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Kim, Ekaterina; Høyland, Knut Vilhelm; Frederking, Robert

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Publisher's version / Version de l'éditeur:

<https://doi.org/10.1016/j.ijimpeng.2023.104578>

International Journal of Impact Engineering, 176, C, 2023-03-20

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Short Communication

Reconstructing ice force-displacement development in structural assessments of freshwater, polycrystalline ice impacts

Ekaterina Kim^{a,*}, Knut Vilhelm Høyland^b, Robert Frederking^c^a Centre for Autonomous Marine Operations and Systems (AMOS), Norwegian University of Science and Technology, 7491 Trondheim, Norway^b Department of Civil and Environmental Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway^c Ocean, Coastal and River Engineering Research Centre, National Research Council of Canada, Ottawa, Ontario K1A 0R6, Canada

ABSTRACT

Using the ISO19906 local pressure-area relationship $p = 7.4A^{-0.7}$ as a process pressure-area curve to validate numerical ice models and reconstruct force-displacement development in damage assessment studies may lead to overestimation of the energy absorption capacity of ice found in nature. This is because the way this relationship is derived is different from how it is used in structural assessments of ice impacts. In the following paragraphs, we explain (with examples) how to reconstruct realistic ice force-displacement relationships in the absence of empirical force histories while focusing on freshwater, polycrystalline ice crushing, within the brittle regime, against a rigid structure.

1. Background

The design and operation of ships and offshore structures in icy waters are usually contingent on an estimation of ice impact actions and corresponding structural damage. This requires an estimation of ice forces, the corresponding ice pressure over the design area, and on the extent of the structural damage caused by the ice. The latter requires an estimation of the demand for the energy dissipation (E_k), including the fraction dissipating in respectively the ice ($E_{s,ice}$) and the structure ($E_{s,str}$). E_k determines how much of the total kinetic impact energy must be dissipated by deformation of the structure and/or the ice feature.

The principle of estimating the damage and energy dissipation in the structure is illustrated in Fig. 1, but here adapted to ice-structure impacts. To determine $E_{s,ice}$ and $E_{s,str}$ force-deformation relationships for the ice and the structure are typically established by a decoupled approach where the impacts of deformable ice against a rigid structure and rigid ice impacts against a deformable structure are estimated independently. The crushing of the ice and damage to the structure are determined such that the total energy dissipation is equal to the demand for energy dissipation ($E_k = E_{s,ice} + E_{s,str}$).

Alternatively, a coupled approach can be used where structural damage is estimated by a direct simulation of the impact event. This requires validated material models for ice and the structure (including fracture). Currently, as a part of the ice model validation process, in absence of the experimental data, it is a common practice (see, e.g., Amdahl [1]) to run a simulation with a deformable ice shape against a

rigid structure and compare simulation results with a pressure-area curve $p = CA^q$ (C, q coefficients) which may lead to overestimation of the ice forces and energy absorption capacity of ice found in nature.

This paper focuses on the reconstruction of a force-displacement development (i.e., the ice-force curve in Fig. 1) in the absence of empirical force histories. A five-steps procedure is presented in Fig. 2 with details and examples in sections below.

To get from the force-distance plot to a pressure-areas plot (and vice versa) it is possible to use a geometric relation between the ice and the structure to convert distance x to contact area $A(x)$ (and vice versa). The penetration (crushing) distance can be converted to a crushed volume $V(x)$ and crushed mass (using ice density), and hence, CSE on a mass basis (ref. Equation A in Appendix).

What we are looking at are the relations which are not aspect ratio dependent, as opposed to one that are, for example equation (A.8-21 in ISO 19906).

2. Reconstructing force-displacement development

There are several approaches: (1) semi-empirical methods, e.g., constant strength approach, pressure-area models (e.g., Daley [3]), and vicious fluid approach; see, e.g., Nevel (1986) [20] and Kurdjumov and Kheisin [15], (2) data-driven methods, e.g., deterministic and probabilistic approaches to ice impact loads in ISO 19906 [10]; Gagnon [8], Frederking and Sudom [7]; Ritch et al. [18] (see Table 1), and (3) numerical simulations (e.g., Liu et al. [17]). The further discussion on

* Corresponding author.

E-mail address: ekaterina.kim@ntnu.no (E. Kim).

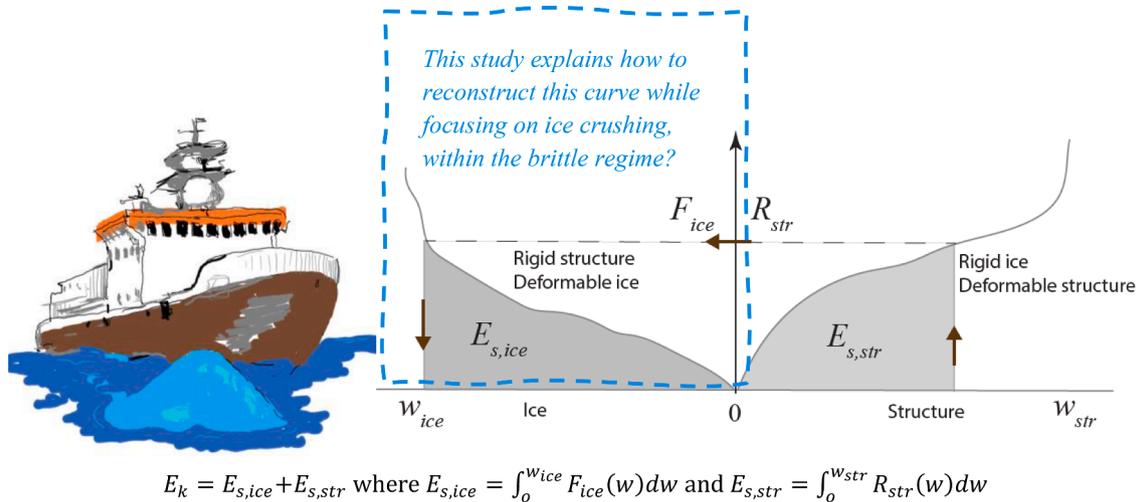


Fig. 1. An estimation of forces and damage (deformation) for ice-structure impacts adopting the approach for ship collisions (DNVGL RP-C204 [5]). The ice-force curve to the left, the resistance curve to the right. $E_{s,ice}$ and $E_{s,str}$ – strain energy dissipation in ice and in structure, w_{ice} , w_{str} – deformation of ice and structure, F_{ice} – ice force, R_{str} – structure’s resistance.

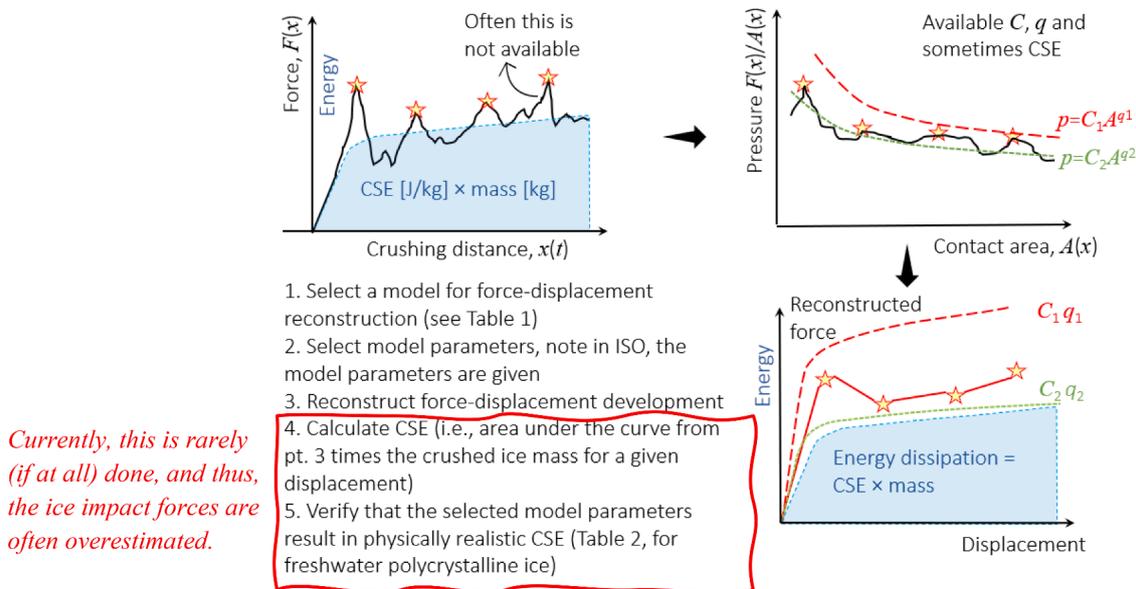


Fig. 2. Step by step procedure for reconstructing force-displacement development in damage assessment applications. CSE – crushing specific energy (for definition ref. Appendix).

numerical modelling of ice is omitted herein. In engineering applications, there is no agreement on how to model ice crushing behaviour nor on how to validate the model, especially when it comes to the fracture/spallation, hard-zone and soft-zone evolution, and creation and flow of melt/slurry of the crushed ice.

Currently, interpretations based on full-scale data provide the best estimates of force-displacement relationships. The probabilistic model in ISO 19906 clause A.8.2.4.3.5 “Global ice pressures from ship ramming tests” is rarely (if at all) used in damage assessment applications but is most appropriate where few interactions per year are expected (e.g., iceberg impacts on the Grand Banks). The form of the process pressure-area relationship is $p = CA^q$, where the coefficients C and q , are random and with distributions of them derived from ship impact tests (Jordaan et al. [11]). ISO 19906, in clause A.8.2.4.7.3 Impact actions, describes a probabilistic methodology using random ice properties (C and q) and ice edge shape.

The local ice pressure relation presented in ISO 19906 clause A.8.2.5.4, $p = 7.4A^{-0.7}$, is the mean plus three standard deviations of ice

pressure data from both iceberg ice and multiyear ice interactions from indentation tests and measurements on fixed structures. It is incorrect to apply this relation to determine the energy absorption capacity of ice.

Note that the damage assessment approach (explained in Background) does not require accurate modelling of all the force fluctuations (provided the maximum force is accounted for) but rather needs a correct representation of area under the force-penetration curve (i.e., the energy absorbed by the ice). It is therefore important also to consider the amount of energy spent on crushing a unit mass of ice (see Fig. 2). Table 2 gives some values of energy spent on crushing a unit mass of ice (CSE) for spherically ended indenters and initially flat ice surfaces where the effect of sample boundaries was minimized. Additional details on CSE of iceberg ice can be found in Kim and Gagnon [13]. CSE values for different indenter/ice shapes and speeds can be found in Frederking [6]. Factors, such as loading rate, loading history (e.g., quasistatic tests vs impact tests), temperature, and ice age may affect the CSE value of ice beyond what is reported in Table 2. In future it could be valuable to conduct more dynamic testing on ice as to minimize risks of

Table 1

Force-displacement formulations for indentation/impact into an ice wall with a spherically ended indenter with the radius R as an example.

Modelling approach	Force-displacement development	Eq.
<i>Semi-empirical methods</i>		
The constant strength model	$F_{CST}(x) = pA(x) = p\pi(2Rx - x^2)$	(1)
Pressure-area model	$F(x)_{CST_SOFT} = pA(x) = C\pi(2Rx - x^2)^{1+q}$	(2)
Viscous fluid model	$F_{VT}(x) = \frac{4}{5}\pi(3\mu k^3)^{0.25}\nu^{0.25}(2Rx - x^2)^{1.25}$	(3)
<i>Data-driven methods</i>		
ISO 19906* probabilistic	$F_{ISO}(x) = CA(x)^{q+1}$, C and q are randomly sampled form certain distributions for each force-displacement realization	(4)

F - force resisting the motion of the spherically ended indenter, p is the crushing pressure, and x is the penetration depth; $A(x)$ is the projected circular contact area as a function of penetration depth; ν is the indentation/impact speed, k is the proportionality coefficient between the contact pressure and the thickness of the crushed ice layer, and μ is the dynamic viscosity of the crushed ice layer; C and q are empirical coefficients. In accordance with the semi-empirical methods, the following ice parameters are required for the prediction of the ice load: the value of the contact pressure (p) (Eq. 1), parameters C and q (in Eq. 2) and the value of $(3\mu k^3)^{0.25}$ (in Eq. 3). *Recommendations from ISO clause A.8.2.4.3.5. Note that the maximum contact area for these ship trials is about 6 m^2 .

Table 2

Experimental data on mass-specific energy absorption capacity (CSE as defined in Appendix) of polycrystalline freshwater ice at approximately -10°C . **

Ice type and test conditions	Grain size, mm; [range]	CSE, kJ/kg; [range]	Test type and data source
Lake Ladoga ice (February) $T_{air} = -10^\circ\text{C}$ to -5°C	[2 to 100]	8.8 ± 1.8 [5.3-12.3]	d/b, Kheisin and Likhomanov [12]
Laboratory-grown freshwater granular ice*, $T_{ice\&air} = -10^\circ\text{C}$	[1.0 to 2.4]	14.3 ± 1.4 [11.9-17.1]	i/c, derived from Kim et al. [14]
Iceberg ice, $T_{air} \approx -10^\circ\text{C}$	[7.4 to 100]	2.96 ± 1.13 [1.30-6.09]	i/v, derived from Pond Inlet tests
Laboratory-grown freshwater columnar S2 ice ^(a) , $T_{air} = -12^\circ\text{C}$	[1.0 to 3.0]	13.2 ± 2.7 [7.7-18.0]	d/b, Timco and Frederking [19]

Notations: d/b = drop-ball, i/c = spherically-ended indentation at constant speed, i/v = spherically-ended indentation at variable speed, a loaded along the columns.

*Can be served as the upper limit to the energy absorption capacity of freshwater polycrystalline ice

** It is anticipated that in connection with a larger amount of spalling or major fractures, the CSE values obtained for ice edge indentations or sharper indenters will be lower than that in this table.

Note that combining Eq. A (in Appendix) and Eq. 1 and expressing the nominal crushed volume as a function of penetration and the indenter radius, one gets a linear dependency between the contact pressure and the specific energy, $p = \rho \cdot \psi_m$ (where ρ is the ice density and ψ_m is CSE). In other words, a constant pressure implies a constant CSE, but not vice versa.

underestimating the energy absorption capacity of ice for a particular application.

3. Application example

To demonstrate the presented procedure, we will compare results of the calculations using four models from Table 1 and compare the calculation results with the empirical force histories from Pond Inlet tests in view of the CSE values from Table 2.

Fig. 3 presents results of the calculations. These reported calculations are meaningful for sufficiently large ice specimens and sufficiently large,

strained volumes. The term ‘sufficiently’ means that the crushed ice volume and the volume of damaged ice beneath the indenter, inside which the material can be regarded as polycrystalline, constitute a small fraction of the specimen but are large enough to assume that collectively the grains surrounding the crushed volume behave as a homogeneous material (Dempsey et al. [4]).

In Fig. 3, for the constant strength theory, the pressure (in Eq. 1) was calculated as the arithmetic product of the ice density and CSE (from Table 2, iceberg ice). In the pressure-area model, the parameter q was set to -0.1 and C to 3.2 MPa . This is in line with the IACS approach for Polar Class vessels where $q = -0.1$ and C corresponds to PC3 class. The parameters μ and k have never been measured directly. Their product has only been estimated by recalculating back from the drop ball tests or from the ship structural response data (e.g., see Appolonov et al. [2]). The value of $(3\mu k^3)^{0.25}$ was set to $(2835 - 233 \nu)^{9/4} \text{ kg}/(\text{s}^{7/4} \text{ m}^{7/4})$ and ν is in m/s as recommended in Likhomanov et al. [16] for freshwater ice. The latter value was derived by processing drop-ball test data from the Arctic and Antarctic Research Institute as well as drop test data from the National Research Council of Canada (refer to Likhomanov et al. [16] for details).

Force displacement development based on ISO 19906 (Clause A.8.2.4.3.5) global pressure area equation (A.8-25) was computed using lognormally distributed parameter C (with mean and standard deviation equal to 3 MPa and 1.5 MPa , respectively) and normally distributed parameter q with mean of -0.4 and standard deviation 0.2 . These distributions of C and q are based on ship rams and developed by Jordaan, et al. [11]. The ISO pressure-area (p - A) model was applied with randomly generated C and q coefficients. 50000 events, each one a random selection of a C and q value, were run, and equations (A) and (4) were used to determine the CSE at the end of the indentation ($x = 0.23 \text{ m}$) for the Pond Inlet 3 m^2 spherical indenter. The CSE values were then ranked and the force-indentation depth curve corresponding to the 10^{-2} exceedance value identified.

Note that the average CSE values (from Table 2) were used to obtain the results with the constant strength model, and thus the corresponding force-displacement curve in Fig. 3 can be treated as a baseline when comparing the models.

The comparison between the predicted and measured force-displacement data show that within the context of constant CSE, the assumption of $q = -0.1$ (the process pressure-area model underlying IACS UR [9]) is reasonable. Our calculations showed that the highest value from IACS UR ($C = 6.0 \text{ MPa}$) corresponded to the CSE of laboratory-grown freshwater ice at -10°C and is also recommended for PC1 ice class vessels where there is a greater chance to hit stronger freshwater ice features. The other C 's values (e.g., $C = 3.2 \text{ MPa}$ and $q = -0.1$) for lower classes (PC3) fit to the CSE from the Pond Inlet tests.

It is reasonable that the CSE (1.6 kJ/kg) from the ISO approach (data from ship rams with multi-year ice with mean C and q) is lower than the mean value (2.6 kJ/kg) from the Pond Inlet tests with the largest indenter. Naval architects have worked hard over decades to develop bow form that minimize ice forces, and multi-year ice floes have rather non-planar shapes whereas the Pond Inlet tests were designed to obtain the resistance of fully confined ice to be used for the local scantling design.

4. Summary remarks

Four conceptually different approaches can be used to reconstruct force-displacement curves in the absence of explicit empirical data. In the semi-empirical models, the overall constitutive response of ice can be approximated via one or more constant parameters, and in the data-driven models all parameters are given in ISO 19906.

The strength model can predict the average component of the force-penetration record needed in damage assessment studies when an appropriate CSE value is provided.

The pressure-area model and the data-driven approach in the ISO

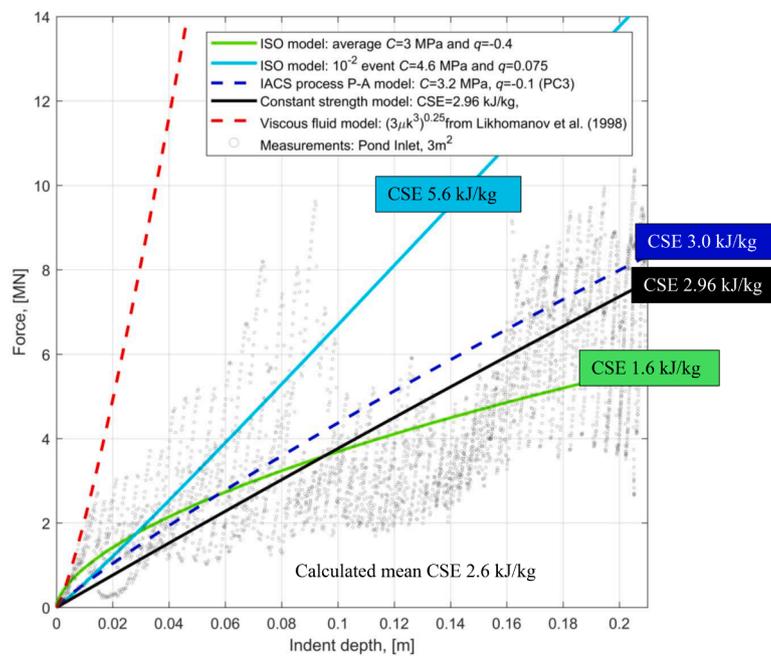


Fig. 3. Models' predictions and the Pond Inlet test data for $R=2300$ mm. We applied the ISO (clause A.8.2.4.7.3) approach for the Pond Inlet tests, so only the ice properties are random. In the ISO model, the C and q values are from the global pressure distribution of Jordaan et al. [11]; reported mean and 10^{-2} values. The calculated CSE values at the end of the Pond Inlet penetration (for $R=2300$ mm indenter) are [2.3, 3.2, 2.8, and 2.0] kJ/kg with the mean value of 2.6 kJ/kg. IACS model is from Daley [3].

clause A.8.2.4.3.5 are capable of predicting the average (quasi-static) force-displacement development; however, one must be careful in setting the ice parameters since it is easy to underestimate/overestimate the crushing specific energy of ice.

To accurately represent this energy absorption capacity of the ice in damage assessment studies (or ice model validation for damage assessment studies), one should perform verification of the ice parameters in the models, i.e., C , q or $(3\mu k^3)^{0.25}$, depending on the chosen approach. Some current practices skip this important verification step against CSE.

The global pressure-area model in ISO 1906 Clause A.8.2.4.7.3 and Clause A.8.2.4.3.5 fit the crushing specific energy of approximately 5.6 kJ/kg for a 10^{-2} spherically-ended indentation event and CSE of \approx (12–14) kJ/kg for a 10^{-4} event.

The process pressure-area relationships underlying Polar Class requirements of the International Association of Classification Societies for PC1 ($p=6.0A^{-0.1}$) and PC3 ($p=3.2A^{-0.1}$) fit the crushing specific energy of 14 kJ/kg and 3.0 kJ/kg, respectively for spherically-ended indentation.

CRediT authorship contribution statement

Ekaterina Kim: Conceptualization, Methodology, Software, Data curation, Investigation, Validation, Visualization, Writing – original draft, Project administration. **Knut Vilhelm Høyland:** Conceptualization, Methodology, Resources, Validation, Writing – review & editing. **Robert Frederking:** Conceptualization, Methodology, Resources, Validation, Writing – review & editing.

Appendix: specific energy definition

The energy absorbed per unit mass of crushed material, the so-called *crushing specific energy* (CSE), is also known as the impact crushing strength and the specific energy of the mechanical destruction of ice. In quasi-static indentation tests with rigid indenters, the CSE is defined as:

$$\text{CSE} = \frac{\int_{x=0}^{x=u} F(x) dx}{\rho \cdot V(x=u)}, \quad (\text{A})$$

where ρ is the ice density, $F(x)$ is the measured indentation force as a function of penetration depth x , and $V(x=u)$ is the nominal crushed volume, which is the volume of the indentation at the penetration depth $x=u$. CSE when multiplied by the mass of the crushed ice, for a given crushing distance,

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgments

The authors wish to thank Robert Gagnon from the National Research Council of Canada for sharing some of the experimental data on indentation of ice. We also thank Jørgen Amdahl from the Norwegian University of Science and Technology for his comments on application of crushing specific energy in damage assessment studies. This work is a part of investigations conducted within the Centre for Autonomous Marine Operations and Systems (AMOS) and the Centre for Sustainable Arctic Marine and Coastal Technology (SAMCoT) at the Norwegian University of Science and Technology. The authors would like to acknowledge the support from the Research Council of Norway through the SAMCoT CRI (project no. 203471) and through the AMOS CoE (project no. 223254) and the support from all SAMCoT and AMOS partners.

is equal to the energy dissipated in ice, i.e., area under the ice load-deformation curve.

References

- [1] Amdahl J. Impact from ice floes and icebergs on ships and offshore structures in Polar Regions. *IOP Conf Ser* 2019;700(1):1–16.
- [2] Appolonov EM, Didkovsky AV, Kuteinikov MA, Nesterov AB. Improvement in design models for ice load evaluation under vessel impact against ice. *J Ships Offshore Struct* 2011;6(3):249–56.
- [3] Daley, C.G., 2000. Background notes to design ice loads - IACS Unified Requirements for Polar Ships, Prepared for IACS Ad-hoc Group on Polar Class Ships and Transport Canada.
- [4] Dempsey JP, Defranco SJ, Adamson RM, Mulmule SV. Scale effects on the in-situ tensile strength and fracture of ice Part I: Large grained freshwater ice at Spray Lakes Reservoir. *Int J Fract* 1999;95:325–45.
- [5] DNVGL RP-C204. Structural design against accidental loads, Recommended practice, Det Norske Veritas. Germanischer Lloyd; 2019.
- [6] Frederking R. Ice Behaviour Under Indentation Loading - Medium-Scale Field Test. In: Proceedings of the 25th IAHR International Symposium on Ice; 2020.
- [7] Frederking R, Sudom D. Local ice pressure distributions during 1990 Hobson's choice Ice Island multi-year ice indentation tests. In: Proc. 19th IAHR International Symposium on Ice. 2; 2008. p. 815–27.
- [8] Gagnon RE. Re-analysis of load and pressure data acquired from ice impacts during the CCGS Louis St-Laurent 1994 Arctic Voyage. In: Proceedings of the 22nd IAHR International Symposium on Ice, Singapore, August 11 to 15, 2014; 2014.
- [9] IACS. Unified requirements for polar ships: I2 – structural requirements for polar class ships. In: International Association of Classification Societies; 2019.
- [10] ISO19906. Petroleum and natural gas industries – Arctic offshore structures. Second edition. International Organization for Standardization; 2019.
- [11] Jordaan I, Fuglem M, Matskevitch D. Pressure-area relationships and the calculation of global forces. In: IAHR Ice Symposium, Beijing; 1996. p. 166–75.
- [12] Kheisin DE, Likhomanov VA. Experimental determination of specific energy of mechanical disintegration of ice at an impact. *Problems Arctic Antarctic* 1973;41: 55–61 [In Russian].
- [13] Kim E, Gagnon R. A preliminary analysis of the crushing specific energy of iceberg ice under rapid compressive loading. In: Proceedings of the IAHR Ice Symposium; 2016. Paper ID 18467.
- [14] Kim E, Golding N, Schulson EM, Løset S, Renshaw CE. Mechanisms governing failure of ice beneath a spherically-shaped indenter. *Cold Reg Sci Technol* 2012;78: 46–63.
- [15] Kurdjumov V, Kheisin D. Hydrodynamic model of the impact of a solid on ice. *Prikladnaja Mekhanika* 1976;12(10):103–9 [in Russian].
- [16] Likhomanov V, Stepanov I, Frederking R, Timco GW. Comparison of results of impact tests on laboratory and natural freshwater ice with hydrodynamic model predictions. In: Proc. of the Eighth International Offshore and Polar Engineering Conference; 1998. p. 452–9.
- [17] Liu Z, Amdahl J, Løset S. Plasticity based material modelling of ice and its application to ship–iceberg impacts. *Cold Reg Sci Technol* 2011;65(3):326–34.
- [18] Ritch, et al. Local ice pressures measured on a strain gauge panel during the CCGS Terry Fox bergy bit impact study. *Cold Reg Sci Technol* 2008;52(2008):29–49.
- [19] Timco GW, Frederking RMW. Drop impact tests on freshwater ice: spherical head. In: IAHR Ice Symposium; 1990. p. 776–8.
- [20] Nevel DE. Iceberg impact forces. *Proc. IAHR Symposium on Ice* 1986;3:345–69. Iowa City, Iowa.