Investigation of the mechanical properties of organoplastic under shock wave loading conditions

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Abstract. The paper presents results of dynamic tests of a typical representative of new composite and damping materials: organoplastics. Compression testing was performed using the traditional Kolsky method and its original modification. The strength and deformation properties of organoplastics under conditions of uniaxial stress and uniaxial deformation were studied. When the organoplastic is compressed transversely to the Kevlar fabric layers under conditions of a uniaxial stress state, the material begins to break down (to lose the layer cohesion) at a stress of about 200 MPa, while under the conditions of uniaxial strain, it retains its apparent integrity at stresses up to 500 MPa. The small value of the lateral thrust factor indicates a large internal strength of the material in tension in the radial direction.

1. Introduction
It is known that objects of aerospace technology can be subjected to intensive dynamic impacts during operation due to various factors of explosive, shock or other nature. In modern designs, various composite materials are widely used, both as supporting structural elements and as damping materials.

To prevent the destruction of a construction of new technology under the impact of shock wave loads, a special layer of organoplastics (aramid–epoxy composite) is included in the structure of their shell, which reduces (dampens) the acting loads. Since the physical-mechanical properties of composite materials under conditions of intense dynamic effects depend on the strain rate, the data on the properties of the composite materials obtained at high strain rates are required to ensure and confirm the stability of such structures.

The investigated material (organoplastic) is a light polymer composite material consisting of a fibrous high-strength filler of organic nature (aramid fibers) distributed in a matrix of polymer (epoxy) resins. It is used in aircraft structures in which special strength and lightness is required, as well as in manufacturing of individual armour protection. In aeronautical engineering, the organoplastics ensure the fan case impenetrability when the blade breaks as a result of multicycle fatigue and in the case of birds or some foreign objects getting into the engine.

2. Experimental methods
To investigate the mechanical properties of organoplastics under compression, an apparatus [1] was developed, where the Kolsky method was used [2]. A gas gun of caliber of 20 mm was used...
as a loading device. The pressure bars of a diameter of 20 mm were made both of high-strength martensitic-aging steel and high-strength aluminum alloy D16T.

To study the properties under conditions of uniaxial deformation, a test sample was placed in a rigid jacket of original configuration [3] equipped with strain gauges to measure its deformation in the circular direction. Under conditions of the jacket elastic operation, this permits obtaining the radial stress component $\sigma_r(t)$ in the specimen [4, 5], which together with the longitudinal stress component $\sigma_x(t)$, determined by traditional formulas of the Kolsky technique, allowed one to obtain the pressure dependence in the specimen $P(t) = -\frac{1}{3}[\sigma_x(t) + 2\sigma_r(t)]$, the shear stress $\tau(t) = \frac{1}{2}[\sigma_x(t) - \sigma_r(t)]$, and the coefficient of lateral pressure (thrust) $\xi(t) = \sigma_r(t)/\sigma_x(t)$. All these quantities are parametric processes, so the relationship between them should be considered throughout the test.

The experimental setup allows one to vary the strain rate in a wide range. To cover the entire area, the strikers are fired at different initial velocities, and longer strikers are used to provide sufficient deformation at lower speeds. The strikers used in the experiments were made of steel and D16T alloy of length varying from 200 mm to 400 mm, which permits exciting the loading impulses of duration ($t = 2L_{str}/C_{str}$) from 80 to 160 microseconds.

3. Tested specimens

The specimens for testing shaped as cylinders of diameter of 20 mm and height of about 9 mm were cut from a pressed plate consisting of a great many layers of fabric of aramid fibers with equal strength of the weft and the base. Such dimensions (the ratio $L/D \approx 0.5$) correspond to the minimum error in the measurement of stresses introduced by inertia forces [6].

It should be noted that the end surfaces of the organoplastic specimens are not flat and smooth due to manufacturing technology. To reduce the influence of these errors and to improve the acoustic contact between the ends of the measuring bars and the ends of the specimen, a viscous lubricant layer was applied onto these surfaces before the test.

The specimens were loaded perpendicular to the fabric layers.

4. Results of the tests

Some of the tests were carried out using steel measuring bars (and steel confining jacket), which permits obtaining a large stress level in the specimen and, correspondingly, high strain rates. To obtain the properties at low strain rates, when the amplitude of the registered signal from the transmitting bar is small, we used bars (and a jacket) made from D16T alloy.

As a result of processing the experimental data according to the formulas of the Kolsky method, the dynamic stress-strain curves are obtained for compression under uniaxial stress conditions, as well as for uniaxial deformation (volumetric stress state). Analysis of these curves allowed us to determine the moduli of loading and unloading branches, strength characteristics, lateral expansion ratio, and parameters of shearing strength.

4.1. Investigation of the behavior in a uniaxial stress state

Figure 1 shows the characteristic diagrams of organoplastic deformation under the conditions of a uniaxial stress state obtained at different strain rates in order to determine the magnitude of the load that leads to destruction of the material. Here, the solid curves show the true dynamic $\sigma_s-\varepsilon_s$ curves, and the dashed lines in the lower part of the graph show the corresponding strain rate change curves $\dot{\varepsilon}_s-\varepsilon_s$. By varying the striker speed, i.e., the amplitude of the loading wave, we could choose loading regimes in which the sample either retained its apparent integrity and strength (curves 1–3) or was fractured (curves 4–5). One can see that, in tests without a jacket (under the conditions of a uniaxial stress state) at a stress above 200 MPa, the fracture processes begin in the material, i.e., the stress decreases with a significant increase in the strain.
Figure 1. Effect of strain rate on the behavior of organoplastic.

The obtained stress-strain curves of organoplastic are nonlinear in the loading part. At the beginning of the diagrams, there is a significant (from 0.3 to 1.5%) section with practically zero stress. The main reason for this may be the non-flatness of the end faces of the specimen and, as a consequence, the presence of a small gap between the ends of the loading measuring bar and the specimen. On the other hand, the sample consists of Kevlar tissue layers impregnated with binder alternating with epoxy resin layers. At the initial moment of the specimen loading at a sufficiently low stress level, a nonlinear elastic deformation of the polymer binder occurs both inside the Kevlar layers and between these layers, which causes a delay in the appearance of the transmitted pulse. In addition, the velocity of the wave propagation in the composite sample is much lower than in the measuring bars, which is also the cause of the delay in the initial section of the diagram.

Next, the layers of the epoxy binder and Kevlar fabric layers are compressed. The material begins to resist the deformation more strongly, which leads to an increase in the stress according to a nearly linear law, up to values determined by the incident pulse amplitude. If this amplitude is insufficient to destroy the specimen, then after the loading pulse termination, the specimen is also unloaded according to a nearly linear law up to a stress level of \( \sim 30 \text{ MPa} \) and then with a gradually decreasing deformation modulus.

It is clearly seen that when the specimen breaks down in testing under conditions of free extension, this leads to a drop in the stress level in the sample after a certain maximum and to a synchronous increase in the strain rate. With preservation of the the specimen integrity, the strain rate curve monotonically decreases after attaining its maximum on the loading branch. On the unloading branch, the strain rate has negative values.

The growth in the stress of the destroyed specimen (curve 5 in figure 1) after deformation of 0.15 can be explained by the exhaustion of the longitudinal deformation of relatively weak layers of the binder and the mutual compression of contiguous layers of the Kevlar fabric, which has a great strength.

The study of the material endurance under repeated loading at loading energies insufficient
for visible fracture is illustrated in figure 2. The same specimen was loaded several times with different gradually increasing loading energies (strain rates). It can be seen that the loading branch of the chart, which has a nonlinear character, is repeated from experiment to experiment, and the increasing loading energy causes only an increase in the level of the stress achieved in the specimen. The average value of the modulus of the loading branch in the range of considered strain rates is $\sim 4.3$ GPa, the unloading modulus is 5.5 GPa.

The visual analysis of samples after testing indicates that the sample, after compression with insignificant loading energy, retains its apparent integrity and initial length, and only on the lateral surface, there is some extrusion of Kevlar fibers, apparently due to their straightening in the fabric when compressed. At loads greater than 200 MPa, the irreversible destruction occurs, i.e., the material is delaminated, and a greater delamination is observed at the end where the load is applied (figure 3).
Figure 5. Diagrams of compression under uniaxial strain.

An attempt was made to measure the Poisson’s ratio by a “direct” method, by attaching the strain gages directly to the lateral surface of the specimen (figure 4) and by its loading between the ends of the measuring rods under uniaxial stress conditions.

Certain difficulties arise when recording the signals from the strain gauges glued to the lateral surface of the specimen, since the sensors detect not only the integral peripheral (circular) deformation, but also the possible displacements and extrusion of individual layers of the fabric.

Based on the results of several experiments, the average Poisson’s ratio was 0.05.

4.2. Investigation of the behavior under uniaxial deformation

The results of compression tests under conditions of uniaxial deformation (in a rigid jacket equipped with strain gages on the lateral surface) are presented below. Figure 5 shows curves in the “axial stress–axial strain” axes. Also, the corresponding strain rate curves are shown by dotted lines.

The average value of the module of the loading branch is $\sim 6.6 \text{ GPa}$, unloading — $7.6 \text{ GPa}$. Under conditions of radial expansion confining, the material retains its apparent integrity at stresses up to 500 MPa. This is also shown by the unloading branches. The appearance of the specimens is almost the same as that of the original, only on the lateral face of the specimen, there is a slight extrusion of the fibers from the Kevlar fabric layers.

An analysis of the loading branches of the charts showed that, with an exception of the initial section (delay of the curve appearance due to the gradual removal of the gap), the organoplastic has compression modulus almost independent of the strain rate. The material unloading is also nonlinear and has a slightly steeper slope. It is impossible to trace the course of the diagram until the specimen is completely unloaded, since the duration of the pulses reflected and transmitted through the specimen greatly exceeds the duration of the incident pulse due to the polymer binder viscosity and cannot be completely registered because of the insufficient length of the measuring bars.

Figure 6 shows the initial pulses in the measuring bars and on the circular surface of the jacket. It is clearly seen that the basic assumption of the Kolsky method that of forces are equal
at the end faces of the specimen, $\varepsilon^I(t) + \varepsilon^R(t) = \varepsilon^T(t)$, is satisfied throughout the test, and the reflected and transmitted pulses have duration significantly longer than the loading wave. The transmitted pulse has a significant delay in appearance relative to the beginning of the reflected pulse.

The longitudinal compression of the specimen causes its transverse expansion according to the Poisson’s ratio. However, since the radial deformation of the specimen is limited by the jacket, a near-uniaxial deformation state and a volumetric stress state arise in the specimen. For such a stress-strain state, the Poisson’s ratio cannot be estimated, but only the coefficient of lateral thrust. The value of the radial stress component is determined by registering the signals from the confining jacket, which together with the signals from the strain gauges on the measuring bars permit obtaining the tangential stress and pressure in the specimen, and also to estimate the lateral thrust ratio.

For one of the experiments, figure 7 shows the curves of variation of the axial and radial stress components, as well as the pressure in the specimen as a function of the volume strain. One can see that the radial stress component is much smaller than the axial one. It should be noted that the results of measuring on the circular surface of the confining jacket determine the stress developed on the inner surface of the jacket. This stress is taken as the radial component of the stress in the specimen.

Another possible reason for the small value of the radial stress can be the inhomogeneity of the lateral surface of the specimen and the presence of a certain gap between the outer surface of the specimen and the inner surface of the jacket. Due to a gap between the specimen and the jacket, its participation in the formation of volumetric stress-strain state is inadequate.

The large internal tensile strength of the material (Kevlar fibers in the fabric) in the radial direction as compared to the compression strength (layers of the polymer binder) in the axial direction is also a cause of large difference between $\sigma_r$ and $\sigma_x$. This respectively leads to a small value of the lateral thrust coefficient, whose curve in the loading and unloading sections is shown in figure 8. It should be noted that since the lateral thrust ratio is defined as the quotient of the radial stress component to the axial one and these quantities are sufficiently small at the initial and final loading stages, the quotient of two small quantities with possible errors and distortions can be sufficiently large.

In figure 8a, the dotted line additionally shows the curve of the time variations in the tangential stress. Depending on the pressure developing in the specimen (figure 8b), this curve practically coincides at the loading and unloading stages.

Figure 9 shows the curves of tangential stress changes as a function of the pressure developing in the specimen obtained for different loading energies. One can see that they almost coincide at
Figure 8. Variation in the lateral thrust ratio and tangential stress depending on time (a) and on the pressure in the sample (b).

Figure 9. Changes in the tangential stress as a function of the pressure in the specimen.

loading and unloading of the specimen. For small load values, this curve can be approximated by a linear relation, whereas the linear dependence is violated for large load amplitudes. A reason for this may be a non-linearly elastic deformation of the polymer binder.

Conclusions
The study has shown that when the organoplastic is compressed transversely to the Kevlar fabric layers under uniaxial stresses, the material begins to break down (to lose the layer cohesion) at a stress of about 200 MPa, while under the conditions of confining radial expansion, it retains its apparent integrity at stresses up to 500 MPa. The small value of the lateral thrust factor indicates a large internal strength of the material in tension in the radial direction, since the Kevlar fibers in the fabric have a high tensile strength.
Acknowledgments
Dynamic investigation was financially supported by the Russian Science Foundation (grant No. 15-19-10032).

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