

New model and method simulating effective protection of space vehicles from high-velocity debris

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Abstract

Protection of space vehicles from natural and man-made debris is a significant practical problem. Thin barriers, placed in front of the main body of the object, crush high- velocity particles into fragments and thereby reduce probable penetration. The replacement of the solid plate by a grid of high-strength material lightens the protective structure, with clear benefit for space vehicle applications.

Keywords: Space Vehicles, Debris, Grid, High - velocity interaction, Lagrangian method, Probabilistic approach, Fragmentation

Introduction

The process of high- velocity interaction between grid barriers and compact elements (aluminum balls) is considered in Lagrangian 3-D formulation. To solve this problem 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, or penetration and fracture of thin barriers by a projectile along surface normal, etc. 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.

Basic relations and solution method

To describe the processes of deformation and fracture of solids we used a model of a compressible and perfectly elastoplastic body. Basic relations describing the medium motion are based on the laws of conservations of mass, momentum and energy [Stanjukovich (1975); Wilkins M.L. (1964)], and are closed by Prandtl - Reuss relations under the von Mises flow condition. The equation of state was taken in the form of Tate and Mie - Gruneisen [Stanjukovich (1975)]. Plastic deformations, pressure and temperature are known to affect yield strength and shear modulus, therefore the model was supplemented by the relations recommended in [Steinberg et al. (1980)]. Reaching a limiting value for equivalent plastic deformation was used as a fracture criterion at intensive shear deformations [Stanjukovich (1975); Kreyenhagen et al. (1970)].

To calculate elastoplastic flows we used a procedure implemented on tetrahedral cells and based on the combined application of Wilkins method [Wilkins M.L.(1964; (1985)] intended to calculate the internal points of the body and Johnson method [Johnson et al. (1979); Johnson (1981)] to calculate contact interactions. The number of computational cells was about 800 000. To solve the problem, the authors used their own 3-D program [Gerasimov (2007)].

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. The ideology and methodology of a probabilistic approach to the problem of the fracture of solids is completely described in [Gerasimov (2007)].

The experimental results

High - velocity collisions between projectiles and grid barriers were also experimentally investigated using two-stage light-gas installations modified to throw particles 0.5 mm in diameter at velocities (2.5 - 5) km/s [Gerasimov (2007)]. Projectile - aluminum particles (2 mm in diameter) and a barrier - two steel grids (wire diameter 0.32 mm and 0.2 mm, respectively). The first grid: steel, density = 7.9 g/cm³, the shear modulus = 86 GPa, yield point = 0.28 GPa, cell size 0.5 × 0.5 mm, wire diameter = 0.32 mm. The second grid: steel, density = 7.9 g/cm³, the shear modulus = 86 GPa, yield point = 0.28 GPa, the cell size 0.356 × 0.356 mm, wire diameter = 0.2 mm. The tank: duralumin, density = 2.64 g/cm³, shear modulus = 26.9 GPa, yield point = 0.12 GPa, thickness = 1.9 mm.

Figure 1 shows the investigated assembly, consisting of a tank element of a space vehicle and two grids, which were placed at some distance from each other and the tank. The numbers in Figure 1 indicate the results of separate experiments. The Table 1 presents a brief description of two typical experiments on the interactions of aluminum projectiles, a grid barrier and the element of the protected tank, where V =

initial velocity of the projectile. As is seen from the results of the experiments there were no penetrations or damage to the tank wall, thus the grid barrier has successfully fulfilled its function.

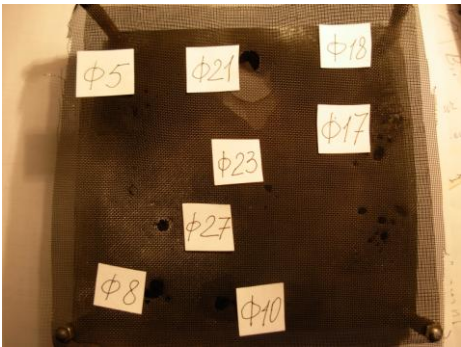


Figure 1. The face of assembly "grid - tank element"

Table 1. Experimental data

Test number	Projectile	Tested barrier and protection	V, km / sec	Experiment results
Φ 5	Duralumin ball 2 mm in diameter	"tank" + 0.32 mm grid + 0.2 mm grid	2.0	Through penetration both grids. The depth of craters from the fragments is 0.3-0.5 mm
Φ 23	Duralumin ball 2mm in diameter	"tank" + 0.32 mm grid + 0.2 mm grid	3.0	Through penetration the both grids. The depth of craters from the fragments is 0.27-0.45 mm

Numerical results

The results of numerical calculations of the projectile interaction with the first grid are presented below. Figure 2 presents a top view of a spherical particle and of the first grid element, as well as a two-dimensional section of the configuration.

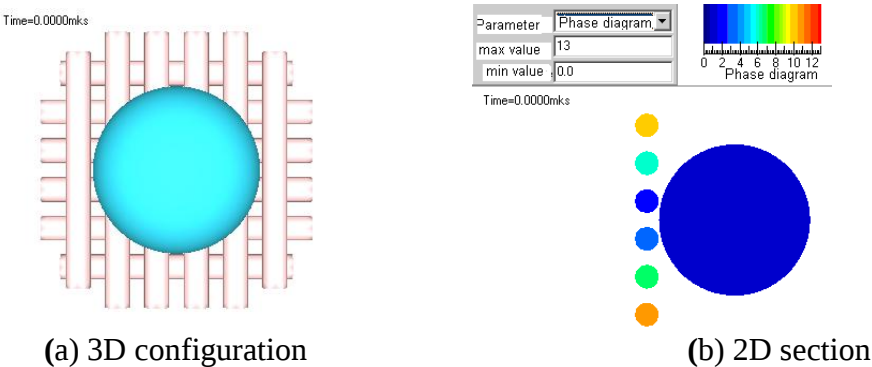


Figure 2. The initial configuration of the grid and a spherical particle

The calculations proved the experimental data on the protective properties of grid barriers. Then numerical experiments were carried out for the velocities of the particle collision with the first grid barrier $V = 2$ km/s.

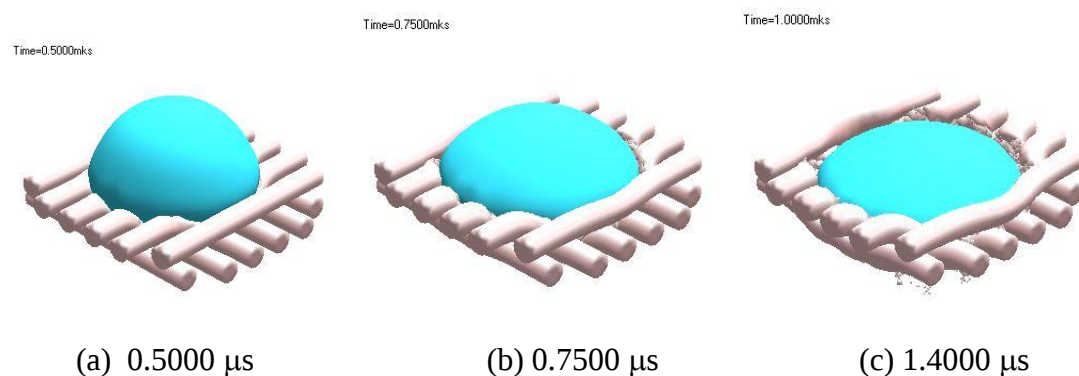


Figure 3. The configurations of the grid and the spherical particle in 3D image for $V=2$ km/s

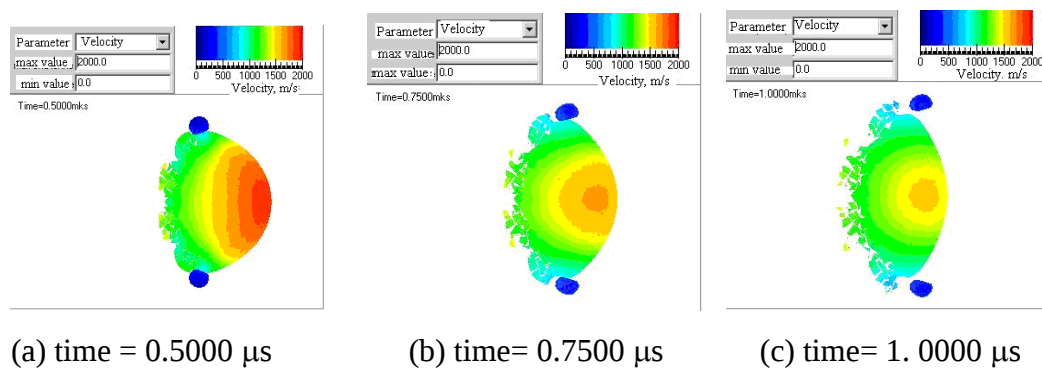


Figure 4. 2D Section of the grid and the spherical particle. Velocity distribution. $V=2$ km/s

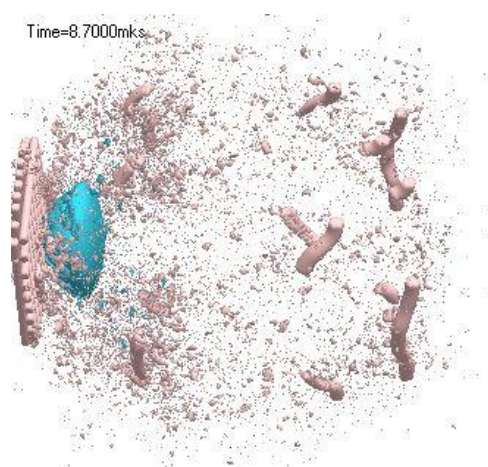


Figure 5. Contact of cloud fragments with the second barrier (grid)
 $t=8.7000\mu\text{s}$ $V=2$ km/s

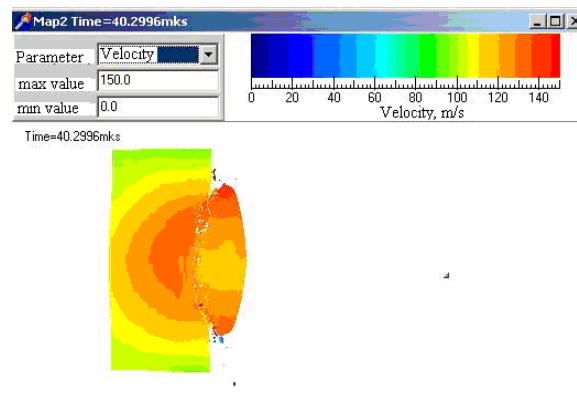


Figure 6. Particle fragment impact on the main body: distribution of current velocity, time = 40.2996 μ s, $V=2$ km/s

Figure 6 demonstrates that the particle fragment did not penetrate the main body of the space vehicle and made only a small dent on the surface. The same result was obtained for the collision velocity of $V = 3$ km/s.

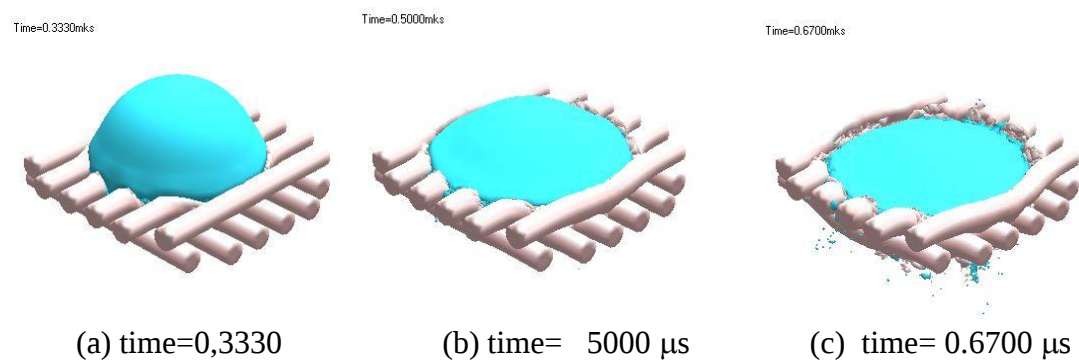


Figure 7. The configuration of the grid and the spherical particle in 3D image for $V=3$ km/s

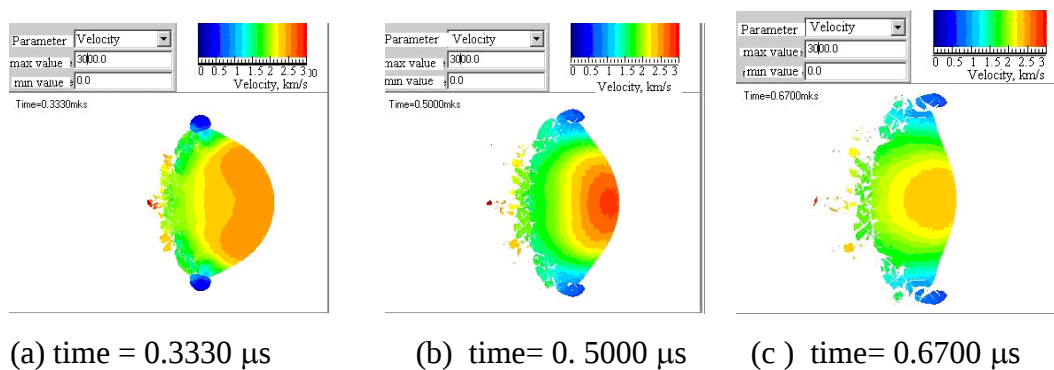


Figure 8. 2D Section of the grid and the spherical particle. Velocity distribution. $V=3$ km/s

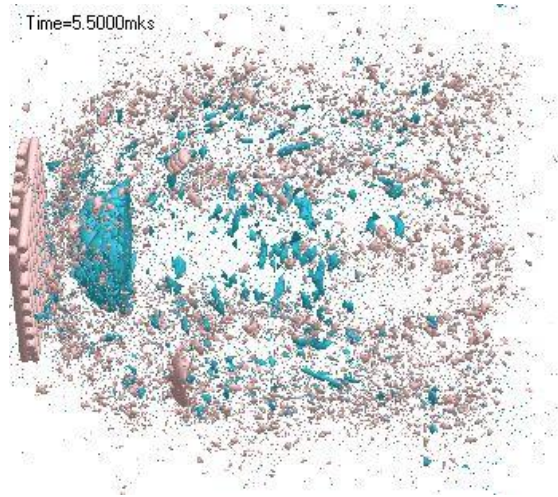


Figure 9. Contact of cloud fragments with the second barrier (grid)
 $t=5.5000\mu s$ $V=3$ km/s

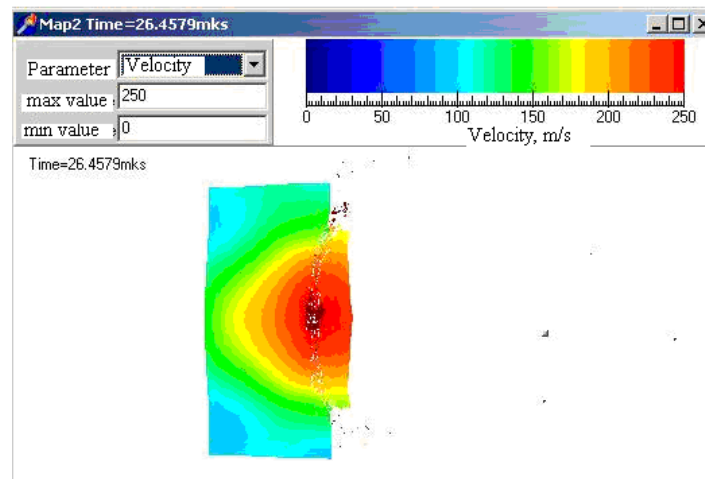


Fig. 10. Particle fragment impact on the main body: distribution of current velocity,
time = 26.4579 μs , $V=3$ km/s

As seen in Figures 3-10, the fragmentation of the incident particle intensifies with increasing collision velocity, as evidenced by the intense formation of material jets penetrating through the meshes (Fig. 7c). In figures number 6 and number 10 show a portion of the ball passing through the two grids, which does not penetrate the tank shell. The results for the initial velocity $V = 2$ km / s and $V = 3$ km / s, respectively. Dimensions calculated crater close to the size of the experimental craters (Table 1).

Conclusion

This paper presents numerical research into the interaction of high-velocity particles and barriers – grids which are used to protect space vehicles — and demonstrates the efficiency of grid shielding structures.

The data obtained proved the possibility of the proposed approach and Lagrangian numerical techniques were used to reproduce completely, from the physical point of view, in three-dimensional formulation the interactions of the spaced grid barriers and

protected space vehicle elements with high- velocity particles from fractured structures and vehicles, as well as fragments of cosmic bodies, and to inform the selection of the most effective protection systems.

In the course of numerical experiments the protection consisting of the two grids proved to be more effective as compared with an equivalent by mass solid barrier. The experimental results proved the adequacy of the numerical method and the simulations provide some qualitative support for the proposed protection mechanism.

References

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