The penetration modeling of flat obstacles in Ansys Autodyn program

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Abstract. The article is devoted to mathematical modeling of flat obstacles punching in Ansys Autodyn software package with the use of finite element method. The tasks of punching flat, composite, two-layer barriers with a drummer at a right angle and 45 degrees angle are considered. With the help of modeling in Ansys Autodyn, the behavior of obstacles is investigated in time and after they are punched by a drummer. In the work, numerical and semi-analytical solutions of the problems were obtained, the results of the solution were presented, comparisons were made and corresponding conclusions were made. A numerical simulation of high-speed collision of barriers with a drummer was carried out, and the rate of through penetration of barriers consisting of several layers was obtained. The layers in the barriers are made up of various materials. The results of numerical simulation of the barrier and the impactor with a conical head are given.

Keywords: Ansys Autodyn, mathematical modeling, simulation of high-speed collision, semi-analytical solution, punching flat obstacles.

1. Introduction

Modern aircrafts, including spacecraft, artificial satellites, orbital stations, are continuously subject to collisions with various particles (large cosmic dust, fragments of meteorites, and so on) during operation. Constant collisions, especially high-speed collisions, lead to an accumulation of damage in the material of the apparatus construction and in the future to failure [1]. In this regard, the above devices are supplied with special protective coatings. As a rule, the protective coating consists of a material other than the outer layer of the structure, since the protective layer has a different purpose. For example, if the main material of the outer layer of the aircraft is metal (alloy), then ceramics can act as a protective layer. The advantages of using ceramics for protective layers are, firstly, that ceramics have greater strength, at least along one of their directions, due to the anisotropy of physical and mechanical properties, in contrast to metals. Secondly, ceramics better absorb energy during collisions.

The existence of high-performance computing, the availability of the necessary mathematical and software allow us to consider mathematical modeling as one of the most effective ways to assess the strength, predict durability and optimize structures and manufacturing processes, which are based on the processes of impact and explosion. One of the most effective automated engineering analysis systems is the Ansys Autodyn software package [1]. This work also uses the Ansys Autodyn package. This package for numerical calculations of shock processes is also used in [2, 14].

A number of works are devoted to the problems of modeling of obstacles punching, in which obstacles consisting only of ceramics, only of metals and composite are considered. However, the most interesting are the works devoted to modeling of multilayer barriers [5, 6].

A review of papers in which analytical dependencies were proposed for calculating the limiting velocities of penetration of two-layer barriers is given in [3]. A common drawback of these works is the fact that the most important components of the process of breaking through the barrier are not taken into account [12]. First, the destruction of the impactor and the associated decrease in the kinetic energy of
the impactor are not taken into account. Secondly, the destruction of ceramics and the cost of this kinetic energy of the impactor are not taken into account consistently or not at all.

This article proposes a model that takes into account the processes of deformation and destruction of the striker, the destruction of the ceramic cone and the deformation of the substrate.

The aim of this work is to calculate the rate of through punching of flat, composite obstacles by the striker, by methods of numerical and semi-analytical solutions, as well as to compare the results.

2. Materials and method of research

2.1. Mechanical statement of tasks

Elastic steel drummer with conical head of structural steel (Structural Steel) hits at an angle of 90° and 45° degrees on the combined obstacles, rigidly fixed at the edges (figure 1). Barriers consist of a set of plates, which consist of different materials (table 1) and are rigidly fixed at the edges.

![Figure 1. The results of the decision in the program.](image)

Plate size - 20×20 cm;
The thickness of each of the plates - 0.5 cm;
Diameter of the drummer - 0.9 cm;
The height of the drummer - 5.5 cm.

| Barrier number | Barriers consist of the following materials: | Weight, kg | Barrier thickness, cm |
|----------------|----------------------------------------------|------------|-----------------------|
| 1              | 1 layer is made of B₄C (boron carbide); 2 layer is made of S7 grade steel | 2.052      | 1                     |
| 2              | 1 layer is made of 1600 grade steel; 2 layer is made of S7 grade steel | 3.1292     | 1                     |

Boron carbide B₄C has a low density and other useful parameters that make this substance indispensable in the manufacture of protective products armored plates. The characteristics of the materials that make up the barriers were taken from the works [7, 8].

2.2. Mathematical formulation of the problem.

The equations underlying the problem include the equation of motion, the equation of energy, the equations describing the property of the material, the law of conservation of mass, contact, initial and boundary conditions.
The boundary conditions the plate along the contour is rigidly fixed, mathematically it can be represented as \( u_{x=\pm a} = 0, \quad u_{z=\pm a} = 0 \) where \( a \) is the length and width of the plate.

Initial conditions: \( u|_{t=0} = 0, \quad \dot{u}|_{t=0} = v_i \),

where: \( v_i \) is the speed given at the initial moment of time.

For the material of the drummer, we use an elastic material model. For her, Hooke’s law is fulfilled:

\[
\sigma_{ij} = \lambda J_1(\varepsilon) \delta_{ij} + 2\mu \varepsilon_{ij},
\]

where \( \varepsilon_{ij} \) is the strain tensor, \( J_1(\varepsilon) \) is the first invariant of the strain tensor, \( \lambda, \mu \) are Lame constants.

\[
\mu = \frac{E}{2(1+\nu)}, \quad \lambda = \frac{E\nu}{(1-2\nu)(1+\nu)}.
\]

\( E \) is Young’s E-module, \( \nu \) is Poisson’s coefficient.

For the plate material, an elastic-plastic material model was used. The condition of the beginning of plasticity:

\[
(\sigma_1 + \sigma_2)^2 + (\sigma_2 + \sigma_3)^2 + (\sigma_3 + \sigma_1)^2 = (\sqrt{2}\sigma_m)^2,
\]

where: \( \sigma_1, \sigma_2, \sigma_3 \) are the main stresses, \( \sigma_m \) is the yield strength.

Contact interaction of two surfaces is described using the following formulas: \( z_1 + z_2 = \alpha(w_1 - w_2) \) for points of contact area, and \( z_1 + z_2 > \alpha(w_1 - w_2) \) for points outside the contact area.

Moving points \( M_1 \), belonging to one contact surface and \( M_2 \) belonging to another contact surface, occurring due to deformation of parts of bodies near the point of tangency, we denote by \( w_1 \) and \( w_2 \), and the movement of points at the origin is \( w_0^1 \) and \( w_0^2 \). Obviously, the quantity \( \alpha = w_0^1 + w_0^2 \) represents the convergence of contiguous bodies as a result of their compression, at which the distance between points \( M_1 \) and \( M_2 \) decreases by the value of \( \alpha - w_0^1 + w_0^2 \) [9].

2.3. Methods for solving the problem

2.3.1. Semi-analytical method for solving the problem

In the work of Ilyushin [10] considered the analytical method of solving the problem of penetration of barriers, and obtained the formula of the speed of the projectile after penetration of the projectile solid and multilayer barriers.

2.3.2. The method of solving the problem in ANSYS Autodyn

To calculate tasks in ANSYS, the finite element method is used. The essence of this method is that the continuous medium is replaced by a finite number of structural elements of finite size, connected with each other only at the nodal points. Thus, we superimpose a grid on our object and consider the movement of particles in time.

The process of implementation of FEM in the problem was divided into several stages:

– the choice of a mathematical model;
– the creation of a geometric model of the object;
– setting the properties and models of materials;
– the creation of a finite element grid;
– setting the boundary conditions;
– modeling loads;
– setting the solver;
– the solution of equations and the calculation of stresses in the nodes;
– analysis of the results[13].

In this study, we used a spatial grid of tetrahedral or hexahedral. The computational grid in the area of collision of the barrier with the striker was crushed to improve the accuracy of the calculation. Poor grid quality, even in the case of accurate modeling of other stages can lead to incorrect results. On the one hand, the smaller the size of the final element, the higher the accuracy of the calculation, on the other hand, too thick mesh weights the model and increases the calculation time [11].
2.4. **Numerical and semi-analytical solution of problems**

Consider the interaction of obstacles and the drummer at right angles. The thickness of the barriers 1 cm, cross size: square 20 cm on the edges of the plate clamped obstacles. From the list of obstacles (table 1), you want to determine the minimum speed of the striker for through punching obstacles.

The numerical results of the tasks (table 2) were obtained by a series of excrement in the Ansys Autodyn software package.

For semi-analytical solution of the problems, the equations obtained in the works of Ilyushin [1] were used. And the following values were used:

- Cone height - 0.6975 cm;
- The radius of the cone - 0.45 cm;
- \( R = 0.45 \text{ cm} \) (the radius of the base of the drummer);
- \( H = 5.5 \text{ cm} \) (the height of the drummer);
- \( m = 0.025145 \text{ kg} \) (the mass of the projectile);
- \( \varphi = 30^\circ \) (the angle between the axis of the drummer and the perpendicular to the contact plane of the drummer and the obstacle);
- \( \mu = 0.8 \) (friction coefficient);
- \( k = 3.5 \times 10^8 \text{ Pa (kg / m} \cdot \text{s}^2) \) (shear yield strength).

**Table 2. Results of numerical solution of the problem at an angle of 90°.**

| Barrier | \( V_0 \) at an angle of 90°, m/s | \( \varphi_0 \), radians | \( e \), cm |
|---------|---------------------------------|------------------------|-----------|
| 1       | 795                             | \( 2\pi/5 \)           | 0.9231    |
| 2       | 720                             | \( 2\pi/5 \)           | 0.9549    |

where \( V_0 \) is the average minimum speed of the drummer for the through penetration of the barrier, obtained in Ansys Autodyn; \( e \) is the maximum deflection of the obstacle, taken from experiments; \( \varphi_0 \) is the bend angle of the destructive part of the barrier, taken from experiments.

Semi-analytical solution of the problem is calculated using Matlab. Writing down the necessary equations and variables in Matlab, and calculating the average velocity of the striker (\( V \)) for punching obstacles, the following results were obtained (table 3).

**Table 3. Results of semi-analytical solution of the problem at an angle of 90°.**

| Barrier | \( V \) at an angle of 90°, m/s |
|---------|--------------------------------|
| 1       | -                              |
| 2       | 733.95                         |

3. **Results**

3.1. **The results of the process of breaking down barriers in Ansys Autodyn**

The process of impact proceeds as follows. First, an object moving at a certain speed enters into contact with the system, and the speed of its movement decreases sharply. The system is in motion. However, due to the inertia of the mass of the system, its particles do not begin to move simultaneously. It takes some time for the deformation wave to spread from the point of impact throughout the system. The leading edge of the wave moves through the system at the speed of sound propagation in a given medium. After contact, the object moves together with the shock-sensing system, and the speed of their movement as the deformation and elastic forces of the system gradually decreases.

At the obtained speeds in Ansys Autodyn the drummer breaks through the obstacles and causes serious deformation of the barrier in the impact area. When the striker penetrates into the barrier, the elements of the plates under the striker begin to be removed (figure 2), due to the impact of stresses on
the Mises in the barrier sharply increase, after which there is a sharp drop in stresses. The results are partially presented.

![Image](image.png)

**Figure 2.** The results of the decision in the program.

3.2. **Comparison and verification of results**

Table 4 shows the results of solving problems obtained by numerical and semi-analytical methods.

| Barrier | Semi-analytical $V$ at an angle of 90°, m/s | $V_0$ at an angle of 90°, m/s | $V_0$ at an angle of 45°, m/s |
|---------|-------------------------------------------|-----------------------------|-------------------------------|
| 1       | -                                         | 795                         | 1057                          |
| 2       | 733.95                                    | 720                         | 1030                          |

where $V_0$ is the average minimum velocity of the striker for through penetration of the barrier obtained in Ansys Autodyn (numerical solution); $V$ is the average minimum speed of the striker for through penetration of the barrier obtained by the semi-analytical method.

First of all, we note the high efficiency of using a metal substrate in terms of resistance to penetration of the composite barrier - an increase in the thickness of the all-ceramic barrier leads only to a slight decrease in the residual velocity, while the use of substrates gives a greater effect.

From the list of obstacles, on the basis of the results of the numerical and semi-analytical solution, the strongest barrier consisting of a ceramic layer (B$_4$C boron carbide) and a metal layer (Steel S7) was determined.

Calculations made with the help of Ansys Autodyn software package show how significantly different the rate of penetration of the barrier at right angles and at an angle of 45°, as well as the results obtained by numerical and semi-analytical solution of the problem differ by about 5-10%. This indicates a fairly accurate result obtained when solving problems of this type in the program Ansys Autodyn.

Comparing the numerical results obtained in this work with the experimental and numerical calculations presented in [12] in tables 1 and 5, which also considers the punching of two-layer barriers with a substrate, the difference reaches about 7-13%. Given that the paper [12] considers barriers consisting of other materials and the thickness of the ceramic layer varies from 5 to 11 mm, and the thickness of the substrate from 5-8 mm, it can be concluded that the results obtained in this paper have a good match with the results presented in [12].

**Conclusions**

1. The perforation penetration rates of two-layer ceramic-metal and metal barriers at angles of 90 and 45 degrees were obtained, taking into account the structural characteristics and physicomechanical properties of the materials of the impactor and obstacles.
2. Verification of the velocities obtained by a numerical method in the Ansys Autodyne package and experimental ones was carried out. The speeds obtained by a numerical method with the correct setting of the solver in the Ansys Autodyne program differ from the experimental ones by 5-10%.

3. When calculating the speed by the analytical method, the detected deficiencies in the calculations of Ilyushin and introduced corrections.

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