Research of the behavior of metal plates subject to ice ball

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Abstract. The paper summarizes the results of ice destruction at shock loads (up to 1500 m/s). A brief literary review was sufficient for formulating research tasks, including impact experiment and a computational experiment. The results of impact experiment (≤159 m/s) were presented. The freezing temperature of ice samples varied from − 10°C to − 21°C. Similar pattern of ice destruction was noted in the quantitative test, which conducted especially for validation of the numerical method. The results of an underwater explosion of 4 kg of EE under 130-days-old "needle" ice cover are represented. Some capability of non-commercial software package is demonstrated. The impact resistance of single and double plates was qualitatively and quantitatively evaluated. It was established that the plates could protect against impact by an ice ball only up to 500 m/s.

1. Introduction

Research of the behavior of ice under shock loads is an extremely important scientific problem. It is known that ice is a poorly studied natural material. Ice destruction concepts have been developed. From the point of view of destruction, ice may have no analogues in nature [1, 2]. This can be explained by complex mechanical properties, anamalous ductility, the presence of phase transitions in the process of deformation, etc. In [3-5], physical and mechanical properties of ice are described.

The current research is included in the author's series of works [6,7] devoted to the study of ice destruction under shock and explosive loads. In [8,9] the state of arts of the topic is described in detail (as of the end of 2014).

We highlight some of the already known research, and those closest to this topic. The phenomenological ice model from [10] is the most famous one according to publication activity. Experimental testing and analytical modeling of ice impact and fragmentation at turbo fan engine inlet were conducted in [11]. In work [12] ballistic tests, in which both solid (steel) and fragmenting (ice) spherical projectiles were fired at specimens of carbon-fibre-reinforced polymer (CFRP) composite. Massive ice block subject to steel projectile normal impact have been experimentally and numerically studied in [13]. In [14] a constitutive relation for ice at high strain rates and an algorithm for its numerical integration were developed.

The mentioned allowed us to formulate the current tasks that are solved below. The aim of the current work is to study the impact resistance of single and double plates subject to impact by an ice ball in a velocity range up to 1500 m/s. Some plates are simulators of spacecraft elements, including heat exchangers. The work deals with experimental and theoretical research. Both experimental and theoretical studies were performed at the Research Institute of Applied Mathematics and Mechanics of Tomsk State University (hereinafter, RIAMM).

2. Experimental

The first part of the article outlines experimental studies of the destruction of ice upon impact and explosion. The ones consisted of impact experiments and full-scale experiments. Impact ice experiments were made both by the RIAMM and the Society for Practical Bullet Shooting [15]. A mobile laboratory "Explosive Destruction of Natural Materials" was organized specifically for studying ice under explosion (hereinafter, mobilab). It is developing as an alternative to the American research program ScICExe [16]. At present time, the mobile laboratory has the status of an initiative project, its permanent partners are KuzbasSpetsVzryv Ltd and the Ministry of Emergencies in the Tomsk Region [8].

2.1 Impact experiments

This subsection presents the results of an impact experiment. Research objects are ice blocks. The ice block freezing time was 72 hours. The freezing temperature ranged from -10°C to - 21°C.

Table 1 shows the results of death crater measurements for the case of normal impact and inclined (α = 45). It is seen that in the case of a normal impact for all samples, the penetration depth of the impactor was greater than its diameter. With an inclined impact, the penetration depth was less than the diameter of the ball. At the minimal ball velocity, one can note a slight decrease in the penetration depth with increase in the ice freezing temperature. At the maximal ball velocity, the effect is opposite and more pronounced.

Table 1 – Impact experiment results

		The depth of steel ball penetration L_k, mm		
4.5 mm steel ball	Nutation angle, α	90		45
	Freezing temperature	- 10 °C	- 21 °C	- 21 °C
	Initial Steel Ball Velocity V_o, m/s			
	110	5.7	5.2	3.9
	154	8.2	-	-
	159	5.2	7.2	-

The morphology of ice destruction impacted by steel ball was ordinary. Some of its features will be mention in section 4. After penetration, the ball did not deform.

2.2 Full-scale underwater explosion test

This subsection focuses on the results of full-scale experiments. To be more exact, full-scale ice cover underwater explosion tests are summarized here (hereinafter, UNDEX). Research objects are snow-covered ice, bare ice and “needle” one (In accordance to Nomenclature of Sea Ice from 1974). In the current research, we will focus only on the first ice cover. The freezing time of river ice was approximate 130 days. Others types of ice cover were discussed in [6].

In all cases, the explosion was carried out in the water under the ice. There was no air gap between explosives and ice. Emulsion explosives (EE) were used only. The explosive had a cylindrical shape and a mass of 4 kg (TNT equivalent 3.25 kg). At the detonation moment, EE was located horizontally to the ice cover. Water and air temperature were 4ºC. The depth of the water under the ice cover was approximately 5 meters (hydroimpact was excluded). The river bottom was flat. The initiation point of explosion was at the top of EE charge. The experiments were carried out in the spring of this year on the Tom River in conjunction with KuzbasSpetsVzryv Ltd.

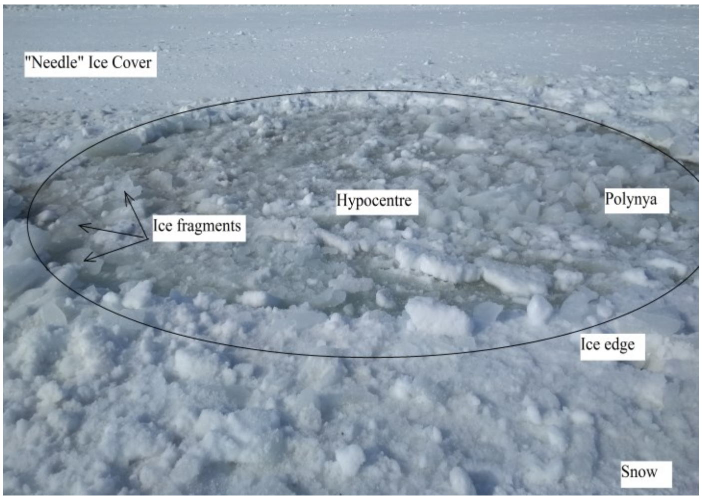

Figure 1. “Needle” ice cover after blow of up 4-kg-EE-explosive.

Figure 1 shows the polynya in the “needle” ice cover after the explosion of 4-kg-EE explosives. The thickness of the ice is 60 cm. The thickness of the snow is approximate 10 cm. It was close to the circle shape. The fragmentation height was 8 meters. The ice edge had stepped shape. Compared to last year (snow-covered ice), the morphology of ice destruction was different. The ice fragments after the “needle” ice explosion were much smaller than the ones after the explosion of a snow-covered ice. A similar pattern was observed earlier for several years at the experiment site. According to the results of 10 blasts, polynia diameter was approximate 4.5 m. Which in turn, is almost twice as much as last year. In experimental site, detonation products (hereinafter DP’s) remains were detected too.

3. Mathematical model of ice fracture under dynamic loads

Below is a phenomenological model of ice deformation and destruction. From the point of view of this model, ice is modeled by a porous, compressible, elastic-plastic medium without phase transitions with averaged physical and mechanical property from [1-4]. The governing equations are based on the fundamental laws of conservation of mass, momentum and energy. A complex model of continuum mechanics to describe the material behavior under dynamic load is used. The model is described in detail in [9]. To describe the shear strength of a body, the Prandtl − Reuss constitutive equations and the von Mises yield condition were used [17]. Pressure in DP is described by Landau – Stanyukovich polytropie [18]. The shock adiabat of ice and water is given in [19]. In the process of material destruction under dynamic loading, new free surfaces, including fragmentary destruction are allowed.

Deterministic fracture model of the material is used. A well-known fact is that the destruction of any material is accompanied by the formation of both “tear-off” or “spall” fractures and “shear” fracture. Sometimes one type of destruction can prevail over another, for example, during an adiabatic shear. Therefore, when modelling materials fracture, both types should be considered. For the first time, this concept was implemented in [20].The use of different failure criteria is quite possible. This makes it possible to simulate the destruction process of the most close to real one.

3.1 Software package

To simulate modern multi-contact dynamic problems of mechanics solids, a software package was developed [21]. It is a non-profit development. The program package consists of a solver program and a viewer program. At present, there are more than five versions of both programs. The following shows the capabilities of the latest version of the program (see Fig.2).

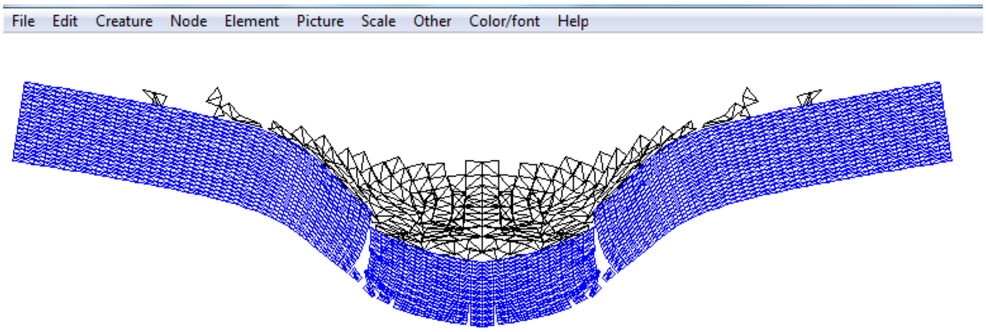

Figure 2. The Interface of Impact_2D, computer code developed by Yu. Orlov. Blue color indicates ice. Computer Program Certificate is 2010615392

A 2-cm-diameter ice ball perforates an aluminum plate at 1500 m/s (see figure 2). One can see plug formation in the plate in figure 2. The deflection of the plate, the amount of ice destruction, the inlet and outlet diameters of the holes in the plate, the time of perforation, the pressure at the control points, and the velocity of the free surface were quantified. These results are not discussed in this article.

4. Numerical method

This section outlines the numerical research method. It шы based on the Lagrangian approach for describing the motion of continuous media. In substance it is the development and modification of well-known methods from [22, 23]. According to Vasiliy Fomin's terminology [24], it contains a new way for isolating the discontinuity surfaces of materials. In fact, any lagrangian method has serious problem with overlapped triangle elements after impact loading, for example, as in deep penetration task. To solve this problem, the algorithms element erosion, nodes splitting and algorithm for constructing the free surface were proposed and developed. The last algorithm for modeling the contact boundary in the explosion of thick ice (200 cm or more) is described in [9]. The improved algorithm was proposed in [8].

As described earlier, the new way does not impose serious restrictions on the solution of modern multi-contact dynamic problems of solid mechanics. The most important algorithm for modeling the problems of deep penetration and perforation of plates is a nodes splitting algorithm. A similar it was proposed in [25, 26]. However, in the present approach, several ways of splitting nodes are possible. This allows us to use various failure criteria of solids, including for functionally graded materials, structure with non-uniform inclusions, etc. In this algorithm, it is not necessary to store any information in the nodes as in [27].

4.1 Test calculations

Before interpreting the numerical results as a forecast, it is necessary to solve the question of the reliability. For this purpose, it is necessary to conduct qualitative, quantitative and internal tests (in accordance with Victor Selivanov's terminology). These tests will verify both the mathematical model and the numerical method. In [9] several tests, including two internal tests (frontal impact of two metal cylinders, and the Taylor's test) were made by the authors. One quantitative test was conducted in [10]. The following subsection of the article present the results of quantitative test. There, ice was as target only. In work [28] ice was as impactor which interacted with a thin aluminum plate at low velocity. However, in this article we will focus on the first quantitative test. The subject of comparison was the integral characteristics of the interaction process, including the depth of penetration or residual displacement of the plates.

4.2 Deep penetration of a steel ball into ice block
This subsection outlines task of penetrating a steel ball into the ice block. The target is an ice block. Its dimensions were (15×15×15) cm. The sample was made by freezing fresh water in a refrigerator. The freezing temperature is -17C, the freezing time is more than 48 hours. The impactor is a steel ball with a diameter of 4.5 mm. Initial velocity range varied from 100 to 150 m/s.

Below we compare the results of numerical simulation and laboratory impact experiment. The experimental results are taken from [29]. The subject of comparison was the depth of the impact crater and its shape.

Figure 3 shows the configuration of bodies at the final stage of interaction. In this case, the initial velocity was 150 m/s. Obviously, the steel ball was not destroyed. This can be explained by the strength properties of steel and ice, respectively. After removing the ball from ice, the crater was V-shaped. The destruction zone in ice did not reach the back surface of the ice block. All fracture foci concentrated near the impact crater. A splash of the surface layers of ice to the outside took place. A similar pattern of ice destruction was observed in the experiment from Subsection 2.1.The penetration time did not exceed 100 μs. The depth of penetration of the ball into ice was 7.2 mm (in the experiment) and 8.4 mm (in the computational experiment). In both cases, the depth of penetration of the ball exceeded its original diameter.

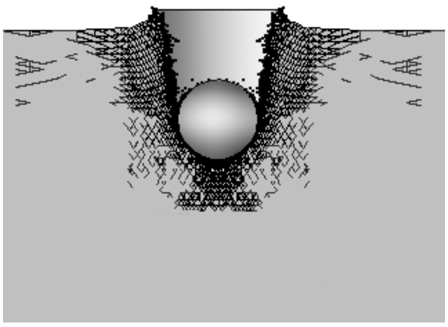

Figure 3. The cross section of the impactor and the target at 75 μs
Steel ball's impact implemented from the top down.

Thus, the results of numerical modeling are qualitatively and quantitatively consistent with the experimental results. The quantitative characteristics of penetration in the experiment and numerical simulation differed no more than 10%. The pattern of ice destruction consisted of a V-shaped crater in the ice block, the absence of foci of destruction near the back surface, and the metal ball was not deformed.

5. Numerical simulation results

This section presents the results of numerical simulation of the destruction of single and double plates subjected to ice ball. Post penetration analysis, including the time of penetration, the time of formation of the centers of destruction in the bodies, the diameter of the hole after impact, profile free surface velocity etc, was implemented.

5.1 Projectile and objects of research
Research objects were an aluminum plate, a two-layer plate (upper layer is aluminum plate, lower one is asbotextolite plate) and asbestos-laminate plate. There is a slip condition at the contact boundary of the layers. The projectile is 10-mm ice ball. The initial velocity range ranged from 500 to 1500 m/s. Computational experiments were carried out for an axisymmetric 2D statement using a non-commercial software package. The finite element models of body are built in automatic mode. The purpose of computational experiments is assessment the impact resistance of these targets.

5.1.1 Post-perforation analysis

In this subsection, we focus on the future results of numerical simulation, which are presented in the following sections. Table 2 presents the post-perforation analysis, which was made for each research objects, regardless of the initial velocity.

Table 2. Post-perforation analysis

Case 1	**Case 2**	**Case 3**	
500	1000	1500	Ice Ball Initial Velocity [m/s]
100			Perforation simulation time [μs]
+/-	+/-	+/-	The first foci of destruction[a]
+/-	+/-	+/-	Spallation plate / “Cork”[b]
No			Hydrostatic pressure at control points [GPa]
Yes			Velocity free surface of the plates [m/s]
Yes			Plate hole diameter [mm]

[a] in this case, the time of their formation is established both ball and plates
[b]in this case, only their presence at the time of 100 μs

In all cases, the interaction process time was modeled up to 100 μs. After this point in time, the deformation patterns remained practically unchanged, and the residual velocity reached “steady motion” area. Initially, the occurrence of the first foci of destruction in bodies was recorded. Their evolution has allowed us to trace the mechanism of formation of the “cork” or spall plate. In this article, the hydrostatic pressure and ballistic limit not computed. But,velocity of the free surface of the plates and the diameter of the inlet and outlet hole were obtained.

5.2 Numerical study of single aluminum plate subjected normal ice ball impact

In this subsection, we focus only on the destruction of a single aluminum plate subject to ice ball impact. A series of computational experiments consisted of three cases. The cases differed only in the initial velocity of the projectile, which was 500 m/s, 1000 m/s and 1500 m/s, respectively. The plate thickness is 5 mm. Below are presented and analyzed the initial and final configurations of bodies, ice ball’s velocity and velocity of leading fragments of the plate after impact.

Figure 4 illustrates the collision of an ice ball with aluminum plate with 500 m/s. It is seen that pre-fracture stage (elastic deformation) lasted no more than 1 μs. At 2 μs, the ice ball begins to destroyed in the zone of contact with the target. At 4 μs there are many cracks inside the ball, but it still retains its original shape. From 6 μs to 100 μs, the ice ball breaks into fragments that fly apart in the radial direction. In this case, the metal plate did not deform.

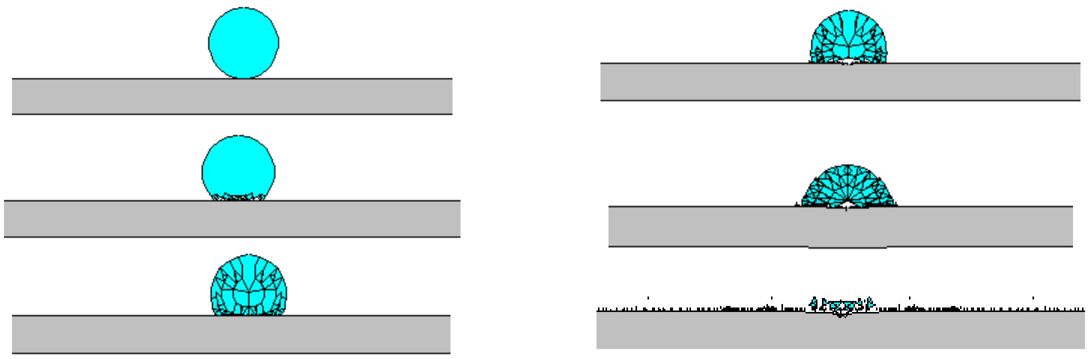

Figure 4 Cross-section of a ball and a metal plate at 0, 2, 4 μs (left row pictures) and 6, 10, 100 μs (right row pictures). The impact is modeled from the top down (Case 1) The initial velocity is 500 m/s.

Figure 5 shows the behavior of this plate at 1000 m/s and 1500 m/s. This figure makes it possible to make a comparative analysis of areas of destruction at some points in time. The areas of the destruction of bodies by 2 μs were approximately the same. In contrast to the previous case (see Fig. 3), the foci of destruction are marked on the back surface of the aluminum plate. On the 10[th] μs, the ball is starting perforating plate. At this time, an ice ball is almost destroyed. Axial deflection of the plates is also noted. In the second case, through perforation of the aluminum plate occurred. The diameter of the hole in the plate was larger than the initial diameter of the ball. In the second case, at 100 μs there was a conglomerate of material in the form of a “cork”. The velocity of the leading fragments will be given below in the paper.

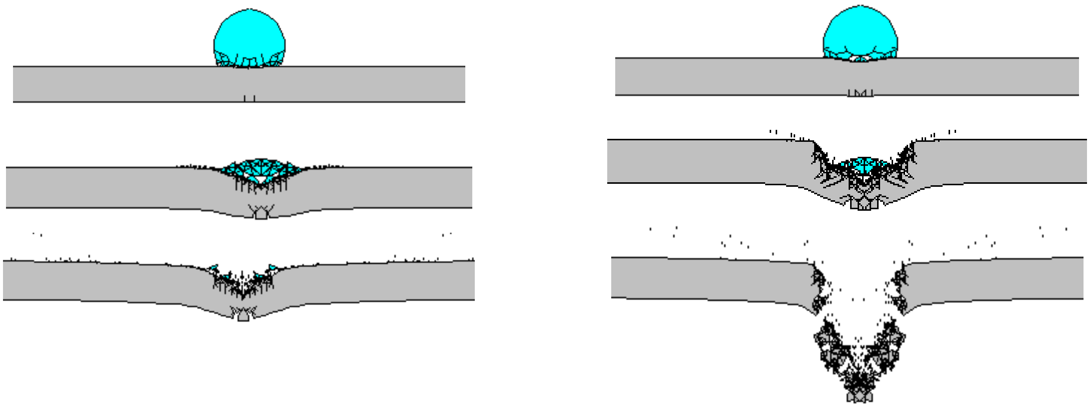

Figure 5 Cross-section of ice ball and aluminum plate at 2, 10, 100 μs
(left pictures at V_o = 1000 m/s, Case 2) and at 2, 10, 30 μs (right pictures at V_o = 1500 m/s, Case 3)

Figure 6 illustrates the time dependence of the relative residual velocity of ice ball. It can be seen that the stage of “steady” motion took place at the end of the perforating through, after 15 μs. Changing velocity can be divided into segments of "fast" and "slow" falling. The segment of the “fast” velocity falling was much larger than the segment of the “slow” it and lasted up to 8 μs.

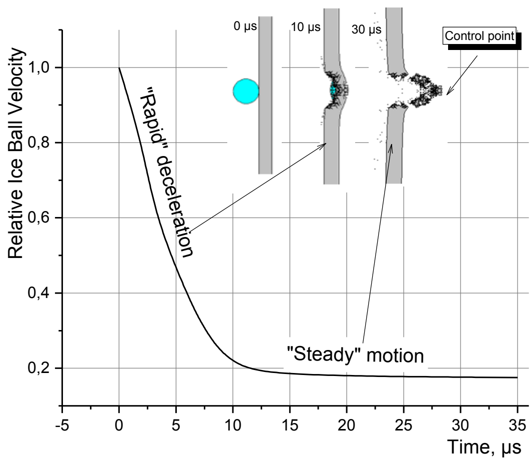

Figure 6 Residual velocity of projectile versus Time Case 3, V_0 = 1500 m/s

It should be noted that the curve in Fig. 6 is typical for the case of through target penetration. Thus, only at initial velocity of 1500 m/s, the aluminum plate was perforated by ice ball. The task of calculating the ballistics limit in this case did not arise.

5.3 Numerical study of double plate subjected to normal ice ball impact

In this subsection, the research object is a two-layer plate. The top 4.4-mm layer is asbotekstolit. The bottom 2.5 mm layer is aluminum (according to the nomenclature of Russian construction materials D16). This structure simulates a spacecraft element. Recently [29], impact resistance of such structure under impact loads was studied. Below only one computational case was considered, initial velocity was 1500 m/s.

Figure 7 shows the chronogram of perforation of double plate with an ice ball. These time instants make it possible to compare the morphology of plate destruction with the previous case (see subsection 5.2).

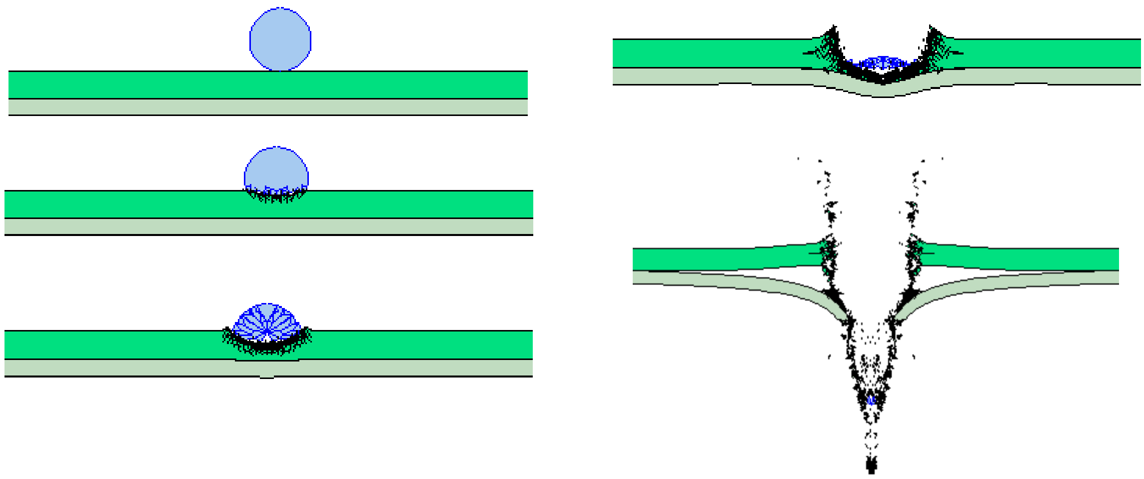

Figure 7 Cross-section of ice ball and double plate at 0, 2, 4, 10 and 70 μs (Case 3, V_o = 1500 m/s)

In this case, the pre-fracture stage was also no more than 1 μs. At time 4 μs, the ball is significantly destroyed, its shape is close to oval. The double plate is slightly noticeably deformed in the axial direction. Foci of material stucture in the upper layer are concentrated in the contact zone only. The bottom layer is still intact, and there is no gap between the layers. Most likely, the destruction of ice occurred according to one scenario. At 10 μs, the ice is almost completely destroyed. Remains of ice and fragments of asbotextolite begin to interact with lower layer. Layer greatly flexes axially. Further there is a perforation of the double plate. At 70 μs, there was a gap between the layers, holes in the upper and lower layers, and the remains of the aluminum “cork” moving in the axial direction (a quantitative assessment of their velocity will be given below). The diameter in the upper layer was almost twice as large as in the lower.

At a qualitative level, the computational results are consistent with the experimental results from [7]. The morphology of destruction, including the shape of the hole, zones of destruction in the contact area are only implied.

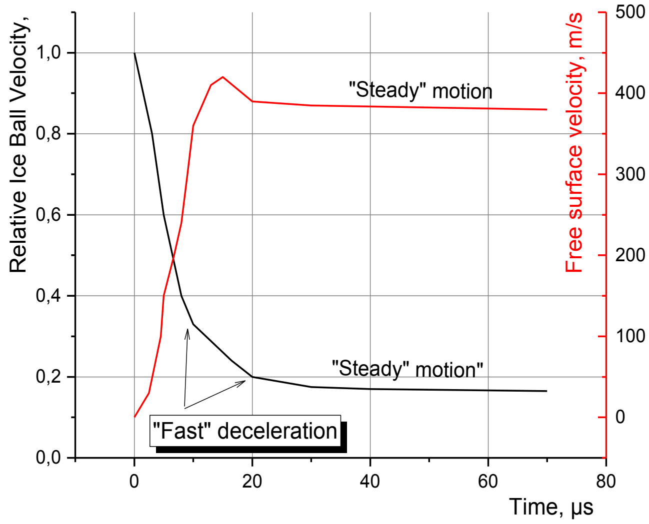

Figure 8 Relative ice ball velocity versus Time (black curve) and free surface velocity profile (red curve)

Figure 8 illustrates the time dependence of the ball's velocity and the velocity profile of the free surface of the plate. To build the profile, a control point was selected in the lower layer of the double plate. A detailed analysis of the curve in figure 8 showed that the segment of slow velocity falling lasted from 10 μs to 30 μs. After 40 μs, the stage of "steady" motion is noted. The segment of fast velocity falling was up to 10 μs.

It can be seen from the profile that the wave output occurred at 13 μs, at the velocity of the leading fragments was approximate 410 m/s. After perforation of the double plate, it was 390 m/s. Perforation lasted no more than 20 μs.

5.4 Numerical study of asbotekstolit plate subjected to normal ice ball impact

The last research object is asbotekstolit plate. The plate thickness is 8.75 mm, which in turn is smaller than the diameter of the ice ball. A series of computational experiments consisted of three computational case. In these cases, the initial velocity was 500, 1000 and 1500 m/s. The body's interaction modeled to 100 μs. After this point in time, the patterns of destruction in the bodies did not change. As in the two previous subsections, a post-penetration analysis was performed.

In the beginning, we analyze the numerical results in the first computational case. The evolution of ice ball destruction is shown in Fig. 9. The stage of ice pre-fracture is observed up to 1 μs. This fact was in previous cases. The first foci of destruction in the asbotextolite plate were fixed at 5 μs. At this time, the destruction zone took an I-shape. It should be noted that the destruction zone was concentrated close in the contact area with impactor. Further, the destruction zone extends through the plate to its back surface. From the 10 μs to 30 μs, the cross section of the plate is destroyed. The ice is also destroyed, an V-shaped crater formed on the front side of the plate. The back side of the plate is deformed in the axial direction, the "cork" begins to separate from the plate. Its diameter is much smaller than the original diameter of the ball. From 50 μs to 100 μs, the "cork" is separated from the plate, it is divided into two identical parts.

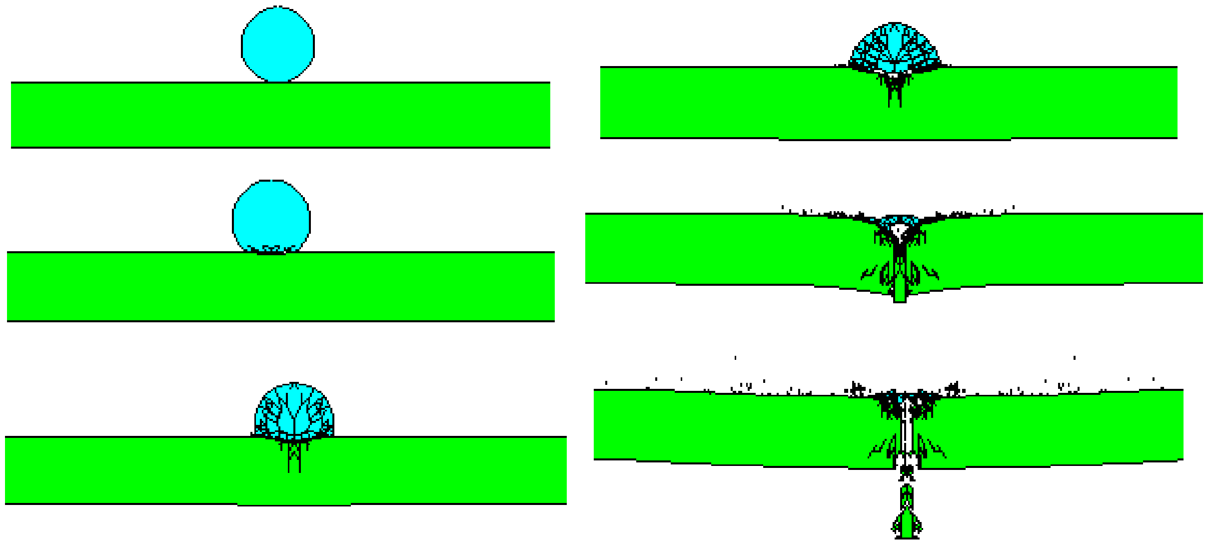

Figure 9 Cross-section of ice ball and single asboteksolit plate at 0, 2, 6, 10, 30 and 100 μs (Case 1, V_o = 500 m/s)

Below are the results of the third computational case, here the initial velocity was equal to 1500 m/s. The second computational case is not discussed. Obviously, in the second case the plate will be perforated by ice ball.

Figure 10 shows the configurations of interacting bodies at 10 μs and 100 μs. In both pictures, the ice has completely destroyed as a result of the collision with plate. There was no significant deflection of the plate, as in the case with a double plate. The diameter of the hole in this case is much larger than in the previous one. Fragments of the plate which flew out from the back side is greatly destroyed. No "cork" of the plate material in this case was not observed. Obviously, the plate is perforated by ice ball.

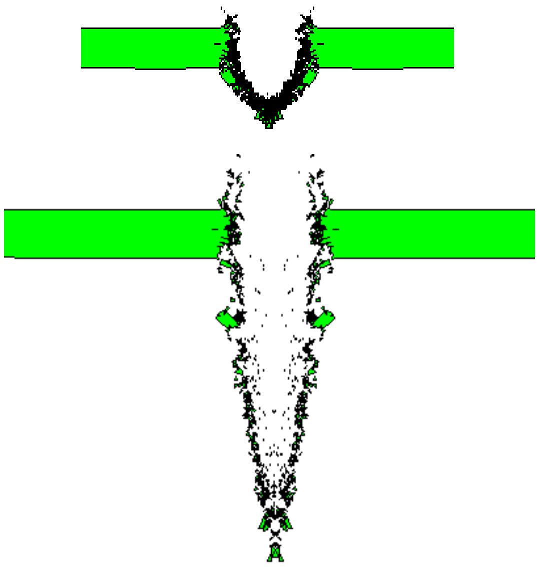

Figure 10 Cross section of Single plate after impact of ice ball
. Top picture corresponds to 10 μs, Bottom picture corresponds 100 μs.
(Case 3, 1500 m/s)

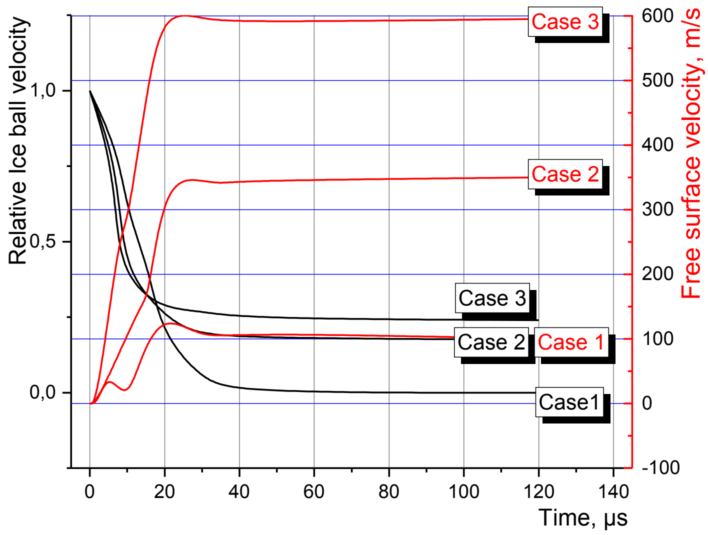

Figure 11 Residual velocity of ice ball versus Time (black curves)
Free surface velocity versus Time (red curves)

Figure 11 shows the time dependence of the residual velocity and free velocity profiles for all three computational cases. Let us analyze each family of curves separately.

First, we analyze the velocity curves, which are highlighted in black. Obviously, in the first case, there was no perforation, so the residual ball's velocity after 40 μs tended to zero. Ice ball interaction with asbotextolite plate occurred no more than 40 μs. The curves for the other two cases become parallel after 20 μs. In the latter case, the perforation of the plate lasted approximately 20 μs. In the previous subsection, the perforation of the plate lasted approximately such time. According to computational results, the perforation of the plate in the second case lasted approximately 30 μs. In both cases, residual velocity was close to the value of 200 m/s.

In the figure 11, velocity curves are highlighted in red. The axial component of velocity was considered. The control point at which the computation were corresponded to the separated fragment from the back of the plate. The greater the initial velocity was, the greater was the velocity of the free surface. In the first case, the free surface velocity was 100 m /s, in the second case it was approximate 340 m/s, and in the last case it approximate was 595 m/s. The shock wave exit to the free surface is fixed approximate at 20 μs.

6. Discussion

Impact resistance of single and double plates subject to ice ball impact in the range up to 1500 m/s has been studied. Qualitative and quantitative assessment is performed. Under the qualitative assessment is understood, first of all, the morphology of the destruction of bodies, including presence of spall plates, and so on. Under quantitative assessment is understood post-penetration analysis, including the time of initiation of the first fracture foci, the evolution of macro-cracks, the diameter of the inlet and outlet holes in the plate, the time of perforation (if there was one), residual velocity of the ice ball, its relative shortening, etc. The time dependences of the residual velocity and the free surface velocity plates are plotted.

A 5-mm-aluminum plate subject to ice ball impact could resist perforation only at 500 m/s. At 1000 m/s, plastic deformation of the plate occurs in the axial direction. The ice ball does not knock out the "cork", but a small aluminum fragment flies from the back plate surface. Most likely, the fragment can be dangerous for subsequent layers, for example, thin layers of fiberglass. At 1500 m/s, the ball is completely destroyed. It knocks out a "cork" whose diameter is larger than its original diameter. In all cases, the time dependence of residual velocity was close to the hyperbolic ones.

A similar situation is noted for a double plate. At 1500 m/s, the asbotextolite is destroyed, and a "cork" is formed in the aluminum layer. The diameter in the asbotextolite layer is larger than in aluminum. To put it briefly between the layers there was a gap. At 500 m / s, only the asbotextolite layer was destroyed. The pattern of destruction of the upper layer in all cases was the same Asbestextolite plate had smallest impact resistance. At 500 m/s, the ice ball was already knocking the "cork" out of the plate. Moreover, in this case, the velocity of the free surface was approximately 100 m/s.

Numerical modeling of these problems revealed the main features of destruction mechanism of the ice ball. In all cases, the stage of pre-fracture in the ice (plastic deformation) lasted no more than 1 μs. Before strong destruction of the ball took oval shape. The time dependence of the velocity of the ball is hyperbolic. On the velocity curves, plot of a rapid decrease velocity, plots of a slow decrease in velocity, and plot of "steady motion" can be identified. The size of these sections depended on the initial velocity.

7. Conclusion

1. The paper provides a brief overview of the research topic. However, it allowed us to formulate a number of research tasks, which were solved in the article. The most comprehensive review has been given in [9]. According to the above, it is necessary to develop numerical methods and build a phenomenological model of ice destruction under shock and explosive loads. The most important point is to take into account the influence of temperature of ice formation on its strength. The results of full-scale experiments on the ice destruction at underwater explosion were not found in literature.

2. By the help of mobilab and KuzbasSpetsVzryvz Ltd, the full-scale underwater explosive test was carried out. The research object was a 130-day "needle" ice cover of this year. 4-kg-EE was used only. The morphology of ice destruction, including the ice edge, the size of the ice fragments, the height of their expansion, the shape and size of the polynya were obtained. Compared to UNDEX-2018's results, the ice fragments were significantly smaller. However, the state of the ice edge was very similar. In both cases, it had a stepped shape. The polynya diameter was 4.5 meters, which is almost two times more than last year.

3. Ice is described by a single-phase elastic-plastic medium, taking into account the formation of both "tear-off" or "spall" fractures and "shear" fracture. Fundamental conservation laws are the basis of a system of equations. The ice destruction model is based on a deterministic approach. Pressure in DP is described using Landau − Stanyukovich polytrope. To describe the shear strength of a body, the Prandtl − Reuss constitutive equations and the von Mises yield condition were used. Physical and mechanical characteristics of ice are taken fom [2,3]. In [3] the shock adiabat is described.

4. The numerical method is based on the Lagrangian approach to the description of the motion of continuous media. To put it another way, it contains a new way for isolating the discontinuity surfaces of materials. In substance it is the development and modification of well-known lagrangian methods from [1, 2]. A non-commercial software package was used to solve modern dynamic multi-contact problems of the solid mechanics. We used the latest version of the software product [21]. The verification of the method was carried out by solving quantitative, qualitative and internal tests. The article presents only a quantitative test. Others tests were conducted also, but not presented here.

5. A qualitative and quantitative assessment of the impact resistance of single and double plate subjected to impact of an ice ball (≤ 1500 m/s) was performed. The morphology of ice destruction and metal and asbestextolite plates, including the time of perforation, the diameter of the inlet and outlet holes, the speed of the leading fragments was obtained numerically. The free surface velocity

profiles and time dependences of the backward velocity were ordinary. In this range of velocity, the impact resistance of the plates was up to 500 m/s. In all cases, ballistic limit has not been calculated.

Notation

RIAMM **-** Research Institute of Applied Mathematics and Mechanics of Tomsk State University,
ScICExe –American research program "Science Ice Exercise"
UNDEX – Under water explosive, type of full-scale experiment
Mobilab - Mobile laboratory "Explosive Destruction of Natural Materials", initial author's project
KuzbasSpetsVzryv Ltd – company and mobilab's partner
EE - Emulsion explosive, civil explosive (Emulast AS-FP-90)
TNT – trinitrotoluene
D16 - aluminum alloy, according to the Nomenclature of construction materials of Russia
DP – detonation product

Acknowledgments

The reported study was funded by RFBR according to the research project № 19-08-01152.

Notifications

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