THEORETICAL AND EXPERIMENTAL INVESTIGATION OF DYNAMICAL DEFORMATION AND FRACTURE OF FIBER-REINFORCED COMPOSITES

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ABSTRACT

This paper presents the experimental results and theoretical investigations of dynamical deformation and fracture of epoxy-based composite cylinders reinforced by glass-fiber or organic-filament materials subjected to pulse loading. The latter is induced by an explosion of a spherical explosive charge in the geometrical center of the shell. The cicumferential deformation of a central and distal sections were measured in the experiments by strain sensors pasted onto the outer surface. The specimen wall thickness and explosive weight were varied.

KEYWORDS

Composites, dynamical deformation, explosive loading, ultimate strain, fracture, elastic properties.

EXPERIMENTAL RESULTS AND THEORETICAL ANALYSIS

In a number of papers (for example, Chamis and Smith, 1984; Daniel et. al., 1981) the dependence of elastic and strength properties of some types of composites on characteristic strain rate at the values $\dot{\varepsilon}\approx10^2$ sec^{-1} is pointed out. In this connection the development of experimental techniques, analogous to those reported in works of Ivanov and Tsypkin, 1987; Al-Salehi et al., 1989; Al-Salehi et al., 1990; Stepanenko et al., 1992 for behavior study of fiber-reinforced composites at the limit of their carrying capacity is of interest.

The experiments on internal pulse loading were performed at circular cylindrical shells, produced by ring winding of two types of fibers: glass-fiber and organoplastic (aramid) fiber, impregnated by epoxy compound.

The results of static tests of circular specimens of examined materials by means of NOL-methods (using hard semidiscs) has shown that the elasticity modulus and ultimate strength in circumferential direction are $E_{gl} = 65.0 \pm 5$ GPa and $\sigma_{gl} = 1.54$ GPa for glass fiber composite, $E_{ar} = 116.0 \pm 5$ GPa and $\sigma_{ar} = 2.01$ GPa for organic fiber composite. The density of materials is: of glass-fiber composite - 2.03 g/cm^3, organic-fiber composite - 1.32 g/cm^3.

The diagram of experimental assembly is presented in fig. 1. Pulse loading was induced by an explosion at the geometric center of the tube specimen of spherical high explosive (HE) charge made of the alloy of TNT and RDX in proportion 50/50. HE charge was initiated in its center by means of small-size electric blasting cap . The charge with detonator was fixed at paper tube which was inserted into centering sleeve, welded together with four studs to the base.

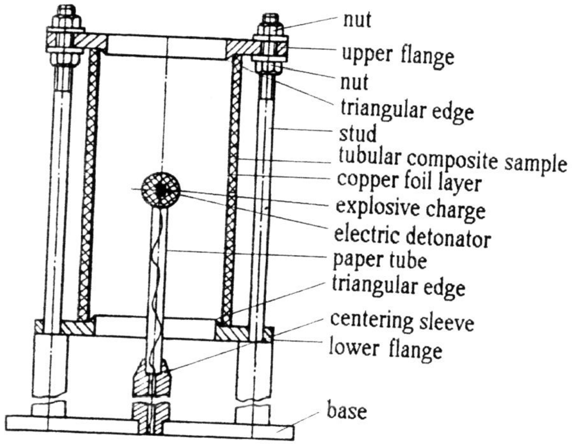


Fig. 1.

Tube specimens with internal diameter 100 mm were tested. The specimen length was chosen so that free edges in registering the deformation process have no effect on the character of strain stressed state in the central part of the specimen. The thickness of the specimen walls ranged from 1.7 mm to 5 mm. Fixing of the upper flange was accomplished by the nuts and for the specimen to freely expand in radial direction and in the same time to avoid the possibility of its displacement as a hard whole. Centering of the specimen was provided by special 3 mm high triangular projections on the flanges. The shells were pasted inside by annealed copper foil 0.1 mm thick in one or several layers.

During the experiments circumferential deformation was registered in central cross-section and in a cross-section remote from the central one of the specimen. Deformation process was registered by resistance strain gauges, analogous to those described in works of Dewhurst et al., 1974 and Shitov et al., 1976, pasted onto the outside surface. All the specimens were loaded only once. Characteristic test results are presented in Fig. 2-4. Fig. 2 presents the dependencies of the size of fracture zone l (mm) of the specimen on the HE charge weight (g) with the thickness of the specimen walls: a) 2.5 mm; b) 5 mm (glass fiber composite - o, organoplastic - •). Fig. 3 presents the exterior view of the specimens with wall thickness 5 mm after the tests - glass fiber composite (left) and organoplastic (right) with the HE charge weight: a) 20 g; b) 40 g. Fig. 4 presents the typical experimental dependencies $\varepsilon = \varepsilon(t)$ (for the specimens with wall thickness 5 mm) organoplastic specimens: curve 1 - specimen No. 8; curve 6 - specimen No. 5; and specimens of glass plastic: curve 2 - specimen No. 5; curve 3 - specimen No. 6. Curves 4 and 5 corresponds to the vibration processes of glass-fiber and organoplastic specimens, which had no damage after loading.

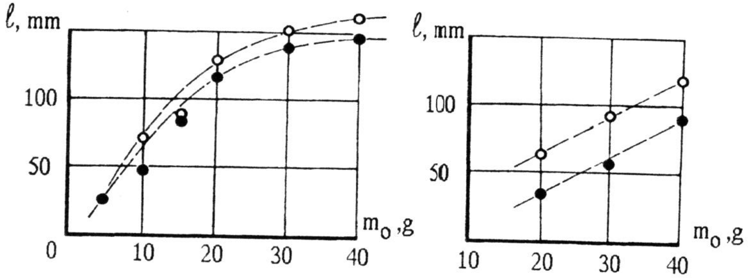
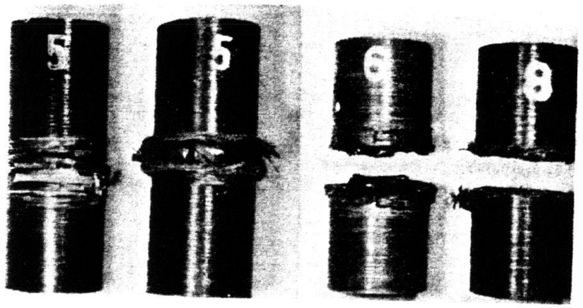


Fig. 2.



(a) (b)

Fig. 3.

In the series of experiments on the specimens with wall 5 mm thick, when the mass of HE charge increases in the specimens from 10 g to 40 g the fracture of glass fiber specimens occurs at smaller masses of HE charges due to dynamic loss of stability of radial axisymmetric vibrations and steep rise of bending forms which is mentioned in works of Ivanov and Tsypkin, 1987; Stepanenko et al., 1992, and at heavier HE charges - as a result of achieving the ultimate tensile strength in glass fiber. The stability loss of axisymmetric form of motion is registered in the oscillograms - curves 2, 5 in Fig. 4, and on residual deformation of copper foil. In none of the experiments of the analogous series at the specimens of different thickness of organoplastic the effects were found which evidence the loss of stability of axisymmetric form of motions of the specimen. The fracture of the specimens occurred in the first phase of motion of the specimen walls from the center (Fig. 4,); and the fracture zone was circular. If in this phase the specimen preserved carrying capacity, then it made quick damping oscillations, whose half-period dropped with a semirange of oscillations (curve 4, Fig. 4).

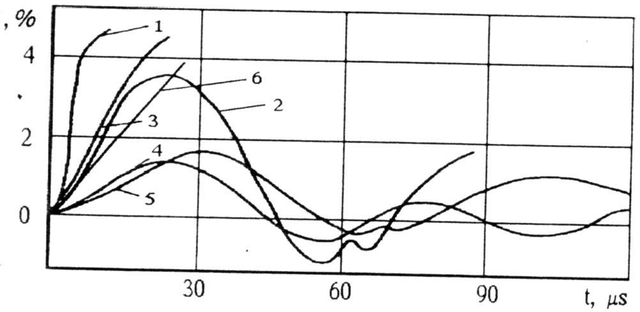


Fig. 4.

Radial oscillations damp considerably quicker in the shell of organoplastic. However, it will be wrong to explain this effect by cracking of adhesive at the beginning of oscillations, as the same cracking takes place in the shells of glass fiber composite, but it does not result in such a rapid damping. The difference of dissipative properties of a power filling is probably manifested here, as well as the fact that the Poisson's ratio $\nu_{\alpha\beta}$ (α - meridian coordinate, β - circumferential coordinate) in unidirectional organoplastic is half as much as the corresponding value for unidirectional glass plastic. The value $\nu_{\alpha\beta}$ is a characteristic of interrelation of radial and axial motions in cylinder shell. The higher $\nu_{\alpha\beta}$, the greater portion of energy of radial oscillations transfers to axial motion and "flows out" from the most heavily loaded part of the

specimen. This together with dissipative properties of glass fiber composites results in considerably more rapid damping of oscillations of the central cross-section of organoplastic specimens.

As it was noted above, calculation of the numerical values characterizing dynamic values of the elasticity modulus and ultimate strength of examined material is connected with registration of the pressure acting on the specimen as a function of time. However, when dynamic stressed state in a specimen is formed by intense short-time (pulse) loading, the values of elastic and strength characteristics of the specimen material may be estimated using approximate equations of motion and energy balance.

After cessation of pressure action until the first deformation maximum is achieved, radial motion of specimen walls is approximately described as follows (Stepanenko et al., 1992):

$$Eh_{gl}\varepsilon(t) + (h_{gl}\rho_{gl} + h_{cu}\rho_{cu})R^2\ddot{\varepsilon}(t) = 0 \qquad (1)$$

where h_{gl}, ρ_{gl} and h_{cu}, ρ_{cu} - the thickness and density of glass fiber composite and copper, respectively, R - the interior specimen radius. Then, choosing at rising interval of oscillogram $\varepsilon=\varepsilon(t)$ smooth section, point t is fixed, corresponding to the middle of this section. The second variable $\ddot{\varepsilon}(t)$ is approximately changed by the ratio $\ddot{\varepsilon}(t)=[\varepsilon(t-\tau)-2\varepsilon(t)+\varepsilon(t+\tau)]/\tau^2$, and by substitution in the equation of motion the value E is calculated. The above calculations were carried out with the oscillograms of five experiments in which the values of h_{gl}, h_{cu} and HE charge weight were different. Besides, in calculations for each experiment the value τ varied. As a result the average value E_{dyn} with spread in values up to 20% was obtained for 5% less than the statistic modulus of elasticity. This result as well as the conclusions of the works Ivanov and Tsypkin, 1987; Aseyev et al., 1992, indicate that the elasticity modulus of glass fiber does not depend on the strain rate.

To estimate the dynamic ultimate strength of glass fiber composites and organoplastic let us use the approximate equation. Detonation products (DP) of spherical HE charge are initiated in the geometry center of tube specimen. They create in the shell axisymmetric stress-strained state which is variable along its longitudinal axis. In a time interval commensurable with the period of natural modes of the ring, the process of transfer of elastic energy along this axis due to the specific properties of fiber composites has weak influence on stress strained state, which is proportional to the dependence of the value of pressure pulse on axial coordinate. The ring shell element acquires a pulse (quantity of motion) approximately equal to the power pulse, acting on the shell element a result of DP pressure. Kinetic energy of ring shell element, acquired due to the work of DP in the element undestructed under tension component, practically completely transfers into potential energy of deformation. Thus, at the boundary of the zone of specimen fracture, when destruction occurred at the tensile phase, in linear approximation we have:

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

From the equality of the extremes in (2) after elementary transformations we obtain:

$$\frac{N}{c} = \frac{i}{1+h/2R}, \tag{3}$$

where ΔV, Δm, ΔS are respectively the volume, the mass and the area of elementary ring; R - the inner specimen radius, h - the thickness of a packet, c - the sound velocity in acoustically analogous material, whose density is equal to generalized density of specimen with regard to the inner metal layer. Elastic properties are determined by the elasticity modulus of the specimen material. Then, if i - the value of specific pulse corresponding to the boundary of fracture zone, then N - the ultimate dynamic tension for the given specimen.

Within the approximation of the theory of point explosion we have the following expression for the value of specific pulse i:

$$i = \frac{2 m_o D}{27\pi R^2 [1+(l/2R)^2]^2} \left\{ 1 + \frac{\rho_1 R^3}{\rho_o r^3} \left[1 + \left(\frac{l}{2R} \right)^2 \right]^{3/2} \right\}^{1/2}, \tag{4}$$

where r_o and m_o - the radius and mass of the HE charge, D - detonation velocity in HE, ρ_1 and ρ_o - the densities of air and HE, l - the size (by the axis) of the fracture zone, formed in the specimen at the first phase of the motion of specimen walls from the center. Substituting for l the results of the series of experiments on the specimens with h = 2.5 mm (Fig. 2, a)) and the data for the specimens with h=5 mm at m_o=40 g and at m_o=20 g (accepting l =0 for glass fiber composite) in (4) and then in (3), we obtain the values of specific pulse, applied at the boundary of fracture zone and ultimate dynamic tensions for glass fiber N_{gl} and organoplastic - N_{ar}. As these values are estimated, let us formulate only qualitative conclusions. At the boundary of fracture zone the value i was observed to decrease by about 10% when the HE charge weight increases.

For organoplastics i exceeds the corresponding value for glass fiber composite approximately by 15 %. At outer inspection of the glass fiber specimens which lose carrying capacity as a result of increase of bending forms of motion it is visible that cracking starts from the outer surface of the specimen. The latter with allowance for regular location of median cracks along the circle made it possible to state that the number of cracks coincides with the number of waves of bending form of motion.

Comparison of the experimental results allows to reveal significant differences in the character of deformation and fracture of glass fiber and organoplastic shells under pulse loading resulting in deformation ranges from 2 to 4%:

- glass plastic specimens in a number of cases as the oscillations begin fail at compression phase forming regularly placed axial cracks, this is not typical of the organoplastic specimens;

- the development of cracks in glass fiber specimens originates from the outer surface and the number of cracks coincides with the number of waves of bending form of motion;

- damping constant of the organoplastic specimens is higher than that of glass plastic ones;

- under deformation glass plastic conducts as a linearly elastic material with constant modulus of elasticity, while organoplastic manifests non-linear viscoelastic properties.

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