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STRUCTURAL MECHANICS AND STRENGTH OF FLIGHT VEHICLES

Numerical Simulation of High-Velocity Element Collisions with Shell and Filler of Aerospace Structures

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Abstract—The fracture pattern of shells with a filler at collision with high-speed projectiles is analyzed. The special features of the projectile and barrier fragmentation and formation of debris fields, and the impact of the shock wave on the filler are revealed.

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INTRODUCTION

It is necessary to study local pulse pressure impact, including shock loading, on the shells with fillers in order to improve protection of up-to-date technique objects and to assess possible accident consequences, etc. The collision of the shell with filler and barriers at an angle was considered in [1]. Experimental and theoretical studies on detonation of high explosive, shielded with a metal shell, at offset impact by steel balls were carried out in [2]. Numerical simulation of laminated plate penetration at an angle with the surface is given in [3]. Approaches to numerical modeling of fracture of solids under intense dynamic loading are considered in [4].

In this paper, we consider some problems of penetration and destruction of shells with solid fillers by projectiles, interacting not only normally but also at an angle to the surface of the shell, in three-dimensional formulation. The problems are solved in a Lagrangian formulation for a wide range of velocities (up to 7000 m/s) taking into account crushing of the material of the interacting bodies.

One of the factors determining destruction behavior of real materials is the natural heterogeneity of their structure, which affects the distribution of physical and mechanical characteristics (PMC) of the material in the volume of the body under study. For crushing being simulated to reflect real behavior of crushable bodies during the experiments, it is necessary to take into consideration natural heterogeneity in the equations of solid mechanics. This is possible using the probability laws of PMC distribution in the volume of the structural element. For that it is necessary to add a random distribution of the initial deviations of the strength properties from the nominal value to physical and mechanical characteristics of the body (simulation of the initial defect structures of the material).

GENERAL RELATIONS

The equations describing the spatial adiabatic motion of a solid compressible medium are differential consequences of the fundamental laws of mass, momentum and energy conservation. In general case, these are the equations of continuity, motion and energy, which have the form described in [5–7]. These equations must be supplemented by the equations considering the relevant thermodynamic effects associated with the adiabatic compression and the strength of the medium. Generally, a deformable solid body changes under the influence of forces in volume and shape by different laws. Therefore, the stress tensor is the sum of spherical tensor and the stress tensor deviator.

The Prandtl–Reuss equations and the von Mises plasticity condition were used to describe the body shear resistance, the equation of the solid state was chosen in the Mie-Grüneisen form [5–7].

The criterion of limit equivalent plastic strain was chosen as a shear fracture criterion [8]. In this case, the computational cell is considered destroyed, if the shear fracture criterion is satisfied. The system of basic equations was complemented with the necessary initial and boundary conditions. At the zero time all projectile points have the axial velocity V_0 according to its sign and the state of barriers is supposed to be unperturbed. The boundary conditions $\sigma_n = \tau_n = 0$ are met on the borders that are free of stress: In a contact area between the bodies, the condition of ideal sliding of one material relative to the other along the tangent and normal condition of impermeability $\sigma_{n1} = \sigma_{n2}$, $v_{n1} = v_{n2}$, $\tau_{n1} = \tau_{n2} = 0$ are met, where σ_n, τ_n are the normal and tangential components of the stress tensor; v_n is the normal component of the velocity vector at the contact point; subscripts *1* and *2* refer to the contacting bodies.

Simulation was performed using the software complex developed in the Research Institute of Applied Mathematics and Mechanics and oriented on high-explosive shock fracture tasks. For three-dimensional process simulation the complex uses the Lagrangian Wilkins method [6, 7] implemented on the tetrahedral mesh. Johnson's method [9, 10] is used to calculate the contact interactions and free boundaries that significantly simplifies the tracking of free boundaries mass-produced in the fragmentation. To describe the destruction, the method of splitting on nodes is used and the initial application of the material inhomogeneity in the PMC to describe the probability of destruction is provided. Three-dimensional space subdivision into tetrahedron is implemented sequentially with automatic meshing routines. The complex offers opportunities for the process visualization. The calculation time depends on the number of calculated cells.

Natural projectile and target fragmentation is calculated by introducing the probabilistic mechanism of distribution of the initial structure defects of the material to describe spall and shear cracks. The property of the equivalent plastic deformation to attain its limit is used as a failure criterion under intense shear deformations [5, 8]. The initial heterogeneity is simulated by distribution of limit equivalent plastic strain in the computational space cells using the modified random number generator, which produces a random variable subjected to the distribution law chosen. Densities of the random variables probability are defined as a normal Gaussian distribution with the arithmetic mean equal to the tabulated value and variable dispersion.

TEST CALCULATIONS

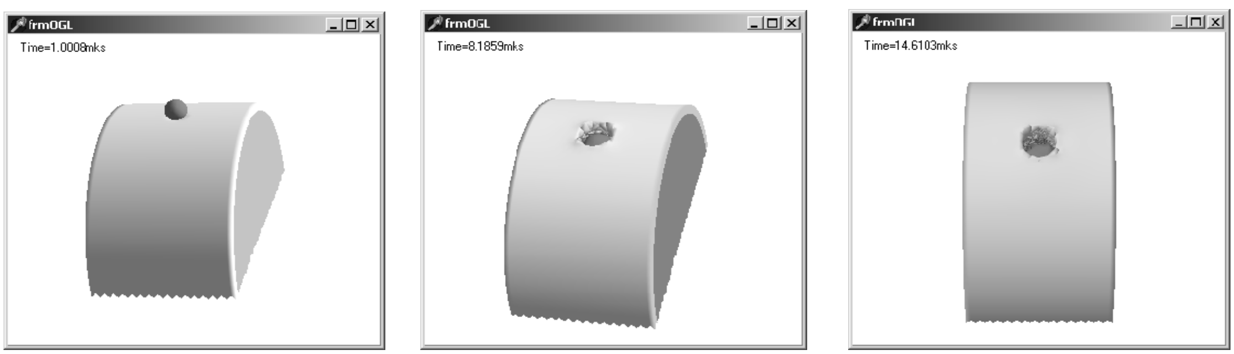
The problem of the two- and three-layer barriers penetration (steel–ceramics and steel–ceramics–steel) by the cylindrical projectile of tungsten alloy in the three-dimensional formulation is considered in [11]. Comparison of numerical results and the experimental data [12] showed a good agreement between the residual lengths (l_c and l_{exp}) and speeds (V_c and V_{exp}) of the projectile, namely, l_{exp} = 0.037 m, V_{exp} = 1120 m/s; l_c = 0.035 m, V_c = 1200 m/s (two-layer barrier); l_{exp} = 0.115 m, V_{exp} = 890 m/s, l_c = 0.01 m; V_c = 855 m/s (three-layer barrier).

To reduce the calculation time, we consider only the upper shell part constituting half of the whole structure. This technique can be used in the case, when the double wave travel time to the boundary is greater than the time of the impact process. This condition is well satisfied for the shells, the radius of which is much larger than the penetration depth of the projectile. The methodology developed by the authors was used on the right and left ends, which enables the reflection of waves to be avoided and the loading of extended objects only on a limited part to be calculated. In [13], the case with non-reflective boundary conditions is described that permit transmitting the elastic-plastic waves beyond the computational domain boundaries without interfering reflections during the simulation of the finite portion of infinite space. On the example of the interaction of the projectile with the half-space in the three-dimensional formulation it was shown that this approach can reduce the size of the computational domain while maintaining accuracy.

THE RESULTS OF NUMERICAL SIMULATION

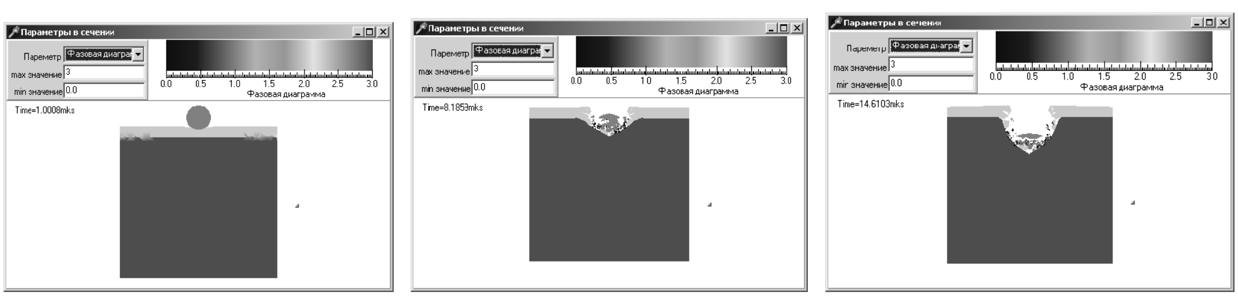
We considered the shell–filler collision with a ball of the tungsten–nickel-iron (TNI) alloy. The impact was normal and at an angle of 45° to the shell generatrix. The projectile speed is 2000 m/s. Dimensions of interacting objects are as follows: the length of the steel shell is 0.08 m; the outer radius is 0.075 m; the inner radius is 0.07 m, and the ball radius is 0.00635 m. The shell material is the steel having the following physical-mechanical characteristics, namely, the density ρ_0 = 7.7 g/cm^3, the shear modulus $G = 8.6\times10^{10}$ Pa, and the yield limit $\sigma_y = 9.4\times10^8$ Pa; the projectile is made of the TNI alloy, ρ_0 =17.1 g/cm^3; the filler has the following characteristics: ρ_0 = 1.75 g/cm^3, $G = 3.47\times10^9$ Pa, the yield limit $\sigma_y = 10^8$ Pa.

Figures 1–6 present the calculation results for three moments of time 1 μs (Figs. 1a–6a), 8 μs (1b–6b), and 15 μs (1c–6c). The spatial configurations of the ball–shell–filler system (Figs. 1a–1c), phase composition (TNI, steel, filler) (Figs. 2a–2c), and 2D cross sections showing velocity distribution in the calculated structure (Figs. 3a–3c) are presented for the case of a normal collision of the ball with a shell. The spatial configurations of the ball–shell–filler system for the same time points (Figs. 4a–4c), phase composition (TNI, steel, filler) (Figs. 5a–5c) are presented for the case of the ball collision with shell at an angle of 45°. Figures 6a–6c show 2D cross-sections for the velocity distribution in the ball–shell–filler system being considered.



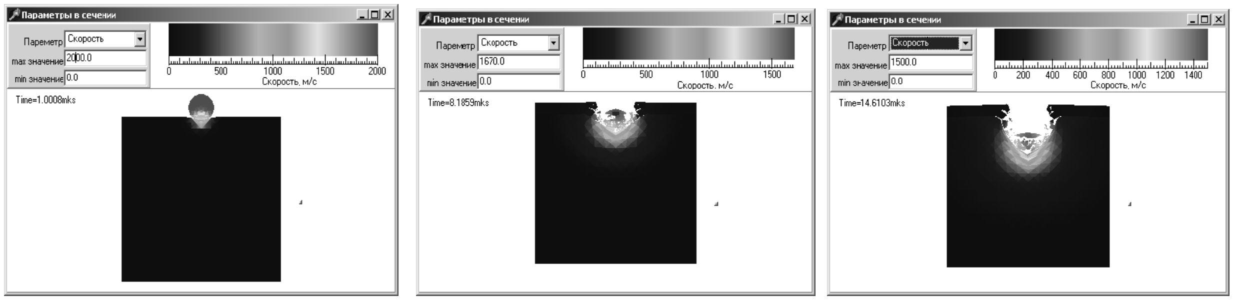
(a) (b) (c)

Fig. 1.



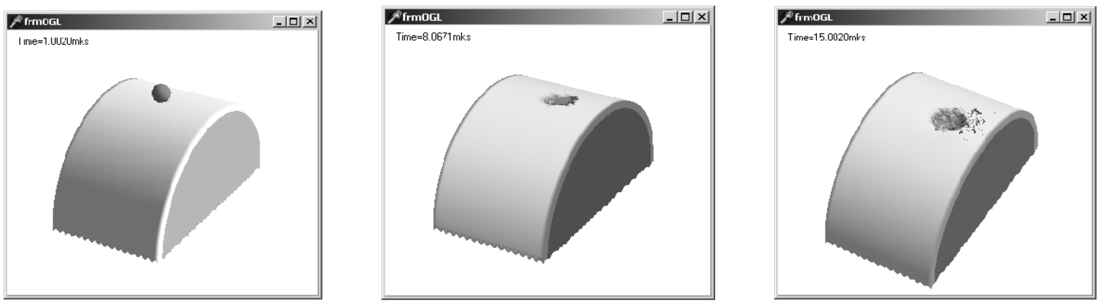
(a) (b) (c)

Fig. 2.



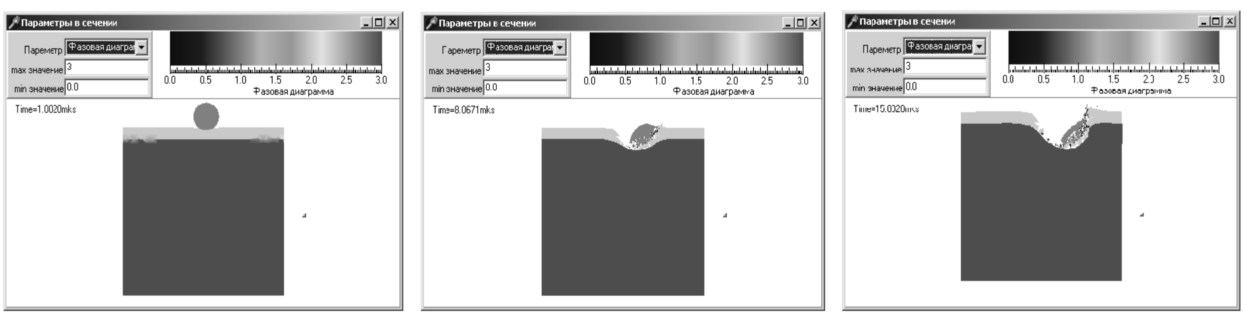
(a) (b) (c)

Fig. 3.



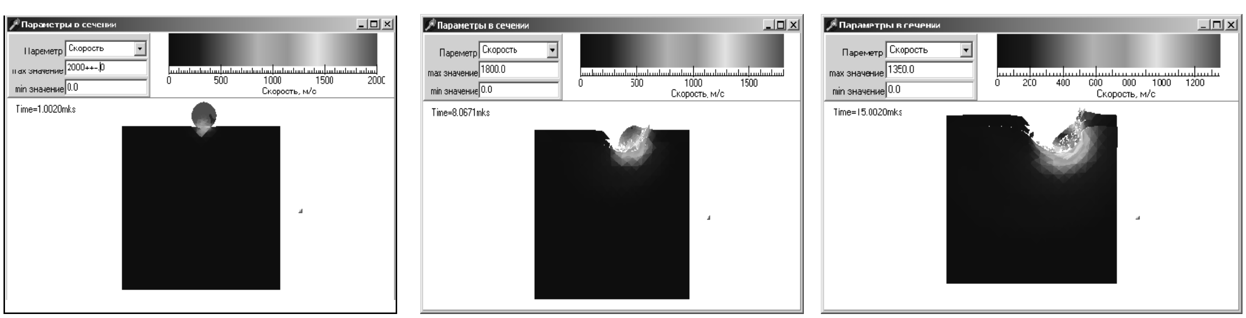
(a) (b) (c)

Fig. 4.



(a) (b) (c)

Fig. 5.



(a) (b) (c)

Fig. 6.

The process of interaction occurrs with intense crushing of the ball and shell and further penetration of fragments in the filler.

The change of pressure with time in the central point of the ball contact with the shell surface is shown in Fig. 7 (curve *1*), pressure change at a point on the inner side of the shell, which lies below the central point of the contact is illustrated by curve *2*. Similarly, curve *3* shows the change of pressure in the external point of the filler. On the curves presented one observes the pressure jump of different amplitude and its further drop with the time. In the case of reactive filler, a sufficiently high value of the pressure amplitude may cause its compromised undermine.

Ball motion in the liquid filler (water) at the penetration of a thin shell, the presence of which does not result in ball fragmentation, is shown in Fig. 8. The outer radius of the aluminum shell is equal to 0.035 m and the inner one is 0.033 m. The shell is 0.05 m long. A steel ball with a radius of 0.003 m was thrown at a velocity of 2560 m/s.

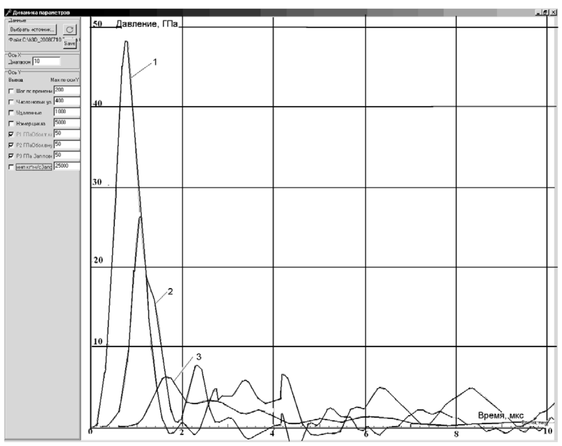


Fig. 7.

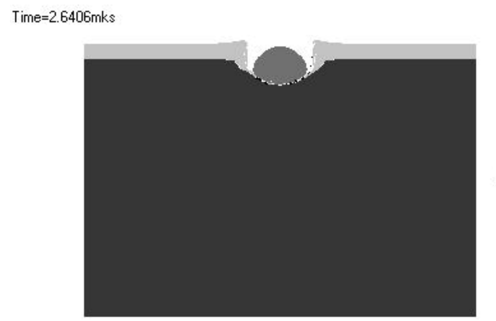
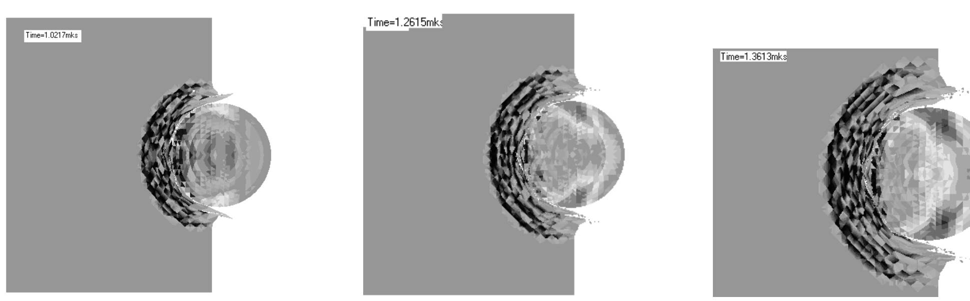


Fig. 8.

Figure 9 presents formation of the shock waves in the liquid and the evolution in time of tangential stresses in the ball.



(a) (b) (c)

Fig. 9.

As is seen from Fig. 9, during the ball penetration into water and shock wave propagation, on the external surface of the ball one observes the rise of tangential tensile stresses, which exceed the limiting values for that brittle steel and can cause separation of the ball into two parts. Since the stress pattern is symmetrical relative to the axis along which the ball moves, then to consider the destruction we used a probabilistic approach [4] to select the meridional crack. In Fig. 10 the formation of the meridional crack is observed in the ball bottom.

In order to verify the numerical simulation results, we compared the calculated data with the experimental results obtained previously in [14] on the vertical stand with the use of a powder gun caliber of 8 mm. A series of the experiments was carried out with velocities 800–2100 m/s, the procedure of the experiments was described in [14]. The stand includes a throwing ballistic installation with electromagnetic muzzle velocity sensor, a reservoir with the test medium into which a metal barrier is placed. A contact sensor recording the moment of the projectile body impact with the barrier is fixed on the barrier. For higher speeds we used the light-gas ballistic unit (LGU) MPH 23/8 and horizontal procedure of the experiment with throwing into evacuated track. LGU MPH 23/8 with a 8 mm caliber enables to have velocities up to 4500 m/s. It was found that when the velocity of the ball was about 2600 m/s, it began to destruct in water. The character of the ball destruction after the impact with water is shown in Fig. 11.

Fig. 10.

Fig. 11.

CONCLUSIONS

Studies have shown the influence of impact velocity, materials of projectile, shell and filler, as well contact angle of projectile with shell on the stress-strain state and the destruction process of the shell with filler and projectile. The results obtained show the capabilities of the proposed probabilistic approach and Lagrangian numerical method, in the complete from physical viewpoint three-dimensional formulation, to reproduce the processes of penetration of inhomogeneous structures with high-velocity elements and fragments of natural and specified crushing, to estimate the effect of the collision velocity, materials of projectile, shell and filler, and contact angle of the projectile with shell on the stress-strain state and the destruction of the shell and filler.

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