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Original

Experimental study of the impact interaction of a rigid wedge and ice

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Abstract: To conduct computational assessments of the stress loading of vehicle with rotary-screw propulsion unit (RSPU) parts and the level of the shock/vibration impact on the crew and passengers, the characteristics of the contact interaction between the parts of RSPU and ice as the support surface are necessary. One of the characteristics of this interaction is the energy spent on the destruction of ice, related to the volume of the destroyed ice.

An experiment was conducted to determine the specific energy of ice destruction upon impact by a pointed body with a shape close to the shape of the RSPU helical ridge. The results obtained make it possible to use them in the virtual simulation of the movement of an all-terrain vehicle with a rotary screw propulsion unit on an uneven ice surface.

Keywords: Ice, wedge-shaped indenter, experimental data, specific energy of destruction, shock interaction model

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1. Introduction

The development of territories with an undeveloped network of paved roads requires the creation and use of vehicles with the ability to move off-road.

When studying the dynamics of vehicle movement on supporting surfaces characterized by small deformation (vehicle movement on asphalt concrete roads, railway rolling stock on rails, etc.), a supporting surface model is used in the form of a combination of stiffness and damping with linear dependences of the force on the actual deformation and its rate. In this case, the deformation of the supporting surface is small, and the traction force occurs due to friction between the vehicle wheel and the supporting surface.

One of the promising types of vehicles for off-road traffic are machines with a rotary screw propulsion unit (RSPU). During the movement of vehicles with RSPU, the emergence of traction force is fundamentally associated with a substantial change in the shape of the supporting surface, which is not restored after the end of interaction with the parts of RSPU. As a rule, in such machines, the rotors are rigidly attached to the vehicle body. Due to this design, when moving on an uneven surface, the interaction of the rotors with the supporting surface can have a shock character. The specified impact loads must be considered in the vibration and stress calculations of the machine when it is designed. One of the types of hard and at the same time uneven surface on which vehicle with RSPU must move is hummocky ice. The absence of an elastic suspension of the rotors and the inadmissibility of their irreversible deformations during the movement of the machine means that the kinetic energy of the vertical and longitudinal-angular oscillations of the machine must be absorbed when the surface layer of ice is destroyed by the ridges of the RSPU. Thus, to perform calculations of vibration and stress loading of machines with RSPU, it is necessary to have information about the characteristics of the process of destruction of the surface layer of ice by RSPU ridges during their impact interaction.

The need to obtain information about the characteristics of the impact interaction of RSPU ridges with ice is one of several applied problems that have become relevant in connection with the development of northern territories, sea, and air spaces.

To date, a considerable number of experimental studies have been conducted to determine the characteristics of the impact interaction of various bodies and ice.

In Chen et al. (2022) the results of an experimental study of the impact of a spherical ice specimen on a rigid target are presented. The purpose of the study is to establish the peak value of the interaction force and the moment of time at which the interaction force reaches its maximum value. The interaction velocities were about 13 to 105 m/s.

In Song et al. (2022) the results of an experimental study to determine the properties of ice when a load that causes shear stresses is applied to it are considered. During the experiments, a special hat-shaped ice specimen was used, and the shear strain rate was in the range of 17000/to 61000/s, that is, they were high.

High strain-rate behavior of ice under uniaxial compression is considered in Shazly et al. (2009). Specimens in the form of disks with a diameter of 17.5 - 18.5 mm and a thickness of 4 - 9 mm were evaluated. The velocity of the loading element of the experimental setup was from 2 to 14 m/s, which corresponded to the strain rate in the range of 60 – 1400/s. One of the results of the experiment was the demonstration of the preservation of a certain amount of carrying capacity after reaching the peak stress (the specimen does not catastrophically lose its load carrying capacity after the attainment of the peak stress).

The interaction of a cylindrical ice specimen with an obstacle is considered in Pernas-Sanchez et al. (2012). The aim of the study was to compare different methods of numerical simulation of ice behavior at high (from 152 to 213 m/s) loading velocities. Dependences of the force of interaction of an ice specimen with a fixed barrier as the functions on the ratio of the diameter and height of a cylindrical specimen are obtained.

The effect of the mass of a spherical ice specimen, impact velocity and kinetic energy on the force of impact interaction are considered in Pernas-Sanchez et al. (2015). Spherical specimens with diameters of 30, 40 and 50 mm were evaluated, the impact velocity varied in the range of 50–250 m/s. The article points out that the ice fragments early in the impact and then behaves like an agglomeration of particles rather than a solid structure. According to the authors, the size of the ice specimen does not affect the force of the impact interaction, but only the impact energy.

In the above-mentioned works, the results of experimental studies with ice specimens, the shape and mass of which differ significantly from similar parameters of characteristic ice fragments involved in the dynamic process of interaction with the rotary screw propulsion unit of vehicles, are considered. The rates of impact interaction used in the considered works are significantly higher than the rates of interaction between ice and RSPU. Thus, to obtain information that can be used in solving the problem of computer simulation of the movement of a machine with rotary screw propulsion units, it is necessary to conduct an experiment with simulation of the conditions of a real impact process of interaction between RSPU ridges and ice.

2. Experimental setup

For the cross-section of a rotary-screw propulsion unit ridge, a wedge-shaped shape is characteristic. Therefore, the conducted experiment consisted of performing an impact with a wedge-shaped indentation on an ice specimen.

For research ice with A6 structure was used (Cherepanov, 1976). Such ice forms in fresh or lightly salted water (salinity is less than 2.0 ppm). Ice was obtained by freezing fresh water.

When developing the experimental methodology, as the basis the well-known Drop Ball Test (DBT) method was taken. This method is used to determine the dynamic strength of ice (Prato & Longana, 2018). During the destruction of ice due to the fall of a massive body on it, energy is spent not only on the actual destruction of the ice, but also on "squeezing out" (removal) of the destroyed ice from the contact zone. This means that the amount of energy expended to stop a falling massive body depends not only on the properties and volume of the ice being destroyed, but also on the shape of the indenter. Considering the above, during the experiment, the shape of the indenter was chosen (Figure 1) like the shape of the RSPU ridge, in the interests of developing which the described study was conducted.

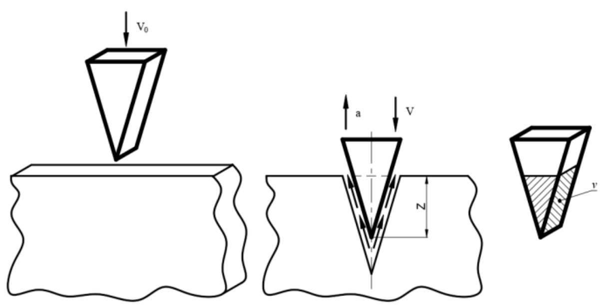

Figure 1. Scheme of the experiment. Trajectory of movement of ice squeezed out from the area of interaction between the indenter and ice.

The ice used in the experiment was obtained by freezing fresh water. Since in the natural environment along the perimeter the ice subjected to impact by the RSPU ridge is "captive" to other ice, to create conditions comparable to natural conditions during the experiment, the ice was frozen in a form that also served as an external reinforcement during the impact loading of ice. The mold was made of sheet steel, to increase the stiffness of the mold walls were reinforced with rings (Figure 2). The diameter of the mold is about 0.6 m, the height is about 0.5 m, the mass of ice is about 150 kg.

The wedge-shaped indenter, which interacted with ice, is shown in Figure 3. The indenter is made of steel, its height in the direction of movement is 0.1 m, the wall thickness is 10 mm, and the angle at the top is close to the angle at the top at the RSPU ridge.

Figure 2. Mold with ice.

Figure 3. Wedge-shaped indenter with an acceleration sensor.

During the experiment, the indenter acceleration was measured and recorded. An ARJ-A-D acceleration sensor with a measurement range of up to 500 m/s² was installed on the base of the indenter (Figure 3). DC-204A recorder was used to remember the level of accelerations, data was recorded at a frequency of 2 kHz.

The experiment was conducted using a pendulum impact tester shown in Figure 4. The design of the moving part of tester allows you to change the impact energy by changing the mass of the moving part and the drop height.

During the experiment the velocity of the indenter now of impact on the ice was 5.9 m/s, the kinetic energy was about 1100 J.

Figure 4. Pendulum impact tester for impact ice breaking.

To analyze the process of interaction of the indenter with ice, high-speed shooting was conducted. Some moments of impact interaction between the indenter and ice are shown in Figures 5 - 7.

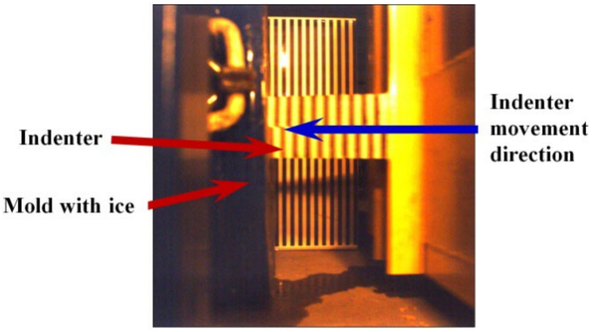

Figure 5. The beginning of the indenter and ice interaction.

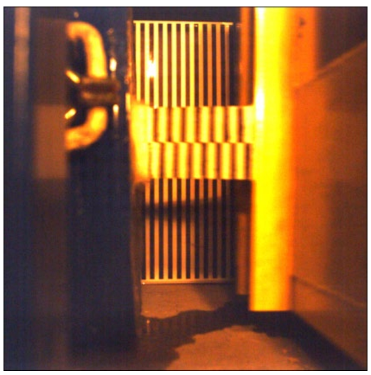

Figure 6. The beginning of the period of intensive indenter and ice interaction
(t = 0.002 c).

Figure 7. Intense interaction of indenter and ice, ejection of broken ice (t = 0.024 c).

3. Experimental results

Figure 8 shows the cavity in the ice mass formed by the impact of the indenter. Figure 8 we can see that "global" (comparable to the size of the entire massif) ice destruction does not occur. In the ice mass, cracks are observed that are local in nature and do not propagate in depth. Measurements of the dimensions of the formed cavity and corresponding calculations show that about 1% of the ice mass is destroyed and damage affects about 11% of the upper surface of the ice. Such a small proportion of the damaged surface and the mass of destroyed ice, as well as the fact that the cracks formed do not reach the walls of the mold, show that the process of impact interaction between the indenter and ice obtained in the experiment is like a process as if it occurred in natural conditions during impact on ice not bounded by mold walls.

Figure 8. Destruction of ice because of its impact interaction with the indenter.

Figure 9 shows the dependences of acceleration on the time of the indenter obtained in four experiments with the velocity of the pendulum now of impact of 5.9 m/s. The duration of the period of impact interaction between ice and the indenter varies from 0.035 s to 0.042 s. The maximum indenter acceleration on impact varies from 260 m/s^2 to 354 m/s^2.

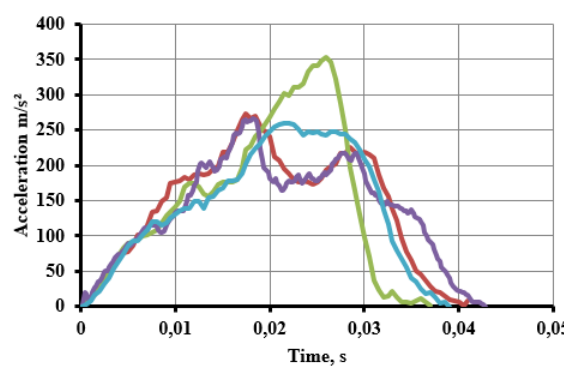

Figure 9. Dependences on the time of indenter acceleration at an initial impact velocity of 5.9 m/s.

The velocity of the indenter during the impact (Figure 10) is determined by integrating the acceleration over time.

$$v(T) = V_0 - \int_0^T a(t)dt, \qquad (1)$$

Where: V_0 - velocity of the indenter before impact; v(T) - velocity of the indenter at time T; a(t) - acceleration of the intender.

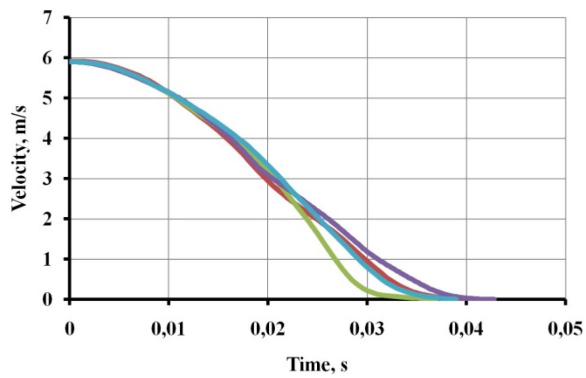

Figure 10. Dependences of the instantaneous velocity of the indenter on time at an initial impact velocity of 5.9 m/s.

The displacement of the indenter (Figure 11) is determined by integrating its velocity over time.

$$z(T) = \int_0^T v(t)dt \qquad (2)$$

Where: z(T) - displacement of the indenter at time T.

The force in the contact interaction between ice and the indenter is calculated by the formula:

$$f(T) = m_i \cdot a(T), \qquad (3)$$

Where: $f(T)$ - force in contact interaction at time T:

m_i - mass of the indenter.

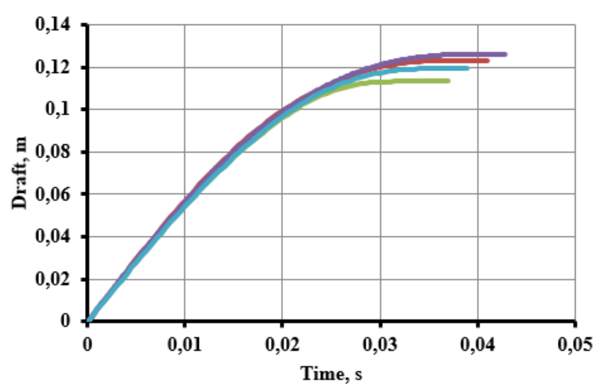

Figure 11. Dependences of the displacement of the indenter on time at an initial impact velocity of 5.9 m/s.

Using the dependencies z(T) and f(T), the dependence of the force in the contact interaction between ice and the indenter on the displacement of the latter was obtained (Figure 12).

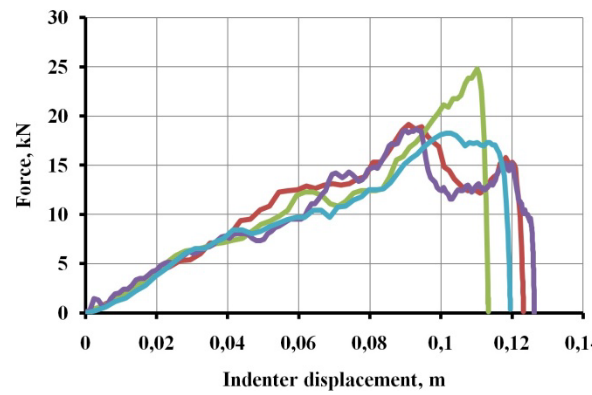

Figure 12. Dependences of the force in contact interaction on the displacement of indenter at an initial impact velocity of 5.9 m/s.

The energy of ice destruction is defined as

$$E_0 = \frac{m_i \cdot V_0^2}{2} \qquad (4)$$

where: E_0 - kinetic energy of the indenter before impact.

The volume of broken ice is determined considering the geometrical dimensions of the indenter and the magnitude of its displacement ("immersion" into the ice).

$$v_i = h \cdot z_i^2 \cdot \tan(\frac{\alpha}{2}), \qquad (5)$$

Where: v_i - volume of broken ice; z_i - indenter width:

α - wedge angle at the indenter tip.

The specific energy of ice destruction by an indenter is defined as:

$$\varepsilon_{cr} = \frac{E_0}{v_i} \qquad (6)$$

Where: ε_{cr} - specific energy of ice destruction.

As a result of averaging the results of processing four experiments with an impact on ice with a wedge-shaped indenter, the average value of the specific energy of ice destruction was obtained - 2.67 kJ/dm^3.

4. Model of the indenter interaction with ice

From Figure 12 up to a certain amount of displacement of the indenter ("immersing" it into an ice mass), the force acting on the indenter increases linearly. This indicates a close to linear dependence of the force of resistance to the penetration of the indenter on the volume of ice being destroyed. At the same time, as the indenter approaches its maximum value, the force of resistance to penetration into ice sharply decreases. This indicates that the penetration resistance force of the indenter depends on the penetration velocity.

When solving several problems of virtual simulation of the dynamics of vehicles, an approach is widely used based on the dependence of the damping component of the force of interaction of vehicle parts with the supporting surface from the relative moving velocity of the contacting elements. The widespread use of this approach is explained by the simplicity (though relative) of the implementation of computational algorithms for virtual simulation of the dynamics of vehicles.

Based on the assumption that the force of resistance to penetration of an indenter into ice depends on the penetration velocity, let us consider the dependence of the damping component of this force on the penetration rate. In this case, damping will be defined as the ratio of the force of resistance to penetration to the velocity of the indenter, i.e.

$$d(v) = \frac{f(v)}{V} \tag{7}$$

Where: *f(v)* - damping.

The dependence *d(v)* obtained from the results of processing the results of the experiment is shown in Figure 13 ("black" curve).

Considering the monotonicity of changes in the velocity of the indenter (Figure 10) and the actual displacement of the indenter (Figure 11), the dependence of damping on the volume of broking ice is obtained (Figure 14, "black" curve).

Figure 13 shows that when the penetration velocity is less than 1 m/s, as it decreases, damping increases. From Figure 14 in a wide range damping linearly depends on the volume of ice being destroyed, and a sharp increase in the damping value on the right side of the graph is associated with a decrease in the indenter penetration velocity.

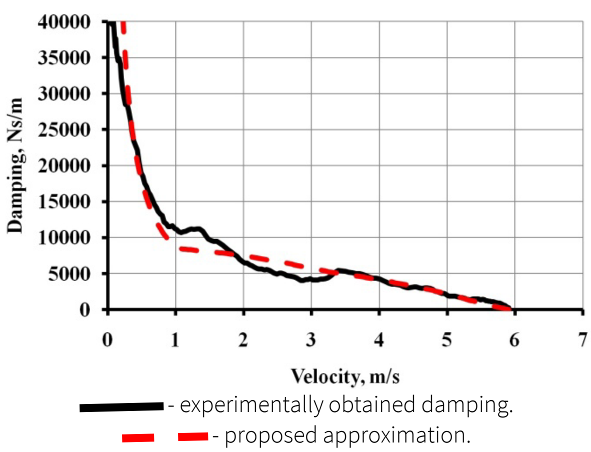

Figure 13. Dependence of damping from the velocity.

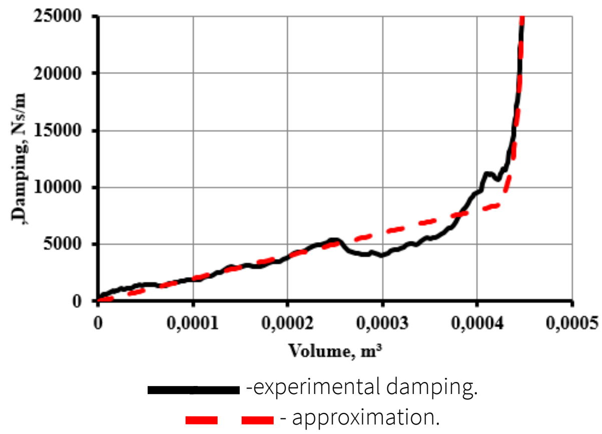

Figure 14. Dependence of damping from the volume of broken ice.

Based on the analysis of the obtained dependences of damping on the velocity and volume of ice being destroyed, the following approximate dependence of damping on the volume of ice being destroyed (v) and the velocity of penetration of the indenter (V) is proposed.

$$d(v,V) = \begin{cases} k_d \cdot v; \ V > 1 \text{ м/с} \\ \frac{k_d \cdot v}{V}; \ V \leq 1 \text{ м/с} \end{cases} \tag{8}$$

Where: d – damping:

k_d-coefficient of dependence of damping on the volume of destroyed ice in a linear section.

As a result of the experiment, for the investigated shape of the indenter, the coefficient of dependence of damping on the volume of ice being destroyed (kd) was $2{\cdot}10^6$ Н·с/м^4. The obtained value of the coefficient of damping dependence on the volume of ice being destroyed can be used to "adjust" the model of the damping component of the contact interaction of the RSPU ridge with the ice support surface. In this case, the main part of the energy of the impact interaction of the RSPU and ice during the movement of the vehicle on an uneven surface will be absorbed due to damping in the contact between ice and the RSPU ridge.

As for the stiffness component of the model of contact interaction between the RSPU ridge and ice, it should depend linearly on the value of the ridge penetration into the ice mass. In this case, the stiffness coefficient of this component should be determined by considering the value of the penetration of the RSPU ridge into the ice support surface in the static position of the vehicle.

Experience in the operation of vehicles with RSPU indicates that not only the ridges of RSPU, but also the base cylinder of the RSPU met the supporting surface. Therefore, the model of the contact interaction of the RSPU with the supporting surface should consider the possible contact from the base cylinder with ice. The interaction of the base cylinder and ice is characterized by a large contact area and, therefore, a significant destruction of ice in this contact area is unlikely. This means that the nature of the contact interaction between the base cylinder and the ice mass is determined by the stiffness properties of the RSPU and by the stiffness of the walls of the base cylinder. In this case, the contact interaction model of the base cylinder and the ice support surface should include the greatest possible stiffness, which, however, is limited by the stability of the software used for virtual simulation of the vehicle drive.

The proposed contact scheme in the model of interaction between a RSPU and ice is shown in Figure 15.

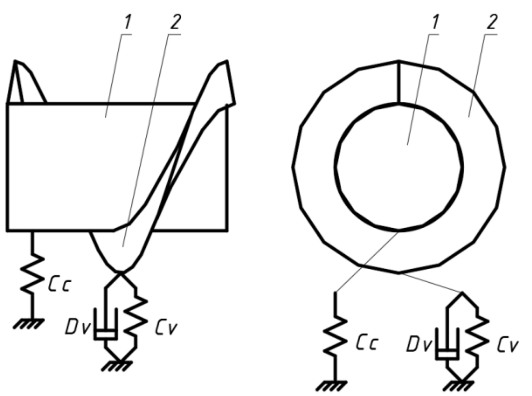

Figure 15 - Scheme of the contact model of the RSP and ice: 1 – base cylinder of RSPU; 2 – RSPU blade; Dv – damping in contact between the RSPU blade and ice; Cv – stiffness in contact between the RSPU blade and ice; Cc – stiffness in contact between base cylinder and ice.

5. Conclusions

As a result of the research:

- The specific energy of ice destruction during its impact interaction with an indenter having a shape close to the shape of the ridge of rotary-screw propulsion unit of a vehicle was determined.
- A model of impact interaction between a wedge-shaped indenter and ice, which allows for computer virtual simulation of the ride of a vehicle with a rotary-screw propulsion unit along a significantly uneven ice surface is proposed.

Conflict of interest

The authors have no conflict of interest to declare.

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References

Chen, S., Gad, E., Zhang, L., Lam, N., Xu, S., & Lu, G. (2022). Experiments on an ice ball impacting onto a rigid target. *International Journal of Impact Engineering*, *167*, 104281.
https://doi.org/10.1016/j.ijimpeng.2022.104281

Cherepanov, N. V. (1976). Classification of ice of natural reservoirs. Trudy AANII, 331. [In Russian]

Pernas-Sánchez, J., Pedroche, D. A., Varas, D., López-Puente, J., & Zaera, R. (2012). Numerical modeling of ice behavior under high velocity impacts. *International Journal of Solids and Structures*, *49*(14), 1919-1927.
https://doi.org/10.1016/j.ijsolstr.2012.03.038

Pernas-Sánchez, J., Artero-Guerrero, J. A., Varas, D., & López-Puente, J. (2015). Analysis of ice impact process at high velocity. *Experimental Mechanics*, *55*, 1669-1679.
https://doi.org/10.1007/s11340-015-0067-4

Prato, A., & Longana, M. L. (2018). A novel approach for the investigation of low energy ice impacts. *International Journal of Impact Engineering*, *121*, 12-19.
https://doi.org/10.1016/j.ijimpeng.2018.06.003

Song, Z., Chen, R., Guo, D., & Yu, C. (2022). Experimental investigation of dynamic shear mechanical properties and failure criterion of ice at high strain rates. *International Journal of Impact Engineering*, *166*, 104254.
https://doi.org/10.1016/j.ijimpeng.2022.104254

Shazly, M., Prakash, V., & Lerch, B. A. (2009). High strain-rate behavior of ice under uniaxial compression. *International journal of solids and structures*, *46*(6), 1499-1515.
https://doi.org/10.1016/j.ijsolstr.2008.11.020