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Discrete element method modeling of propeller blade profile ice impact experiments

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ABSTRACT

This paper studies the failure of ice under impact loading by modeling propeller blade profile ice impact experiments. Discrete Element Method (DEM) tool LIGGGHTS-INL was used for the simulations. The experiments were performed at VTT Technical Research Center of Finland in 1993. In the experiments, laboratory grown, columnar grained, saline ice was impacted with an impactor tool with propeller blade profile attached to a pendulum device. Impact load on the impactor tool and the pressure distribution were recorded. The purpose of this paper is to numerically replicate the experiments to further analyze the failure mechanics of ice under impact loading. First, we simulated uniaxial compressive failure of ice to establish an anisotropic material model for columnar grained ice used in the experiments. The compressive strength of ice measured during the experiments was compared with simulation results. Then, we simulated the propeller blade profile impact tests. Tangential and longitudinal forces on the impactor tool were obtained from the simulations and compared with the experimental results. Simulation results seemed to agree with the experimental records. Finally, we obtained stress distribution in the ice block from the simulations. Stress distribution showed that the ice failure occurred due to propagation of a crack. This differs from the common approach of using strength-based failure criterion such as Mohr-Coulomb to model ice failure in propeller ice interaction processes. Thus, failure model with crack propagation may also need to be considered in propeller ice interaction models depending on the loading mode.

KEY WORDS: Propeller-ice impact; Numerical ice mechanics; Discrete element method; Ice failure.

INTRODUCTION

Crushing and fragmentation of ice under impact loading has a key role in propeller-ice interaction processes. Nevertheless, mechanics of ice failure under impact loading is not fully understood. Experimental investigation of propeller ice interaction processes in full scale is challenging because of ithe complex setup needed. Thus, investigations focused on measuring the ice load on propellers via indirect methods such as measuring the additional torque on propeller shaft or instrumenting propellers with strain gauges (Jussila, 1983; Jussila and Koskinen, 1989; Kannari, 1988; Koskikivi and Kujala, 1985). These methods provide insightful data on ice loads on a propeller but not mechanics related to ice failure process. This has been circumvented by using idealized lab scale experiments to further investigate the ice failure processes during propeller ice interaction events. Experiments have been performed for variety of propeller ice interaction events such as ice milling (Bach and Myland, 2017) and indenter impact (Bohm et al., 2022). Experimental data and observations provide valuable insights yet, underlying mechanics of failure processes are challenging to investigate from experiments due to the fast nature of the processes and the lack of data on stresses causing the failure events. Thus, numerical modeling can be used as an extension of the experiments to further investigate the failure processes. Also, numerical models allow for larger parametric studies which are challenging with experimental approach. In this paper, we use Discrete Element Method (DEM) model to replicate the propeller blade profile ice impact experiments carried out at VTT Technical Research Center of Finland (Soininen, 1998). Two-fold objectives of this study are to develop DEM techniques to simulate impact failure of ice and to investigate the underlying failure mechanics of ice under the impact of a propeller blade.

DEM simulations are used widely to model ice deformation and failure phenomena. Main advantages of using DEM are that, complex material behavior can be replicated by using simplified interaction laws between particles and the macroscopic material behavior in the simulation can be directly compared to experimentally measurable properties. DEM simulations have been used previously to analyze uniaxial compressive failure experiments (Ji et al., 2017), ice block contact failure experiments (Prasanna et al., 2022), shear box experiments of ice rubble (Polojärvi et al., 2015; Prasanna and Polojärvi, 2023; Sorsimo and Heinonen, 2019), ice rubble punch through tests and (Polojärvi and Tuhkuri, 2009) and ice rubble cohesion experiments (Afzali et al., 2021; Zhai et al., 2021). It is worth mentioning here that the propeller blade profile impact experiments modeled here differ from the abovementioned work due to very high strain rate of deformation which brings forth the novelty to this work.

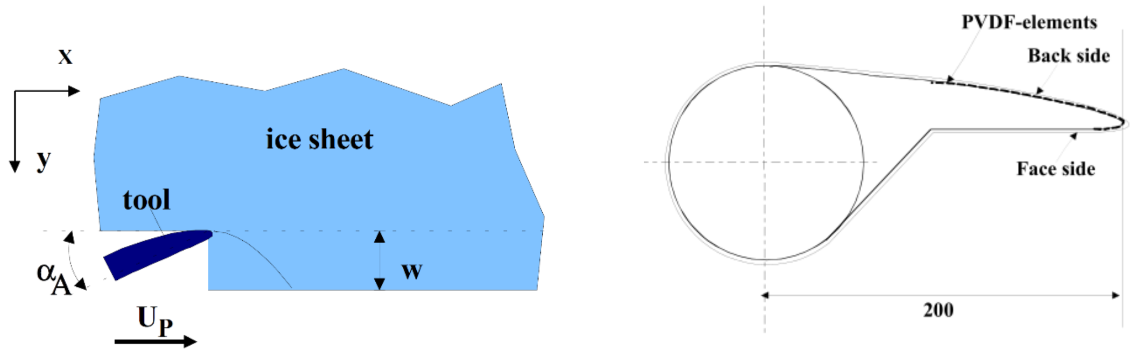
METHODS

This section describes the propeller blade profile ice impact experiments and their results, the DEM tool used and the method to set up ice impact simulations.

Ice impact experiments

Figure 1 presents an illustration of ice impact experiments, which are described in detail in Soininen (1998). In the experiments, an impactor tool with propeller blade profile was impacted against laboratory grown, columnar grained, saline ice. The impactor tool had been made by attaching a leading-edge section of a propeller blade to a steel shaft with a 55 mm radius as shown in Figure 1b. Blade profile shape was a full-scale replication of part of the propeller of the car ferry Gudingen. Thus, the objective of the experiments were to study the failure mechanics of ice under the impact of a propeller blade. The ice was grown using saline water harvested from sea, and the ice thickness was 20 cm. A pendulum rig was used to attain the target impact speed of 8 m/s. The impact force on the indenter, and the pressure on the impactor surface were measure by using force transducers and piezoelectric pressure sensitive elements (PVDF) respectively. High speed video recording was also done for the visual observations. Experiments were conducted varying the angle of attack, α, and the cut width, w. Compressive strength of the ice along and across the grain direction were also measured during the experiment campaign by uniaxial compressive failure tests.

The video recordings revealed that the failure process was cyclic, where ice was crushed and extruded periodically as the blade proceeded through the ice sheet. Total force records also showed cyclic patterns which were corresponding to the cyclic failure events. PVDF measurements showed that the ice pressure was acting predominantly on back side of the blade profile compared to the face side. This was because, ice was flaking from the leading edge of the blade profile to the free edge of the ice sheet which in turn relieved pressure on face side.



(a) (b)

Figure 1: (a) An illustration of the propeller blade profile ice impact experimental setup. (b) Profile of the impactor tool. Figures reproduced from Soininen (1998).

LIGGGHTS-INL

LIGGGHTS-INL (Chen et al., 2022; Guo et al., 2020) is a Discrete Element Method (DEM) particle simulation software based on LIGGGHTS release version 4.0.0 (Kloss et al., 2012) and developed at the Idaho National Laboratory. One of the key extensions in LIGGGHTS-INL is the bonded-particle model (BPM) based on Potyondy and Cundall (2004). In LIGGGHTS-INL ice is modeled as a lattice of spheres connected by a cylindrical bonds. Failure of these bonds mimic crack formation within the material and coalesce of individual cracks leads to formation of larger cracks and fragmentation. Bonds can fail either due to tensile/compressive , $\bar{\sigma}$, or shear, $\bar{\tau}$, stress calculated as,

$$\bar{\sigma} = \frac{F_n}{A} + \frac{|M_s|R}{I}, \tag{1}$$

$$\bar{\tau} = \frac{|F_s|}{A} + \frac{|M_n|R}{J}. \tag{2}$$

In the equations, F_n, F_s, M_n and M_s are normal force, shear force, normal moment and shear moment respectively, while A, R, I and J are area of the cross section area, bond radius, moment of inertia and polar moment of inertia respectively. Bonds fail if $\bar{\sigma}$ is greater than tensile/compressive strength or if $\bar{\tau}$ is greater than shear strength. Tensile and shear strength of the bonds are set as input parameters, while the compressive strength is set to be 5 times tensile strength. Bonds fail instantaneously once the failure criterion has met assuming brittle behavior. Energy dissipation is modeled by using a linear damping model. Contact interaction between particles is modelled by using the Hertzian contact model, where the contact force is proportional to the overlap between spheres.

Simulation setup

In this paper we use the modeling technique described in Prasanna et al. (2022) to develop a material model for columnar grained ice used in the experiments. A bond-sphere lattice mimicking the grain structure of ice was used where, particles were arranged in random packing in horizontal plane (XY plane of Figure 1a) while hexagonal closed packing in the vertical plane (perpendicular to the XY plane of Figure 1a). This takes into account the anisotropic grain structure of columnar grained ice where an columnar grain is modeled by using several DE particles along the thickness of ice in Z direction. Then, uni-axial compressive failure of an ice specimen of 0.07×0.07×0.15 m (length×width×height) was simulated to calibrate the material parameters of the model. Loading along and perpendicular to the XY plane were considered loading across and along the columnar grains respectively. Simulations of compression across the vertical columnar grain structure and along the grain structure were performed (Figures1a and b respectively). Compressive strength from the simulations were compared with experimental results and material parameters of the BPM were calibrated so that the simulation results match the experiments. Then, the same parameters were used to simulate the ice impact experiments.

Ice impact experiment simulations were set up as follows. A bond-sphere lattice of 0.6 m length and 0.3 m width was used to model the ice specimen. Lattice was 70% and 30% consisting of spheres with 4 mm and 3 mm diameter respectively. Particle diameters were selected to mimic the typical grain size of laboratory grown saline ice. The Impactor tool was set up as a solid mesh object with 8 m/s constant velocity in X direction while the Y direction movement was fixed. The upper Y boundary of the specimen was set to fixed, to restrict the translation of the specimen due to impact force. Columnar structure of the lattice was oriented perpendicular to the impactor travel direction. Simulations were performed for w = 50 mm and 100 mm with α = 7°. Table 1 summarizes the main parameters of the simulations.

Table 1: Simulation parameters.

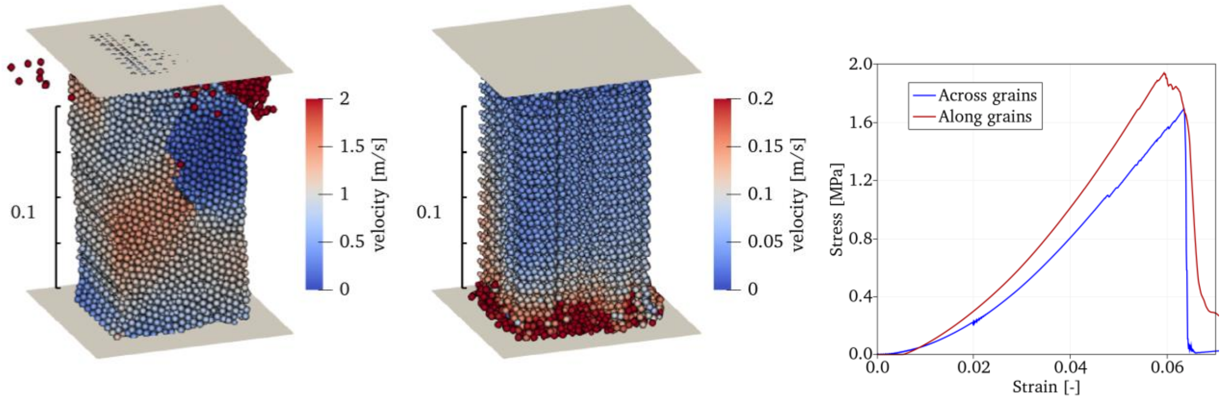
	Parameter	**Value**	**Units**
Particles	Young’s modulus	2.0	GPa
	Coefficient of restitution	0.8	-
	Friction coefficient	0.5	-
	Diameter	3,4	mm
Bonds	Young’s modulus	2.0	GPa
	Tensile strength	400	kPa
	Shear strength	400	kPa
	Compressive strength	2.0	Mpa
	Diameter	3,4	mm

RESULTS

This section reports the simulation results. First, results of uni-axial compressive failure simulations are presented. Then, the ice impact experiment simulations are presented and compared with the experiment results.

Uni-axial compressive failure simulations

Figure 2 presents the failure patterns and stress-strain curves obtained from the uni-axial compressive failure simulations. Specimens fail by shearing when loaded across the columnar grains (Figure 2a) while spalling was the failure mode when loaded along the grains (Figure 2b). The ice impact experiment report does not specify the failure modes in uni-axial compressive failure experiments. However, failure pattern observed in the simulations agree well with experimental observations found in literature (Kuehn and Schulson 1994). Stress-strain curves presented in Figure 2c shows that stress increases almost linearly with strain and drops abruptly indicating brittle failure. Peak of the stress-strain curves corelate to compressive strength of the ice and, it is 1.94 MPa and 1.69 MPa when loaded along the grains and across the grains respectively. Respective compressive strengths obtained from the experiments were 2.16 MPa and 0.99 MPa.

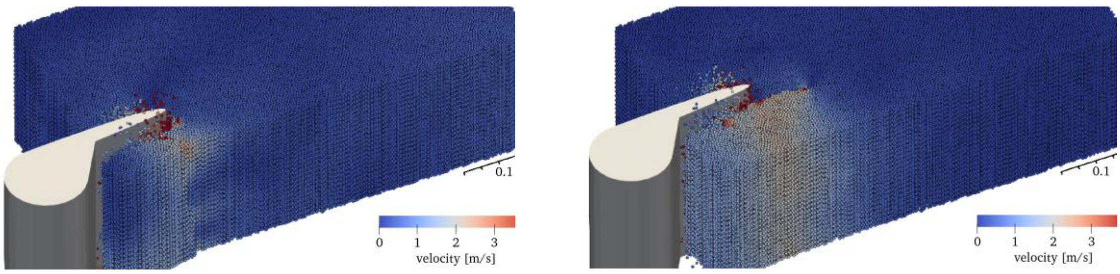


(a) (b) (c)

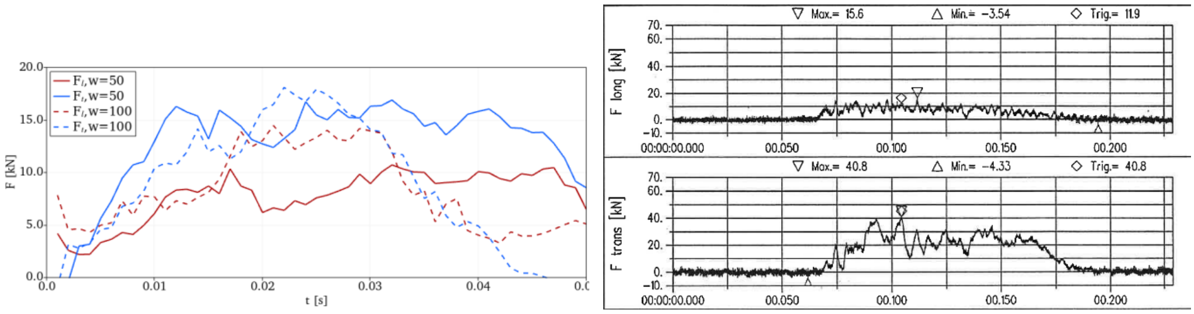
Figure 2: Failure pattern in uni-axial compressive failure simulation of specimen loaded (a) across the grains and (b) along the grains. (c) Stress-strain curves from the simulations.

Ice impact experiment simulations

Figure 3a and b present snapshots from two ice impact simulations with cut width, w = 50 mm and 100 mm respectively. Force-time curves of transverse and longitudinal forces, F_t, and F_l, respectively, from the simulations are shown in Figure 3c. Transverse and longitudinal directions were defined along the Y and X axes respectively. Snapshots show the cyclic failure process where ice fragments are breaking off as the indenter passes through the ice sheet. Force-time curves also show the cyclic peaks and valleys correspond to these failure events. Maximum F_t reached about 18 kN in both cases, while maximum F_l was 12.5 kN and 14.8 kN in w = 50 mm and 100 mm simulations, respectively. Increase in F_l in w = 100 m simulation can be explained by the larger fragments which need higher force to extrude from the ice sheet. Maximum F_t did not show significant increase here as it is related to the impactor geometry. Figure 3d presents records of F_t and F_l from an experiment with w = 50 mm. Maximum F_t and F_l observed in the experiment were 40.8 kN and 15.8 kN respectively. Comparing simulation results with experiments, it seems simulations underestimate transverse force.



(a) (b)



(c) (d)

Figure 3: Snapshots from the propeller blade profile impact simulations with (a) w = 50 mm and (b) w = 100 mm. (c) Force-time curves from the simulations. (d) Force time curve from the experiment with w = 50 mm.

Local pressure on the impactor tool obtained from the simulation is presented in Figure 4. These results show that the pressure on back side of the indenter was much higher compared to the face side. This is apparent from the force results as well where F_t was higher on back side. Moreover, it is also noticeable that the maximum pressure occurs close to the nominal centerline of the blade profile. PVDF measurements from the experiments also showed a similar behavior where back side was highly pressured and the maximum pressure occurring about 20 mm above the centerline. Ice sheet was floating on water in the experiments and had through thickness temperature gradient which in turn caused reduced ice strength in the bottom half of the ice sheet.

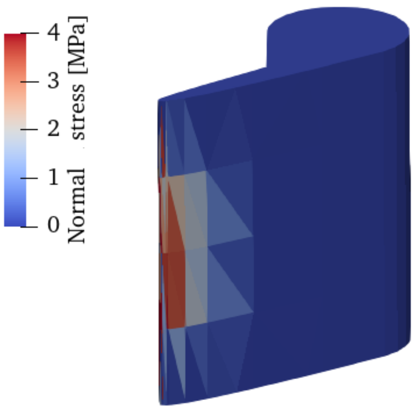
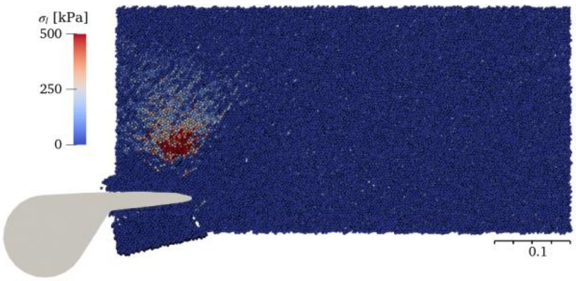


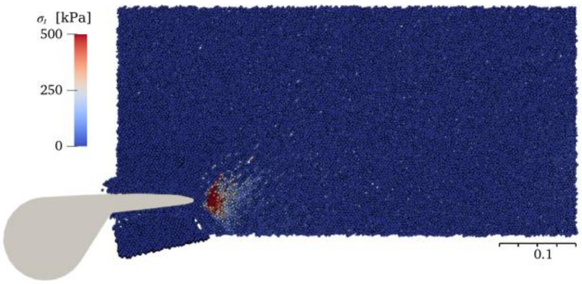
Figure 4: Normal stress distribution on the blade profile impactor tool.

ANALYSIS

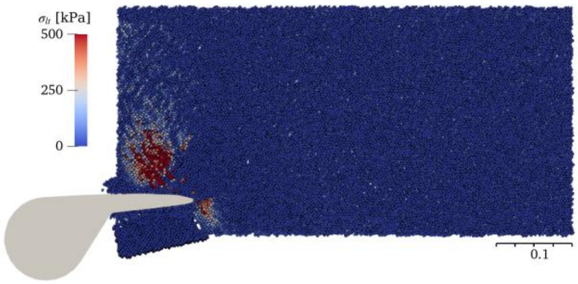
In this section we use simulations to analyze the underlying mechanics of ice failure in blade profile impact experiments. Cauchy stress tensor of particles was obtained from the simulations to investigate the stresses within the ice block. Figures 5a and b present normal stress in tangential and longitudinal direction respectively, while Figure5c shows the shear stress distributions in the ice block onset of a failure event. Tangential and longitudinal directions were defined along Y and X axes, respectively. In Figure 5b it is noticeable that there is a crack opening in front of the leading edge of the impactor tool, and the crack is propagating ahead of the impactor tool. The stress distribution at the crack tip is tensile. Thus, the ice failure here can be characterized as crack propagation. Crack initiation occurs due to high stress concentration at the leading edge. Then, the crack is further opened due to the impactor tool acting as a wedge driven into the crack mouth. Wedge shape is created by the alpha angle. A shear plane formation would have exhibited different failure mechanisms where final failure occur due to coalescence of microcrack forming along the shear plane than a propagating crack tip. It is also important to note here that the high stress areas in transverse direction are reaching up to the fixed boundary. This means that there is a boundary effect on the stresses and the transverse force on the impactor is partially due to compression of the ice sheet in that direction.



(a)



(b)



(c)

Figure 5: Stress distribution within ice block in simulation with w = 50 mm. (a) Longitudinal stress, (b) transverse stress and (c) shear stress.

DISCUSSION

Our simulation results demonstrate that LIGGGHTS-INL bonded particle model can be used to successfully simulate the impact failure of ice. Simulations were able to reproduce the failure patterns and pressure distribution on the indenter fairly well. Impact force obtained from the simulations were in agreement for longitudinal force, but the transverse force was underestimated. One of the main reasons for this discrepancy is the smaller specimen size in simulations. Experiments were performed on a large ice sheet with more than 10 times transverse length compared to impactor indentation. Thus, there was sufficient ice mass for transverse force build up. Longitudinal force was not affected by the limited size of the ice specimen in the simulation. This is because it is related to force required for crack propagation and the specimen was large enough in the longitudinal direction. However, transverse force observed in the simulations can be overestimated compared to a real propeller ice interaction event since the boundary effects pointed out in the analysis section. This further emphasis the fact that a free ice block impacting a propeller may exert different force than observed in the experiments due to free boundary condition and momentum transfer during the impact. It is also worth mentioning here that the uni-axial compressive failure simulations used to parametrize the ice material model exhibits shear plane formation and spalling. Using the same parameterization to simulate failure governed by crack propagation could also be one of the reasons for discrepancies between simulations and experiments in blade profile impact simulations.

The stress analysis in the ice sheet showed that ice failure during the impact occurs due to crack propagation in ice. This contradicts with the common approach of using strength-based failure models such as Mohr-Coulomb failure criterion to model ice failure in propeller ice interaction events (Belyashov and Shpakov, 1992; Ssoininen, 1998; Wind, 1984). Mohr-Coulomb failure criterion assumes that the ice is failing by formation of a macroscopic shear plane consisting of interconnected micro-cracks. This is the typical failure mode of ice under confined compression as observed in the uniaxial compressive failure simulations. However, the ice failure under propeller impact does not show shear plane formation but crack propagation. This also explains ice flaking from the leading edge of the blade profile to the free edge of the ice sheet as propagating cracks tend to curve towards free boundary (Thouless et al., 1987). Thus, crack propagation may also need to be considered in propeller ice interaction models depending on the loading mode. It is also worth mentioning here that further experiments can be used to verify the failure mechanisms. Advanced imaging technologies such as digital image correlation can be combined with ice experiments to analyze failure mechanisms (Ahmad et al., 2023).

CONCLUSIONS

In this paper we used discrete element method simulation tool LIGGGHTS-INL to model the propeller blade profile ice impact experiments. Two-fold objectives of this work were to develop a DEM simulation technique to simulate propeller blade profile ice impact events and, to study the underlying mechanics of the ice failure under impact loading. Following conclusions can be drawn from the simulation results and analysis.

- LIGGGHTS-INL with columnar ice model described in Prasanna et al. (2022), can be used to model ice failure under propeller blade profile impact.
- Simulations were able to capture the overall ice failure patterns and force on the indenter.
- Stress distribution within the ice sheet obtained from the simulations showed that there is strong boundary effect in the experiments. Thus, a free floating ice block impacting a propeller may exert different force than observed in the experiments due to momentum transfer during the impact.
- Ice failure under propeller blade impact seems to be governed by crack propagation. Thus, failure model with crack propagation may also need to be considered in propeller ice interaction models depending on the loading mode.

The current study focused on replicating propeller blade profile ice impact experiments using DEM simulation tool. The instinctive next step would be to extend the study to simulate a propeller blade ice interaction event, where a free-floating ice block is impacting a rotating blade.

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REFERENCES

Ahmad, W., Prasanna, M., Gharamti, I. E., Bossuyt, S., Tuhkuri, J., 2023. Developing methods of using Digital Image Correlation for ice research. in: Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions (POAC) 23.

Afzali, S., Taylor, R., Bailey, E., Sarracino, R., Boroojerdi, M.T., 2021. Investigation of the effect of block size, shape, and freeze bond strength on flexural failure of freshwater ice rubble using the discrete element method. Journal of Offshore Mechanics and Arctic Engineering 143. https://doi.org/10.1115/1.4050057

Bach, C., Myland, D., 2017. An experimental method for model propeller-ice interaction in air: Concept and first results, in: Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE. https://doi.org/10.1115/OMAE2017-62248

Belyashov, V.A., Shpakov, V.S., 1992. On mechanics of ice crushing by propeller blades.

Bohm, A.M., Herrnring, H., von Bock und Polach, F., 2022. SPLITTING-TESTS of LABORATORY-MADE GRANULAR ICE with A PROPELLER-LIKE INDENTER, in: Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE. https://doi.org/10.1115/OMAE2022-78186

Chen, F., Xia, Y., Klinger, J.L., Chen, Q., 2022. A set of hysteretic nonlinear contact models for DEM: Theory, formulation, and application for lignocellulosic biomass. Powder Technol 399. https://doi.org/10.1016/j.powtec.2021.117100

Guo, Y., Chen, Q., Xia, Y., Westover, T., Eksioglu, S., Roni, M., 2020. Discrete element modeling of switchgrass particles under compression and rotational shear. Biomass Bioenergy 141. https://doi.org/10.1016/j.biombioe.2020.105649

Ji, S., Di, S., Long, X., 2017. DEM simulation of uniaxial compressive and flexural strength of sea ice: Parametric study. J Eng Mech 143. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000996

Jussila, M., 1983. Ice loads on propulsion system of an ice breaking tug. Proceedings of the 7th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC) 2, 575–590.

Jussila, M., Koskinen, P., 1989. Ice loads on CP-propeller and propeller shaft of small ferry and their statistical distributions during winter ’87, in: Proceedings of the International Offshore Mechanics and Arctic Engineering Symposium. pp. 351–358.

Kannari, P., 1988. Full scale and model tests performed with nozzle and open propeller simultaneously. Proceedings, The 9th International Symposium on Ice 1, 772–781.

Kloss, C., Goniva, C., Hager, A., Amberger, S., Pirker, S., 2012. Models, algorithms and validation for opensource DEM and CFD–DEM. Progress in Computational Fluid Dynamics, an International Journal 12, 140–152.

Koskikivi, J., Kujala, P., 1985. Long-term measurements of ice induced loads on the propulsion machinery of product tanker Sotka. Winter Navigation Research Board, Report No. 42, Finnish Board of Navigation 42.

Kuehn G.A., Schulson E.M, 1994. The mechanical properties of saline ice under uniaxial compression. Annals of Glaciology 19. https://doi.org/10.3189/1994AoG19-1-39-48

Polojärvi, A., Tuhkuri, J., 2009. 3D discrete numerical modelling of ridge keel punch through tests. Cold Reg Sci Technol 56, 18 – 29.

https://doi.org/10.1016/j.coldregions.2008.09.008

Polojärvi, A., Tuhkuri, J., Pustogvar, A., 2015. DEM simulations of direct shear box experiments of ice rubble: Force chains and peak loads. Cold Reg Sci Technol 116, 12 – 23. https://doi.org/10.1016/j.coldregions.2015.03.011

Potyondy, D.O., Cundall, P.A., 2004. A bonded-particle model for rock. International Journal of Rock Mechanics and Mining Sciences 41, 1329 – 1364. https://doi.org/10.1016/j.ijrmms.2004.09.011

Prasanna, M., Polojärvi, A., 2023. Breakage in quasi-static discrete element simulations of ice rubble. Int J Mech Sci 259. https://doi.org/10.1016/j.ijmecsci.2023.108595

Prasanna, M., Polojärvi, A., Wei, M., Åström, J., 2022. Modeling ice block failure within drift ice and ice rubble. Phys Rev E 105. https://doi.org/10.1103/PhysRevE.105.045001

Soininen, H., 1998. A propeller-ice contact model. VTT Publications 3 – 116.

Sorsimo, A., Heinonen, J., 2019. Modelling of ice rubble in the punch shear tests with cohesive 3D discrete element method. Engineering Computations (Swansea, Wales) 36, 378 – 399. https://doi.org/10.1108/EC-11-2017-0436

Thouless, M.D., Evans, A.G., Ashby, M.F., Hutchinson, J.W., 1987. The edge cracking and spalling of brittle plates. Acta Metallurgica 35, 1333 – 1341. https://doi.org/10.1016/0001-6160(87)90015-0

Wind, J., 1984. Dimensioning of high power propeller systems for arctic icebreakers and icebreaking vessels. International Shipbuilding Progress 31, 131 – 148. https://doi.org/10.3233/isp-1984-3135702

Zhai, B., Liu, L., Ji, S., 2021. Numerical Analysis of Ice Rubble with a Freeze-Bond Model in Dilated Polyhedral Discrete Element Method. CMES - Computer Modeling in Engineering and Sciences 129. https://doi.org/10.32604/cmes.2022.018652