Journal of Applied Mechanics and Technical Physics, Vol. 48, No. 3, pp. 445–449, 2007

MODELING THE DEFORMATION OF ROCK WITH ROUGH SURFACES OF BLOCK CONTACT UNDER QUASISTATIC AND DYNAMIC LOADING CONDITIONS

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UDC 539.0

The effect of layers consisting of small particles or asperities on contact surfaces on the deformation of a block medium as a whole and the failure of the blocks constituting the medium was studied experimentally. The samples were subjected to quasistatic uniaxial compression perpendicular to the contact surfaces. Numerical modeling was performed of wave propagation during pulse loading of a pair of blocks having rough surfaces of contact and made of a material with elastic characteristics close to the characteristics of marble and limestone.

Key words: *block medium, layers, experiment, numerical modeling.*

Rock masses consist of homogeneous blocks divided by layers with weaker strength properties [1]. The presence of such layers and their characteristics have a significant effect on the deformation of the medium as a whole, in particular, on the propagation of elastic waves in it [2], and on the failure of the blocks constituting the medium. The layers are modeled using various methods. In experimental studies [3], materials of the type of rubber play the role of layers between solid blocks, and in calculations, the layers are replaced by elastoplastic and viscoelastic elements connecting the blocks. The effect of the rigidity of the layers is studied in modeling experiments [4], in which thin layers of various materials located between Plexiglas blocks are used as interblock contacts.

The present paper gives results of an experimental study of the effect of layers consisting of small particles of the material of the blocks on the deformation of the medium as a whole and on the failure of its constituent blocks. The layer consists of multiple small asperities on the contact surfaces or a thin layer of fragments of various sizes (the maximum size of the fragment is 4 mm) which separates blocks with even end faces. A segment of the block medium is modeled by pairs of cement cylinders having their end faces in contact and subjected to uniaxial quasistatic compression along the symmetry axis.

Experiments were performed on a Zwick/Roell Z100 TC-FR100TL.A4K material test machine. Loading was performed by the cross-head moving at a constant speed of 0.05 mm/min; the average compressive strain of a pair of blocks was measured by a cross-head movement sensor, and the applied force by a built-in force sensor. The frequency of entering the measurements into the database was 1 sec^{-1}.

Cylindrical samples (height and diameter of about 30 mm) made of M-400 cement without impurity were used. The end faces with asperities were produced using compression moulds with bottom made of a porous material. Protrusions of various sizes distributed randomly were formed at the end faces of the samples. Large protrusions (about 0.5 mm high) occupied about one-fourth of the surface, and the space between them was filled with small asperities of significantly smaller sizes. The end faces adjoining the anvils of the facility were even and were separated from the anvils by duralumin plates and fluoroplastic to reduce friction. The internal structure of the material was mainly homogeneous, with a small amount of voids of various sizes resulting from the introduction of air bubbles into the cement solution.

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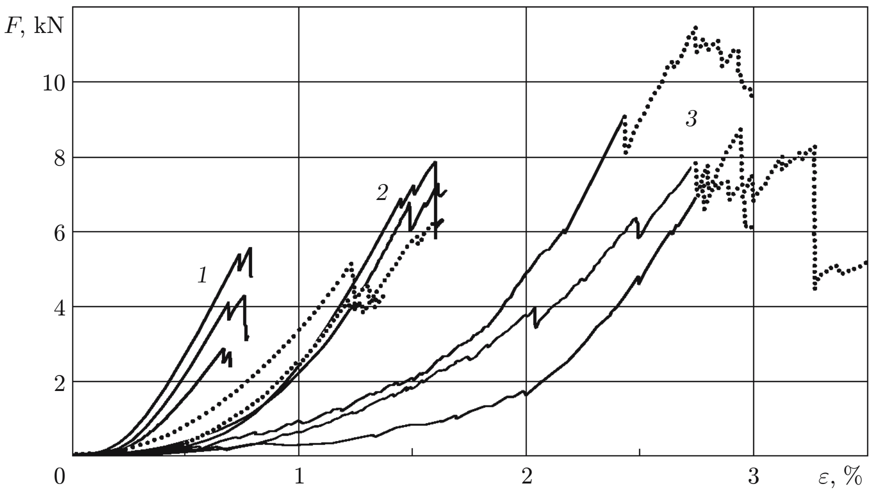

Fig. 1. Experimental curves of the relative compressive strain ε of the samples versus the applied force F: 1) even contact surfaces; 2) rough contact surfaces; 3) layer of fragments between the end faces.

Figure 1 gives experimental curves of the relative decrease in the height ε of a pair of samples versus the applied force F for cylinders with even and rough end faces and for cylinders separated by a layer of fragments obtained from a sample of the same set as the samples tested. The initial thickness of the layer and the characteristic size of most of the fragments is approximately equal to 4 mm.

In the case of even surfaces of contact of the cylinders, except for the small nonlinear segment corresponding to the initial strain redistribution in the samples, there is a linear relation between the strain and the applied force, which is retained until the moment of formation of the first longitudinal cracks. As the number of cracks increases, the rigidity of the pair decreases. The samples are separated by longitudinal cracks into columns of various cross-sectional size. Generally, the behavior of a pair of samples with even end faces is similar to the behavior of a unified block of a fragile material.

In the case of rough surfaces of contact, a nonlinear relation between the applied force and the relative decrease in the height of the pair of samples is observed throughout the experiment. As the compressive strain increases, the rigidity of the pair increases continuously until crack formation begins. Visual observation shows that the process of compression of the pair of blocks has several stages. First, the samples come into contact by means of large protrusions. The contact surface area is very small; therefore, the protrusions in contact fail under a small force applied. Then, large protrusions on one of the samples come into contact with small protrusions on other sample, resulting in an increase in the contact surface area and the rigidity of the pair. Some of the small asperities fail due to the pressure from the large asperities. When the rigidity of the pair becomes close to the rigidity of the material, numerous cracks are formed in the places of accumulation of large protrusions, where the strains resulting from the contact of the samples are concentrated.

The spread in the strength of the samples under identical loading conditions can be due to the nonuniformity of the internal structure (different sizes and number of voids and their distribution over the volume), the difference in the drying period, and the initial density of the solution. In addition, in samples with rough end faces, the strength is affected by the arrangement of large protrusions at the end faces. If they are arranged more uniformly, the strength of the pair increases. Thus, dotted curves 2 in Fig. 1 correspond to samples in which large asperities were concentrated closer to the center. The strength of these samples is much lower than the strength of the other two samples, in which large asperities are distributed more uniformly.

If between the blocks there is a layer of fragments of the same material, the behavior of the pair of blocks generally differs little from the behavior of the pair with rough contact surfaces. The difference is that failure of the blocks begins only after complete failure of all fragments and transformation of the fragmental layer into a fairly homogeneous powder mass that does not produce stress concentration. In Fig. 1, the dotted segments of curves 3 correspond to transition from the failure of the fragments of the layer to the failure of the cylinders.

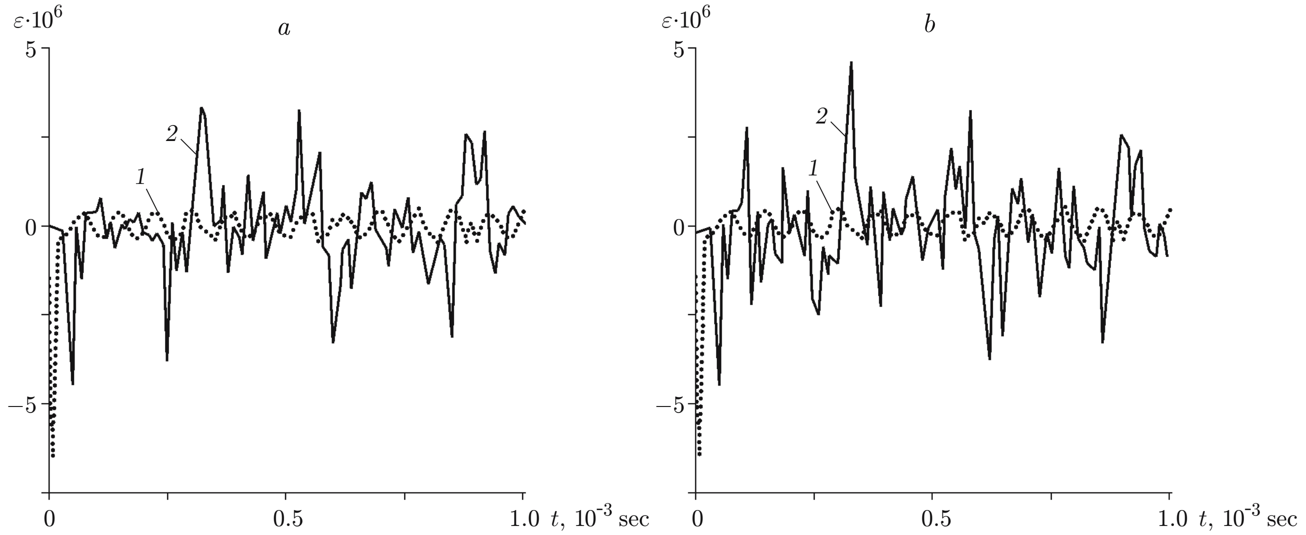

Fig. 2. Calculated curves of the longitudinal strain ε versus time t for $d = 2$ (a) and 18 mm (b): 1) the point at the center of the left end face subjected to impulse loading; 2) the center of the left block.

The results of the experiments lead to the following conclusion: if a medium consists of blocks which have rough surfaces in contact or are separated by layers of fragments and is loaded by a compressive force directed perpendicular to the contact surfaces of the blocks, its averaged stress–strain state can be modeled using a homogeneous material whose rigidity increases with increasing compressive strain (but cannot exceed the rigidity of the blocks). The region of block contact can also be replaced by a layer of such material. In addition, it follows from Fig. 1 that despite the spread in the strength of samples of the same set, the presence of the layer considerably increases the strength of the pair compared to the strength of the pair of blocks with even contact surfaces. This increase in the strength is likely due to the fact that as the elements of the layer fail, a cement powder layer is formed between the cylinders, which facilitates a more uniform stress distribution.

Numerical experiments using the ANSYS finite-element complex were performed to study the effect of the contact surface roughness on the propagation of longitudinal compression–tension strain wave in contacting two-dimensional blocks of linearly elastic material. The calculation results were compared with the results obtained by replacing the zone of block contact by a thin homogeneous layer with a decreased elastic modulus. The region of contact of rough surfaces was modeled by a transverse row of rhombus-shaped holes which separated the paired block into two equal parts. The holes served as gaps between the protrusions in contact, whose width in the narrowest part was identical for all hole sizes and was equal to 2 mm. Interblock contact was specified similarly in the modeling experiments in [4].

A two-dimensional model (in the case of plane deformation) was constructed of four-node finite elements with a Lagrangian representation of the elastic medium. Near the holes, the mesh step was decreased to a value approximately equal to 0.1 of the minimum characteristic hole sizes. The material of the blocks was linearly elastic, Young's modulus was $35 \cdot 10^3$ MPa, the density was 3000 kg/m^3, an Poisson's ratio was 0.15 (values close to the characteristics of marble and limestone). The paired block had length $L = 1$ m and width $H = 0.25$, and the calculations were performed for various thickness of the layer consisting of alternating holes and intervals between them (the layer thickness d, equal to the hole size, was varied from 2 to 18 mm). The width of the homogeneous layer with decreased elastic modulus was equal to 18 mm, i.e., the maximum width of the contact region for all values of the modulus.

At the right end face of the paired block, movement in the direction of load application was not allowed, and at the left end face, an impact by a force of 1 kN and a duration of $2 \cdot 10^{-5}$ sec was specified. The propagation of elastic waves was calculated for a time interval of 10^{-3} sec. The top and bottom boundaries of the blocks and the hole contours were free from stress. The time required for the initial perturbation to completely pass through the paired block and return to the end face subjected to the impact was about $3 \cdot 10^{-4}$ sec.

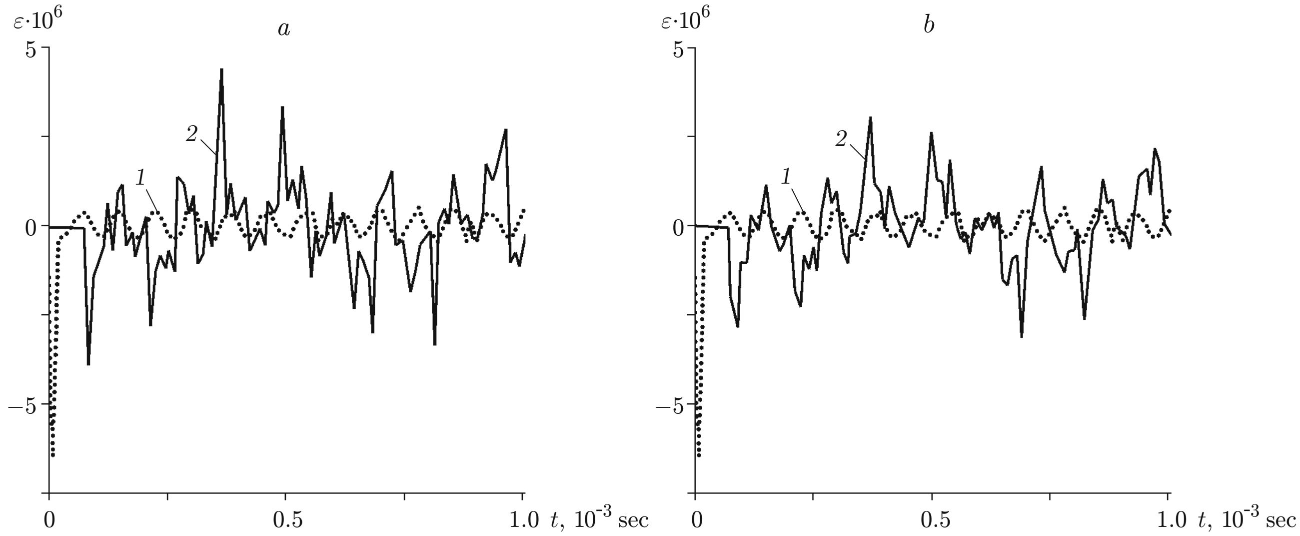

Fig. 3. Calculated curves of the longitudinal strain ε versus time t for $d = 2$ (a) and 18 mm (b); 1) the point at the center of the left end face subjected to impulse loading; 2) the point on the longitudinal symmetry axis in the right block near the layer.

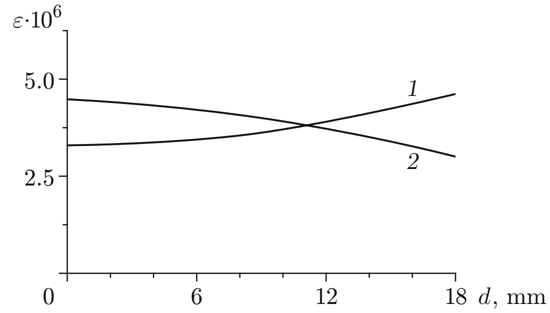

Fig. 4. Maximum longitudinal strain ε versus hole size d in the layer: 1) left block; 2) right block.

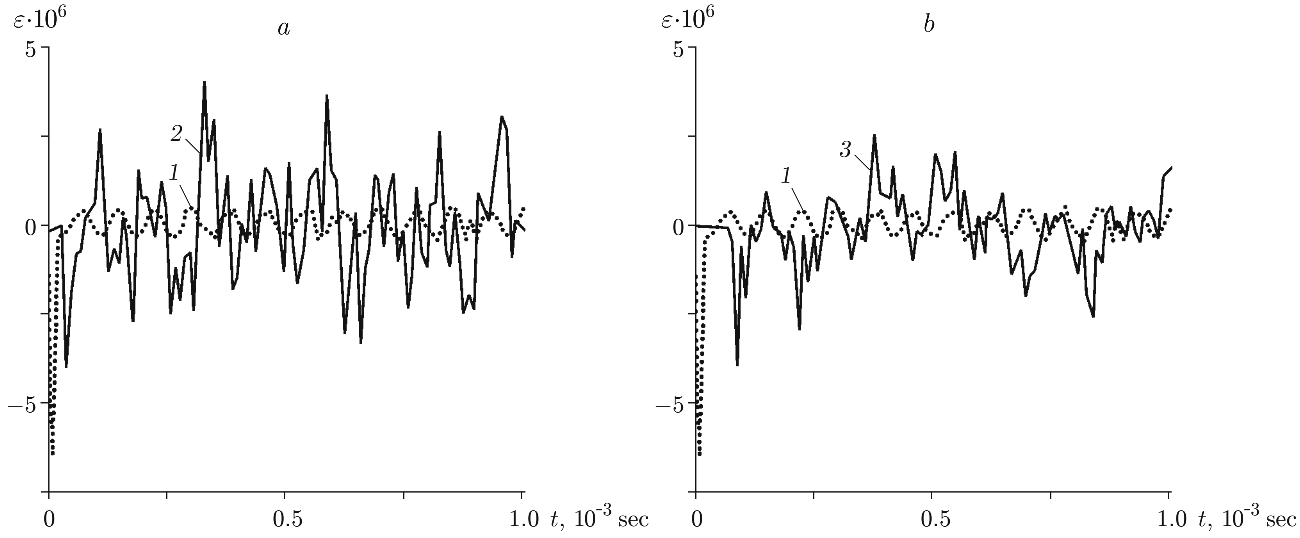

Fig. 5. Calculated curves of the longitudinal strain ε versus time t for a homogeneous layer: 1) the point at the center of the left end face subjected to pulse loading; 2) the center of the left block; 3) the point on the longitudinal symmetry axis in the right block near the layer.

Figures 2 and 3 show changes in the nature of wave propagation due to an increase in the roughness size on the contact surfaces. In the first block (subjected to impact), the maximum fluctuation amplitude increases, and in the second block, it decreases. A comparison of the curves of $\varepsilon(t)$ for various layer thicknesses d shows that the curve of the fluctuation amplitude versus layer thickness is nonlinear (Fig. 4). Figure 5 shows the curves for the case where the zone of contact of rough surfaces is replaced by a homogeneous layer with Young's modulus 10 times smaller than that of the block material.

We denote by h the total width of the intervals between the holes in the row. In the absence of holes, it is equal to the block width H. For the problem with a homogeneous layer, we denote the elastic modulus of the blocks by E, and the elastic modulus of the layer by E^*. A comparison of the curves of $\varepsilon(t)$ for a homogeneous layer for various values of Young's modulus and the curves of $\varepsilon(t)$ for various hole sizes in the contact region shows that if

$$\frac{H}{h} \approx \frac{E}{E^*}, \tag{1}$$

the calculation results are fairly close. Hence, if condition (1) is satisfied, the region of contact between rough surfaces of blocks in problems of propagation of elastic strain waves can be approximately modeled by a homogeneous layer.

This work was supported by the Russian Foundation for Basic Research (Grant No. 05-01-00728) and the Integration project of the Division of Energetics, Machinery, Mechanics, and Control Systems of the Russian Academy of Sciences No. 4.11.2.

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