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MODIFICATION OF THE KOLSKY METHOD FOR STUDYING PROPERTIES OF LOW-DENSITY MATERIALS UNDER HIGH-VELOCITY CYCLIC STRAIN

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A modification of the Kolsky method with the use of the split Hopkinson bar is proposed, which allows testing low-density materials under cyclic loads of an identical sign. Cyclic dynamic testing of specimens is based on the essential difference of acoustic impedances of the material of the specimen tested from the material of pressure bars. The choice of the support-bar length several times greater than the loading-bar length allows registration of strain pulses in several cycles. Results are presented for the proposed modification of the Kolsky method used for tests in compression of foam plastic of two densities under three loading cycles.

Introduction. The most developed and justified technique for high-velocity testing of various materials is currently the Kolsky method with the use of the split Hopkinson bar [1]. In addition to traditional single-cycle tests in compression, tension, and torsion, this method allows testing with registration of several cycles of pulsed loading.

The use of the traditional Kolsky method for cyclic tests involves certain difficulties. First, correct registration of strain pulses in several loading cycles is complicated by interference of waves in pressure bars. Second, for an identical length of pressure bars, the pulse ε^t that passed through the specimen and was reflected from the backward face of the support bar in the first loading cycle arrives at the specimen simultaneously with the pulse ε^r that was reflected from the specimen and arrived at it for the second time and, hence, can distort the pattern of specimen deformation. To avoid the return of this pulse, Lindholm [2] proposed to use a trap bar attached to the backward face of the support bar. The test facility ensures registration of only one additional cycle of specimen loading.

For correct registration of several loading cycles, Zao and Gary [3] proposed a scheme of strain gauges (two on each pressure bar) and the necessary mathematical apparatus, which allows one to identify the corresponding strain pulses in pressure bars in each loading cycle. The use of this scheme in foam-plastic tests allows one to register four cycles of specimen loading and to study material behavior with significant compaction (up to 80%).

In contrast to [2, 3], where the repeated loading was performed by a pulse reflected from the specimen in the first cycle, cyclic loading in [4] was ensured by using a stepwise anvil. The combination of loading pulses was generated by choosing appropriate cross-sectional areas of the anvil.

In [5–7], a composite impactor loaded the specimen by pulses of an identical sign with a varied interval between the loading cycles. The pulse amplitude and duration were varied by choosing impactor materials and lengths, and the interval between the pulses was varied by setting the gap between the constituent parts of the impactor. To register correctly the corresponding strain pulses and avoid distortion of the stress–strain state of the specimen, we propose to use pressure bars with the ratio of their lengths equal to the number of cycles registered. With the use of a modified test facility, tests with foam plastic were performed under three-cycle loading of the specimen in a rigid confining yoke by pulses of an identical sign.

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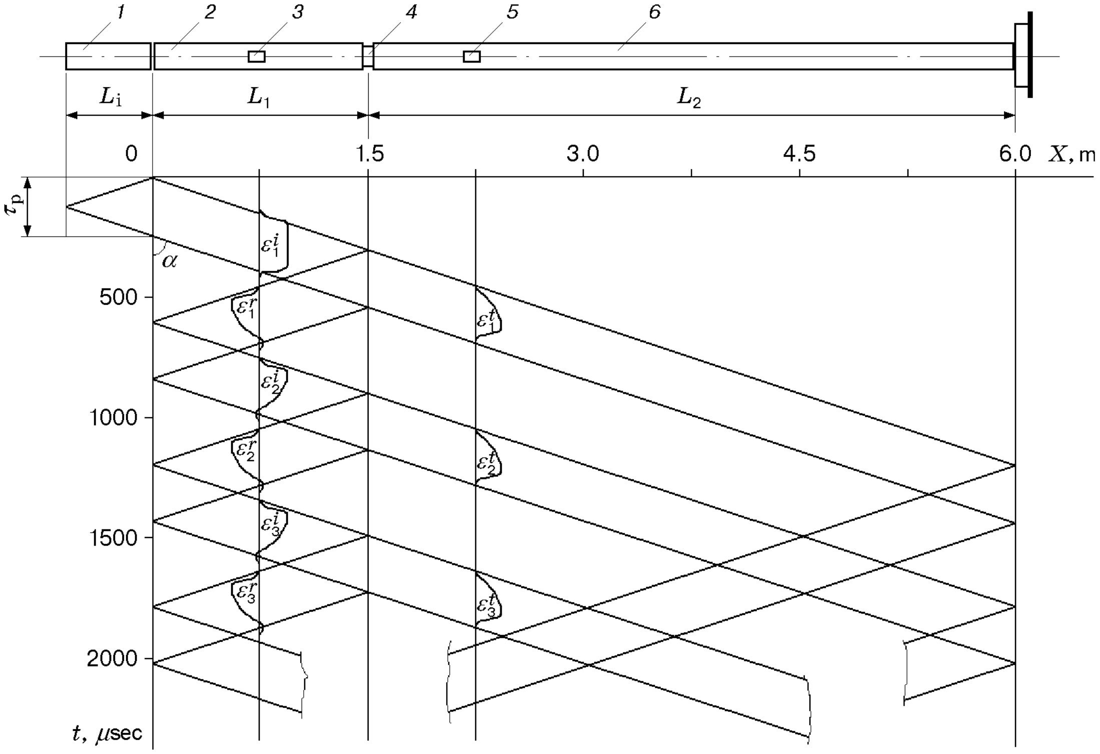

Fig. 1

Test Facility and Test Conditions. A simple modification of the test facility [8–10] was used for cyclic dynamic tests of low-density materials. Its operation is based on the Kolsky method [1] with the use of the split Hopkinson bar as the main measurement tool. Figure 1 shows the scheme of the proposed variant of the split bar and the wave X–t diagram under cyclic loading of the specimen. Impactor 1 excites an elastic pulse ε_1^i in the loading bar 2. The pulse propagates in the bar with a velocity C ($\tan\alpha = C$). The duration of the excited pulse $\tau_{\rm p}$ is determined by the impactor length $L_{\rm i}$. Approaching specimen 4, part of this pulse is reflected as an extension wave ε_1^r, and the other part passes through the specimen into the support bar 6 as a compression wave ε_1^t. The pulses are registered by the strain gauges 3 and 5 glued onto the pressure bars at an identical distance from the specimen. If the acoustic impedances of the bar and specimen materials are significantly different, the amplitude of the reflected pulse may be rather high. The reflected pulse propagates up to the end face of the first pressure bar loaded by the impactor and is reflected from the free face (since there is no longer contact with the impactor) as a compression wave ε_2^i. The secondary wave loads the specimen, a significant part of it is reflected again, etc. Thus, the specimen is subjected to cyclic loading and unloading with a gradually decreasing amplitude. The pause between the cycles is equal to the time of the doubled run of the strain pulse over the loading bar (Fig. 1). To conduct tests with cyclic loading of specimens and registration of repeated loading cycles in one test, one has to eliminate the return of the compression wave ε_1^t transmitted through the specimen from the backward face of the support bar back to the specimen. In this case, the length of the support bar should be greater than the length of the loading bar by a factor equal to the number of cycles supposed to be registered. Taking this into account, we used a loading pressure bar of length $L_1 = 1.5$ m and a support bar of length $L_2 = 4.5$ m, which allowed us to register three loading cycles. The pressure bars and the impactor were made of the D16T alloy.

Foam-plastic specimens of densities $\rho = 0.19$ and 0.67 g/cm^3 in the form of pellets 20 mm in diameter and 10 mm long were prepared for testing. To study the properties of foam plastic under conditions of volumetric stressed state and uniaxial strain, the specimens were tested in a rigid confining yoke. The specimen diameter was slightly smaller than the inner diameter of the yoke (≈0.2-mm gap). All tests were performed at room temperature. Impactors 200 and 300 mm long were used for specimen loading, which made it possible to generate loading pulses of duration up to 130 μsec and amplitude up to 200 MPa.

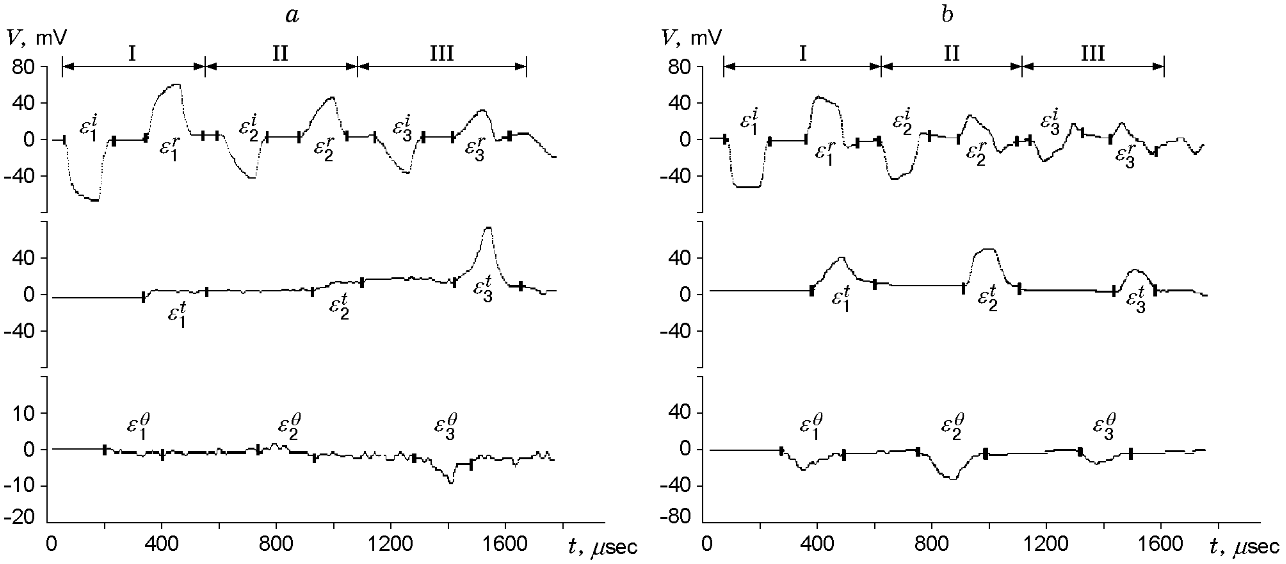

Fig. 2

Test Results. The oscillograms obtained in foam-plastic tests registered three beams: from the loading pressure bar, from the support pressure bar, and from the confining yoke. Figure 2a and b shows the oscillograms obtained in testing foam plastic of density $\rho = 0.19$ and 0.67 g/cm^3, respectively. The vertical strokes indicate the incident (ε_1^i, ε_2^i, and ε_3^i) and reflected (ε_1^r, ε_2^r, and ε_3^r) pulses on the first beam in the oscillograms, the pulses transmitted through the specimen on the second beam (ε_1^t, ε_2^t, and ε_3^t), and the pulses of circumferential deformation (ε_1^θ, ε_2^θ, and ε_3^θ) from the confining yoke on the third beam in the first, second, and third loading cycles, respectively. The ordinate axis shows the voltage registered by oscillograph channels. The duration of each cycle is marked by Roman numbers in Fig. 2. It should be taken into account that, since the signal from the support bar (pulse ε^t) is additionally amplified (because of its low value) and inverted thereby, its has the opposite polarity in the oscillogram registered. The reflected and transmitted pulses do not return to the "zero" line after the loading process is terminated, i.e., the process of unloading of the foam-plastic specimen is longer than the interval between the registration of the incident and reflected pulses because of the viscoplastic character of the deformation process. In addition, the amplitude of the reflected pulse is quite significant (up to 80% of the amplitude of the initial incident wave). As is shown above, this is caused by the significant difference in acoustic impedances of the pressure bar and the specimen.

A special feature of the behavior of foam plastic of density $\rho = 0.19$ g/cm^3 is the small amplitude of the transmitted wave (and hence, of the signal from the confining yoke) in the first and second cycles of specimen loading. Only after some compaction and choosing the gap between the side surface of the specimen and the inner surface of the yoke, the specimen starts to transmit a wave of a rather large amplitude. In this case, the signal from the yoke appears (see Fig. 2a). The signal from the yoke is several times lower than the amplitude of the transmitted wave and is almost absent in the first two cycles (indiscernible at the background of noise). In the oscillogram of testing foam plastic of density $\rho = 0.67$ g/cm^3 (see Fig. 2b), the amplitude of the transmitted wave already in the first cycle is sufficient to ensure registration of the signal from the confining yoke. This signal was not used in the present work to determine the stress and strain of the specimen material. The method of registration of the signal from the yoke and its use for determining the shear-strength parameters are described in detail in [8–10].

Processing of initial strain pulses yields dynamic diagrams with additional loading cycles. Figure 3 shows the strain diagrams for foam-plastic specimens of densities $\rho = 0.67$ (curve 1) and 0.19 g/cm^3 (curve 2) in the confining yoke for close amplitudes of the loading pulse. The mean strain rates in the first, second, and third loading cycles were, respectively, 2300, 800, and 300 sec^{-1} for curve 1 and 2600, 1800, and 1000 sec^{-1} for curve 2.

As is noted above, because of the large viscosity of foam plastic, the specimen does not have enough time to become completely unloaded after the action of the load is terminated, i.e., the stresses in the specimen do not decrease to zero. Therefore, the line of unloading after a cycle is broken at a certain level of stresses and corresponding strains. The next loading cycle starts exactly from this value of strain and the final level of stress. Viscous effects

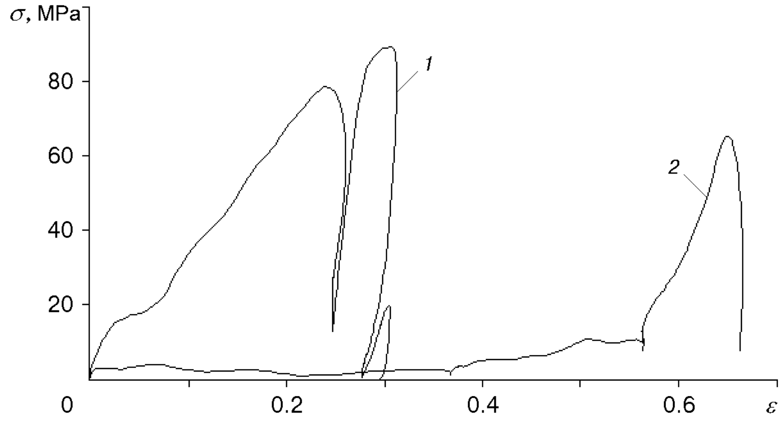

Fig. 3

are most profoundly manifested in low-density foam plastic. Its typical feature is greater deformability than that of foam plastic of density $\rho = 0.67$ g/cm^3, i.e., only after compaction of the specimen corresponding to deformation higher than 50% (i.e., after increasing density by more than a factor of 2) and choosing the gap size does the growth of stresses registered in the specimen begin. Apparently, the increase in stresses in the specimen occurs not only because of the increase in density but also due to the change in the type of the stress–strain state of the specimen (the confining yoke starts to work), which is confirmed by the pulse from the yoke present exactly in the third loading cycle (see Fig. 2a). The effect of the changes in loading conditions on the deformation process is manifested only in the third loading cycle for specimens of density $\rho = 0.19$ g/cm^3 and already in the first one for specimens of density $\rho = 0.67$ g/cm^3. A significant decrease in stresses in the third loading cycle for foam-plastic specimens of higher density is caused by the decrease in the amplitude of the reflected pulse after the second loading cycle, which, in turn, is caused by the significant compaction of the material and, as a consequence, by the increase in the amplitude of the transmitted wave and the corresponding decrease in the amplitude of the reflected wave.

It is seen in Fig. 3 that the absolute values of loading branches increase from one cycle to another. The loading branch of the diagram for foam plastic of density $\rho = 0.67$ g/cm^3 in the first cycle of specimen loading is nonlinear, which may be caused by compaction and changes in the initial structure of the material. It should be noted that the absolute values of the loading branches of foam plastic of lower density in the third cycle (after compaction) and foam plastic of higher density in the first cycle are close to each other. In contrast to the loading branches of the strain diagram, the absolute values of the unloading branches remain almost unchanged from one cycle to another and depend weakly on the strain rate.

In the general case, the mechanical characteristics of foam plastics are determined by a large number of chemical, physical, and technological parameters, which affect the properties of the polymeric matrix, density distribution, and anisotropy of the cellular structure. Therefore, the description of elastic and strength properties of foam plastics with only strain or density used as a parameter is incomplete.

Conclusions. High deformability of the materials tested, significant nonlinearity on loading branches, and significant difference between loading and unloading branches, which is apparently caused by the complicated rheology of foam plastic, were observed in experiments.

The proposed modification of the Kolsky method may also be used in tension tests by the Nicholas technique [7], since the reflected pulse has also a high amplitude in this case because of the significant difference in cross-sectional areas of the pressure bars and the specimen (12 : 1).

REFERENCES

1. G. Kolsky, “Mechanical properties of materials under high loading rates,” *Mekhanika*, No. 4, 108–119 (1950).
2. U. S. Lindholm, “Some experiments with the split Hopkinson pressure bar,” *J. Mech. Phys. Solids*, **12**, 317–335 (1964).
3. H. Zao and G. Gary, “Large strain range dynamic testing at high and medium strain rates, using a common scale SHPB,” *J. Physique IV*, **7**, 341–346 (1997).

4. K. Ogawa, “Impact-tension compression test by using a split Hopkinson bar,” *Exp. Mech.*, **24**, No. 2, 81–85 (1984).
5. A. M. Bragov and A. K. Lomunov, “Elastoplastic properties of aluminum alloy AMg6M with high strain rates,” *Prikl. Mekh. Tekh. Fiz.*, **29**, No. 6, 168–171 (1988).
6. A. M. Bragov, A. K. Lomunov, and A. A. Medvedev, “A modified Kolsky method for the investigation of the strain-rate history dependence of mechanical properties of materials,” *J. Physique IV*, **1**, C3-471–C3-475 (1991).
7. A. M. Bragov and A. K. Lomunov, “Methodological aspects of studying dynamic material properties using the Kolsky method,” *Int. J. Impact Eng.*, **16**, No. 2, 321–330 (1995).
8. A. M. Bragov, G. M. Grushevsky, and A. K. Lomunov, “Use of the Kolsky method for studying shear resistance of soils,” *DYMAT J.*, **1**, No. 3, 253–259 (1994).
9. A. M. Bragov, V. P. Gandurin, G. I. Grushevsky, and A. K. Lomunov, “New potentials of Kolsky method for studying the dynamic properties of soft soils,” *Prikl. Mekh. Tekh. Fiz.*, **36**, No. 3, 179–186 (1995).
10. A. M. Bragov, G. M. Grushevsky, and A. K. Lomunov, “Use of the Kolsky method for confined tests of soft soils,” *Exp. Mech.*, **36**, No. 9, 237–248 (1996).