations. Oscillograms 1 refers to axisymmetric vibrations and oscillograms 2 to flexural vibrations. From these oscillograms, one can approximately determine the frequencies of the flexural vibrations and establish that the axisymmetric motion of the ring is superimposed on the flexural motion; the frequency of the axisymmetric vibrations f_{exp} differs markedly from the frequencies of the flexural modes $f_{2,\text{exp}}$ $(n = 2)$ and $f_{3,\text{exp}}$ $(n = 3)$, whereas the higher frequencies of the corresponding harmonics of flexural vibrations coincide with those of axisymmetric vibrations.

Experimental values of flexural vibration frequencies agree well with calculations using formula (2) for two types of composite rings. For a glass-reinforced ring ($d = 100.65$ mm and $D = 109.70$ mm), the flexural

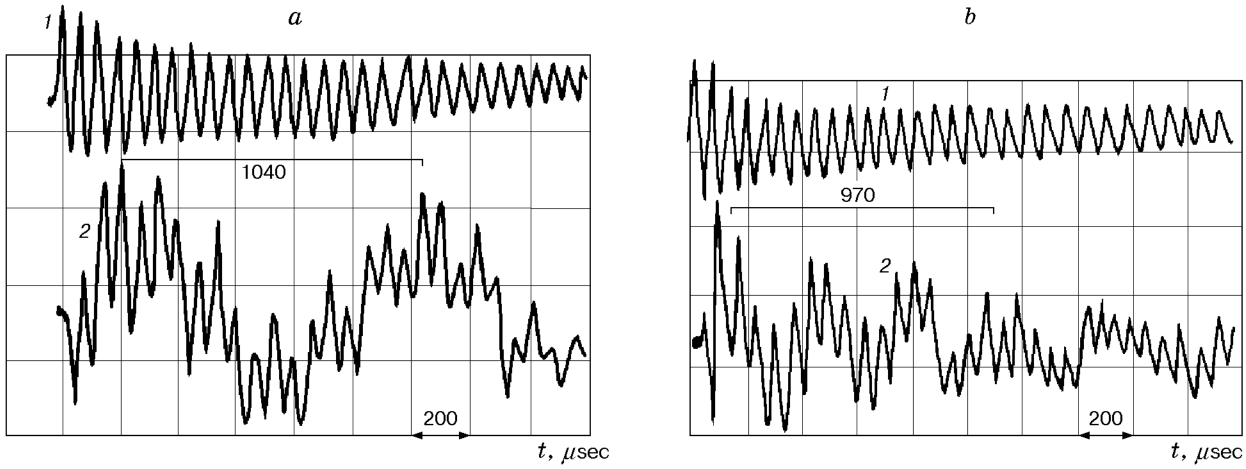

Fig. 4. Oscillograms of axisymmetric (1) and flexural (2) vibrations of glass-reinforced plastic rings for $n = 2$ (a) and 3 (b).

frequency calculated by formula (2) for $n = 2$ is $f_{2,\text{theor}} = 1046$, and the experimental value of this frequency determined for the first period is $f_{2,\text{exp}} \approx 1000$ (Fig. 4). For the same ring, the flexural frequency calculated by formula (2) for $n = 3$ is $f_{3,\text{theor}} = 3390$, and the experimental frequency determined for the first three periods of vibrations is $f_{3,\text{exp}} \approx 3100$ (Fig. 4).

An analysis of the axisymmetric and flexural vibrations (Fig. 4) shows that: 1) for thin-walled rings ($h/R \ll 1$), the frequencies of axisymmetric and flexural vibrations differ by an order of magnitude; 2) the logarithmic decrement of flexural vibrations is much larger than that of axisymmetric vibrations.

The experiments performed show that damping and frequency characteristics can readily be determined for different vibration modes by loading ring specimens from the inside by a HE charge. The damping characteristics depend on the load intensity: the logarithmic decrement increases with load rise.

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