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Numerical Investigation of the Steel Ball-Ice Plate Low-Speed Collision

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Abstract: **This study devoted to the investigation of the ice deformation process. The importance of this problem relates to the existence of many industrial applications. For example, the ice impact on the aircraft wings can lead to the plane crash. The seismic survey of oil and gas deposits in Arctic regions are complicated by the ice-water contact reflected waves. Thus, the detailed understanding of the ice deformation process is important. One of the difficulties is the crucial dependence of the ice behavior on multiple factors: internal structure, purity, salinity, temperature, intensity of the applied loading. The computational selection of the appropriate model based on the experimental data validation can be treated as a reasonable approach. In this paper, the problem of the low-speed impact of the steel ball on the ice plate is investigated. The experimental data for different striker velocities are available in the open literature. The full 3D dynamic loading problem was simulated in the Abaqus software, based on the explicit finite-element method on structured meshes. Two basic mechanical models (linear isotropic elastic and elastoplastic) are considered. The obtained results showed the possibility of the experimental data reproduction.**

Keywords: **computer simulation, ice rheology models, deformable solid body, linear elasticity, plasticity**

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CONTENTS

1. INTRODUCTION

The problem of the correct simulation of the dynamic ice deformation is in a high priority. This process is occurred in many applied areas, for example, the aviation industry and the seismic survey of oil and gas deposits in the Arctic region. The detailed understanding of the ice mechanics may help researchers to develop new technologies.

There are a lot of research works, devoted to the investigation of the ice mechanical properties. For example, the basic engineering properties of the sea ice were carefully reviewed in the paper [1]. The process of the equiaxed and monocrystalline ice fracturing under the high-velocity impact was experimentally investigated in paper [2]. More modern review of the ice mechanical properties is the paper [3]. It was shown that the tensile strength and compressive strength vary in a wide range while the temperature changes. The difference of the ice mechanical properties in standard material characterization test under compression and in high-velocity tests were highlighted. Recently, the researchers experimentally obtained the strength, deformation, and modulus of elasticity of the ice under different temperature and loading strain rate [4].

Many researchers are working on the problem of the reliable mechanical model construction to describe the ice deformations. For example, in the paper [5] the constitutive relation for the ice at high strain rates and an algorithm for its numerical integration was proposed. It was based on the Drucker-Prager plasticity criterion and described the different behavior in tension and compression modes. In the paper [6], the 3D rate-dependent peridynamics model was proposed and successfully validated by the dynamic ring Brazilian disc ice test.

Recently, the experimental study of the steel ball strike on the ice plate was conducted [7]. The usage of a wide range of the collision velocity led to the registration of the different deformation curves that contain the information about the ice rheology. The current work is an attempt to apply simple mechanical models to describe the observed ice deformations. For this purpose, the full 3D finite-element simulation was carried out with the Abaqus software. The linear elastic model and the elastoplastic model were used sequentially to reproduce experimental data. To obtain the best fit, the yield stress value was further treated as an additional free parameter of the model.

2. MATHEMATICAL MODEL AND NUMERICAL METHOD

In our work, the process of the steel ball collision with the ice plate was investigated numerically. Previously, the experimental study was carried out in the laboratory of the other research group [7]. The cases of different initial ball velocity values, ranged from 0.431 m/s to 2.230 m/s, were tested. The obtained diagrams of the reaction force – penetration depth are presented at the **Fig. 1**. It was proved, that the increase of the collision velocity results in the penetration depth increase.

In this paper we obtained the numerical solution of the same problem in a full 3*D* formulation. All dimensions and material parameters were taken from the paper [7]. The ball radius was 38 mm, and the length, width and height of the ice plate were 2000×2000×550 mm. The used material parameters for the ice were C_p = 3940 m/s, C_S = 2493 m/s, ρ = 917 kg/m^3. The used material parameters for the steel were C_p = 5700 m/s, C_S = 3100 m/s, ρ = 7800 kg/m^3.

The finite element method incorporated in the Abaqus software was used. The mesh

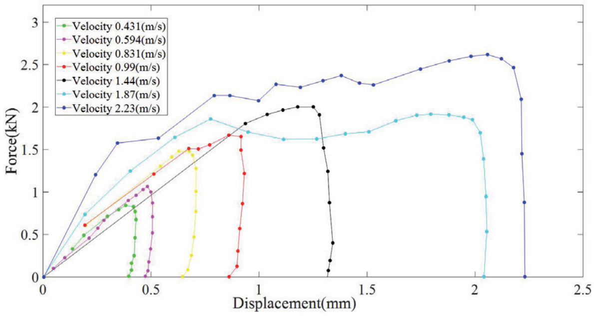

Fig. 1. *The reaction force – penetration depth diagrams, obtained experimentally (from the paper* [7]*). Different colors represent different collision velocities.*

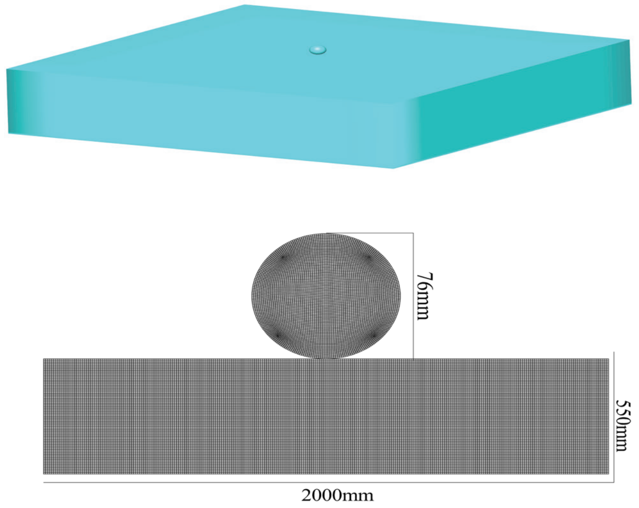

Fig. 2. *The integration domain: 3D view (top) and 2D slice (bottom).*

was hexagonal one and contained more than 600 thousands of nodes. The used integration domain is shown at the **Fig. 2.**

Two different mathematical models were used to describe the dynamic deformation of the ice. The first one is the isotropic linear elastic model. The relationship between stress and strain is set by the Hooke's law in the tensor form as

$$\sigma = c\varepsilon. \tag{1}$$

Here σ is the stress tensor, ε is the strain tensor and c is the fourth order elastic tensor. The mechanical properties of the elastic material are density ρ, Young's modulus E and Poisson's ratio ν. In the matrix form, for the 3D case the system of equations (1) is written as

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{12} \\ \varepsilon_{13} \\ \varepsilon_{23} \end{Bmatrix} = \begin{bmatrix} \frac{1}{E} & -\frac{\nu}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & \frac{1}{E} & -\frac{\nu}{E} & 0 & 0 & 0 \\ -\frac{\nu}{E} & -\frac{\nu}{E} & \frac{1}{E} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G} \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix}. \tag{2}$$

The relationship between the Young's modulus E, Poisson's ratio ν, and shear modulus G is

$$G = \frac{E}{2(1+\nu)}. \tag{3}$$

It is also possible to describe the material properties in terms of the Lame's parameters λ and μ, or with the shear wave velocity C_S and pressure wave velocity C_p:

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)}, \quad \mu = \frac{E}{2(1+\nu)}, \tag{4}$$

$$C_P = \sqrt{\frac{\lambda + 2\mu}{\rho}}, \quad C_s = \sqrt{\frac{\mu}{\rho}}. \tag{5}$$

The second treated model was the elastoplastic one. To consider the inelastic material behavior, the plasticity model, based on the von Mises criterion was utilized. When the material reaches its maximum distortion energy, it begins to yield. This condition can be expressed in terms of the second invariant J_2 of the stress tensor deviator as $J_2 = k^2$, where $k = \sigma_y / \sqrt{3}$ and σ_y is the yield stress value. Numerically, this model can be considered as the additional correction step after the pure elastic step.

In the computer simulation, the top surface of the ice was treated as a free boundary. At all other sides the zero displacement boundary conditions were used. To minimize the computational time, the simulation started with the minimum initial distance between the ball and the ice. The total time for the numerical simulation was 0.2 s with a time step of 10^{-8} s.

3. SIMULATION RESULTS

3.1. ELASTIC MODEL

At the initial stage, we simulated the displacement and force on the ice surface for seven given collision velocities using the elastic model to describe the ice behavior. The time dependencies of both observed parameters are presented at the **Fig. 3.**

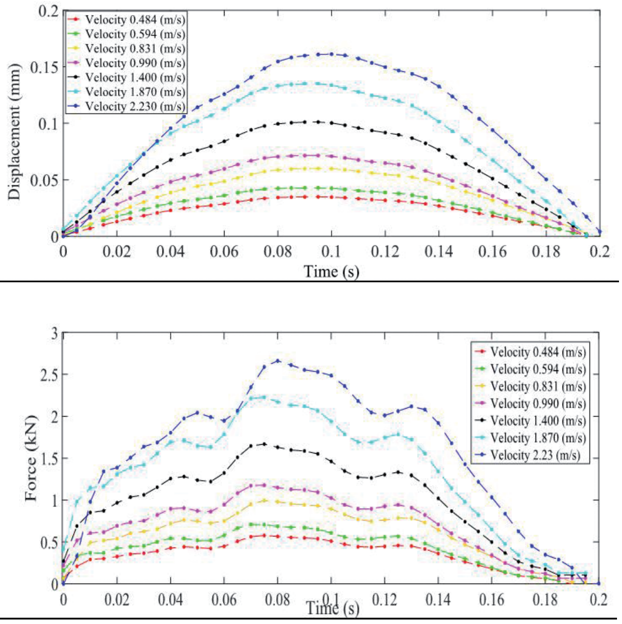

Fig. 3. *Time dependencies of the displacement (top) and the force (bottom). Linear elastic model.*

Based on the calculated time dependencies, the reaction force – penetration depth diagrams were calculated (see the **Fig. 4**). The results are dramatically different. The summary of maximum observed displacements is presented in the **Table 1**.

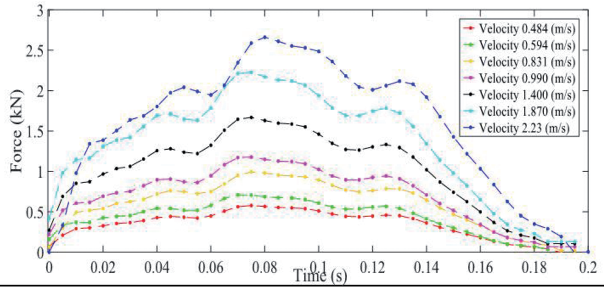

Fig. 4. *The reaction force – penetration depth diagrams, obtained numerically. Linear elastic model.*

Table 1

Numerical and experimental [7] maximum displacements on the ice surface. Linear elastic model

Velocity, m/s	Experimental Displacement, mm	Numerical Displacement, mm	Error, times
0.484	0.430	0.040	10.77
0.594	0.507	0.043	11.81
0.831	0.708	0.060	11.80
0.990	0.932	0.072	13.03
1.400	1.341	0.101	13.26
1.870	2.054	0.135	15.20
2.230	2.230	0.161	13.84

The displacement and reaction force measured on the ice surface significantly depended on the collision velocity. Less velocity produced less penetration depth, and higher velocity produced higher penetration depth. However, in all considered cases, the observed penetration depth was at least ten times less than the experimental one. Also, that the isotropic linear elastic model doesn't describe adequately the ice behavior, observed at the laboratory experiments.

3.2. ELASTOPLASTIC MODEL

At the second stage, the elastoplastic model was considered. Initially, the yield stress was set equal to 0.34 MPa. For the same collision velocities, the obtained time dependencies of both parameters are presented at the **Fig. 5.** The updated reaction force – penetration depth diagrams are presented at the **Fig. 6**. It is clearly seen, that for the case of 2.23 m/s the error is small enough.

To obtain the better fitting between the experimental and numerical results, further the yield stress value was treated as the free

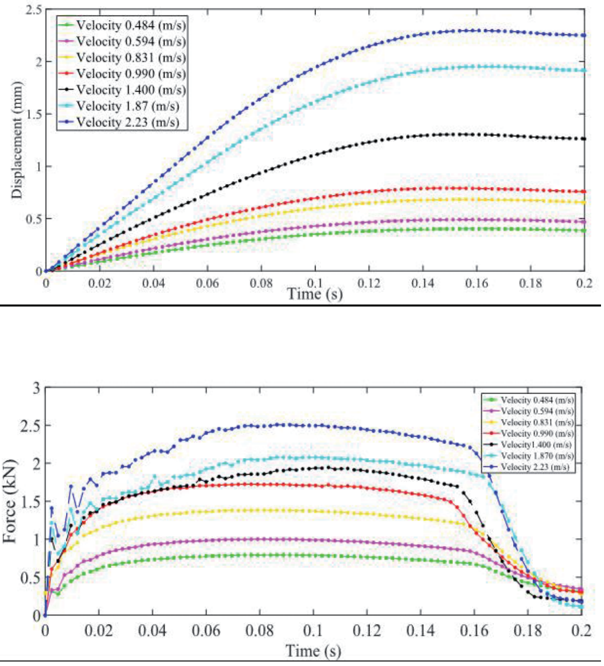

Fig. 5. *Time dependencies of the displacement (top) and the force (bottom). Elastoplastic model.*

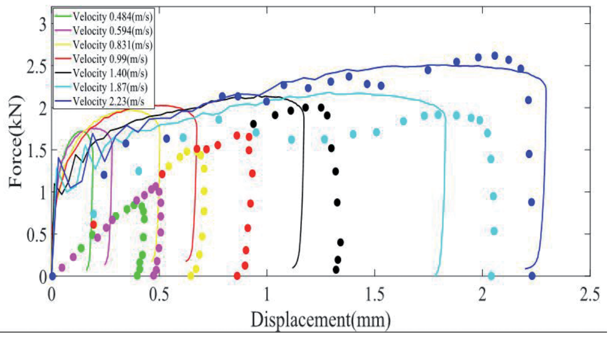

Fig. 6. *The reaction force – penetration depth diagrams, obtained numerically. Elastoplastic model. The yield stress is 0.34 MPa.*

parameter. Based on the multiple simulations, the best values were extracted (see the **Fig. 7**).

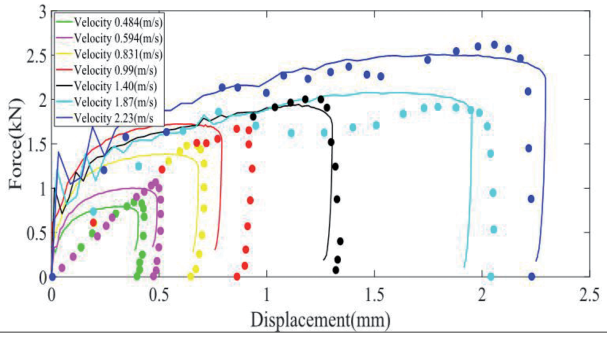

Fig. 7. *The reaction force – penetration depth diagrams, obtained numerically. Elastoplastic model. The yield stress was fitted.*

The summary of maximum observed displacements is presented in the **Table 2.** These data reflect more better reproduction of the experimental results.

Table 2

Numerical and experimental [7] maximum displacements on the ice surface. Elastoplastic model

Velocity, m/s	Experimental Displacement, mm	Numerical Displacement, mm	Error, times
0.484	0.430	0.403	1.065
0.594	0.507	0.490	1.034
0.831	0.708	0.68	1.036
0.990	0.932	0.790	1.178
1.400	1.341	0.1304	1.027
1.870	2.054	1.952	1.052
2.230	2.230	2.295	0.971

4. CONCLUSION

The problem of the ice plate deformation under the steel ball impact was numerically investigated. Two mechanical models were used to describe the dynamic behavior of the ice: linear isotropic elastic model and elastoplastic model. The comparison of the ball penetration depths for different collision velocities with experimental data was done.

It was found that the elastic approximation drastically underestimates the real maximum penetration depth. So, this model can't be practically used. The usage of the elastoplastic model with the given yield stress value allowed us to reproduce only one experimental cure. To achieve the better coincidence with experimental data the yield stress value fitting was applied. It led to significantly better results. The possible explanation of this effect is the different mechanisms of ice destruction (melting, micro fracturing, etc.) for different energies of the strike. The reveal of these effects can be the direction of the further research.

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