Paper No. 150147

New Model and Method for Simulation of the Combined Protection of Space Vehicles from High-Velocity Debris

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The process of high-velocity collision of discrete-continuous protection elements of spacecrafts with spherical projectiles, simulating fragments of celestial bodies and man-made debris, was considered in the three-dimensional Lagrangian formulation. The problem was solved taking into account the probabilistic nature of crushing interacting bodies materials. The approach proposed to solve the problem of fragmentation enables fully from the physical point of view in three-dimensional formulation to reproduce the processes of barriers breaking by high-velocity elements. We evaluated the efficiency of various combinations of solid and mesh plates for the antimeteoritic protection of spacecrafts, as well as protection from man-made debris.

Keywords: space vehicles, debris, grid, high - velocity interaction, lagrangian method, probabilistic approach, fragmentation

Introduction

The increased duration of spacecrafts flights and a high concentration of debris of the destroyed satellites in the near-Earth space raise the possibility of collisions of manned and unmanned spacecrafts with natural and man-made fragments. Therefore the problem of reliable protection of these space vehicles intended to study the near-Earth and deep space is of special urgency. Collision of fragments with the bodies and other spacecraft elements can cause their penetration and destruction, disrupt normal functioning and cause even more serious consequences for the manned vehicles. The protection against large fragments is realized by the removal of the protected vehicles from the collision orbit and various protective shields are used for fine particles. The results of numerical and experimental studies on the interaction of high-velocity particles with solid and mesh screens are presented in [1, 2]. It is of great practical interest to compare the combined protection systems including various combinations of solid and mesh plates and their spatial position relative to one another.

Basic relations

The equations, describing the spatial adiabatic motion of the solid compressible medium, are differential consequences of the fundamental laws of conservation of mass, momentum and energy. In general they comprise the following equations [3-6, 7-13] - the continuity equation; the equations of motion and the energy equation. These equations are added with the equations taking into account the thermodynamic effects associated with the adiabatic compression of the medium and strength of medium. They are necessary to close the system of equations describing the motion of a solid compressible medium.

In general case under the influence of forces on a solid deformable body both the volume and the shape of the body change, and by different dependencies. Therefore, the stress tensor is represented as the sum of the spherical tensor and the deviator of stress tensor. To describe the body shear strength we used the Prandtl-Reuss ratio [9, 12], as well as the plasticity condition of Mises. In numerical calculations stress reduction procedure was applied to the flow circle [5]. The equation of state of a solid component was selected in the form of Mi-Grüneisen [7]. Destruction process in real materials is always determined by the structure of the medium, the presence of inhomogeneities, usually caused by the different orientation of grains in a polycrystalline material, or by inhomogeneities in the composition of composite materials and the difference in micro strength inside a grain and on intergrain or interface boundaries.

The question is that how in the framework of deformed solid mechanics, i.e. in the system of equations describing the intensive dynamic deformation, to take into account the heterogeneity of the internal structure of real materials and its influence on the processes of natural fracture. It seems natural that for the adequacy of the results of numerical modeling of the destruction process to the experimental data, it is necessary to make corresponding disturbances in physical - mechanical properties of the medium under study, i.e. to set a random distribution of the factors determining the strength properties of the material. In this paper the physical and mechanical characteristics of the medium, which are responsible for the strength, are considered to be distributed randomly over the material volume. The density of the probability distribution of these parameters was selected as different distribution laws, variable dispersion for this parameter distribution and other medium characteristics. Such parameters as yield strength, tensile strength, maximum strain and other constants determining the time of the damage in various theories of strength and criteria of fracture, directly dependent on the number and size of defects, and should be distributed over the volume randomly, with variance depending on material homogeneity. As the fracture criterion under intense shear deformations we used reaching by achieve an equivalent plastic strain or the specific value of the work of plastic deformation of its limit value [3.14]. In this case the calculated cell is considered damaged when the equivalent plastic strain reaches the limit value. The initial heterogeneities were simulated by distribution of the limit equivalent plastic strain in cells of the computational mesh using a modified random number generator, which was issued a random variable subjected to the chosen distribution law. In this paper the probability density of random variables were taken as a normal Gaussian distribution with the arithmetic mean equal to the value of table and variable dispersion.

The system of the basic equations is supplemented with the initial and boundary conditions. At the initial time all points of the projectile have the same axial velocity and the barrier state is supposed to be unperturbed. At the free boundaries normal and shear stress components are equal to zero. In the area of contact between the bodies the condition of ideal sliding of one material relative to another along the tangent and impermeability along a normal are specified. To calculate the elastic-plastic flows we used the technique implemented on the tetrahedral cells and based on the combined use of the Wilkins method [5.6] to calculate the internal points of the body and the Johnson method [15,16] to calculate contact interactions.

Test calculations

In [17] the problem of the expansion of the copper shell with a steel ring was considered under the influence of detonation products. Computational mesh used in this calculation consisted of approximately 500 thousand tetrahedral cells. To describe the destruction we used a method of splitting across nodes - when performing failure criterion in the node vicinity the nodes split to form of the fracture surface. To simulate of the initial heterogeneities we used distribution of a limiting value of the equivalent plastic strain in cells of the computational domain by the normal law with a variance of 10 per cent deviation. With the ring expansion one observed localization of deformations at the vertices of radial cracks formed in the initial heterogeneities and the formation of rather great debris. The calculated fragmentation spectrum quite satisfactory agreed with the experimental data [18].

The problem of penetration of the two-layer barrier (glass fiber ST - HT + alloy D16) by a steel ball SH-15 was considered in the three-dimensional formulation [19]. The calculations of the ball collision with the barrier along the normal to the surface were performed. The projectile velocity was 700 and 900 m/s. The comparison of numerical results with the experimental data showed quite satisfactory agreement.

Penetration of two - and three-layer barriers (steel, ceramics, steel-ceramics-steel) by a cylindrical projectile made of tungsten alloy in the three-dimensional formulation was considered in [19]. Comparison of the numerical results (n) and the experimental (e) data [17] showed good agreement between the residual lengths (l_n and l_e) and velocities (V_n and V_e) of the projectile for the cases of two-layer and three-layer barriers. The two-layer barrier: l_e = 37 mm, V_e = 1120 m/s; l_n = 35 mm, V_n = 1200 m/s. Three-layer barrier: l_e = 11.5 mm V_e = 890 m/s; l_n = 10.0 mm, V_n = 855 m/s.

The calculation results

The penetration of the two-layer spaced barriers (steel mesh - aluminum plate, aluminum plate - steel mesh) by a spherical projectile made of aluminum was considered in the three-dimensional formulation. The projectile diameter was 1 mm. The thickness of the barrier layers: steel mesh, wire thickness =

0. 32 mm, the size of 4 mm × 4 mm; aluminum, thickness = 0.5 mm size of 6 mm × 6 mm. Physical and mechanical characteristics of the barrier and projectile materials are given in [17]. Figure 1 represents the initial configuration and a two-dimensional section of the system which was calculated: steel mesh - aluminum plate.

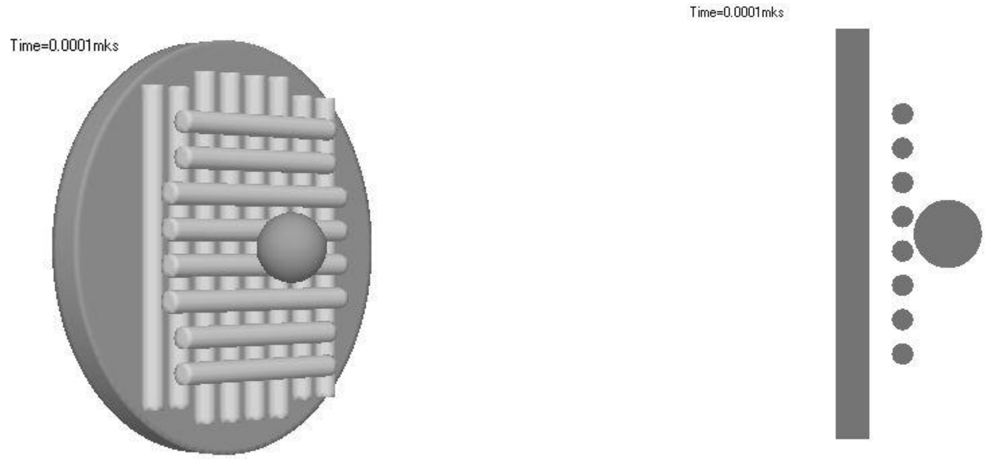

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Figure 1 - Initial configuration (a) and 2-D cross-section (b) of the first two-layer barrier (steel mesh-aluminum plate).

The calculations of projectile and barrier interaction were made for velocity equal to V = 3000 m/s for all variants of the two-layer barriers.

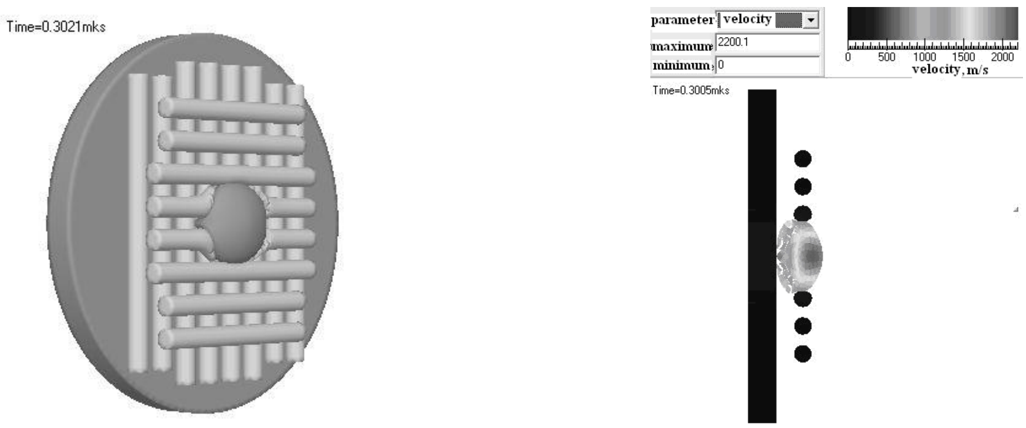

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Figure 2 - Configuration of the system (a) and velocity distribution (b) in the system (2-D cross-section) at a moment of time, t = 0. 300 microseconds in a collision at a velocity V = 3000 m/s.

The results of the two-layer barrier interaction (steel mesh - aluminum plate) in the three-dimensional case and in 2-D cross-section are presented in Figures 2 and 3 for a moment of time t = 0.300 and 6.2842 microseconds. The projectile penetration was accompanied by the destruction of the mesh barriers and the projectile to form a cloud of debris. A small residual part of the projectile, when interacting with aluminum plate, deformed the plate and decelerated without breaking the latter (Fig.2, b). A greater part of the projectile was destructed at the interaction with a steel mesh and the formed cloud of debris had no noticeable effect on the aluminum plate.

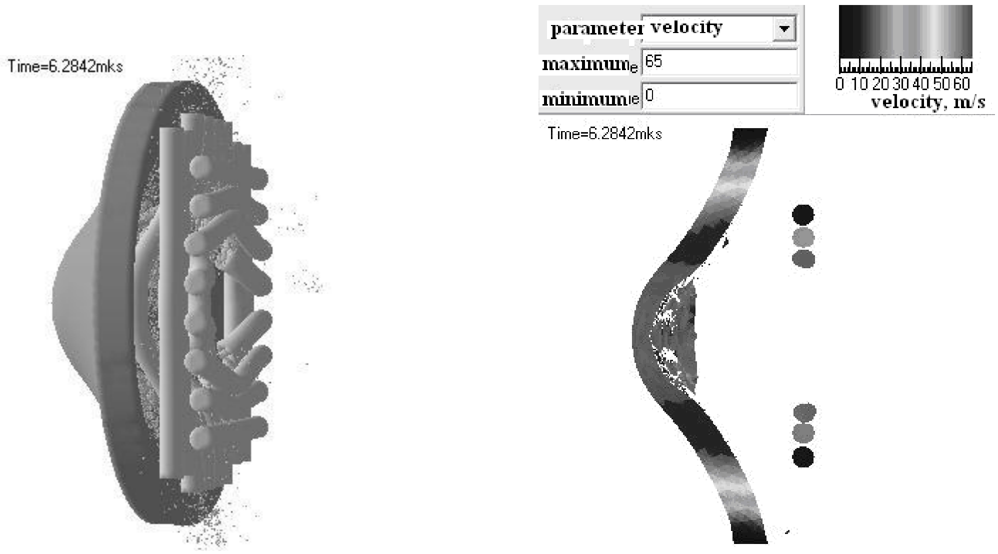

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Figure 3 - Configuration of the system (a) and velocity distribution (b) in the system (2-D cross-section) at a moment of time, t = 6 2842 microseconds in a collision at velocity V = 3000 m/s.

A quite different pattern is observed for the projectile interaction with and barrier - aluminum plate - steel mesh. The initial configuration (a) and 2-D cross-section (b) of the two-layer system is presented in Figure 4.

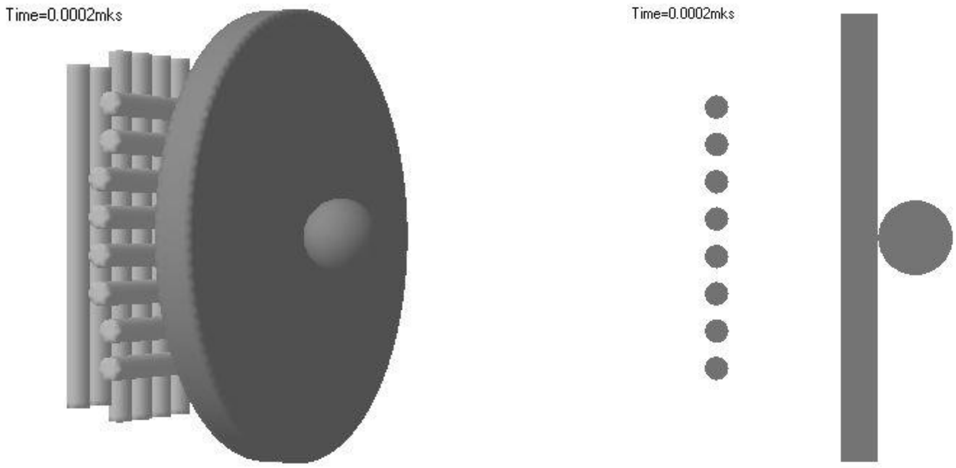

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Figure 4 – The initial configuration (a) and 2-D cross-section (b) of the second two-layer barrier (aluminum-plate - steel mesh)

The projectile penetrated through the aluminum plate slightly destroyed and maintaining a greater part of the original mass. At penetration a plug was also formed (Fig. 5) and this group – the plug and the projectile remains - interacted with the second layer-mesh. The velocity was 1090 m/s and it was sufficient to break through the mesh (Fig. 6).

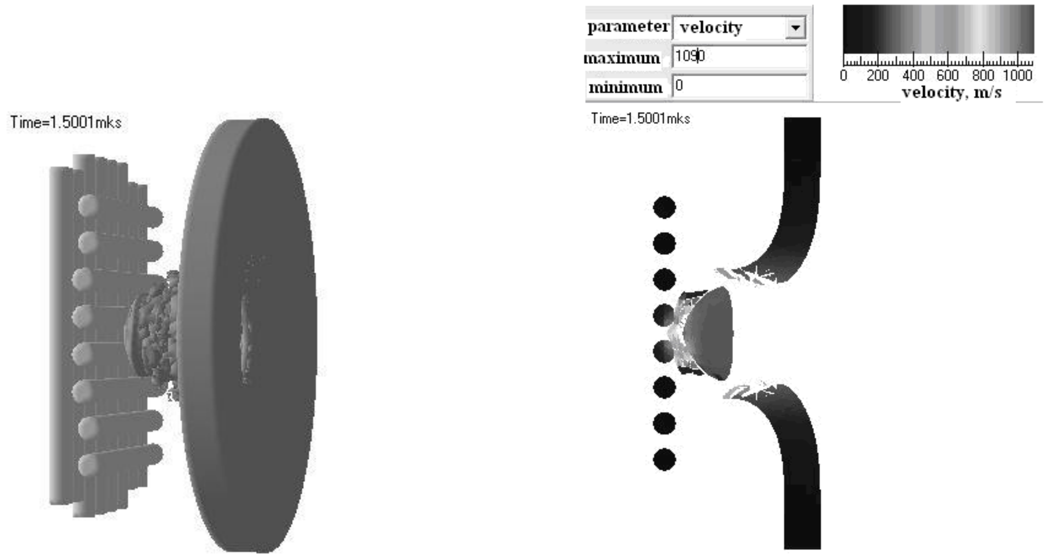

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Figure 5 - Configuration of the system (a) and velocity distribution (b) in the system (2-D cross-section) at a moment of time, t = 1.500 microseconds in a collision at a velocity V = 3000 m/s.

After penetration the projectile remains moved at the velocity of 345 m/s that can be dangerous for the main body of the spacecraft.

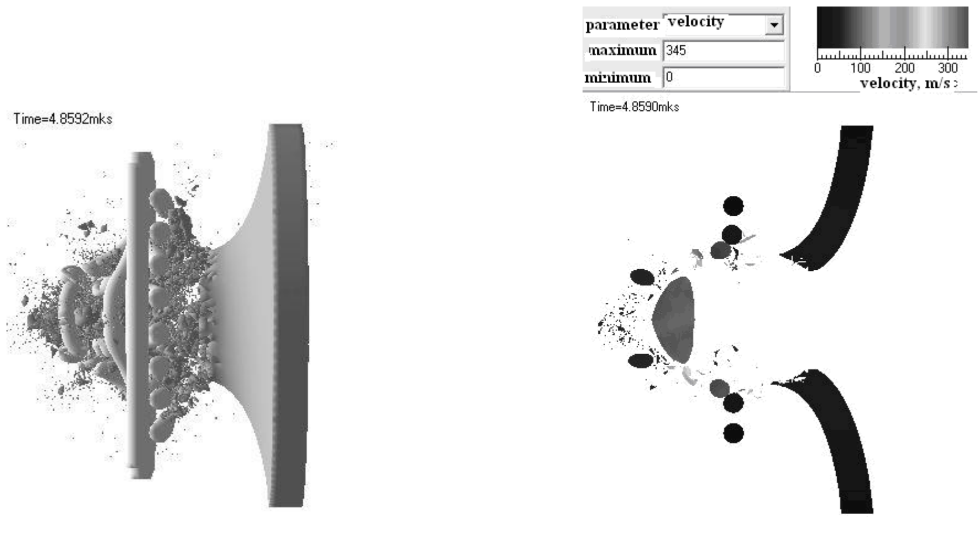

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Figure 6 - Configuration of the system (a) and velocity distribution (b) in the system (2-D cross-section) at a moment of time t = 4.8592 microseconds in a collision at a velocity of V = 3000 m/s.

In contrast to the works considering the penetration process in two-dimensional axially symmetric formulation, the proposed approach provides a more adequate pattern of the destruction of the layered barrier. If in the first case we have fragments as a set of rings, then the three-dimensional formulation based on a probabilistic mechanism of material crushing gives a more realistic picture of the barrier and projectile fragmentations. Ring structures are absent, because they are destructed into separate fragments to form a flow of fragments behind the back side of the system. This flow consists of the fragments of the projectile and layers composing the barrier. It is illustrated by Figs. 5, a and 6, a.

Conclusion

The calculations showed different characters of interactions of the barriers, consisting of a steel mesh - aluminum plate and the barriers of the aluminum plate - steel mesh. In the first case one observes intensive crushing of aluminum projectile on a steel mesh and the movement of the formed flow of fragments and the unbroken part of the projectile in the direction of a solid aluminum plate. The interaction of the projectile fragments with an aluminum plate caused its deformation to form significant buckling in the center but no plate penetration was observed. In the second case one observed the plate penetration and a strong deformation of the projectile without its significant destruction. The remaining part of the projectile penetrated through the second mesh plate maintaining a sufficiently high residual velocity. Effective protection of the first combination of discrete and continuous plates was much higher than the second combination - continuous and discrete plates. Increasing the distance between the barriers leads to significant smearing of fragments beam over the second plate and to marked reduction of the damaging action of the initial projectile. The calculations demonstrated that varying physical and mechanical characteristics of the plates, their combination and spatial arrangement it is possible to affect the desired properties of the designed protection systems of spacecrafts.

Acknowledgements

This work was supported by the Russian Science Foundation (RSF) No.16-19-10264.

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