ECCOMAS Congress 2016
VII European Congress on Computational Methods in Applied Sciences and Engineering
M. Papadrakakis, V. Papadopoulos, G. Stefanou, V. Plevris (eds.)
Crete Island, Greece, 5–10 June 2016

NUMERICAL SIMULATION OF HIGH-VELOCITY INTERACTION ELEMENTS WITH THIN-WALLED STRUCTURES

Alexander V. Gerasimov[1], **Sergey V. Pashkov**[1]

[1] Tomsk State University
36, Lenin st., Tomsk, Russia
ger@niipmm.tsu.ru

Keywords: Numerical Simulation, Structure, Projectile, Fragmentation, Probability.

Abstract. *The process of high-velocity collision of the elements of thin-walled structures with spherical and elongated projectiles, simulating fragments of cosmic bodies, artificial objects, ice particles and damaging elements is considered in three-dimensional Lagrangian formulation. The problem is solved taking into account probabilistic nature of crushing the material of the interacting bodies. Collision proceeds as normal and at an angle to a barrier surface. The approach proposed to solve fragmentation problems enables to reproduce the processes of barriers breaking with high-velocity elements in three-dimensional formulation which is the most complete from the physical point of view. The processes of interaction of the streams of high-velocity elements with thin-walled enclosures at different angles of approach to the latter, as well as the behavior of enclosure fragments and element debris behind the first shell of the construction, are of great practical interest to ensure reliable operation of spacecrafts, aircraft and missile technology. The streams of high-velocity elements may have different physical nature. They may be man-made and natural meteoric particles in space, ice particles in the atmosphere and damaging elements in all media. In this paper we consider processes of plates breaking by clusters of spherical and elongated projectiles and fragmentation pattern, as well as the formation of debris streams in behind-the barrier space.*

1 INTRODUCTION

To solve problem high – velocity interaction a group of elements with thin-walled structures it is necessary to have a reliable and sufficiently universal method to enable adequate reproduction of the processes occurring in solids under high- velocity collision. The natural heterogeneity of the structures of barrier and projectile materials affects the distribution of physical-mechanical characteristics (PMC) of the material, and is one of the most important factors determining the fracture behavior of real materials. One can account for it in the equations of deformable solid mechanics using a random distribution of the initial deviations of the strength properties from a nominal value (simulating the initial heterogeneity of the material). The relations of deformable solid mechanics, used in major recent works on dynamic fracture of structures and materials, ignore this factor. It can distort a real pattern of impact and explosive fractures of the bodies under consideration. The latter is particularly evident in the solution of axisymmetric problems, where the properties at all points on the circumferential coordinate of a calculated element are initially equal due to the use of standard equations of continuum mechanics in the numerical simulation. However in practice there are many problems where fragmentation is mainly a probabilistic process, for example the explosive fracture of axisymmetric shells, where the fragmentation pattern is unknown beforehand. The introduction of a random distribution of the initial deviations of the strength properties from a nominal value in the PMC of the body leads to the fact that, in these cases, the process of fracture becomes probabilistic in nature, and more consistent with the experimental data. To calculate elastoplastic flows we used a procedure implemented on tetrahedral cells and based on the combined application of Wilkins method intended to calculate the internal points of the body and Johnson method to calculate contact interactions. The initial heterogeneities of the structure were simulated by imposing a distribution of ultimate equivalent plastic strain in the cells of the calculated domain by means of a modified random number generator issuing a random variable obeying the selected distribution law. The probability densities of the random variables used were in the form of a normal Gaussian distribution with arithmetical mean being equal to the tabulated value and variable dispersion.

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.

$$\sigma_{ij} = S_{ij} - P\delta_{ij},\ i, j = 1,2,3,$$
$$\delta_{ij} = 1, \quad i = j, \qquad \text{where } \delta_{ij} \text{ - the Kronecker delta.}$$
$$\delta_{ij} = 0, \quad i \neq j,$$

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

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

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 [4] $\varepsilon^p = \varepsilon^p_*$. 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 requires a large amount of experimental data and increased requirements for computer power that limits 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.

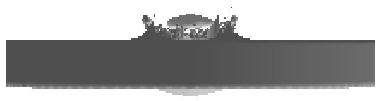
To calculate the elastic-plastic flows, use is made of a technique implemented on tetrahedral cells and based on joint application of the Wilkins method for calculating interior points of the body and the Johnson method for calculating the contact interactions [2, 5-6]. Three-dimensional domain was successively partitioned into tetrahedrals with subroutines of automatic meshing. The ideology and methodology of applying a probabilistic approach to solids fracture are completely described in [7].

3 TEST CALCULATIONS AND EXPERIMENTS

Figure 1 presents the results [8] of numerical simulation of ricocheting a steel ball-projectile with a diameter of 0.8 cm at interaction with a 0.95 cm-in-thick titanium barrier with a diameter of 8 cm for a time moment t=13.23 μs. The projectile initial velocity was 3600 m/s, angle of impact from the normal to the barrier was 75°.

In numerical study we obtained the following values of crater parameters, namely, a major crater axis was 30.5 mm, a minor axis - 15 mm and crater depth – 8.2 mm. The experimental data were characterized by the following values, namely, the major crater axis was - 28 mm, the minor axis was 16 mm and the crater depth was 7 mm.

a b



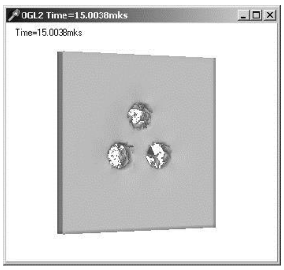
c d

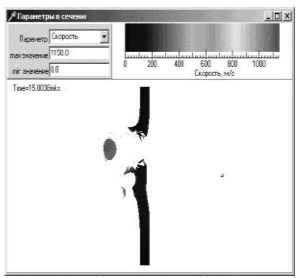
Figure1: Numerical simulation of a steel ball ricocheting at interaction with titanium barrier (t = 13.23 µs ; V = 3600 m/s; $\alpha = 75$ °): a - top view; c, d - a side and end views; b - experiment (photos of the steel ball in the initial state and the trace in the titanium plate after their interaction).

4 COMPUTATIONAL RESULTS

Previously, the interaction of cylindrical elements with barriers at lower angles of impact and erosion fracture mechanism making it impossible to consider the interaction of the fragments with each other and with the barrier was considered in [9, 10]. In [11], the authors numerically investigated the interaction of ice projectiles with the barriers made of aluminum alloy and asbotextolite. The problem was solved in a two-dimensional formulation for the case of axial symmetry.

In this paper, the interaction of a group of three steel balls with an aluminum plate is considered in three-dimensional formulation. A ball radius was 0.28 cm. The thickness of each plate - 0.35 cm sized 5x5 cm. The impact velocity is 1500 m/s. The balls were arranged in a circle of radius 0.75 cm.





a b

Figure 2: Configuration of balls - barrier system at instant of time $t = 15\,\mu s$ for impact angle of 0^0 from a normal: a - general view; b - plane section.

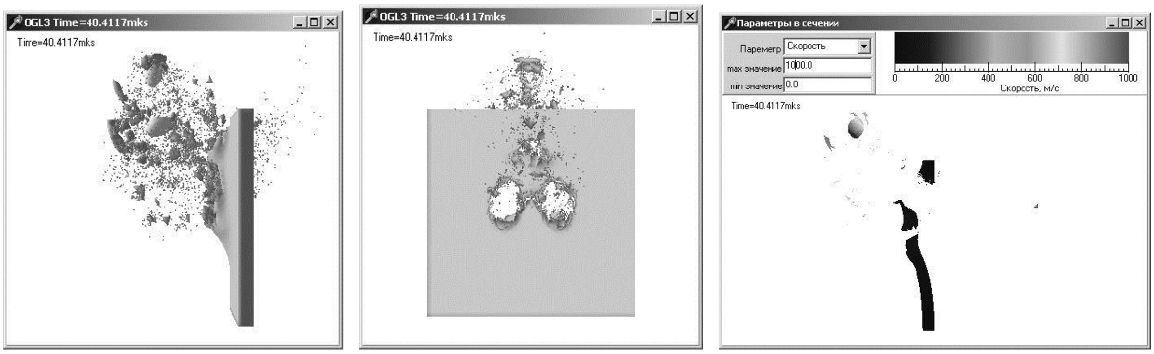
Figure 2 shows the results of interaction of an aluminum plate with a cluster of steel balls. As is seen from Figure 2 after the collision the area of undestroyed material between the holes was quite large and the velocity of projectiles after the barrier breaking fell to 1130 m/s (Figure 2,b). The increase in the impact angle to 45^0 (Figure 3) caused the decrease in the area of undestroyed material between the punched holes and the formation of a significant fragmentation flow behind the barrier.

a b c

Figure 3: Configuration of balls - barrier system at instant of time $t = 38,4$ μs for impact angle of 45^0 from the normal: a, b - general views; c - plane section.

Two left Figures 3a and 3b show different views of the punched holes and the fragmentation field. Plane section of balls - barrier system and velocity distribution in the section is shown in Figure 3c. Such presentation of the results obtained is used for the subsequent figures. In the case under consideration there are two leading balls, followed by the third one. The velocity of the balls after breaking fell to 980 m/s.

Changing the direction of the impact by 180^0 (Figure 4), when there is one leading ball, one can observe cracks in the bridges between the holes and the velocity of the projectiles also falls to 980 m/s.

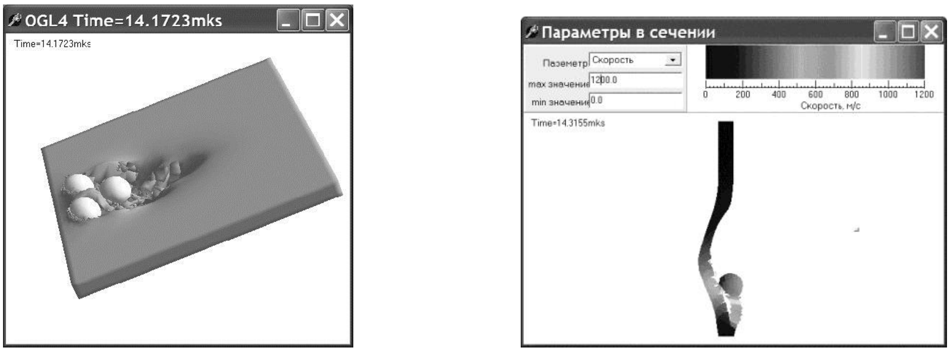


a b c

Figure 4: Configuration of balls - barrier system at instant of time $t = 40,4$ μs for impact angle of 45^0 from the normal: a, b - general views; c - plane section.

The next group of calculations was related to the study of projectile ricocheting at the following angles of impact: 70^0 (Figure 5), 75^0 (Figure 6) and 78^0 (Figure7). With the increase in the angle of impact the area of the deformed material and the values of aluminum plate deflections decreased. If at the angle of impact 70^0 (Figure 5b) we see the formation of cracks on the barrier face in the contact with the projectile, then for the angle of impact 75^0 (Figure

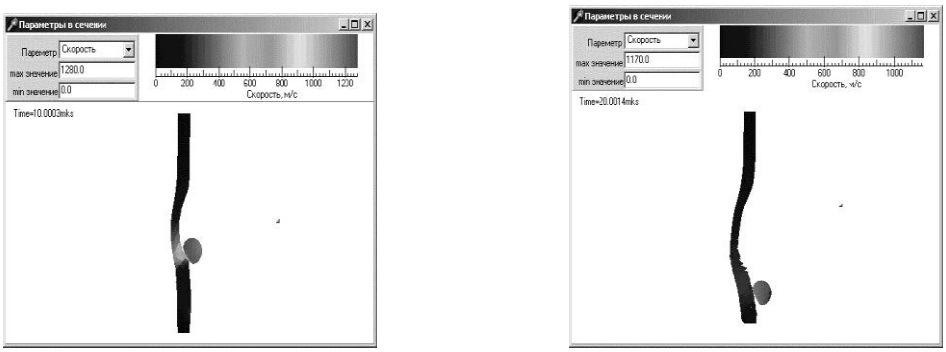
6d) the number and size of cracks decrease. At an angle of impact 78^0 (Figure 7d) one observes no cracks and reduced area of dents caused by balls-projectiles interactions with the plate.



a b

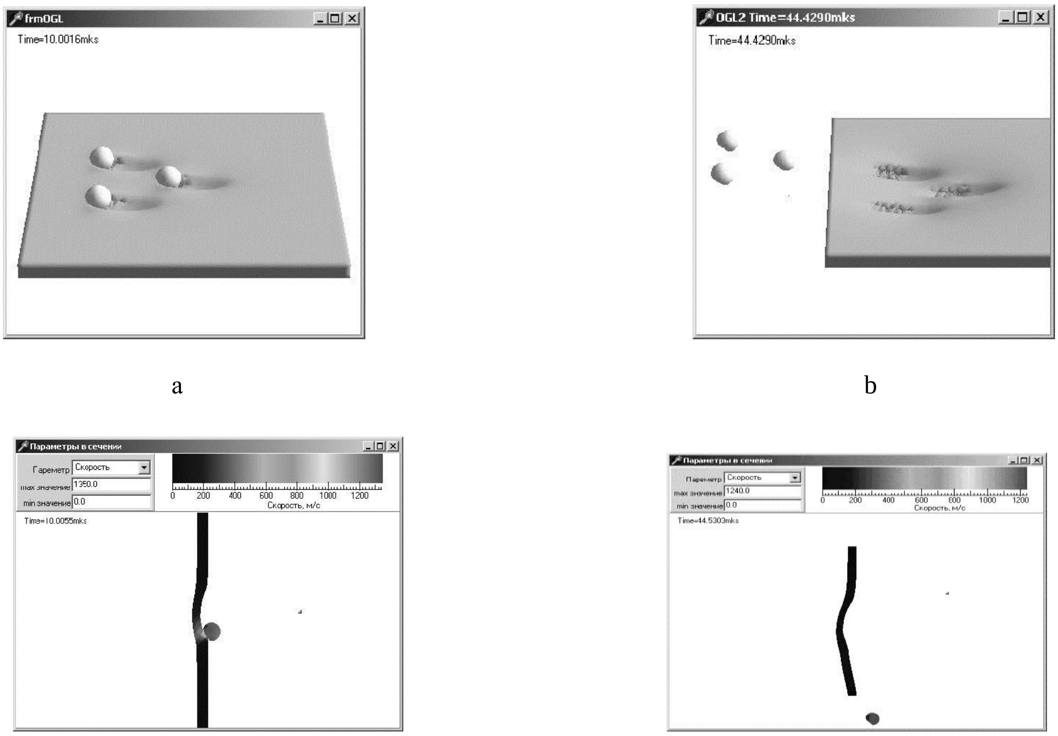
Figure: 5. Configuration of balls - barrier system at instant of time $t = 14{,}3$ μs for impact angle of 70^0 from the normal: a - general view; b - plane section.

a b



c d

Figure: 6. Configuration of balls - barrier system at instant of time $t = 10$ μs (a, c) and $t = 20$ μs (b, d) for the impact angle of 75^0 from the normal: a, b - general views; c, d - plane sections.

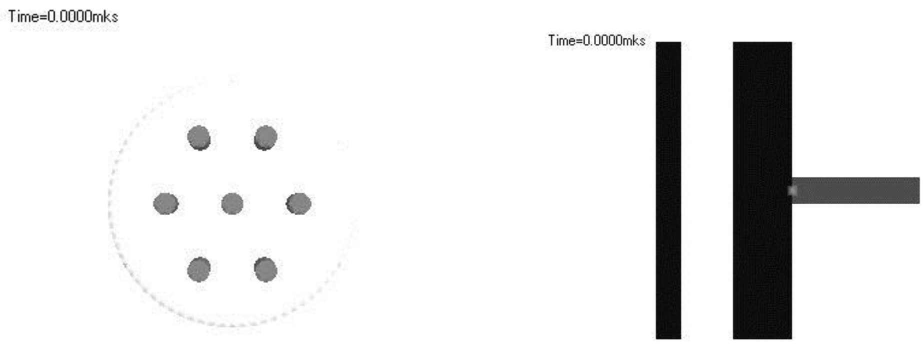


a b

c d

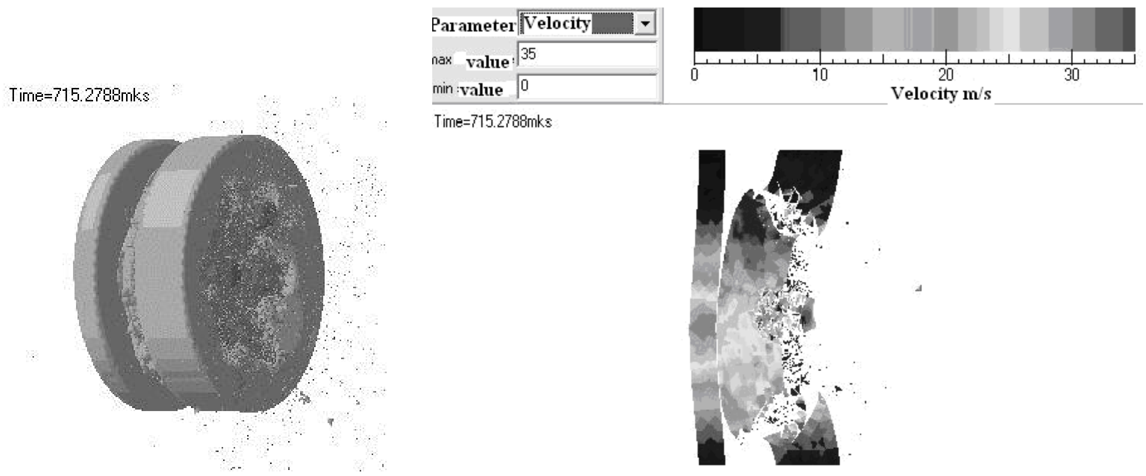
Figure 7: Configuration of balls - barrier system at instant of time $t = 10\,\mu s$ (a, c) and $t = 44{,}5\,\mu s$ (b, d) for the impact angle of 78^0 from the normal: a, b -general views; c, d – plane sections.

In this paper we considered the interaction of a group of seven rods of tungsten alloy with the system of steel plates. The radius of the rod was 1, 5 cm, length was 15 cm. Thickness of the first plate was 7 cm, the second was 3 cm, the distance between them was 6 cm, diameter was 35 cm. Collision speed was 1000 m / s. Rods arranged in a circle with a variable radius R. One projectile was located in the center, the other six circumferentially uniformly. The distance between the center of the first projectile and the remaining centers R during calculations varied.



a b

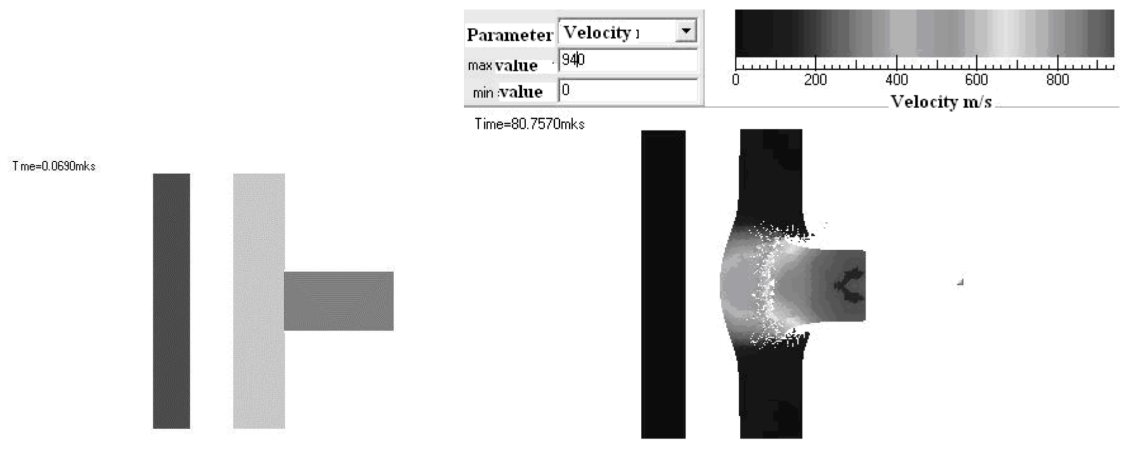
Figure 8: Initial configuration of system "obstacles - projectiles":
a - three-dimensional pattern; b-2D cross-section of a three-dimensional computational domain.



a b

Figure 9: Interaction of a projectiles with the barrier at R = 9 cm
a - three-dimensional pattern; b -2-D cross-section of a three-dimensional computational domain.

Figure 10 shows the results of calculating the penetration of a single projectile with a mass equal to mass of seven projectiles. It can be seen that the size of the mass which is knocked out (more light area in Figure10, b) much less of mass, which is knock out seven projectiles (Figures 8-9).



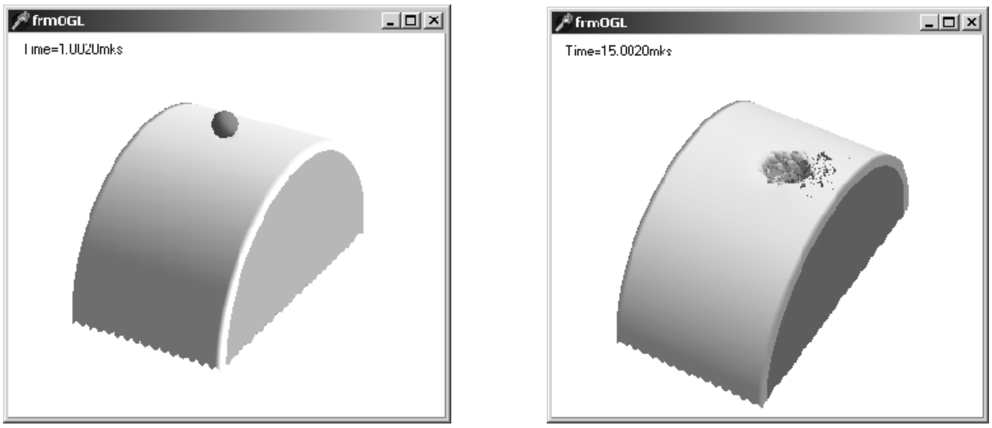
a b

Figure 10: The interaction of a single projectile with obstacles: a - initial configuration of the system "barriers - projectiles "; b-2-D cross-section of a three-dimensional computational domain.

In this paper, a number of problems of penetration and destruction of shells with solid or liquid filler by projectiles interacting not only normally but also at an angle with the surface of the shell in three-dimensional formulation is considered. Problems are solved in a Lagrangian formulation for a wide range of velocities (up to 7 km / s) with the crushing of the material interacting bodies.

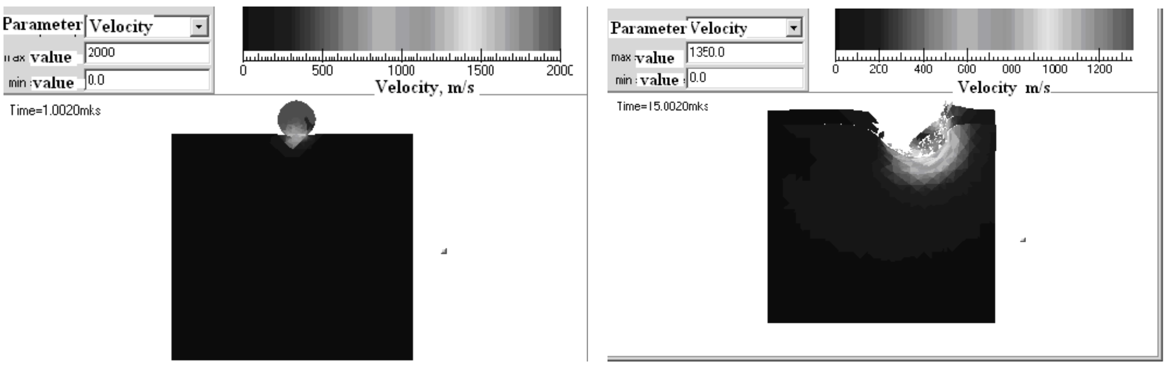
To reduce the calculation time only the upper shell part constituting half of the whole structure was considered. This technique can be used in the case when the double wave travel time to the boundary is greater than the time of the impact process. This condition is well satisfied for shells whose radius is much larger than the penetration depth of the projectile. On the right and left ends was used developed by the authors a technique that allows you to avoid the effect of reflected waves and calculate the loading of long objects only on a limited part of them.

Collision shell and filler with a ball of the tungsten alloy is considered. The impact was normal and at an angle 45 to the generatrix of the shell. Velocity of projectile was 2 km / s. Dimensions of interacting objects are as follows: length of the steel shell was 8 cm; outer radius was 7.5 cm; inner radius was 7 cm; radius of the ball was 0.635 cm. The shell material - steel having the following physical-mechanical characteristics: density = 7.7 g / cm3, the shear modulus = 860 kbar, yield limit = 9.4 kbar; projectile - a tungsten alloy: density = 17.1 g / cm3; filler has the following characteristics: density = 1.75 g / cm3 = 34.7 kbar, yield limit = 1 kbar.



a b

Figure 11: The collision of the ball with a shell at an angle of 45^0: a-1μs, b-15μs.



a b

Figure 12: The velocity distribution in the structure upon impact at an angle of 45^0: a-1μs, b-15μs.

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

5 CONCLUSION

The probabilistic approach proposed and numerical technique developed on its basis enable us to simulate the processes of barrier breaking in a wide range of angles of impact. The decrease in the angle of collision causes projectile ricocheting and change in the nature of the aluminum plate deformation. It is possible to explore projectile and barrier fragmentations as well as the nature of the forming fields of fragmentation behind the barrier.

The paper compares the effectiveness of the impact of the group of projectiles and we made an assessment of their impact on the degree of damage obstacles. The calculation results showed greater risk of exposure to the group of rods for the protecting shell of the spacecraft relative to the impact of a single projectile with a mass equal mass of seven percussionists, and the same rate. The developed numerical method allows to simulate the interactions of shells spacecraft with high-speed long rods in a wide range of speeds and angles of impact, and also to investigate the processes of fragmentation barriers and a nature of fields of fragmentation .

This work was financially supported by RF Ministry of Education in the framework of state task № 2014/223 (project code 1567).

REFERENCES

[1] *Physics of explosion.* K. Stanjukovich ed. Nauka, 1975.

[2] M.L. Wilkins, *Computer simulation of dynamic phenomena*. Springer,1999.

[3] A.V. Gerasimov, S.V. Pashkov, Numerical simulation of the perforation of layered barriers. *Composites: Mechanics, Computations, and Applications. An International Journal.* **4,** 97-111, 2013.

[4] K.N. Kreyenhagen, M.H. Wagner, J. J. Piechocki, R. L. Bjork, Finding the ballistic limit in a collision with multilayer targets. *AIAA J.*, **8**, 42-47, 1970.

[5] G.R. Johnson, D.D. Colby, D.J. Vavrick, Tree-dimensional computer code for dynamic response of solids to intense impulsive loads. *Int. J. Numer. Methods Engng.*, **14**, 1865-1871, 1979.

[6] G.R. Johnson, Dynamic analysis of explosive-metal interaction in three dimensions. *Trans. ASME. J. of Appl. Mech.*, **48,** 30-34, 1981.

[7] *Theoretical and experimental studies of high-velocity interaction of bodies*, A.V. Gerasimov ed. Tomsk University Press, 2007.

[8] A.V. Gerasimov, A.A. Konyaev, S.V. Pashkov, Modeling rebound someone compact shock when you hit the plate of finite thickness . *Proc. of All-Russian conference "Up-to-date Ballistics and Related Matters of Mechanics."* Tomsk, Tomsk University Press, 2009.

[9] I.E. Khorev, S.A. Zelepugin, A.A. Konyaev, V.N. Sidorov, V.E. Fortov, Breaking obstacles by a group of high-velocity bodies. *Doklady Physics*, **44,** 818-821, 1999.

[10] S.A. Zelepugin, A.A. Konyaev, V.N. Sidorov, I.E. Khorev, V.K. Yakushev, Experimental and theoretical investigation of encounter of a group of particles with protecting elements of spacecraft. *Space Research*, **46**, 529-539, 2008.

[11] V.P. Glazyrin, Yu.N. Orlov, Yu.N. Orlova, Analysis of barriers breaking with ice projectiles. *Russian Physics Journal*, **56**, 41-43, 2013