POAC'23
Glasgow, United Kingdom

Proceedings of the 27th International Conference on
Port and Ocean Engineering under Arctic Conditions
12-16 June 2023, Glasgow, United Kingdom

PAPER LENGTH is 10 (ten) pages plus References

Numerical investigation on center loading on a circular plate of model ice

Wei-hang Zhao [1], Yu-kui Tian [1*], Chao-ge Yu [1], Xu-hao Gang [1], Peng Lu [2]
[1] China Ship Scientific Research Center, Wuxi, China
[2] Dalian University of Technology, Dalian, China

ABSTRACT

When ice structures such as floating bodies underneath the ice cover interact with sea ice, flexural failure is the main form of ice cover failure. Therefore, the research on the flexural strength of ice is of great significance for ice loading prediction. In this paper, aiming at the model ice in CSSRC (China Ship Scientific Research Center) SIMB (Small Ice Model Basin), the mechanical properties of the model ice were obtained by physical experiments, and FEM (the finite element method) was used to establish a numerical model of the model ice circular plate center loading based on LS-DYNA. The load-time curve of the model ice center loading process was obtained through the numerical model, and the numerical calculation results were checked by using the experiment data to ensure the reliability of the numerical calculation model. At the same time, the influence of mesh size on the calculation accuracy of the numerical model was analyzed. The crack propagation and stress distribution of the model ice flexural failure were discovered. The numerical model established in this paper can provide a reference for the prediction of mechanical properties of model ice and establishes a preliminary foundation for further research of the mechanism of ice loading under the vertical interaction between the structure and the ice cover.

KEY WORDS: Model ice; Circular plate; Finite element method; LS-DYNA; Crack propagation.

INTRODUCTION

The breaking failure of ice sheet caused by the force applied vertically with structure operating in ice area such as floating body underneath the ice cover is gradually becoming an important scenario in the polar exploration and utilization engineering. When the floating body underneath the ice cover apply force vertically, the ice sheet will appear shearing, bending, and other failure forms and then break, among which flexural failure is the main failure form of the ice sheet. Therefore, the flexural strength tests of ice are of great significance for the design and evaluation of the structural strength and safety manipulation of floating body underneath the ice cover. Due to the strict requirements of test conditions and the development of numerical technology, the flexural strength of ice can be explored by numerical simulation. At present, among the simulation methods for the flexural strength of ice, the commonly used methods are the discrete element method and the finite element method(Gang,2021). The discrete element method is a calculation method suitable for discontinuous media mechanics, but the result deviation in the continuum stage restricts its application to dynamic failure problems. The finite element method has the advantages of fast calculation efficiency and high calculation accuracy and has been widely used to simulate the interaction between ice and structures. At present, scholars from many countries have carried out a lot of work on the mechanical strength of ice through the finite element software LS-DYNA. Based on LS-DYNA, Li (2020) used various homosexual elastoplastic fracture models to simulate sea ice, simulated the collision process between ice, rigid flat plate and elastic plate in air, water surface and underwater, and explored the influence of collision velocity and collision angle on the structure-ice-fluid interaction process. Wang (2021) used LS−DYNA to simulate the vertical icebreaking process of cylinder based on S−ALE (structured arbitrary Lagrange-Euler) method and penalty function fluid-structure interaction algorithm and verified the feasibility of calculating structure-ice interaction problems by finite element method. Von Bock und Polach et al. (2013) applied LS−DYNA to select the Lemaitre damage model (*153_MAT_DAMAGE3) to simulate the model ice and analyzed the dependence of the load response on the microstructure of the model ice. The pore distribution of the model ice had little effect on the failure load (up to 6%) but had a large effect on the failure mode due to local stress concentration. Herrnring et al. (2022) applied LS−DYNA to select an ideal elastoplastic material model based on the Mohr-Coulomb failure criterion to simulate model ice. To maintain the quality and energy of the model as much as possible, the node splitting technique was used instead of the commonly used element erosion technique. As stated above, LS-DYNA has been widely used to simulate the mechanical behavior and failure of sea ice and model ice, but the simulation of the center loading test of the horizontal disk of model ice still needs to be further studied. Therefore, based on the central loading test of the circular plate of the small ice basin of CSSRC in the early stage, the model ice mechanical properties obtained by the test were used as the material input parameters of the numerical model, and they were numerically calculated based on the finite element method. The numerical calculation results were checked by the central loading test data of the circular plate, and the accuracy of the numerical calculation method was verified, to provide a reference for the prediction of the ice mechanical characteristics of the model.

ESTABLISHMENT OF NUMERICAL MODEL OF MODEL ICE

Explicit integration method

The circular plate center loading tests were used to vertically load the central area of the disk ice specimen under the circumferentially uniform support. The contact between the indenter and the ice disk specimen occurred during loading, and the explicit nonlinear finite element method can be used to solve such contact problems (Guo,2021). The calculation method used by the nonlinear finite element program is the explicit integration method.

The LS-DYNA explicit integration method uses the central difference method to integrate time in the format:

$$\begin{cases} v_{\frac{n+1}{2}} = v_{\frac{n-1}{2}} + a_n \left(\Delta t_{\frac{n+1}{2}} + \Delta t_{\frac{n-1}{2}} \right) / 2 \\ d_{n+1} = d_n + v_{\frac{n+1}{2}} \Delta t_{\frac{n+1}{2}} \\ \Delta t_{\frac{n+1}{2}} = \left(\Delta t_n + \Delta t_{n+1} \right) / 2 \end{cases} \quad (1)$$

The time step of the display algorithm cannot exceed the critical time step:

$$\Delta t \le \Delta t_{cr} = \min\left(L^e / c\right) \tag{2}$$

$$c = \sqrt{E / \rho} \tag{3}$$

$$\Delta t = l / c \tag{4}$$

Where L^e is the characteristic length of the element mesh, c is the stress wave velocity, E is Young's modulus, and ρ is material density. The length of the critical time step is related to the length of the cell and the characteristics of the material, which is calculated automatically in LS-DYNA and has a default time step scaling factor of 0.9. When the calculation result is unstable, it can be reduced to 0.8 or less (Zhao,2003).

Failure and fracture are all engineering concepts, which means that after reaching a certain criterion, the structure, component, or a certain part of the component, withdraws from the structure and no longer affects the force of the overall structure. From the finite element concept, the basic means of simulating the above mechanism are the same. That is, when a certain index is met, the mass, stiffness and stress, and strain of a unit are set to zero (or very close to zero). In this way, it no longer plays a role in the overall structure calculation, and thus realizes the simulation of the exit working mechanism (Li,2008).

Basic settings of the numerical model of model ice

In the numerical calculation, the ice specimen was loaded as shown in Fig.1. During modeling, the annular support below the ice specimen was set as a fixed boundary, the cone indenter had only the degrees of freedom in the Z direction, and the load was applied downward on the upper surface of the ice specimen at a constant loading speed.

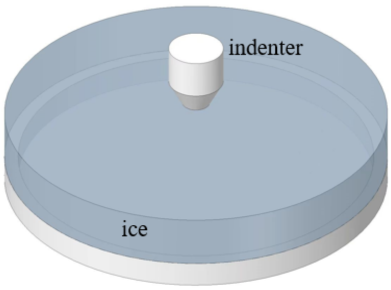


Figure 1. Schematic diagram of circular plate test

The main parameters of the numerical model are shown in Table 1. To simulate the fragmentation phenomenon of the model ice, a fine mesh was used in the central area of the model ice, and a large gradient mesh was used in the outer part, as shown in Fig. 2. Through the circular plate center loading tests, the numerical calculation condition was determined. Among them, the loading speed of the cone indenter was 2.5mm/s.

Table.1 Main parameters of the numerical model of the horizontal disc test

Ice specimen radius (mm)	Ice specimen thickness (mm)	Ring support outer diameter (mm)	Ring support inner diameter (mm)	The radius of the lower surface of the tapered indenter(mm)
70	20	70	60	5

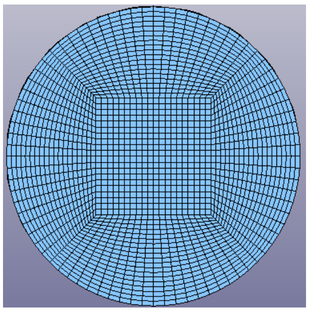


Figure 2. Model ice meshing

When using the finite element method to simulate the model ice mechanics test, it is necessary to determine the material model parameters that match the macroscopic characteristics of the material. Common model ice constitutive models include elastoplastic model, elastic brittleness model, etc. According to Karr and Choi (1989), model ice materials are considered isotropic in their undeformed state. In this paper, this assumption was adopted, so the isotropic elastoplastic fracture model (*MAT_ISOTROPIC_ELASTIC_FAILURE) in LS-DYNA was selected to simulate the model ice. The failure criterion for the material is the Von Mises yield criterion (Qian,2020), and the von Mises yield condition is given by the following equation:

$$\phi = J_2 - \frac{\sigma_y^2}{3} \tag{5}$$

where the second stress invariant is defined as:

$$J_2 = \frac{1}{2} s_{ij} s_{ij} \tag{6}$$

The yield stress is a function of the effective plastic strain and the plastic hardening modulus:

$$\sigma_y = \sigma_0 + E_p \varepsilon_{eff}^p \tag{7}$$

The plastic tangent modulus is defined as the input tangent modulus Et:

$$E_p = \frac{EE_t}{E - E_t} \tag{8}$$

The pressure is given by the expression:

$$p^{n+1} = K\left(\frac{1}{V^{n+1}} - 1\right) \tag{9}$$

where K is the bulk modulus.

When the effective plastic strain of the unit reaches the plastic failure strain or the pressure reaches the failure pressure, the element loses its ability to bear tension:

$$p^{n+1} < p_{\min} \text{ or } \varepsilon_{eff}^p > \varepsilon_{\max}^p \tag{10}$$

The material parameters of the model ice are shown in Table 2. The specific parameters of density, plastic hardening modulus and plastic failure strain were obtained by the model ice mechanical test (Zhao,2022). According to the relevant ice mechanics numerical simulation data, the range of other material parameters was obtained, and finally the specific parameters were given by trial and error.

Table.2 Model ice material parameters

Material properties	parameter
density /g•cm^{-3}	0.92
Shear modulus /Mpa	76.9
plastic hardening modulus /Mpa	94.7
Yield stress /Kpa	93
Bulk modulus /Mpa	75
plastic failure strain	0.05
Failure pressure /Kpa	-110

A rigid body model was selected to simulate the annular support and cone indenter, and the material parameters were defined using the keyword *MAT_RIGID, as shown in Table 3.

Table.3 Ring support and indenter material parameters

Material properties	Value
density /g•cm^{-3}	7.83
Elastic modulus /GPa	207
Poisson's ratio	0.33

LS-DYNA provides a variety of contact algorithms for explicit analysis, divided into single-sided contact, point-to-face contact, and face-to-face contact. The contact between the subglacial surface of the model and the upper surface of the annular support had a large contact area and symmetrical shape, so the surface contact was selected. Since the ring support was modeled using shell elements, the Automatic Contact Algorithm (ASTS) in surface contact was chosen. The automatic contact algorithm can consider the influence of element thickness, allowing contact to appear on both sides of the shell element, making it more accurate when calculating contact forces. The contact between the upper surface of the model ice and the lower surface of the cone table indenter also adopted surface contact, and the erosion contact algorithm (ESTS) in surface contact was selected because the ice breakage effect of the erosion contact simulation model is good. Use erosion contact to control time steps and automatically invoke negative volume failure criteria for all solid elements in the model, which circumvents procedural errors due to negative volumes by removing solid elements that produce negative volumes.

To ensure the accuracy of the calculation results, the number of elements and nodes of the model ice body was large when dividing the mesh, but the number of elements had a great influence on the calculation time. Therefore, the grid convergence of the model ice simulation model was analyzed by selecting four meshes with different numbers of elements, (the number of elements was 8645, 17290, 38295, and 70740), and then the calculation results of meshing different number of elements were compared and analyzed, as shown in Fig. 3.

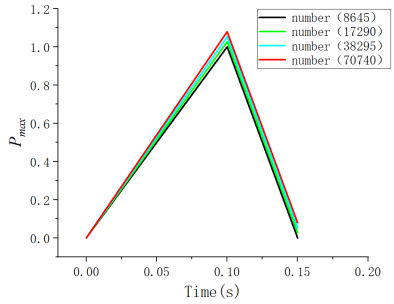


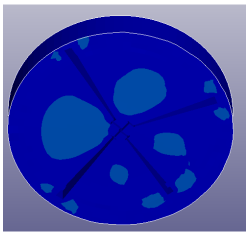
Figure 3. Mesh convergence analysis

It can be seen from Fig. 3 that the calculation results obtained by the model ice simulation model with the number of elements of 8645 and the calculation results of the model with the number of elements of 70740 were only 7% different, which indicates that the convergence of the grid was very good, in order to ensure the calculation efficiency and calculation accuracy, the meshing scheme with the number of elements of 17290 was selected.

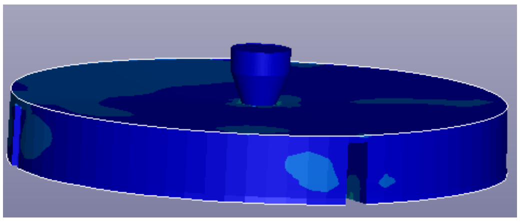
NUMERICAL SIMULATION RESULTS

Crack propagation during model ice failure

By observing the bottom surface of the model ice, it was found that the model ice started to crack from the center of the bottom surface, and the crack extended along the radius direction to the bottom surface boundary, and then extended along the thickness direction to the top surface until it completely failed, as shown in Fig. 4. It can be seen from the failure process of the model ice that the flexural failure of the model ice was essentially the tensile failure of the bottom surface of the model ice, which was consistent with the flexural failure of the sea ice proposed by Lainey (1984), indicating that the numerical model of the model ice can better reflect the characteristics of ice materials.



(a) start (b) develop

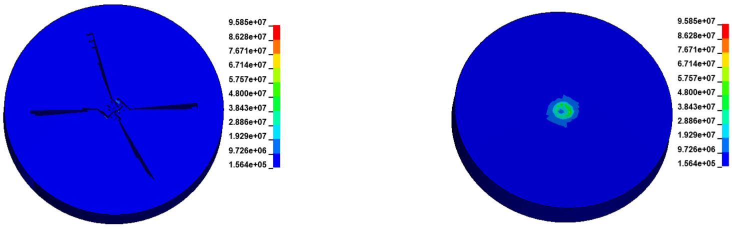


(c) end

Figure 4. Disk model crack propagation

Stress distribution of disk model in failure

This section only studies the stress distribution of the model ice at the time of cracking, and the stress distribution cloud at the time of cracking is shown in Figure 5. It can be seen from Figure 5 that the stress on the top surface was about 5 times the stress on the bottom surface, but model ice is a brittle material, and according to the theory of plate and shell mechanics, the compressive strength of brittle materials is usually several times the tensile strength, so the failure usually occurred at the stretch of the bottom surface.



(a) bottom surface (b) top surface

Figure 5. Stress distribution of disk model in failure

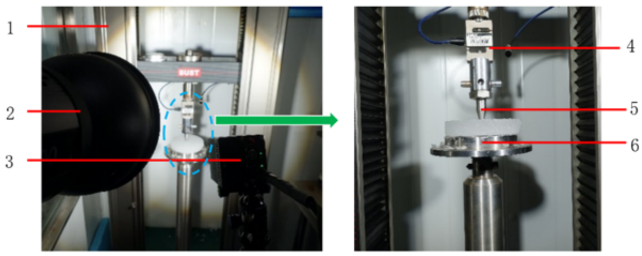
VERIFICATION OF NUMERICAL SIMULATION RESULTS

In the CSSRC SIMB (Fig. 6), the columnar saline model ice (-0.8℃) was made to carry out circular plate center loading tests, and the test results were used to verify the numerical simulation results. This section mainly verifies the numerical simulation results from three aspects: force-time curve, failure phenomenon and stress peak, based on the actual test results.

Figure 6. Interior scene of CSSRC SIMB

Circular plate center loading tests

The disc specimen required for the test was drilled from a flat ice surface with a drill bit. The diameter of the drilled disc specimen was 140 mm, and the thickness of the disc was 20 mm. After sampling, the test operation was carried out in the cryogenic laboratory next to the basin, and the total arrangement of the test was shown in Fig. 7. A sensor was fixed to the upper end of the cone indenter, the model ice was placed on the annular support platform, and the lower end of the platform was connected to the universal testing machine. During the test, the indenter applied a downward load on the top surface of the disc ice specimen at a loading speed of 2.5 mm/s until the ice specimen was bending failure (Tian,2021), and then the force on the ice specimen was recorded.



1-testing machine; 2-spotlight; 3-high speed cameras; 4-load cell; 5-frustum of a cone indenter; 6-annular support platform

Figure 7. Test device layout drawing

Comparison of force-time curve

The numerically calculated force-time curve was compared with the model ice mechanics test force-time curve, and the results were shown in Fig. 8. During the bending process of the ice specimen, both force-time curve showed linear changes without an obvious yield stage, and the failure mode of the ice specimen was an obvious brittle failure. The peak force of the two was similar, and the loading time difference was 0.01s, so the rationality of the calculation model can be verified from the changing trend of the force-time curve.

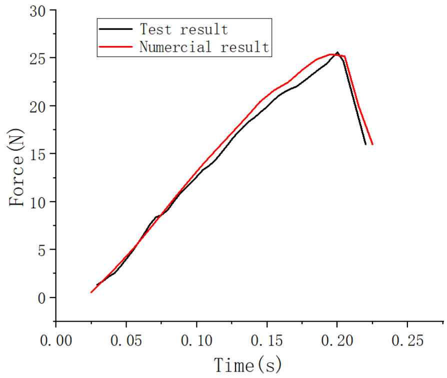


Figure 8. Comparison of force-time curve between numerical calculation and mechanic test

Comparison of damage phenomenon

The numerical calculation of the damage phenomenon of the model ice was compared with the damage phenomenon of the model ice captured by the high-speed camera, and the results are shown in Fig 9. When the ice specimen failed, under the action of the cone indenter, there was a significant deflection change at the center position of the model ice, and the crack propagation and the defects in the thickness direction were more consistent, so the rationality of the calculation model can be verified from the comparison of failure phenomena.

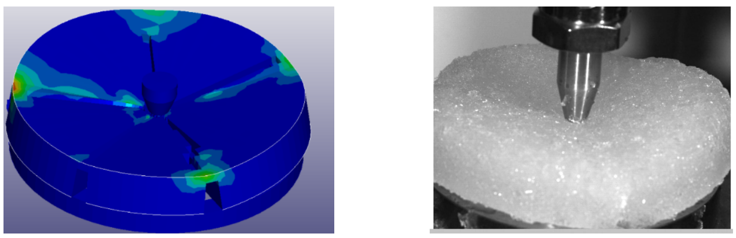


Figure 9. Comparison of numerical calculation and mechanics test failure phenomenon

Comparison of failure stress

In the circular plate test, the failure stress of the model ice was obtained by the relevant calculation formula. According to the theory of plates and shells, the maximum tensile stress in the disc, i.e., the flexural strength, σ_f is determined using Eq. (11).

$$\sigma_f = \frac{3F}{8\pi h^2}\left[4-(1-v)\left(\frac{r}{R}\right)^2-4(1+v)\ln\left(\frac{r}{R}\right)\right] \quad (11)$$

Where F represents the total load $\pi r^2 q$, h is the thickness of the disc ice specimen, r is the radius of the cone indenter loading area, and R is the radius of the disc ice specimen. Besides, ν is the Poisson's ratio, setting as 0.33 according to Timco and Weeks(2010). The flexural strength of the model ice is 88.29 kPa by formula (11).

The bottom surface center element of the model ice numerical model was post-processed and analyzed, and the stress time curve of the element was shown in Fig. 10. The numerical solution calculation result was 86.34kPa, indicating that the calculation accuracy of the numerical model was reliable.

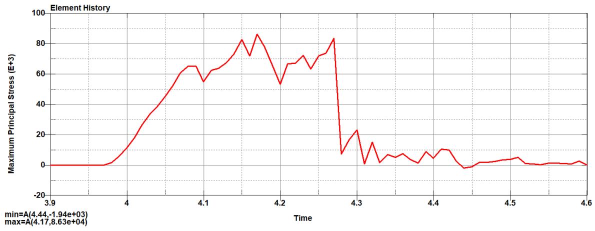


Figure 10. Principal stress-time curve of the central element on the bottom surface of ice

CONCLUSIONS

In this work, a numerical model of circular plate center loading tests of the model ice was established using the finite element software LS-DYNA, the accuracy of the material model was verified by the three-point bending test of the model ice, and the influence of the number of meshes on the calculation accuracy of the numerical model was analyzed. At the same time, the calculation results were checked by the test data in the circular plate center loading tests, which ensured the reliability of the numerical calculation model. Through this numerical model, the crack propagation law and stress distribution of the model ice flexural fracture failure were found. The main conclusions are as follows:

(1) When the cone indenter applied a load downward to the top surface of the ice specimen at a constant loading speed, the model ice began to crack from the center of the bottom surface, and the crack extended along the radius direction to the lower surface boundary, and then extended along the thickness direction to the top surface until complete failure.

(2) It can be seen from the stress distribution cloud of the model ice at the time of cracking that the compressive stress on the top surface was about 5 times greater than the tensile stress on the lower surface, but the model ice was a brittle material, and its compressive strength was usually more than 5 times than the tensile strength, so the failure occurred at the stretch of the bottom surface.

This paper provided a feasible means for predicting the mechanical properties of model ice, and then established a preliminary foundation for the further research of the mechanism of ice loading under the vertical interaction between the structure and the ice cover. In addition, the internal structure of the model ice will continue to be further studied, and the simulation of the anisotropic structure of the model ice will be realized by combining LS-DYNA.

ACKNOWLEDGEMENTS

The study presented in this paper is part of a research project financially supported by the National Natural Science Foundation of China (Grant No.52101331,52192690,52192694) and Ministry of Industry and Information Technology of China (No. [2021]342).

REFERENCES

Gang X H, Tian Y K, Yu C G., 2021. Numerical simulation analysis of flexural strength of columnar saline ice model[J]. *Chinese Journal of Ship Research*, 16(5): 143–149.

Guo T T, Zhang A F, Yu B X.,2021. Underwater collision simulation of the pressure hull with spherical head based on LS-DYNA. *Journal of Ship Mechanics.* 25(02):210-219.

Herrnring H, Ehlers S., 2022. A Finite Element Model for Compressive Ice Loads Based on a Mohr-Coulomb Material and the Node Splitting Technique[J]. *Journal of Offshore Mechanics and Arctic Engineering*, 144(2).

Karr, D., Choi, K., 1989. A three-dimensional constitutive damage model for polycrystalline ice. *Mechanics of Materials.* 8 (1), 55–66.

Lainey L., T. Tinawi., 1984. The mechanical properties of sea ice a compilation of available data. *Canadian journal of Civil Engineering*, 11(4), 884~923.

Li Y C., 2008. *ANSYS 11.0/LS-DYNA Fundamentals Theory and Engineering Practice*. China Water & Power Press: Beijing.

Li J N., 2020.*Study on Hydrodynamic Effects on Ice-Structure Interaction*. Dalian University of Technology.

Qian Y.,2020. *Study on the calculation method for the ice-load of vertical ice-breaking*. Harbin Engineering University.

Timoshenko, S., Woinowsky-Krieger, S., 1959. *Theory of plates and shells.* 2nd ed., McGraw-Hill, New York, USA.

Timco G W, Weeks W F., 2010. A review of the engineering properties of sea ice[J]. *Cold regions science and technology*, 60(2): 107-129.

Tian, Y k, Ji S O, Wang Y H., 2021. Research on sea ice simulation and measurement in small ice model basin of CSSRC[J]. *MARINE ENVIRONMENTAL SCIENCE*, 40(02):277-286.

Von Bock und Polach R B, Ehlers S., 2013.Model scale ice—Part B: Numerical model[J]. *Cold Regions Science and Technology,* 94: 53-60.

Wang C H, Wang J A, Wang C., 2021.Research on vertical upward water breakthrough of cyl inder based on s-ale method. *Chinese Journal of Theoretical and Applied Mechanics*. 53(11):3110-3123.

Zhao H O.2003. *LS-DYNA Dynamic Analysis Guide*. The Publishing House of Ordnance Industry: Beijing.

Zhao W, Tian Y, Yu C., 2022. Experimental Investigation on Breaking Strength of Model Ice with Circular Ice Plate Indentation Tests. *The 32nd International Ocean and Polar Engineering Conference.*