Single and Group Impacts of High-speed Elements on Spacecraft

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Abstract. Creating a reliable system of spacecraft protection from space debris fragments of different shapes and sizes necessitates studying features of interactions of high-speed elongated projectiles with the protected objects. In this paper we consider interactions of single and groups elongated projectiles-rods with a system of spaced layered plates concerning to protection of space and ground facilities by combined barriers. A probabilistic approach to fragmentation of solids under shock loading and proposed numerical technique fully from the physical point of view in three-dimensional formulation enables with sufficient accuracy to reproduce the processes of high-speed elements penetration into multi-layered spaced barriers. In the calculations fragmentation fields were simulated taking into account the interactions of fragments with each other and with the elements of the multi-layered barriers. The results enable to optimize the objects protection by mass-geometric parameters.

Keywords: Numerical simulation, experiment, high-speed projectiles, probability, fragmentation, space debris, protection, high-speed collision, spacecraft, destruction, layered barriers

1 Introduction

The presence in the formed surface layer (ranged from 300 to 2000 kilometers) of a huge number of man-made fragments of various sizes and shapes, formed in the process of destroying the satellites, the last stages of carrier rockets, boosters and other vehicles and equipment, represents a serious threat to the security of automatic and manned space objects. Now the problem of interaction of constructions with high-speed projectiles takes on special significance due to the increasing speed of collisions. It increases the probability of penetration and destruction and violates the normal functioning of the protected objects. In recent years reliable protection of the elements of manned and automatic apparatuses intended to study near-earth and deep space is especially an acute problem due to the increasing duration of flights of these objects. It increases the probability of collisions of these objects with the man-made fragments formed because of the destructions of the orbital constructions. Numerical simulation of high-speed interaction of solids with the protective systems enables to reproduce typical characteristics of the physical processes occurring in the collision, to consider and select the optimum screen circuits.

The penetration along the normal to the surface of the layered barrier was considered in [1, 2]. Between the layers of metal plates we placed a layer of ceramics. In [3] the process of interaction of group of projectiles with the barrier was numerically simulated using erosion criterion to describe the destruction of the barrier material. The results of the ballistic experiment [4, 5] were compared with the computer simulation data. The comparison was performed on the following parameters: residual speed and the residual rod length after the penetration into the first barrier. Throwing of rods was performed on a light-gas two-stage installation of GU-23. In general in the above papers the authors considered single-layer plates and normal impact. It should be noted that for practical problems spaced barriers and impact at an angle are of great interest. For the numerical solution of these problems a reliable and fairly universal method is required to adequately reproduce the processes of destruction and fragmentation occurring in solids at high-speed interaction.

The use of up-to-date computers and numerical methods in this study to solve the problems of high-speed collisions in a three-dimensional formulation, taking into account fragmentations of projectiles and protective elements of spacecrafts, is theoretically and practically an important task. Accounting for fragmentation and interaction of fragments with each other and with the spacecraft body enables to better understand the processes proceeding at high-speed interaction of space debris with a shell of the space object.

Accounting for fragmentation of solids at intensive dynamic loading enables to use the Lagrange approach to the problem of high-speed impact in a fairly wide range of interaction speeds. This approach is especially useful when considering the multicontact interactions of colliding bodies, especially solving the three-dimensional impact problems. The initial structure heterogeneity of real materials affecting the character of the distribution of physical and mechanical characteristics of the material in body volume is an important factor determining the nature of the fracture. One way to account for this fact is the introduction into the equations of solid mechanics random distribution of deviations of the initial strength properties from the nominal value, that is, simulation, thus the initial structural features of the material, namely: the presence of pores, inclusions, dislocations, etc.

2 Basic relations

In this paper in 3D Lagrangian formulation the process of high-speed interactions of spaced layered plates with elongated fragments is considered.

To describe the processes of deformation and crushing of solids we used a model of an ideal compressible elastic-plastic body. Key equations describing the motion of the medium are based on the laws of mass, momentum and energy conservations and Prandtl-Reuss equations and von Mises yield criterion [6, 8].

The equation of state was taken in the form of Tate and Mi - Grüneisen [6]. It is known that plastic deformations, pressure and temperature affect the yield stress and the shear modulus, so the model was supplemented by the relations, which were proven in [9].

To calculate the elastic-plastic flows we used a technique implemented on the tetrahedral cells and based on the combined use of the Wilkins method [8] to calculate the internal points of the body Johnson's method and [10, 11] to calculate contact interactions. Dividing three-dimensional region into tetrahedrons occurred sequentially by means of automatic meshing routines.

As the fracture criterion under intensive shear deformation we used achievement of the equivalent plastic deformation of its limit value [12].

The initial structure heterogeneities were simulated distributing limit equivalent plastic strain into cells of the computational domain using a modified random number generator which issued a random variable subjected to the chosen distribution law. The probability density of random variables was taken as a normal Gaussian distribution with the arithmetic mean equal to the tabulated value and variable dispersion. The equations of solid mechanics, used in current papers on dynamic fracture of constructions and materials, do not take into account the probability factor in the problem of solids fragmentation that can significantly distort the real picture of the impact and explosive fractures of the objects under consideration. This is particularly evident in the solution of axisymmetric problems, where all the points on a circumferential coordinate of the calculated element are initially equal due to standard equations of continuum mechanics used at numerical simulation.

However in practice there is a wide range of tasks where fragmentation is largely random process, for example, the explosive destruction of axisymmetric shells, where the nature of fragmentation is not known beforehand, penetration and destruction of the thin barrier by a projectile along the normal to the surface, the so-called "petaling", and so on [13]. Adding of a random distribution of the initial deviations of the strength properties of the nominal value in the physical and mechanical characteristics of the body leads to the fact that in these cases the destruction process becomes a probabilistic process, which is more consistent with the experimental data used in this study. The most complete the ideology and methodology of the probabilistic approach to the problem of solids destruction is given in [14].

3 Test calculations

The problem of extension of a copper shell with a steel ring under the impact of detonation products was considered [14]. A computational grid used in this calculation was approximately 500 thousand tetrahedral cells. To describe destruction we used a method of splitting nodes. When performing failure criterion a splitting of nodes and the formation of the fracture surface occurred. To simulate the initial heterogeneities we used distribution of the limiting value of equivalent plastic strain in the cells of the computational domain by the normal law with a variance of 10 % deviation.

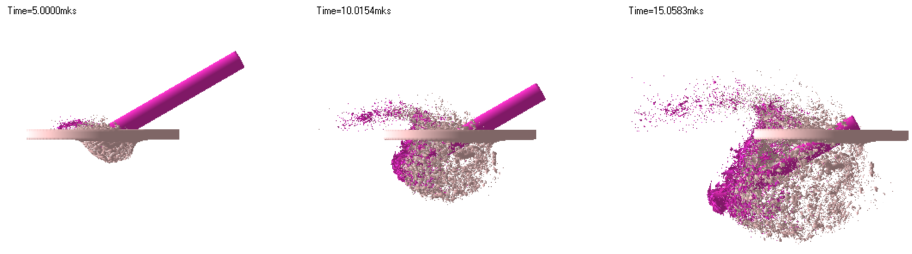
With the extension of the ring one observed localization of deformations on the tops of the radial cracks formed at the initial heterogeneities and the formation of fairly large fragments. The calculated fragmentation spectrum quite satisfactory agreed with the experimental data [15].

In the three-dimensional formulation was considered the problem of penetration of the single-layer barrier (glass fiber ST-NT +alloy D16) by a steel ball SH-15 [1]. The calculations of the ball collision with the barrier were performed at the normal to the surface. Projectile speed was 700 and 900 m/s. Comparison of numerical results with experimental data showed quite satisfactory coincidence.

In the three-dimensional formulation was considered the problem of the penetration of two- and three-layered barriers (steel-ceramics and steel-ceramics-steel) by cylindrical projectile of tungsten alloy [1]. The comparison of the numerical results (n) and the experimental (e) data showed good coincidence of the remaining lengths (ln and le) and speeds (Vn and Ve) of the projectiles for the two- and three-layered barriers. Two-layered barrier: $l_e = 37$ mm, $V_e = 1120$ m/s; $l_n = 35$ mm, $V_h = 1200$ m/s. Three-layered barrier: $l_e = 11.5$ mm, $V_e = 890$ m/s; $l_n = 10.0$ mm, $V_n = 855$ m/s.

4 The calculation results

The process of the cylindrical projectile collision with a flat end with a thin steel plate is shown in Fig. 1.



(a) (b) (c)

Fig. 1. Impact at an angle of 60 degrees (projectile: a tungsten alloy, radius 0.2 cm, length 4 cm, v = 2764 m/s; barrier: steel, radius 1.6 cm, thickness 0.2 cm): (a) 5 μs; (b) 10 μs; (c) 15 μs).

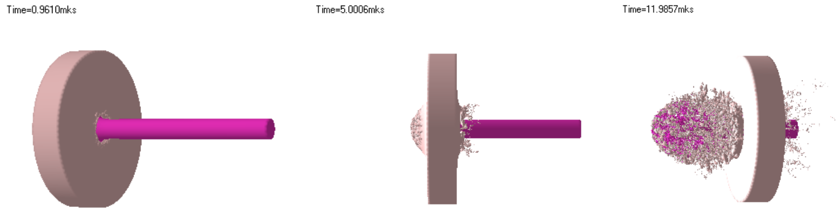
Fig. 1 shows some moments of the projectile interaction ($t = 5$ ms, $t = 10$ ms, $t = 15$ ms) with the barrier at an angle of 60 degrees from the normal to its surface obtained by numerical simulation of the collision process. Comparison of the numerical results Fig. 1 with the experimental data Fig. 2 showed good qualitative coincidence of the obtained picture of the barrier penetration by the projectile as well as of the characteristic features of the fragmentation field formation from the barrier and rod materials. A picture of collision correlates well with the experimental data presented in Fig. 2. One observes the material ejection from the face of the barrier and formation of the original fragment "bubble" on backside. A part of the material from the front end of the projectile was eroded and contributed to the formation of the fragmentation field of "projectile-barrier" system.

Fig. 2. X-ray pattern of steel screen penetration (thickness 6 mm) by a projectile of tungsten alloy 0.4 cm in diameter and elongation of 10 at an angle of 60 degrees at a speed of 2764 m/s.

Fig. 3. Impact at an angle of 60 degrees (projectile: tungsten alloy, radius 0.2 cm, length 4 cm, a barrier: steel, radius 1.6 cm, thickness 0.2 cm, v = 2764 m/s).

The results of the experiment is shown Fig. 2 qualitatively prove the pattern of projectile interactions with the barrier presented in Fig. 3. Quantitative estimation of the calculated and experimental data on the remaining rod length after barrier penetration in the case under consideration was complicated because of projectile crushing in the experiment. This happened because of the nutation angle, which was not incorporated in the calculation. This happened because of the nutation angle, which was not built into the calculation.

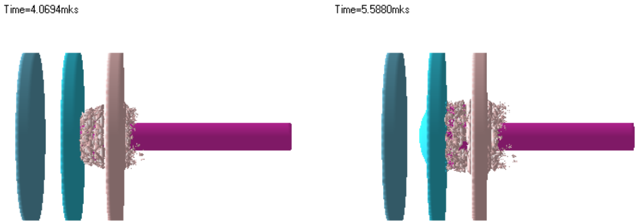
Fig. 4 shows the characteristic features of the rod collision along the normal with a steel plate — a barrier. Here we observe material ejection from the front surface and the formation of fragments flow behind the backside of the plate. The formation of the fragments flow at axisymmetric formulation of the problem of the impact along the normal is possible only by using a three-dimensional approach and taking into account the probabilistic nature of the crushing of barrier and projectile materials.



(a) (b) (c)

Fig. 4. Normal impact (projectile: tungsten alloy, radius 0.2 cm, length 4 cm; barrier: steel, radius 1.6 cm, thickness 0.2 cm, $v = 2732$ m/s): (a) 1 μs; (b) 5.5 μs; (c) 11.3 μs.

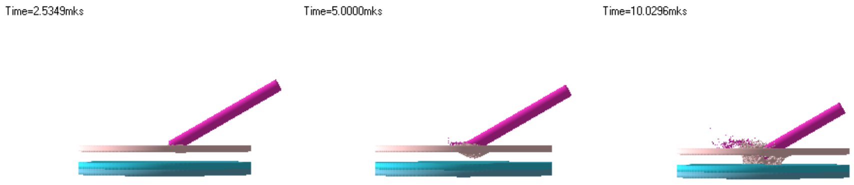
A pattern of barriers and projectile fracture is characterized by the presence of fragments of various sizes with a predominance of a very small fraction, which is typical to high-speed collisions [16].



(a) (b)

Fig. 5. Rod interaction with a spaced barrier consisting of three plates (projectile: radius 0.5 cm, length 8 cm; barrier: steel-Al-Ti, radius 3 cm, thickness 0.5 cm, distance between plates 1 cm, $v = 5000$ m/s): (a) 4 μs; (b) 5.6 μs.

Capability of the proposed technique illustrates the calculations of rod interaction with a spaced barrier, consisting of three plates is shown Fig. 5, and rod interaction with a spaced-layered barrier is shown Fig. 6. Penetration of the spaced barrier was accompanied by the formation of material ejection from the front side of the first plate and fragments flow from the backside. The next



(a) (b) (c)

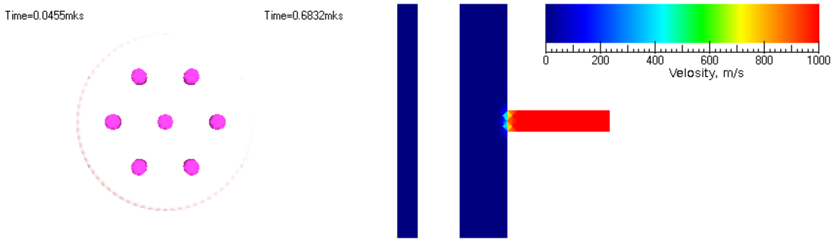
Fig. 6. Rod interaction with spaced-layered barrier (projectile: radius 0.3 cm, length 6 cm, a barrier: steel-Al + Ti, radius 3 cm, thickness 0.3 cm, distance between plates 0.5 cm, $v = 2600$ m/s, collision angle 60 degrees): (a) 2.5 μs; (b) 5.0 μs, (c) 10.0 μs.

plate was subjected to the impact the preserved part of the projectile and fragments flow from the previous plate and the destroyed part of the projectile is shown Fig. 5. Qualitatively the penetration of the system of the spaced plates is much similar to the penetration of one plate, but quantitative characteristics differ greatly. The first stage of the rod collision with a spaced - layered plate correlates well with the results presented in Fig. 6. Further interaction with the layered barrier is determined by the physical and mechanical properties of the layers, it changes the time required to their penetration.

Earlier in [13] the interaction of spherical elements with thin barriers was considered at different angles of collision. In this paper we consider the interaction of a group of seven rods of tungsten alloy with a system of steel plates. Radius of the rod 1.5 cm, length 15 cm. Thickness of the first plate 7 cm and the second 3 cm, the distance between them 6 cm, diameter 35 cm. Collision speed 1000 m/s. Rods were arranged in a circle with a variable radius R. One rod was placed in the center and the other six rods were uniformly placed along the circumference. When calculating we varied the distance between the center of the first projectile and the centers of the rest R. The calculation results presented in Fig. 7–11 enabled to determine the best configuration of rods system to penetrate the first barrier and destruct the second one. Fig. 10 shows the location of rods with flat heads on the front side of the barrier system at the initial time.

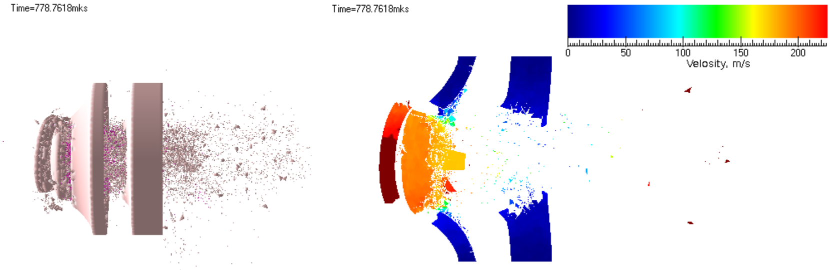
Fig. 12 shows calculations of the collision of a single projectile with a mass equal to that of seven projectiles, which were discussed above. It can be seen that the size of the mass which was knocked out (a) lighter area in Fig. 12, (b) was much less as compared with that which was knocked out by seven projectiles Fig. 8–11.

In the paper we compared the effectiveness of the impacts of the projectiles group and assessed their effects on the degree of the barrier damage. The increase in radius R from 5 cm to 9 cm causes the increase in the volume of material knocked out from first barrier at a noticeable speed drop. At $R = 5$ cm the second barrier is also penetrated and significant flow of the fragments is formed from back and front sides of the barrier, but when $R = 8$ or 9 cm this is not observed. When $R = 10$ cm the projectiles only partially penetrate into the first



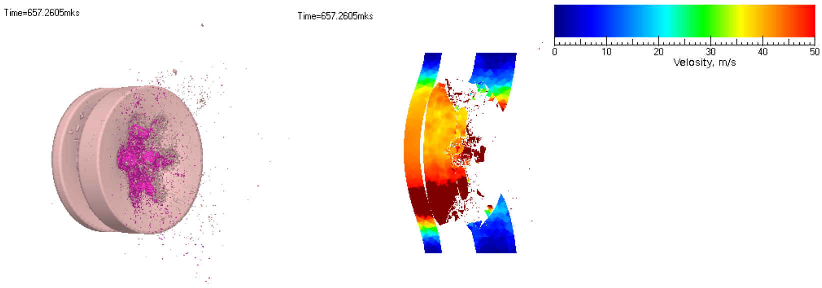
(a) (b)

Fig. 7. Initial configuration of the system "barriers-projectiles": (a) three-dimensional picture; (b) 2-D cross-section of a three-dimensional computational domain.



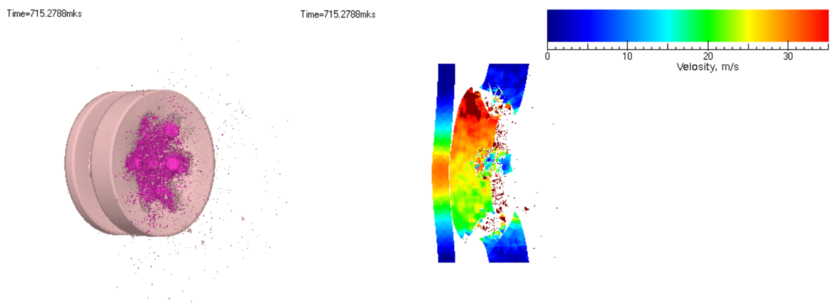
(a) (b)

Fig. 8. Interaction of projectiles with a barrier at $R = 5$ cm: (a) three-dimensional picture; (b) 2-D cross-section of a three-dimensional computational domain. $t = 778.76$ microseconds



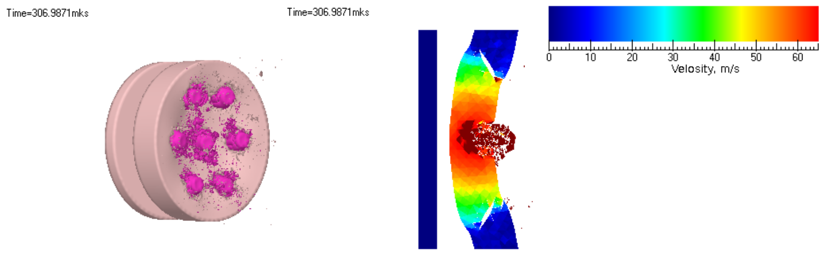
(a) (b)

Fig. 9. Interaction of projectiles with a barrier at $R = 8$ cm: (a) three-dimensional picture; (b) 2-D cross-section of a three-dimensional computational domain. $t = 657.26$ microseconds



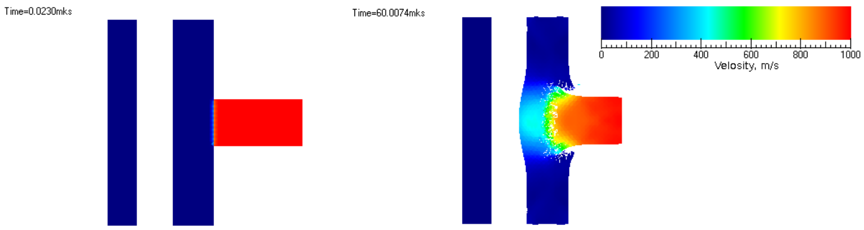
(a) (b)

Fig. 10. Interaction of projectiles with a barrier at $R = 9$ cm: (a) three-dimensional picture; (b) 2-D cross-section of a three-dimensional computational domain. $t = 715.28$ microseconds



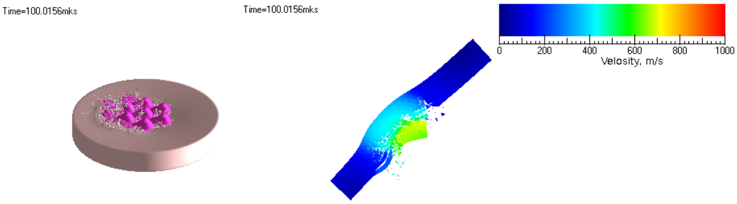
(a) (b)

Fig. 11. Interaction of projectiles with a barrier at $R = 10$ cm: (a) three-dimensional picture; (b) 2-D cross-section of a three-dimensional computational domain. $t = 306.08$ microseconds



(a) (b)

Fig. 12. The interaction of a single projectile with barriers: (a) initial configuration of the system "barriers-projectile "; (b) 2-D cross-section of a three-dimensional computational domain. (a) 0 microseconds, (b) 80 microseconds



(a) (b)

Fig. 13. Interaction of projectiles with a barrier at an angle of 450 from the normal: (a) three-dimensional picture; (b) 2-D cross-section of a three-dimensional computational domain. $t = 100$ microseconds

barrier and no full effect of the collective impact of the group of elements on the barrier is observed. The first barrier bulges toward the second barrier, but it is not punctured and completely destroyed, however one observes the formation of cracks in the circumferential direction. As can be seen from the calculations, there is a certain configuration of the projectiles group, the most dangerous in terms of breaking the barrier and the mass of the ejected material.

The calculation results presented in Fig. 7–12 showed a great danger of the impact of the group of rods on the protected spacecraft as compared with the impact of a single projectile with a mass equal to that of seven projectiles at the same speed. The developed numerical technique enables to simulate the interactions of spacecraft shells with high-speed long rods in a wide range of speeds and collision angles and also to investigate the processes of rods and barriers fragmentations and nature of the forming fragmentation fields.

5 Conclusion

A probabilistic approach and proposed numerical technique enables in full, from the physical point of view, in three-dimensional formulation with sufficient accuracy to reproduce the processes of penetration of multi-layer and spaced barriers with high-speed core elements.

In calculations we fully simulated the fragmentation fields and took into account the interaction of fragments with each other and with the elements of the multi-layer barrier that was extremely important in calculating the protection of spacecrafts, as high-speed particles flows could penetrate the main body of the machine and damage the equipment. Therefore, it is necessary to evaluate the kinetic energy of the fragments and calculate the process of their collision with the main body. The proposed approach enables to calculate the entire process of the projectile interaction with barriers taking into account the formation of fragmentation flows and the collision of the latter with the protected object.

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