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NUMERICAL SIMULATION OF PROTECTION FROM HIGH-VELOCITY ELONGATED PROJECTILES

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Creation of a reliable system of protection for barriers requires investigation of various means for opposing high-velocity elongated projectiles. This paper considers the interaction of projectiles with explosively oppositely flung systems of smooth composite (layers of a tungsten alloy and ceramics) and finned plates as well as with different combinations of rods made from a number of materials. At the moment of contact the rods and the projectile form a cross-shaped configuration. The deformation and destruction of the projectile reduce its penetrability and the possibility of piercing the casing of the object being protected. The paper considers the collision of the formed fragments of rods with protective barriers.

KEY WORDS: *high-velocity impact, destruction, composite and rod systems, elongated projectiles*

1. INTRODUCTION

Creation of reliable means for protecting structures from being affected by high-velocity elongated projectiles-rods dictates the necessity of devising various means of opposing the piercing of barriers by rods.

The most wide-spread method of protecting objects is the use of materials with high physical and mechanical properties of the type of ceramics and composites based on it. A ballistic impact on ceramics and the impact properties of monolithic ceramics were considered in (Field et al., 1989; Ruiz, 1989; Kanel et al., 1996). Lamellar barriers make it possible to prevent damage and destruction of protected constructions either by extending the pressure pulse in a lamellar system due to the multiple reflection of waves from the layers with different acoustic impedances or by the dissipation of the pressure pulse energy in the case of plastic deformation of highly porous interlayers or by crushing ceramic materials.

The second possible method of opposing high-velocity projectiles is the flinging of systems of plates and rods made from traditional and composite materials. As a result of intense dynamic interaction there occur deformation and partial destruction of rods, as well as the deviation of the rods from the collision line. As a result, a rod either rebounds from the barrier surface or deviates from the protected object and does not interact with the barrier. All of these factors reduce the penetrability of projectiles and decrease the probability for the casing of protected object to be pierced.

2. GENERAL RELATIONS

The equations that describe the spatial adiabatic motion of a rigid medium are differential corollaries of the fundamental mass, momentum, and energy conservation laws. Generally they have the form given in (Stanyukovich, 1975; Wilkins, 1967, 1984). These equations must be supplemented with the relations that account for the corresponding thermodynamic effects associated with the adiabatic compression and rigidity of the medium.

To describe the resistance of a body to shear we use the relations given in (Stanyukovich, 1975; Wilkins, 1967, 1984). The equations of state of a solid body were taken in the Mie–Grüneisen form (Kanel et al., 1996; Stanyukovich, 1975). As the criterion of shear failure we used the criterion of the limiting equivalent plastic deformation $\varepsilon^p = \varepsilon_*^p$ (Kreinhagen et al., 1970). In this case, when ε^p attains the limiting value ε_*^p, the computational cell is considered to be destroyed.

The process of destruction of actual materials is determined to a great extent by the internal structure of the medium, therefore to improve the correspondence of a numerically simulated process to experimental data it is necessary to introduce disturbances into the physical and mechanical characteristics of the medium being destroyed, i.e., to assign random distribution of the factors that determine the strength properties of a material. In the present work, we use the variant of simulating the probabilistic mechanism of destruction when the physical and mechanical characteristics of the medium responsible for the rigidity are considered to be distributed randomly over the volume of the material. The probability density of the distribution of these parameters is taken in the form of distribution laws generally depending on the tabulated (average) value of the distributed parameter, on the variable dispersion of the distribution of this parameter. The natural fragmentation of projectiles and barrier is calculated on introducing the probabilistic mechanism of the distribution of initial defects of material structure for describing cleavage and shear cracks. The initial inhomogeneities were simulated by the limiting equivalent plastic deformation being distributed over the shell cells with the aid of a modified random number generator that yields a random quantity obeying the distribution law selected.

The system of basic equations is supplemented with needed initial and boundary conditions. At the initial instant of time all the points of a projectile have an axial velocity V_0 with account for its sign, with the state of the barrier being assumed undisturbed. The boundary conditions are set out as follows: at the boundaries free of stresses the condition $\sigma_n = T_n = 0$ holds. At the place of contact between the bodies the condition of ideal slipping of one material relative to the other along the tangent and the impermeability condition over the normal are formulated: $\sigma_{n1} = \sigma_{n2}$, $v_{n1} = v_{n2}$, $\tau_{n1} = \tau_{n2} = 0$, where σ_n and τ_n are the normal and tangential components of the stress vector; v_n is the normal component of the velocity vector at the point of contact; subscripts 1 and 2 relate to the contacting bodies.

To calculate elastoplastic flows we use the procedure realized on tetrahedral cells and based on the joint use of the Wilkins method to calculate the internal point of the body and the Johnson method to calculate contact interactions (Wilkins, 1967; Johnson et al., 1979; Johnson, 1981). The partition of the three-dimensional region into tetrahedrons is done successively with the aid of the programs of automatic grid generation. The ideology and methodology of the application of the probabilistic approach to the problem of destruction of solid bodies are considered most completely in (Gerasimov, 2007).

3. TEST CALCULATIONS

We considered the problem on expansion of a copper shell with a steel ring on it under the action of detonation products (Gerasimov, 2007).

The computational grid used in this calculation has about 500,000 tetrahedral cells. To describe destruction, we used the method of bifurcation over nodes and the formation of the destruction surface. To model he initial inhomogeneities we used the distribution of the limiting value of equivalent plastic deformation over the cells of the computational grid by the normal law with dispersion of 10% deviation.

As the ring was expanded, we observed the localization of deformations at the tips of the radial cracks formed on initial inhomogeneities and the formation of rather large fragments. The calculated spectrum of fragments agrees quite satisfactorily with the experimental data of (Diep et al., 2004).

In a three-dimensional formulation we considered the problem on piercing a two-layer barrier (glass-cloth-base laminate ST-NT + alloy D16) by a small ShKh-15 steel sphere (Gerasimov and Pashkov, 2013). We calculated the collision of the sphere with the barrier along he normal to the latter's surface. The velocity of the projectile was 700 and 900 m/s. A comparison of numerical results with experimental data showed satisfactory agreement.

In a three-dimensional formulation we considered the problem on piercing two- and three-layer barriers (steel–ceramics, steel–ceramics–steel) by a cylindrical projectile made from a tungsten alloy (Gerasimov and Pashkov, 2013). A comparison of numerical (num) results with experimental (exp) data (Gerasimov, 2007) showed good agreement of residual lengths (l_{num} and l_{exp}) and velocities (V_{num} and V_{exp}) of the projectile for the cases of two-layer and three-layer barriers. The two-layer barrier had: $l_{\text{exp}} = 37$ mm, $V_{\text{exp}} = 1120$ m/s; $l_{\text{num}} = 35$ mm, $V_{\text{num}} = 1200$ m/s. The three-layer barrier had $l_{\text{exp}} = 11.5$ mm, $V_{\text{exp}} = 890$ m/s; $l_{\text{num}} = 10.0$ mm, $V_{\text{num}} = 855$ m/s.

4. RESULTS OF NUMERICAL SIMULATION

We carried out calculations of the means of affecting a high-velocity elongated tungsten-alloy projectile approaching the barrier. The length of the projectile is $L = 0.654$ m, its radius $R = 0.012$ m, and the velocity $V = 1500$ m/s. In the first case, steel plates of different thicknesses were flung opposite to the projectile, in the second case these were tungsten-alloy plates, also of different thicknesses. In all of the variants the velocity of the flung plates was 1000 m/s, directed along the normal to the barrier. The thickness of the steel barrier was 5 cm, the angle of the barrier deviation from the vertical was 60°. The initial configuration of the barrier–plate–projectile system is presented in Fig. 1. Figure 2 contains the results of calculations of

FIG. 1: Initial configuration of the barrier–flung plate–projectile system

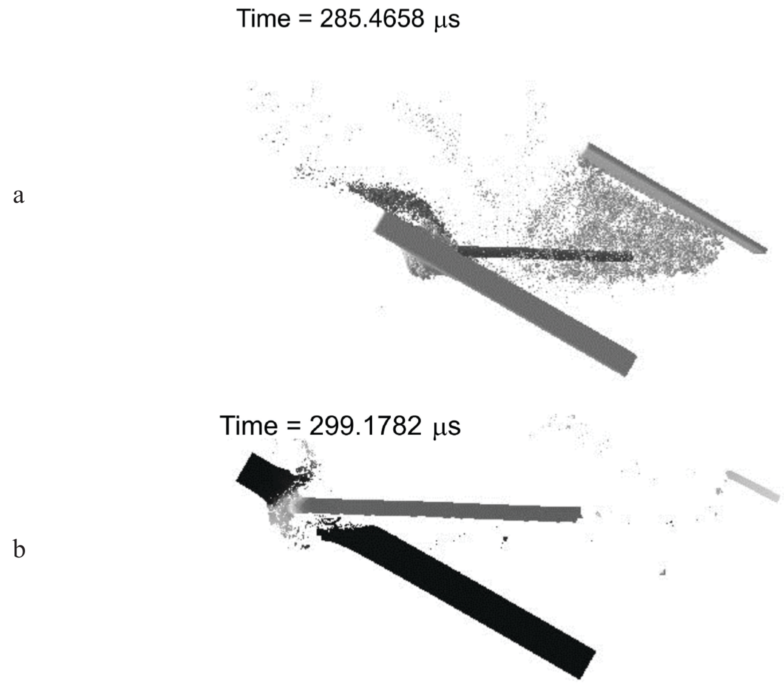


FIG. 2: Interaction of the projectile with the flung steel plate ($H = R$) and barrier: a) three-dimensional picture; b) two-dimensional section of the three-dimensional computational domain

the interaction of the projectile with a steel plate whose thickness H was equal to R. Its is seen from Fig. 2 that the projectile was slightly bent, but this deviation from the rectilinear initial form exerted not any influence on the piercing of the barrier and on the formation of a powerful flow of fragments behind the rear surface of the barrier.

An increase of the plate thickness H up to $1.4R$ led to a greater bending of the projectile (Fig. 3), to the enlargement of the region of destroyed material of the barrier, and to the increase in the quantity of barrier fragments behind the rear and frontal surfaces of the barrier.

Thus, we see that the action of the thicker plate did not improve the protection of the object. Therefore as the next step we calculated the interaction of the projectile with tungsten-alloy plates (Fig. 4) that are denser and have higher physical and mechanical characteristics.

When the projectile is acted upon by a plate of thickness $H = R$ there occur the destruction of the projectile along the surface of contact with the plate, the bending of its axis from the cylindrical symmetry, and slipping along the barrier surface with its insignificant damages (Fig. 4).

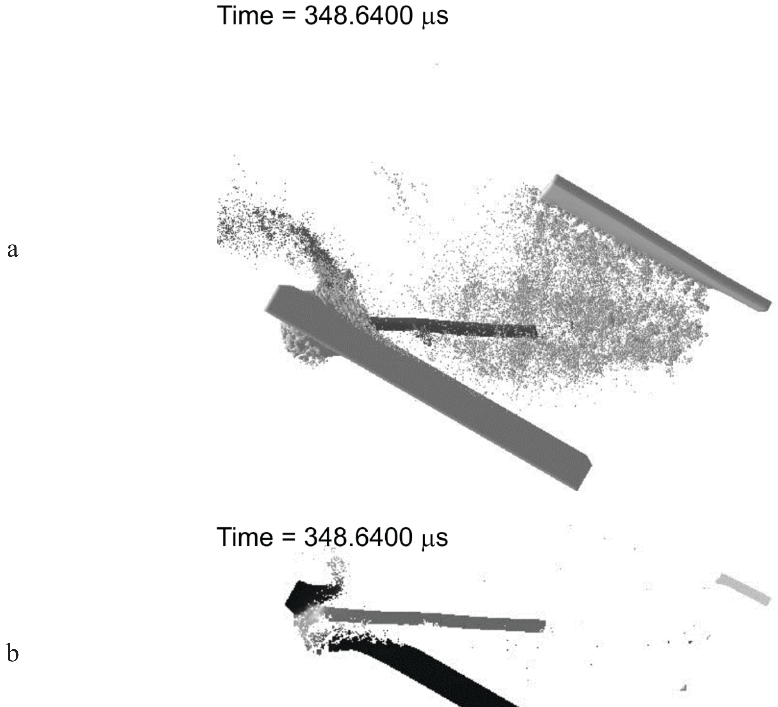


FIG. 3: Interaction of the projectile with a flung steel plate ($H = 1.4R$) and barrier: a) three-dimensional picture; b) two-dimensional section of the three-dimensional computational domain

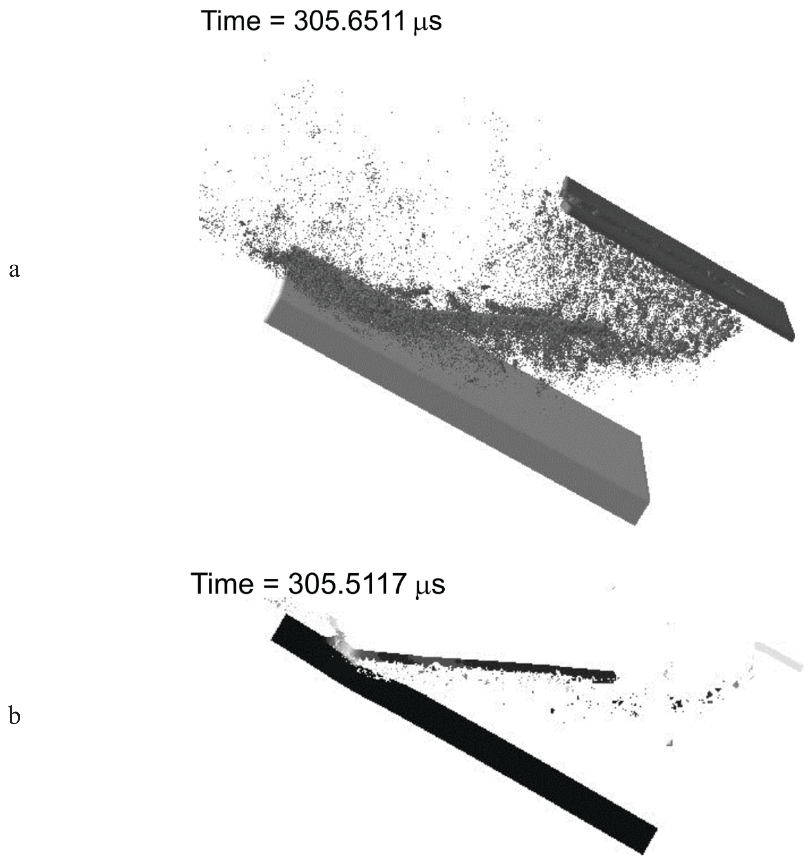


FIG. 4: Interaction of the projectile with a flung tungsten-alloy plate ($H = R$) and barrier: a) three-dimensional picture; b) two-dimensional section of the three-dimensional computational domain

When a plate of thickness $H = 4R$ is used (Fig. 5), its action on the projectile, as compared with the previous variant, is distinguished by more intense destruction of the projectile and by its sliding along the barrier surface. The barrier surface is destroyed less than in the previous case where the thickness of the plate H was equal to R.

Thus, it is seen from the investigations carried out that an increase in the density and in the physical and mechanical characteristics of the material of flung plates improves their protective properties leading to bending, destruction, and rebounding of the high-velocity elongated projectiles. It should be noted that an increase in the plate thickness leads to an increase in the expenditure of the material for their manufacturing and in the amount of the explosive needed for flinging the plates with needed velocity. It should be noted that in this case the loading of an explosive on the protected barrier increased, which is undesirable at all.

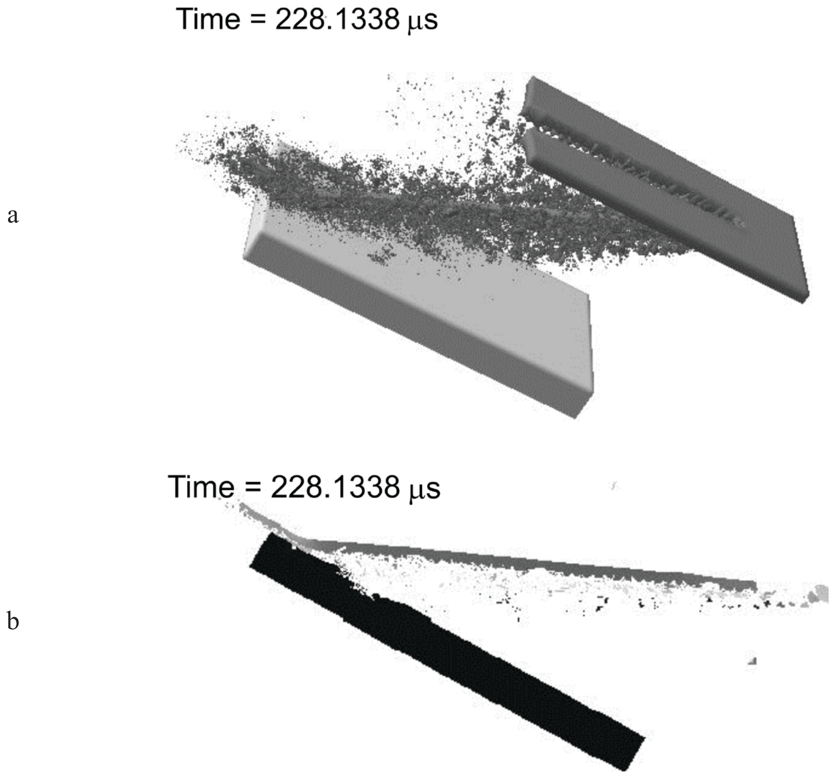


FIG. 5: Interaction of the projectile with a flung tungsten-alloy plate (H = 1.4R) and barrier: a) three-dimensional picture; b) two-dimensional section of the three-dimensional computational domain

The results of the interaction of a projectile with four tungsten-alloy rods are presented in Figs. 6 and 7. The rods are located across the barrier, forming a cross-shaped configuration with the approaching projectile.

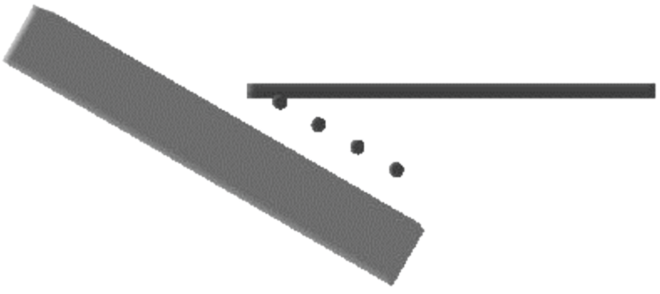


FIG. 6: Initial configuration of the barrier–four rods–projectile system

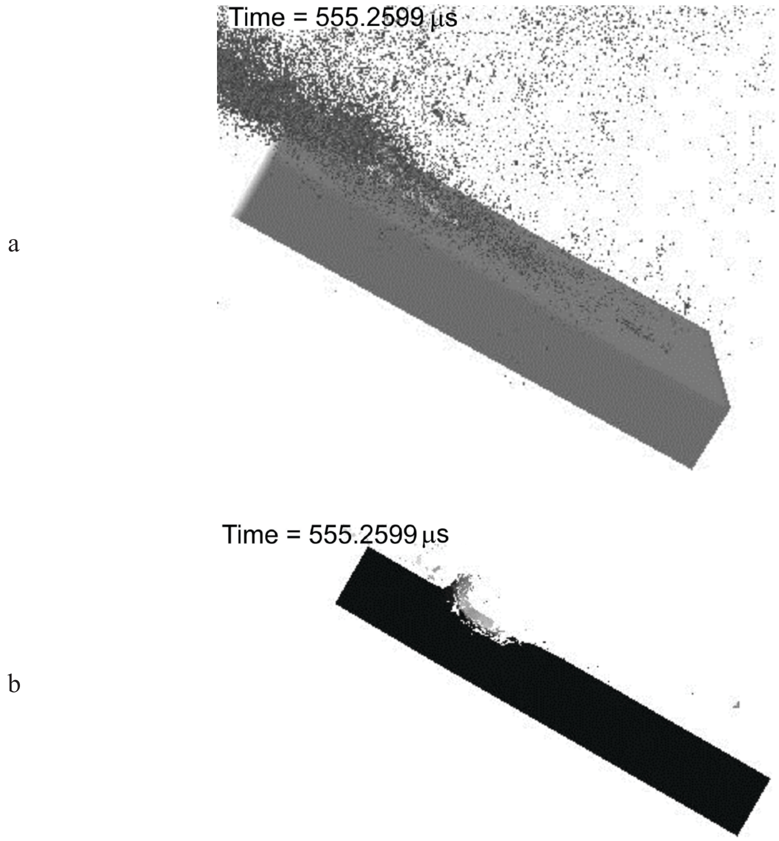


FIG. 7: Interaction of the projectile with rods and barrier: a) three-dimensional picture; b) two-dimensional section of the three-dimensional computational domain

In this case, we observe quite a different picture in the course of flinging the tungsten-alloy rods at the projectile. It is seen from Fig. 7 that during the interaction intense crushing of both the rods and of the projectile takes place. The remaining projectile tail rebounds from the barrier surface, which was destroyed only slightly.

The next construction that was flung consists of two previous systems: the plates and rods (Fig. 8).

The use of a finned plate for protection alters the picture of its interaction with the projectile. The fins deform the rod, forming a system of waves clearly seen in Fig. 9b. Subsequently the waves are destroyed and the resulting fragments rebound from the barrier surface. The computationally observed damages of the barrier are insignificant and involve only the surface layer of the material.

In the present work, we carried out calculations of three other possible variants of the action on a high-velocity elongated tungsten-alloy projectile approaching the barrier. In the first case, two tungsten-alloy plates were flung at the projectile (Fig. 10),

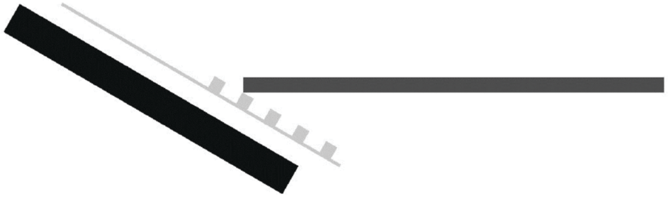


FIG. 8: Initial configuration of the barrier–finned plate–projectile system

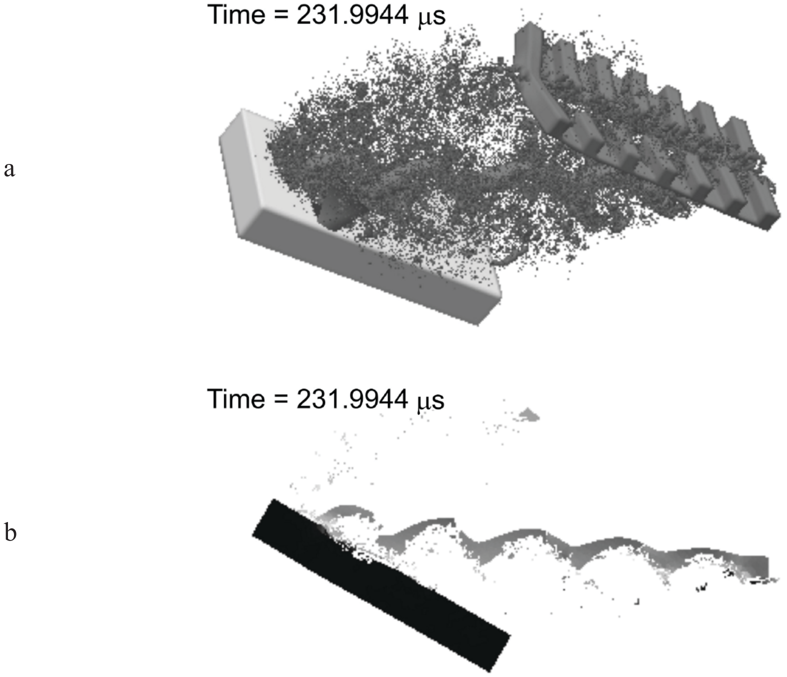


FIG. 9: Interaction of a rod with a flung finned plate and barrier: a) three-dimensional picture; b) two-dimensional section of three-dimensional computational domain

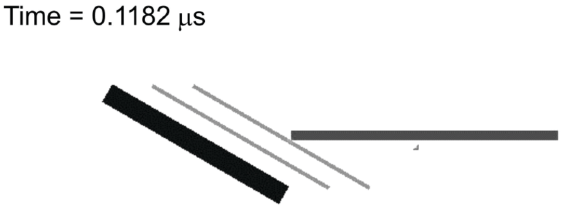
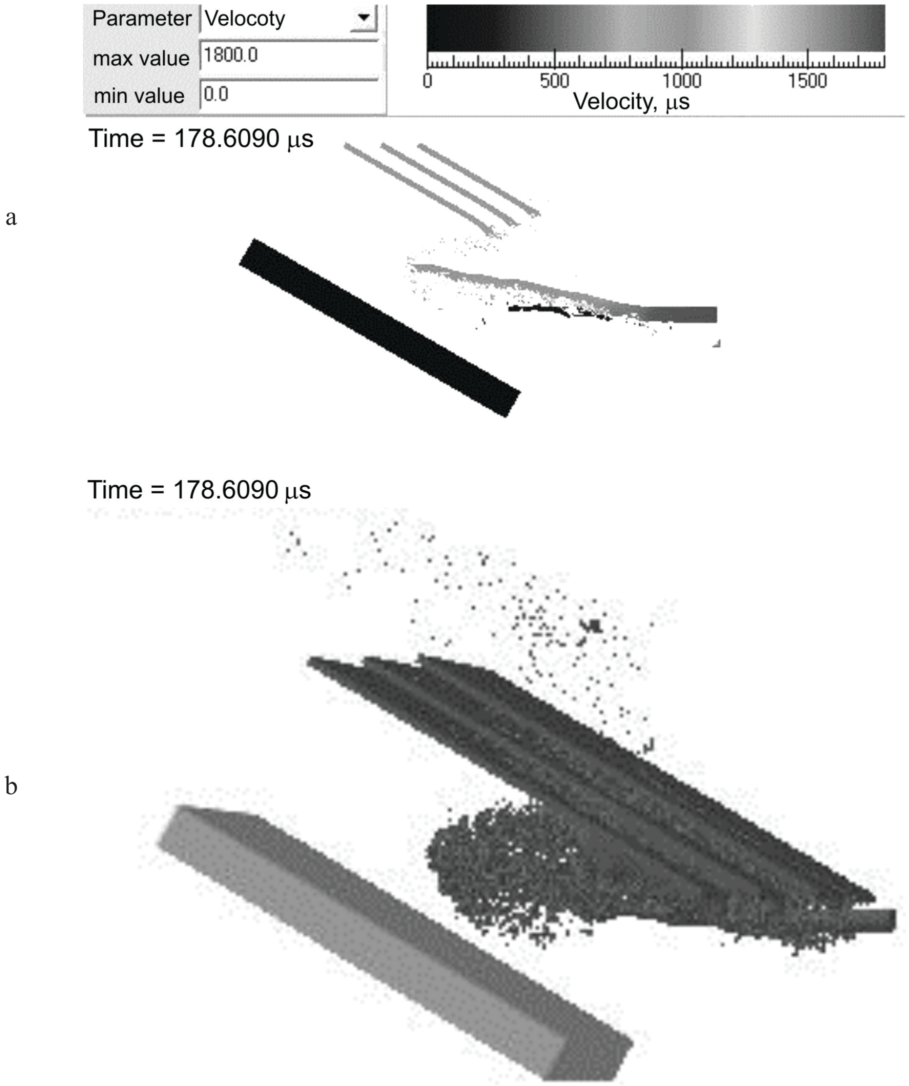


FIG. 10: Initial configuration of the barrier–two plates–projectile system

in the second case three tungsten-alloy plates (Fig. 11), and in the third case it was a three-layer plate (Fig. 12). In the latter case, a layer of ceramics was inserted between two tungsten layers. The physical and mechanical characteristics of the ceramics are given in (Gerasimov, 2007). In all of the variants, the velocity of the flung elements was 1000 m/s and was directed along the normal to the barrier. The barrier had a thickness of 5 cm, the angle of its deviation from the vertical 60°. The projectile had



Parameter Velocoty
max value 1800.0
min value 0.0

FIG. 11: Interaction of the projectile with three plates at the moment t = 178 μs: a) two-dimensional section of the three-dimensional computational domain; b) three-dimensional picture of collision

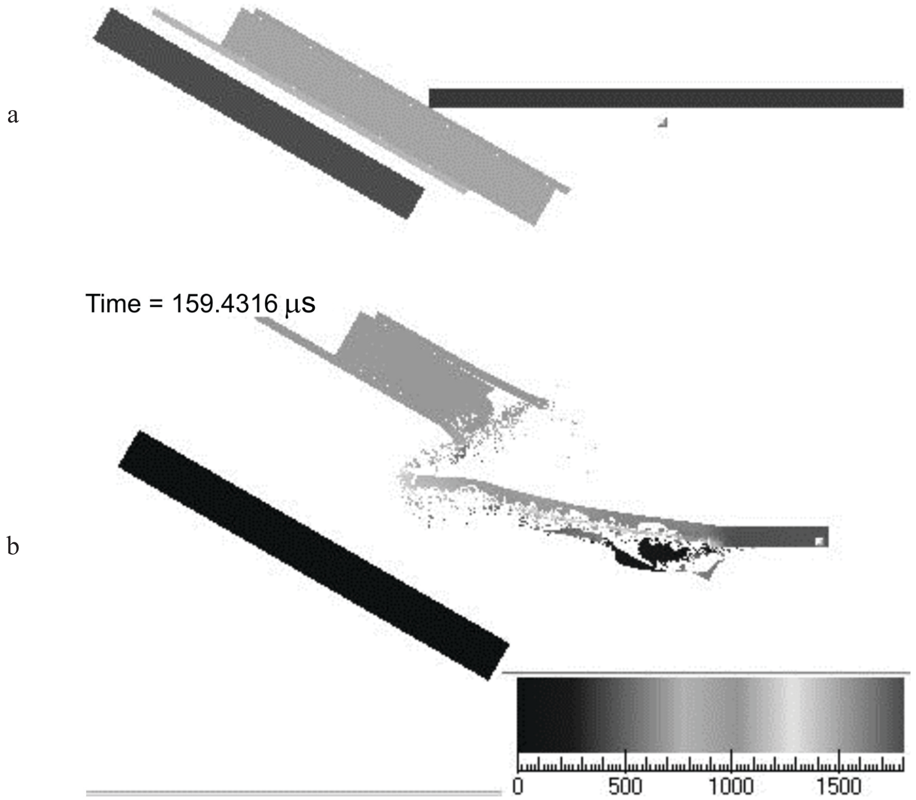


FIG. 12: Interaction of the projectile with a three-layer plate (the middle layer is made from ceramics) at the moment *t* = 159 µs: a) initial configuration of the barrier–two plates–ceramics–projectile system; b) two-dimensional section of three-dimensional computational domain for velocity distribution

a length of 65.4 cm, diameter 2.44 cm, and velocity 1800 m/s. In all of the cases, the tungsten-alloy plates were 25-cm-wide and 50-cm-long, with a thickness of 1 cm.

The interaction of a rod with two plates (Fig. 13) leads to destruction of the material on the rod surface that comes in contact with the plates along most part of rod length. Simultaneously the rod deviates from its initial line of flight. This becomes well evident by the 150 µs of the projectile flight. As is seen from Fig. 14 (307 µs), in the course of the further interaction the rod continues to be destroyed further and deviate more significantly from the initial direction of motion. Its frontal part slides along the barrier surface causing noticeable damages of the latter. When the projectile interacts with three plates, its contacting surface is destroyed more and it deviates more from the direction of collision already by the 178 µs, which leads to the rebounding of the projectile from the barrier surface and preserving the integrity of the latter. Such a character of deformation and destruction of the rod can be attributed to the succession of impacts on the plates.

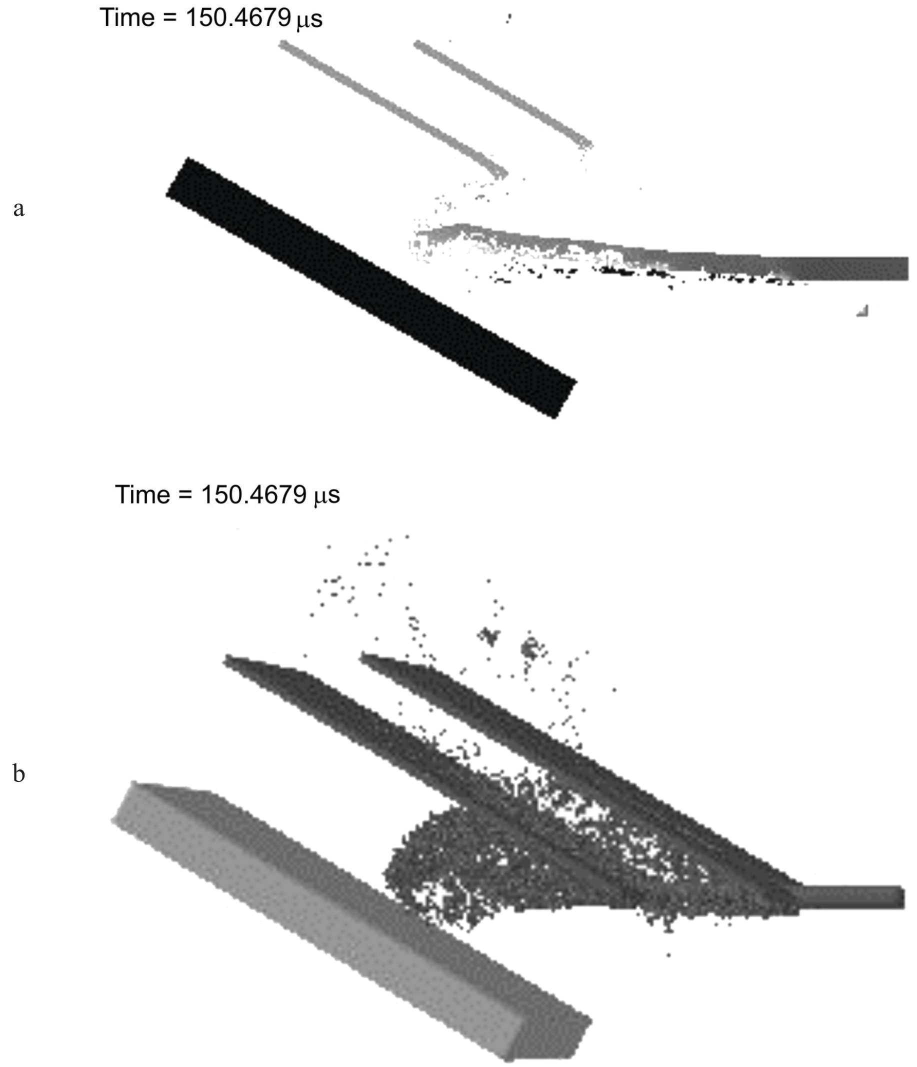


FIG. 13: Interaction of the projectile with two plates at the moment t = 150 μs: a) two-dimensional section of three-dimensional computational domain; b) three-dimensional picture of collision

Each subsequent impact acts on the preliminarily deformed and partially destroyed part of the rod enhancing the action of the previous plates.

In contrast to the above-given results for three tungsten-alloy layers the replacement of the middle layer by a thicker ceramic one (Fig. 12) prolongs the time of interaction of the projectile with the two plates + ceramics system. The action of the ceramic layer causes more intense destruction of the projectile in the zone of their contact and its considerable deviation from the initial trajectory of motion toward the barrier.

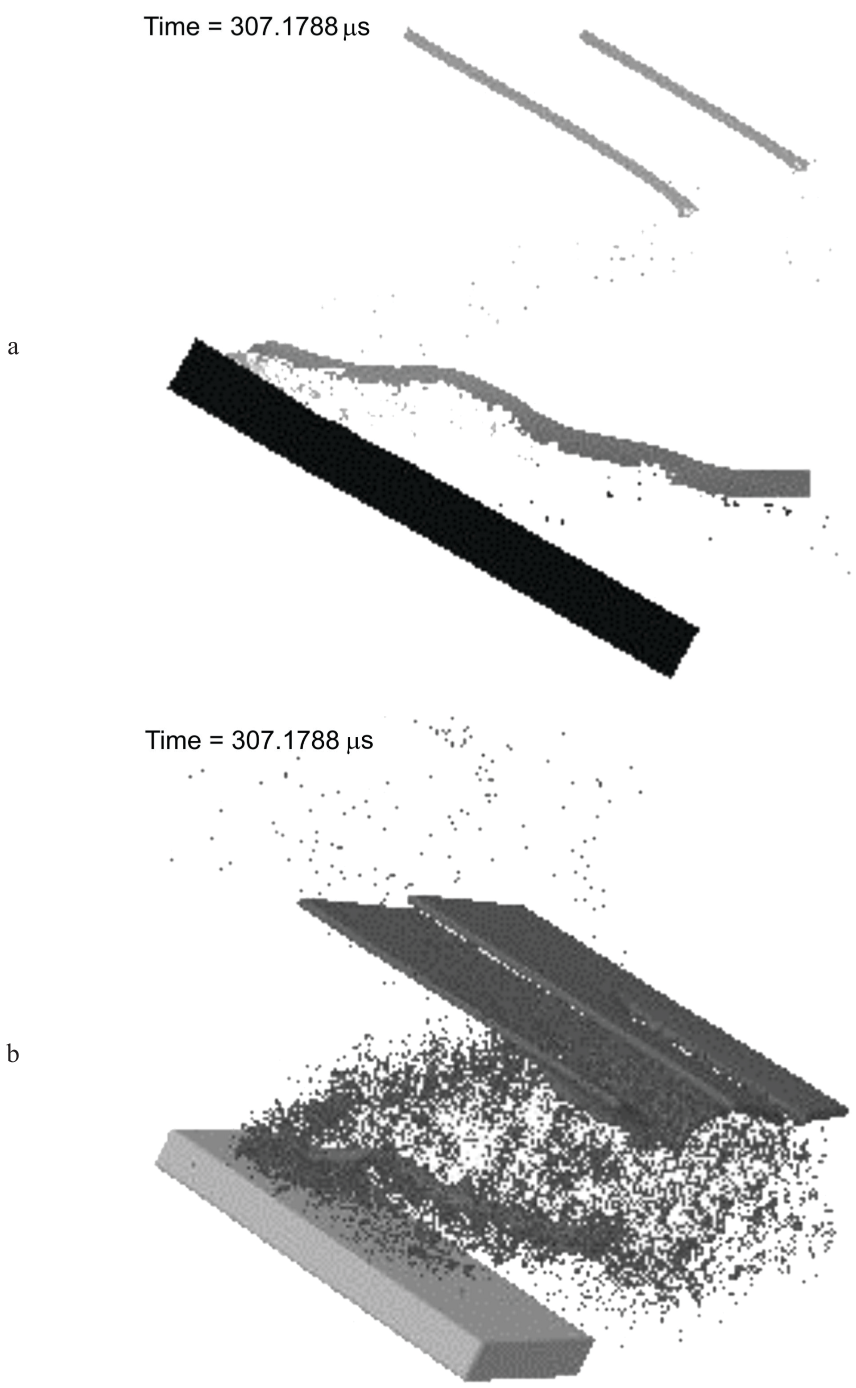


FIG. 14: Interaction of the projectile with two plates at the moment t = 307 μs: a) two-dimensional section of three-dimensional computational domain; b) three-dimensional picture of collision

5. CONCLUSIONS

The aim of the present work was to numerically simulate the spatial processes of deformation and destruction of high-velocity projectiles by the elements of multilayer composite systems and various combinations of rods flung at them, as well as to investigate the action of the fragments of high-velocity projectiles on the main protected barrier. The problems are solved in three-dimensional formulation, because such an approach makes it possible to investigate the processes of dynamic loading by the most real means. The flung multilayer plates include layers made from metal alloys and ceramic materials.

The results of calculations presented in the paper demonstrated that the proposed approaches afford the possibilities of reducing the penetrability of a projectile. In the case of intense dynamic interaction, there occur deformation and destruction of rods, as well as the deviation of rods from the line of collision with a barrier. As a result, the rods are either destroyed or they rebound from the surface of the barrier, or deviate from the protected object and do not interact with it. All these factors reduce the penetrability of projectiles and the probability of piercing the casing of the object being protected. The calculations also showed that the developed three-dimensional numerical technique makes it possible to simulate the processes of high-velocity interaction of long projectiles with laminated plates with ceramic interlayers, with spaced plates, rods, and finned constructions, as well as of the fragments of projectiles with protected objects on collision along the normal and at an angle to the surface of the objects in a wide range of velocities and angles of collision and to investigate the processes of fragmentation of rods and barriers and the character of the fragmentation fields being formed.

The procedure developed accounts for the probabilistic character of the fragmentation of colliding bodies, which leads to the three-dimensional character of the problem even in the case of impact along the normal to the barrier surface. The carried out comparison of theoretical and experimental data showed good agreement of the results, which makes it possible to use the developed technique for calculating mechanical engineering constructions subjected to impact loads and selecting the most effective combinations of materials and geometric parameters of flung elements.

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