Experimental study of the penetrating of plates by projectile at low initial speeds

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Abstract. The research of the penetration process of lightweight plates by a projectile in the range of initial velocities up to 325 m/s was attempted. The projectile was a shell bullet and the barriers were of ice, MDF-panels and plexiglas barriers. The response of barriers to impact loading is studied. High-speed shooting of each experiment is obtained, including photos of the front and rear sides of the barriers. An attempt was made to reproduce the scenario of the destruction of barriers. The results of experiments can be interpreted only as qualitative tests. Projectile was not destroyed.

1. Introduction

The processes occurring in solids under high-speed deformation are now the subject of fundamental and applied research, both in Russian Federation and abroad. This is due, above all, the breadth of application use in various spheres of human life. This includes: the creation of effective anti-shock protection of civilian and military facilities and equipment; welding and explosion cutting; hydrostretching; shock-wave pressing; explosive hardening; safety of the shells of a nuclear reactor in cases of falling into them objects from outside (aircraft, fragments, etc.) or loading from the inside (excessively high pressures that arise when the reactor is broken), etc. Separately, one can single out the protection of space vehicles from the threat of micrometeorites and technogenic debris particles impacting them. In addition, the accumulated experience in the field of high-speed deformation of solids is of interest in medicine, astrophysics and military applications [1-5].

The interaction of solids is accompanied by complex processes, the final role of which is determined by the presence of a number of factors: the initial velocity of the impacting objects, shape, and physics and mechanical property. It should be noted that in most cases, during an interaction, penetration of the bodies into each other takes place, as well as the melting and destruction of the material into separate fragments.

In the quantitative description of high-speed shock phenomena, many complex problems arise, which at present are far from solving and require the use of mathematical modeling and experimental methods of investigation. Certain results can be obtained by carrying out large-scale model tests and full-scale tests using various ballistic set up and explosive accelerators for throwing bodies. For example, the size of the fragment, the level of its destruction, the shape and depth of the crater, the ballistic limit, etc. However, it is necessary to note the technical complexity and high cost of carrying out such experiments, as well as the impossibility of obtaining detailed information on the space-time
distribution of stress fields, deformations and fracture regions. Nevertheless, the importance of obtaining experimental results does not cause doubts.

The laboratory 21 National Research Tomsk State University developed a multifunctional user program complex for solving modern multi-contact dynamic problems of solid body mechanics. Under such problems, one should understand the problems of the penetration and deep penetration by the impactor of complex geometry into structurally heterogeneous barriers. Several solvers have been developed for two-dimensional plane and axisymmetric statements [6]. The software package is developed as an alternative to commercial FEM software LS-Dyna.

A numerical lagrangian method is developed for calculating modern dynamic multi-contact problems of mechanics of a deformed solid. The originality of the method lies in a new way for isolating the surfaces of discontinuity in the continuity of materials, which does not impose serious limitations on the solution of these problems. The numerical method contains an algorithm for splitting nodes, erosion triangulated elements, rearranging the contact and free surfaces, and so on [7].

The latest innovation is the mobile laboratory "Explosive Destruction of Natural Materials", organized in Tomsk State University. The mobile lab expands the research capabilities of the team, and its main goal is full-scale experiments. The one is functioning with the support of the EMERCOM of Russia and KuzbasSpetsVzryv company. Full-scale tests on underwater explosion of ice and explosion of limestone are carried out. The diameters of blasting lanes in the ice and the shape of the explosion crater in limestone were established [8].

In the current research, the behavior of freshwater ice, MDF-panels and plexiglas at impact load are investigated. A snap-analysis of the behavior of these materials under impact loading was carried out. High-speed shooting of the penetration process is obtained. Studied in detail the inlet and outlet openings into the barriers. An attempt has been made to study the morphology of destruction. In all cases, the form of the projectile after penetration is established.

2. Experimental set-up

This section focus on the experimental set-up. The experimental set-up was installed in the Tomsk Field Shooting Society is shown in figure 1. This experimental setup is mobile and designed specifically for snap analysis of the penetration process. The main components were a bullet receiver, light projectors, a special place for targets and a high-speed camera.

![Experimental set-up](image)

**Figure 1.** The experimental set-up. Photo by M. Orlov
The presence of the bullet receiver excludes a detailed study of the impactor after the shock. The one present only in the first experiment, because in this case the form of the impactor was known.

Several light projectors were used. The research objects can be moved independently in the different degrees of freedom.

A high-speed camera (Photron Fastcam APX RS, 10000 frames per second) was used to film the impact loading. There were several camera positions around the barrier. The first position was perpendicular to the barrier is shown in figure 1. The remaining positions were at an obtuse angle and an acute angle to the barrier. This allowed for a more detailed study of the process of penetration.

2.1. Projectile and initial velocity

Only one projectile was used. The projectile is a shell bullet. Weight is 6.9 g. Length is 12 mm. The diameter of the leading part is 9.2 mm. Shell weight is 1.5 g. The shell material is low-alloy steel. Core weight is 2.5 g. The material of the core is plumbum. Initial velocity is 325 m/s. The projectile is depicted in figure 6.

3. Research ice penetration by projectile

The behavior of this ice under impact loads was investigated in [9-11]. The diameter of the crater and the depth of the crater in the ice blocks are revealed after penetrating by the spherical impactor. Earlier, it was established that the impact craters in the ice had a conical shape. The original research of penetration of the ice barriers is presented. One of the main objectives was to establish the main mechanisms of the process of destruction of ice barriers. The results of the interaction of these materials are predictable.

3.1. Sample preparation

The first object of research was freshwater ice. In a laboratory experiment were single-layer, dual-layer and three-layer ice barriers. However, current study single-layered barriers were considered only. The ice was obtained under special conditions: the freezing point was -17 ºC, the freezing time was ~36 hours. Prepared samples were placed in a special container and delivered to the laboratory. 25 samples were prepared. The diameter of each sample was 14.5 cm and the height of the sample was 4.5 cm. This ice was called congelation ice. The physical and mechanical properties of such ice are given in [12].

3.2. Projectile penetration analysis

The presented results are a logical continuation of systematic studies of the behavior of ice under dynamic loads. The following regularities were established in the experiment. After the penetration of the ice barrier, the projectile was not deformed. Most likely that the projectile velocity the barrier and after the barrier was approximately the same. The number of fragments separated from the front of the barrier and from the rear part of the barrier was also approximately the same. This is seen in figure 2. Figure 3 shows the barrier before the impact, and figure 4 shows the barrier after the impact.
Figure 2. The penetration of the ice barrier by projectile

Figure 4 clearly shows four large fragments of ice. These fragments took place in high-speed photography. It is likely that these fragments were formed as a result of the propagation of the main cracks. Propagation direction was from the center to the side surfaces of the ice cylinder. Smaller fragments of ice are noted in the photograph. Unfortunately the projectile is not visible on this photo. Most likely, the distance between the projectile and the barrier is greater than the diameter of the ice barrier.

Figure 3. Ice barrier before impact

Figure 4. Ice barrier after impact.
Scale bar represent 1 mm

Thus, the ice cylinder practically did not resist steel projectile penetration. The ice breaks up into fragments of various sizes, include very small ones (approximately 1 mm). Four fragments of ice (3 cm in size and slightly more) are clearly visible. Projectile after impact remained undamaged. Obviously this is due to the strength properties of the interacting materials.
4. Research MDF-panel penetration by projectile

The MDF-panels as the object of research were selected by the authors for the first time. The use of MDF-panels in modern protective structures is barely possible. More likely, the use of MDF-panels and similar materials is possible as back layers. For example, the MDF-panel can be used as the back of armored door in banks, etc. Current experiment focuses on the expansion of scientific knowledge about the behavior of these materials under impact.

4.1. Research object

The next objects of research were the barriers of MDF-panels. These studies were planned to expand the scientific knowledge about the behavior of this material under shock loads. MDF panels are stronger than congelation ice.

Some mechanical properties are as follows:
- The initial density is 0.95 g/cm³.
- Bending strength is 22 MPa.
- Elastic modulus is 1.7 GPa.
- The thickness of the barrier is 9 mm.
- The diameter of the barrier is 200 mm.
- The number of barriers in the tests is 10 pcs.

4.2. Projectile penetration analysis

In this paragraph, the results of penetration of the MDF plate are presented. It should be noted that high-speed shooting of this process was carried out at different angles to the barrier. This is necessary to fix the cloud of the leading fragments.

Figure 4 illustrates the process of penetrating a barrier by a projectile. Approximate time is 5 microseconds. It was revealed that the penetration was accompanied by the separation of fragments from the front and back sides of the barrier. Debris of broken away from the front of the barrier moved opposite to the movement of the projectile. The vast majority of the fragments were not large (less than a projectile). Only a few fragments measured 1 cm or more.

![Figure 5](image.png)

**Figure 5.** The penetration of the MDF-barrier by projectile
A distinctive feature should be considered the formation of a through hole in the barrier. The diameter of the hole was equal to the diameter of the projectile. And the internal surface of the hole was not damaged. The number of fragments separated from the rear side is more than the number of fragments from the front side MDF-barrier. The state of the projectile after the impact was the same as that subsection 3. However, there were scratches in its cylindrical part.

Figure 5 shows the obverse of the barrier from the MDF-panel. Here the entrance hole is clearly visible. The diameter of the hole was 9 mm, i.e. the diameter of the hole and the diameter of the projectile were the same. There are no annular and radial cracks on the surface.

Figure 6 shows the back side barrier. It is seen that the barrier is more damaged in the rear. There is no near-surface layer 18 mm in diameter. The thickness of the layer is 2.5 mm. The photo shows holes of the specified diameter. There are no cracks on the back side. The research suggests the morphology of destruction the ice and MDF-panel after penetrating were different.

5. Research plexiglas penetration by projectile

The last object of research was organic glass (plexiglas). The choice of plexiglas as an object of research is due to the fact that it is a frost-resistant material and a dielectric. Understanding the dynamic response of plexiglas has important applications on engineering, including some protective structure and aircraft elements.

5.1. Research object

In research [13], the behavior of plexiglas was investigated in the speed range from 500 m/s to 5000 m/s. The behavior of plexiglas at such speeds was predicted, including penetration at all stages, hydrostatic pressure isolines and hydrostatic pressure at control points, shortening of the projectile, speed of free surface, penetrating time, the time of formation of the first foci of destruction, etc. The present research are limited only to the experiment of penetrating the plexiglas barrier by the projectile.

- The initial density is 1.18 g/cm³.
- Tensile elastic modulus is 3 GPa.
- Tensile strength is 70 MPa.
- The thickness of the barrier is 10 mm.
- The diameter of the barrier is 100 mm.
- The number of barriers in the tests is 10 pcs.
5.2. Projectile penetration analysis

Figure 8 illustrates the process of penetrating barrier of plexiglas. As in figures 2, 5 the final stage of the process is shown. A few microseconds ago, the projectile penetrated and destroyed the barrier. It can be seen that the process of destruction of plexiglas differed from the processes of destruction of the MDF-panel and freshwater ice. The cloud of the leading fragments consists of small (about 1 mm) and medium (from 5 mm to 10 mm) fragments. An important point is that this cloud is shaped by the near-surface layers on the back of the barrier. For some time, the projectile is in contact with these fragments. After penetration, the barrier is destroyed by 6 or 7 large fragments (15 mm or more). The form of the projectile after penetration was the same as in the previous case.

![Figure 8. The penetration of the Plexiglas by projectile.](image)

Figure 9 shows the rear side of the plexiglas barrier after the impact. Near the barrier are the fragments of medium size. Most of the fragments previously were back side of the barrier. In the center of the barrier is clearly visible hole. The diameter of this hole is approximately 14 mm. This zone consists of cracks inside the barrier. A significant part of the material from the rear side was beyond the barrier. The front side of the barrier also lost some volume of material. It is visually established that the lost volume of material from the front side was less than the lost volume from the back side of the barrier. From the center of the barrier, the main cracks spread to the lateral surfaces. In the future, according to these cracks, plexiglas destroyed. In research [14] such cracks were called radial.
Figure 9. The rear side of the barriers

Summary

The process of destruction of ice has been studied in detail. The ice was destroyed by various fragments, and there was no precise estimate of the ice fragments. A similar picture of the destruction can be observed in [15]. The projectile did not fail after the penetrating of the barrier. The velocity of the projectile after penetration has not been measured, but there is every reason to believe that it has not changed significantly. The result can be spent as a new qualitative test only.

The process of penetration of the MDF-panel by the projectile is also investigated. In contrast to the previous case, a through hole with a diameter of 9 mm was in the barrier. The destruction of the obverse side of the barrier and the destruction of the rear side of the barrier were different. On the front side there were no damage to the near-surface layer. No annular and radial cracks were observed, extending from the hole to the lateral surfaces of the barrier. After the penetration, the impact did not change its original form.

Later in the current research, the process of destruction of plexiglas was studied. Here, other features of the process of destruction were noted. The quality of the destruction of plexiglas is similar to the destruction of ice. However, in the first case there was a through hole. In this case, the number of medium fragments and large fragments were maximum. After penetration the projectile is not destroyed.

Conclusion

Thus, the process of penetrating barriers by a projectile with an ogive head part at a low initial speed has been studied. In all cases, the barriers were penetrated. In addition, plexiglas and ice were destroyed in fragments. This was explained by the size of barriers and their mechanical properties. In the MDF-panel there was a through hole only. The projectile was not destroyed after the impact.
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