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Numerical simulation of high-velocity projectile interactions with groups of spaced rods and plates

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Abstract

The study of the problem of protecting the elements of constructions from impact loadings is very important due to the constant perfection of the means of shock-wave impact on the objects of modern technology. Creating of a reliable way to protect structures from destruction by high-velocity elongated projectiles dictates a need to develop different ways to counter the penetration into target.

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Keywords: Projectiles; protection; plates and rods;numerical simulation;

1. Introduction

The interaction of projectiles with plates and rods which are thrown towards projectile by HE is investigated. The problem is solved in 3-D statement in view of natural heterogeneity of real materials structure affecting distribution of physical-mechanical characteristics along the volume of the elements of the construction and being one of the factors, defining destruction character of the latter. The necessity to account the given factor for equations of deformable solid mechanics dictates the application of probabilistic laws of distribution of physical-mechanical characteristics into the volume of the construction under consideration. The equations describing spatial adiabatic movement of the strong compressible solid are differential result of fundamental laws of conservation of mass, pulse and energy. In general they have the following form [1-3].

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To calculate elastoplastic flows used technique implemented on tetrahedral cells and based on the combined use of the Wilkins method [4] for calculation of internal body points and Johnson method [5] for calculating contact interactions. The most common way to protect objects is to use materials with high physical and mechanical properties, such as ceramics and composites based on it. Layered barrier enable prevent damage and destruction of protected structures or stretching of the pressure pulse in the layered system due to multiple reflection of waves from layers with different acoustic impedances, or pressure pulse energy dissipation during plastic deformation of highly porous layers or fragmentation of ceramic materials.

The second possible way to counter high-velocity projectiles is to throw groups of spaced plates and rods from conventional and composite materials towards projectiles. As a result of the dynamic interaction and intense deformation occurs the partial destruction of the projectiles or the deviation projectiles from the line of collision. Consequently, the projectiles can rebound from the surface barrier, or deviate from the object to be protected and do not interact with the barrier. All these factors reduce the penetration of projectiles into the protected object. In this work numerical simulation of the interaction of high - velocity projectiles with groups of spaced rods and plates is carried out.

2. The equations describing the motion of a compressible elastic-plastic body taking into account probabilistic nature of fracture

The equations describing spatial adiabatic motion of a solid compressible medium are differential consequences of the fundamental laws of conservation mass, pulse and energy. In general they have the following forms [1-3]:

continuity equation

$$\frac{1}{\rho}\frac{d\rho}{dt}+\frac{\partial v_i}{\partial x_i}=0; \tag{1}$$

equation of motion

$$\rho\frac{dv_i}{dt}=\rho F_i-\frac{\partial P}{\partial x_i}+\frac{\partial S_{ij}}{\partial x_j}; \tag{2}$$

energy equation

$$\rho\frac{dE}{dt}=S_{ij}\varepsilon_{ij}+\frac{P}{\rho}\frac{d\rho}{dt}, \tag{3}$$

where x_i - the coordinates; t - time; ρ_0 - the initial density of the medium; ρ - the current density of the medium; v_i - components of the velocity vector; F_i - components of mass forces vector; S_{ij} - components of stress tensor deviator; E - specific internal energy; ε_{ij} - components of deviator of strain rate tensor; P - pressure.

To equations (1) - (3) we must add the equations taking into account relevant thermodynamic effects associated with adiabatic compression and strength of the medium. In general case, under the influence of the forces on the solid-deformable body, both volume (density) and the shape of the body are changed by different dependencies. Therefore, stress tensor is the sum of spherical tensor and the stress tensor deviator.

$$\sigma_{ij}=S_{ij}-P\delta_{ij},\ i,j=1,2,3,$$
$$\delta_{ij}=1,\quad i=j,$$
$$\delta_{ij}=0,\quad i\neq j,$$

where δ_{ij} - the Kronecker delta.

To describe shear strength of the body the following relations are used:

$$2\mu(e_{ij}-\frac{1}{3}e_{kk}\delta_{ij})=\frac{DS_{ij}}{Dt}+\lambda S_{ij}; \tag{4}$$

$$\frac{DS_{ij}}{Dt}=\frac{dS_{ij}}{dt}-S_{ik}\omega_{jk}-S_{jk}\omega_{ik}; \tag{5}$$

$$2\omega_{ij}=\frac{\partial v_i}{\partial x_j}-\frac{\partial v_j}{\partial x_i}; \tag{6}$$

$$2e_{ij}=\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}, \tag{7}$$

as well as the condition of plasticity

$$J_2=\frac{1}{2}S_{ij}S_{ij}=\frac{1}{3}\sigma^2, \tag{8}$$

where e_{ij} - the components of the strain rate tensor; μ - shear modulus; σ - dynamic yield stress; D/Dt - Yauman derivative.

The equation of a solid state was chosen in the form of Mi-Gruneisen

$$P=\frac{K(1-\Gamma_0\xi/2)}{(1-c\xi)^2}\xi+\rho_0\Gamma_0E, \tag{9}$$

where Γ_0 - Gruneisen coefficient; c, K - constant of the material; ρ_0 - the initial density of the medium; $\xi=1-\rho_0/\rho$.

As a shear failure criterion we used the criterion of limiting equivalent plastic strain [6] $\varepsilon^p = \varepsilon_*^p$. In this case, when ε^p reaches the limit value ε_*^p the calculated cell is considered to be destroyed. The system of equations (1) - (9) is written in a general form for the special motion of a deformable body.

The process of destructing the real materials is largely determined by the internal structure of the medium, the presence of heterogeneities, usually caused by a different orientation of the grains in the polycrystalline material or heterogeneities in the composition of composite materials, the difference in the micro-strength inside the grain and on the intergrain or interface boundaries. Therefore, to improve compliance of numerically simulated process with the experimental data it is necessary to generate disturbances in physical-mechanical characteristics of the medium being destroyed, i.e. to set a random distribution of the factors determining strength properties of the material. The introduction of information about polycrystalline structure of the material into calculation technique required a large amount of experimental data and increased requirements for computer power that limited the ability of the implementation and apply this approach. In view of this, we used a simplified version of probabilistic modeling of fracture mechanism. Physical and mechanical characteristics of the medium responsible for strength are assumed to be randomly distributed over the material volume. The distribution probability density of these parameters is taken as various distribution laws, which are generally dependent on table (average) value of the parameter being distributed, dispersion of the parameter distribution being varied, and other characteristics of the medium. Such parameters as yield strength, tensile strength, maximum strains and other constants, that define the moment of destruction in various theories of strength and fracture criteria, are directly dependent on the number and size of defects and should be randomly distributed over the volume with dispersion depending on material homogeneity.

Natural fragmentation of projectiles and barrier is calculated by introducing probabilistic mechanism for distribution of the initial defects of the material structure to describe tear and shear cracks. As a criterion of failure under intense shear strains we used the achievement of limiting values by equivalent plastic deformation. The initial heterogeneities were simulated so that the maximum equivalent plastic strain was distributed into membrane cells using a modified random number generator, which gave out a random variable obeying to the distribution law selected.

The system of basic equations is added with necessary initial and boundary conditions. At the initial moment of time all points of the projectile have axial velocity V_0 in view of its sign and the barrier state is assumed to be unperturbed. The boundary conditions are as follows, namely, the conditions $\sigma_n = \tau_n = 0$ are satisfied on borders free from stress. Conditions of ideal sliding of one material relative to another along the tangent and impermeability along the normal are set on contact sites between the bodies: $\sigma_{n1} = \sigma_{n2}, v_{n1} = v_{n2}, \tau_{n1} = \tau_{n2} = 0,$ where , σ_n, τ_n are the normal and tangent components of the stress vector; n v is the normal component of the velocity vector at the point of contact; subscripts 1 and 2 refer to the bodies being in contact.

To calculate the elastic-plastic flows we used a technique implemented on tetrahedral cells and based on joint application of the Wilkins method for calculating interior points of the body and the Johnson method for calculating the contact interactions [4, 5,7]. Three-dimensional domain was successively partitioned into tetrahedrons with subroutines of automatic meshing. The ideology and methodology of applying a probabilistic approach to fracture of solids are completely described in [8].

3. Calculation results

The interaction of the rod with two or three plates, thrown in the opposite direction, was previously considered in [8]. In this paper, for the further development of the approach to plates throwing, the interaction of tungsten alloy rod with four plates of similar alloy is considered. The plates moved towards the rod and away from it. The distance between the plates was varied.

Rod radius – 1.2 cm, length – 65.4 cm. Plate thickness - 1 cm, barrier thickness – 5 cm, the angle of projectile deviation from normal was 60º. The sizes the plates and the barrier: width = 15 cm, length = 60 cm, the angle of deviation from the horizontal surface was 30º. The distance between plates and that between plates and the barrier h1, h2, h3 and h4 was varied for different tasks. Projectile velocity V = 2000 m/s, velocities of plates along the normal to the surface and along the surface of the plates V_1, V_2, V_3, V_4 and the distances between the plates also were varied for different tasks. Fig. 1 shows the location of the projectile and the barrier with the plates at the initial time.

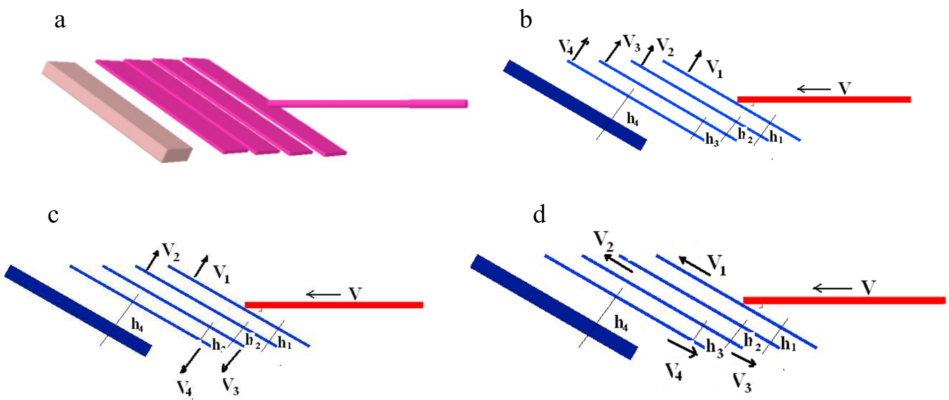

Fig. 1. (a) three-dimensional pattern; (b) 2-D cross-section of a three-dimensional computational domain (the velocity of the plates is directed towards the projectile); (c) 2-D cross-section of the three-dimensional computational domain (the velocity of two plates is directed towards the projectile, and that of other two plates is directed in the opposite direction); (d) 2-D cross-section of the three-dimensional computational domain (the plates velocity is directed along the plane of the barrier);

a b

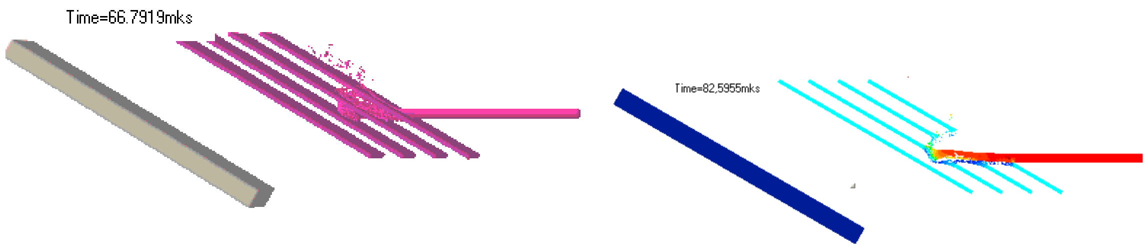

Fig. 2. (a) projectile interaction with the plates (the plate velocity is directed along the normal to the surface); (b) 2-D cross-section of the three-dimensional computational domain

Figure 2 presents the calculations of four plates throwing (Fig. 1, b) at a velocity of 1000 m/s towards the normal to the surface of the plates. The interaction of colliding bodies caused minor damage to the projectile and its deviation from the axially symmetric shape.

a b

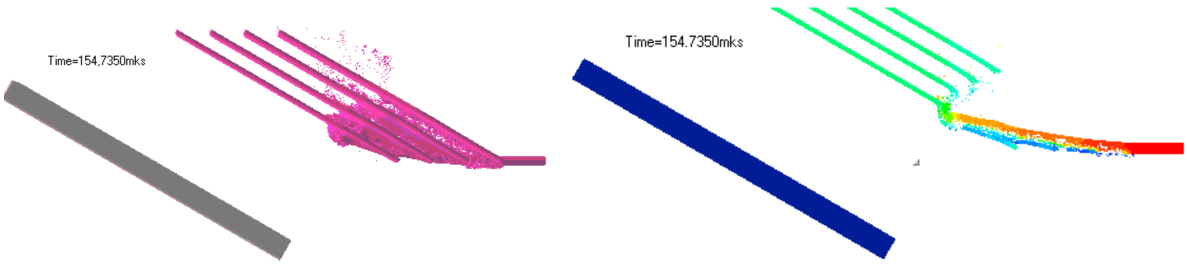

Fig. 3. (a) projectile interaction with the plates (the plate velocity is directed at an angle of 600 to the plates surface); (b) 2-D cross-section of the three-dimensional computational domain

The deviation of the velocity vector from the normal to plates by 300 noticeably changed the pattern of the plates interaction with the projectile (Fig. 3). The damage to the contact surface of the projectile and its deviation from the original direction of impact significantly increased. The deformed part of the projectile was almost parallel to the barrier surface; it can lead to ricocheting or target overflying.

a b

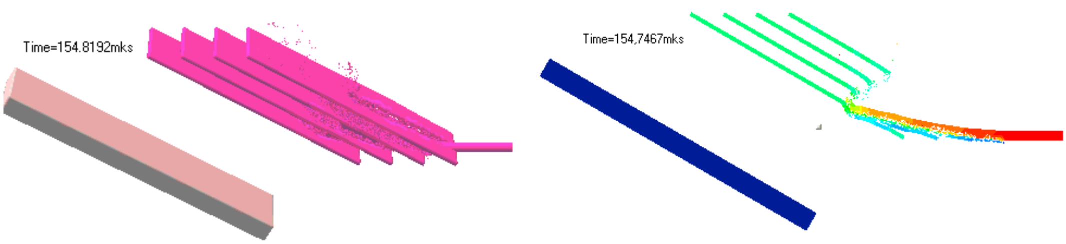

Fig. 4. (a) projectile interaction with the plates (the plate velocity is directed at an angle of 450 to the surface); (b) 2-D cross-section of the three-dimensional computational domain

Figure 4 presents the projectile interaction with the plates, where the vector of velocity deviated from the normal to the plates by 450. It noticeably changed the pattern of destruction and projectile deviation as compared with Fig. 3 and thereby increased probability of ricocheting and projectile deviation from the barrier.

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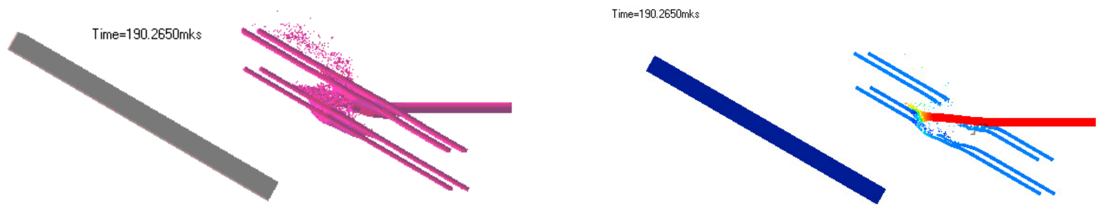

Fig. 5. (a) projectile interaction with sliding plates (Fig.1, d); (b) 2-D cross-section of the three-dimensional computational domain

The effect of plates sliding along their surface at a velocity of 500 m/s (Fig.1, d) is presented in Figure 5. After penetration through the first two plates, the fore part of the projectile was sliding over the third and fourth plates. Projectile deviations and damage were considerably less pronounced than in the cases shown in Figs. 3 and 4.

a b

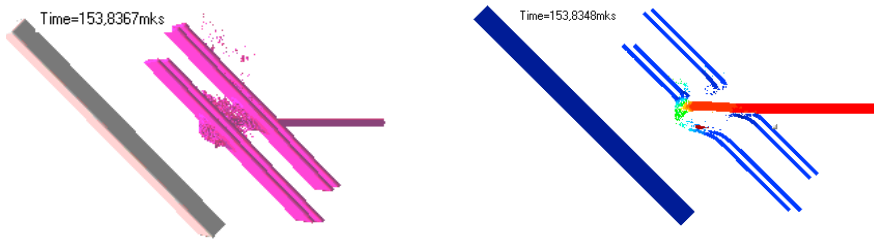

Fig. 6. (a) interaction with sliding plates (Fig.1, d), the angle - 450; (b) 2-D cross-section of the three-dimensional computational domain

Increasing the angle of the barrier and plates inclinations to a horizontal surface up to 450 caused penetration of all four plates and slight deformation of the projectile(Fig.1, d).

The next figures demonstrates the interaction of the spaced-apart rods with a high-speed projectile.In this case, we observe an intensive destruction and a sharp decrease in the destructive capability of the projectile.

a b

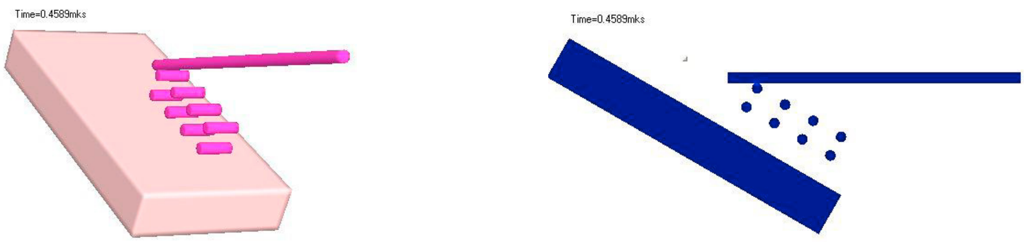

Fig. 7. (a) initial configuration of "barrier - rods- projectile" system; (b) 2-D cross-section of a three-dimensional computational domain.

a b

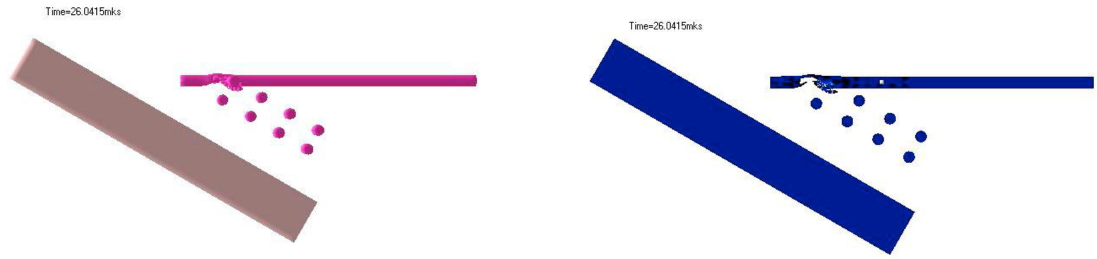

Fig. 8. (a) projectile interaction with rods; (b) 2-D cross-section of a three-dimensional computational domain, time = 26 μsec

a b

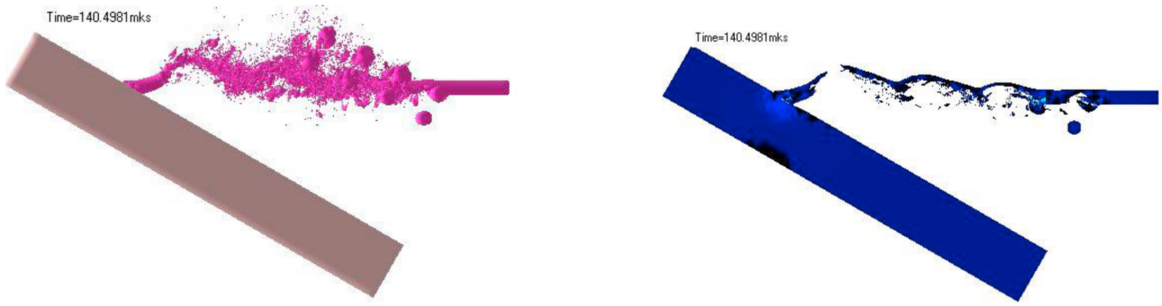

Fig.9. (a) 3-D configuration of "barrier - rods- projectile"; (b) 2-D cross-section of a three-dimensional computational domain, time = 140 μsec.

The figures demonstrates the interaction of the spaced-apart rods with a high-speed projectile. In this case, we observe an intensive destruction and a sharp decrease in the destructive capability of the projectile. Based on the obtained calculations, we can conclude about the two possible methods of protection against high-speed projectiles: the destruction and the flight-path deviation of projectiles resulting in ricocheting of projectiles

4. Conclusions

The calculations demonstrated that the group of plates reduced possible destruction of the protecting barrier. The most effective was plates throwing at the velocity vector directed at an angle of 45^0 to the barrier surface. The other variants with the plates had less pronounced protective effect.

The calculations proved that the proposed approach and a numerical method developed on its basis enable to simulate interactions of high-velocity long projectiles with protection systems in a wide range of velocities and collision angles and to investigate the processes of projectile and barriers fragmentation, as well as the nature of the emerging fragmentation fields.

Acknowledgements

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