Numerical and experimental study of the penetration of a package of woven metal grid by a steel ball

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Annotation: The results of numerical and experimental studies of the penetration and punching by a steel ball of the barriers consisting of packages of metal woven wire grid are presented. In the experiments performed, a packet of meshes was formed by overlaying ten flat woven layers with different sizes of quadrilateral cells. The ball was made of high-strength steel with high yield strength, so that after the experiments it remained intact. Numerical calculations were carried out using the author's program based on a modification of the Godunov method for the calculation of elastic plastic deformation taking into account the accumulation of damage and destruction. Comparison of experimental and calculated data is carried out by fixing the speed of a ball flying behind a barrier and a general dynamic picture of the development of zones of destruction in a barrier.

1. Introduction

At present time, wire nets made from thin wire are considered as promising elements for creating means to protect a structure from shock waves. In addition, the use of the metal mesh woven weaving helps to protect the body of the explosion chambers from fragmentation damage. Protective structure under intense effects may experience deformations including irreversible. Both experimental and numerical methods are used to investigate these properties. In the works [1-6] the results of experimental and numerical studies of the interaction of various forms of projectiles with porous barriers, including with mesh ones, are presented. In [4-6], mesh barriers were considered as protective elements of spacecraft from the impact of high-velocity bodies. Issues of the destruction of projectiles on mesh barriers at velocities of 2.5-5 km/s were investigated. It is shown that the placement in front of the main structures of objects of thin mesh barriers, crushing high-velocity particles into fragments, reduces the probability of its penetration. Replacing a solid plate with a grid of high-strength material reduces the weight of the protective structure. The issues of protecting structures from explosive effects using multilayer bags made of woven metal meshes were considered in [7-11]. In [8, 9, 11], the results of numerical studies of internal explosive loading of cylindrical multilayer chambers, one of the layers of which was a multilayer packet of woven nets, are presented. It is shown that the presence of a package of grids significantly reduces the gas-dynamic loads on the power shells. The results of numerical studies are consistent with experimental estimates. In order to design barriers in the form of a pack of woven metal meshes, it is necessary to know their deformation and strength properties.
In [12–14], the deformation properties of woven mesh packages, so important for successful numerical simulation, were investigated. The package is constructively formed, as a rule, by superimposing layers on each other. Therefore, it can be considered a highly porous structural element with transversely orthotropic properties. As shown in [13], the packet differently resists compression along the normal to the grid layers and stretching in the plane of the layers. In [14,15] the results of experimental studies in which the deformation characteristics under tension are defined are given.

The purpose of this work is to assess the velocity of the ball velocity behind the barrier, as well as to check the adequacy of the mathematical and numerical models used to describe the process of breaking through a package of wire grids.

2. Conditions for conducting experiments

The object of study is a metal mesh woven weaving. The grid is made with the following parameters $l \times l \times d$, where $l$ is the length of the mesh in mm, and $d$ is the diameter of the wire in mm. For the experiment, we selected $2 \times 2 \times 0.5$ mm and $3.2 \times 3.2 \times 0.8$ mm grids. A gas gun with a caliber of 20 mm was used as an accelerating device, and the parameters of the punching process were recorded with an HSFC pro digital camera. The breaking of the metal mesh of woven weaving was carried out with a hardened ball made of high strength steel with a hardness of 62HRC in accordance with the nomenclature of Russian construction materials. The diameter of the ball was 19 mm. The ball was accelerated in a gas gun and punched through a mesh package installed in the receiving catch chamber. In the chamber, the package was fixed by clamping between two metal rings with a bolt tie. The velocity of the ball on approaching the grid ranged from 123 to 294 m / s, after breaking through from 100 to 220 m/s. Before each trial, the fixing equipment (digital camera) was scaled. The interval of shooting one frame is 50 microseconds. The table No 1 presents the values of the velocity after the barrier in the series of experiments for the steel ball at the breakthrough of packages of grids formed of 10 layers.

| Mesh $l \times l \times d$, mm | Number of layers | Initial velocity m/s | Residual velocity m/s |
|-----------------------------|------------------|----------------------|-----------------------|
| #467 $2 \times 2 \times 0.5$ | 10               | 294                  | 220                   |
| #477 $2 \times 2 \times 0.5$ | 10               | 142                  | 130                   |
| #475 $2 \times 2 \times 0.5$ | 10               | 140                  | 123                   |
| #474 $2 \times 2 \times 0.5$ | 10               | 137                  | 125                   |
| #478 $2 \times 2 \times 0.5$ | 10               | 123                  | 100                   |
| #468 $3.2 \times 3.2 \times 0.8$ | 10           | 271                  | 200                   |
| #473 $3.2 \times 3.2 \times 0.8$ | 10           | 179                  | 143                   |

The loss of speed after the obstacle for thin grids increases with an increase in the initial impact velocity in the range of 100–300 m/s and is approximately from 8 to 25% of the impact velocity. For thicker layers, such an assessment is difficult to give due to the small number of measurements taken.

Figure 1 presents the characteristic process of breaking through a packet of wire mesh at successive points in time in the experiment under the number 477. The time report is from the moment of the initial activation of the digital camera.
In the last photo of figure 1, it is clearly seen that after breaking through the steel ball tears off and takes with it a piece of wire mesh.

3. Numerical results
The calculations were carried out using the UPSGOD software package, the implementation of which is based on the modified S.K. Godunov scheme to integrate the system of integral laws of conservation of mass, momentum and energy, describing the behavior of various continuous media in a two-dimensional formulation. A detailed description of all the functionality of this software package is contained in [16]. The model of deformation and destruction of barriers was proposed for concrete barriers in [17] and, in a simplified formulation, was tested for barriers from wire nets in the present work. According to this model, for the deviator components of the stress and strain tensors, three limiting surfaces are introduced: the fluidity surface with partial damage to the structure, the fracture surface, and the fluidity surface of the medium with completely impaired structural strength. Depending on the current level of stress-strain state, the processes of deformation and destruction of the environment, preceding the current point in time, the model of the behavior of the damaged environment includes three variants of the state with the corresponding constitutional equations of
behavior. The first state of elastic deformation is described by Hooke's law for an isotropic single-phase medium. The zone of elastic behavior of the material is limited by the equation of the surface yield strength with partial structural damage. The second state corresponds to the process of equilibrium elastic plastic deformation of the medium with the law of flow associated with the equation of the surface flow. The hardening process (ascending branch of the deformation diagram) is accompanied by the process of accumulation of partial damage to the material. Quantitatively damages are described by a scalar damage parameter $0 \leq \omega \leq 1$, which is calculated using a linear summation circuit for damage. The destruction of the medium occurs when the equality $\omega = 1$ is fulfilled, which corresponds to the condition for the current surface to achieve a yield point at the loading point of a given destruction surface. Finally, the third state, corresponding to the behavior of a material in a destroyed state, is described by a model of an elastic plastic medium with zero resistance to all-round tension. The grid compression law is taken in accordance with the dynamic compression diagram [6-8], given in tabular form with the linear law of unloading at the speed of sound when unloading equal to 3 km/s. When stretching, an elastic connection between stress and strain with an effective modulus $= 1.2 \text{ GPa}$ is assumed. The tensile strength according to experimental data [8] is 115 MPa.

Computer implementation of a simplified model of deformation and destruction of wire barriers is included in the used software package. Verification of the model is carried out by comparing the calculated data with the results of laboratory experiments on the penetration of the steel ball into the obstacles from wire grids.
The dynamics of the development of zones of destruction during the breakthrough is illustrated in figure 2. Here, complete fragmentation zones are marked with a background color. The left half of figure 2 shows the computational grid, on the right half - cells with destroyed material are removed for clarity. Similar to experience 477 in the calculations, the ball tears off a piece of a wire mesh packet and carries it along.

Figure 3 shows the temporal dependence of the calculated speed of movement of the steel ball in experiment 477. In this case, the movement speed of the ball after obstacle was 133.5 m/s, which exceeds the experimentally measured value by 2.7%. Of course, the barrier of 10 layers of thin woven mesh (about 0.5 cm thick) is not able to brake the projectile at the considered impact velocities. In order to estimate the number of layers of such a grid capable of completely stopping the movement of a drummer at a given initial speed, a ball collision with a thicker barrier was calculated. Figure 4 shows the calculated chart of the speed and movement of the ball in a thick barrier. It can be seen that its movement stops approximately 0.5 milliseconds after the impact, and the movement at this moment slightly exceeds 3 centimeters. Thus, it seems that the woven mesh package with a thickness of 4-5 centimeters will be able to completely stop the drummer in question.

4. Conclusion
An experimental study of the penetration and punching of a steel ball into barriers consisting of packages of metal braided wire meshes was carried out. For one of the experiments, a numerical simulation of the breakthrough process was carried out. The movement velocity of the projectile after
punching the barrier is estimated. It has been established that for the final stop of the ball with a packet of thin wire grids considered it is required to make it from a much larger number of layers (4-5 cm thick). A satisfactory agreement between the numerical and experimental results indicated a sufficient adequacy of the mathematical and numerical models used.

The work was carried out with the financial support of the Russian Foundation for Basic Research in accordance with the research project No. 19-08-00320 and the government assignment of the Ministry of Education and Science of Russian Federation No. 9.7057.2017 /BC.

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