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Numerical Simulation of Icebreaker Sailing Through the Level Ice Region by Peridynamics Method

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ABSTRACT

With the global climate change, the development of polar resources has become an international hot issue. As the core equipment of the polar strategy, the icebreaker provides a key guarantee for this problem. However, the icebreaker faces challenges such as structural safety risks, so the ice load is very worthy of attention. The Peridynamics (PD) method is used to simulate the sailing process of the icebreaker in the level ice region. The formation and evolution process of ice cracks are concerned, and the time history of the ice load under the change of key parameters is recorded.

KEY WORDS: Peidynamics; ice load; ice crack; ice-structure interaction.

INTRODUCTION

With the increase of global warming and resource demand, the strategic value of the polar region is increasing rapidly. As the main polar strategic equipment, icebreaker has important economic, military and scientific research value. It not only provides a reliable guarantee for the development of Arctic resources and alleviates the shortage of global resources, but also enhances the national polar military presence and ensures strategic security interests. It also promotes global trade cooperation and economic development by opening up Arctic waterways. The safety of the structure during sailing will be potentially threatened by the ice load on the icebreaker, which is also a key factor affecting the icebreaking performance. At the same time, the generation and propagation of ice cracks during the ice breaking process are random, which depends on the material properties and the complex fracture mechanism of ice. Therefore, the crack generation and ice load characteristics of the icebreaker during sailing have far-reaching research significance and broad research prospects.

Due to the limitation of consumables and cost, numerical simulation is still dominant in the study of icebreaking performance of the icebreaker. At present, many numerical methods have been applied to the study of icebreakers, which are roughly divided into grid-based and particle-based methods according to the description of ice materials. Kim et al. (2024) adopted the hydrodynamic plug-in HydroQus based on ABAQUS to simulate the icebreaking process of Araon, and obtained a very accurate ship motion response. In the simulation, the hydrodynamic force is applied to the ice sheet and broken ice. The influence of hydrodynamic force on ice resistance is analyzed through the breaking process of ice sheet. Based on cohesive element method, Xiao et al. (2025) established a numerical simulation model to simulate the process ship-ice collision, which was validated by in-situ data from the Arctic expedition and statistical analysis. The collision phenomenon and load statistical characteristics under different working conditions such as ship speed and ice thickness are analyzed.

In addition to grid-based methods, particle-based methods are also widely used in the study of icebreakers. Based on the moving particle semi-implicit (MPS) method, Ren and Park (2023) conducted a numerical simulation of the ice resistance and near-field and far-field cracks during continuous icebreaking process of the icebreaker. Different from the simple particle-based method, the hull is represented by a polygon, and the ice is represented by a particle. The ice before fracture is assumed to be a linear elastic material, and the maximum tensile stress theory is used as the fracture criterion. Chen et al. (2023) proposed a method to simulate the change of sea ice bending strength by changing the parameters of sea ice material model, and realized the influence analysis of sea ice resistance during the horizontal navigation of icebreakers. It was proved that the method can better reflect the influence of sea ice bending strength on sea ice resistance.

As a mainstream particle method, the application of discrete element method (DEM) in simulation of ice can more accurately represent the shape of ice particles and material discontinuity, making it an effective numerical tool to describe ice dynamics. Liu and Ji (2022) conducted a comparative study of the numerical models based on sphere-based DEM (SDEM) and dilated-polyhedron-based DEM (DPDEM) in describing the ice plate. The icebreaking processes of icebreaker and ice-going cargo ship were simulated and compared, including average ice resistance and computational efficiency. A bond-failure model considering stiffness softening and energy release was used to simulate the breaking process of ice. Also based on the DPDEM model, Wang et al. (2024) conducted the simulation of icebreaking process of the self-propelled ice-resistant platform (IRSPP) for floating ice. The translation and rotation of six degrees of freedom of the structure are considered. The time history of structural ice force, ice heeling moment and platform motion response under different floating ice thickness is studied, while the influence of sea ice conditions on ice load and the value of ice tilt moment is analyzed. Liu et al. (2026) applied the DEM model to simulate the ship-ice interaction in horizontal ice of different scales, which provided an applicable reference for the numerical simulation of ship-ice collisions of different scales. The applicability of the similarity principle of Froude number and Cauchy number is investigated by numerical examples. The calculated results are compared with Lindqvist and Riska empirical formulas.

In recent years, PD has been favored by many scholars due to its advantages in simulating the damage process of ice. The generation and propagation of cracks are naturally obtained, and there is no need to set additional criteria for crack propagation, pre-existing crack paths, or crack branching. PD has made good progress in the research fields of ice-structure interaction, propeller milling process, underwater explosion ice breaking and so on. For ice-ship interaction, Liu et al. (2018) applied the bond-based peridynamics (BB-PD) method to simulate the ship-ice interaction process and calculated the ice load. The ice-material characteristics, ice-gravel model and ship-ice contact model in the calculation program were focused. Zhang et al. (2021) applied a more complex dynamic model based on the ordinary state-based peridynamics (OSB-PD) to establish the constitutive relationship of ice to study the ice-ship interaction process. In the simulation, ice was simulated as an isotropic homogeneous elastic material. Based on the particle pairing algorithm, OSB-PD structure optimization method and MPI parallel algorithm, the calculation ability of the ship-ice interaction model is further improved (Wang et al., 2023). PD can also be coupled with other methods to improve applicability. Xiong et al. (2026) combined BB-PD with finite element method (FEM) to establish a fast numerical model for ice-ship interaction. The BB-PD method simulates the crack-prone area, while the FEM deals with the conventional dynamics of the intact area. It has been well applied in the simulation of ice-ship interaction. Compared with the pure PD method, the computational efficiency of the coupled model is improved by 42.7 %. Although the above methods have been relatively mature in the study of ice-ship interaction and ice load calculation, there are few studies on crack generation and propagation.

In this paper, the BB-PD method is used to establish the numerical model of the ice-ship interaction on the basis of the open-source software LAMMPS. The accuracy of the numerical model is verified based on the three-point bending test of ice beam. Furthermore, the simulation of interaction between ice and cylindrical structure is conducted. Based on the above results, the numerical simulation of the ice-breaking process of an icebreaker sailing through the level ice region is carried out, in which the effect of ice thickness on ice load is considered.

NUMERICAL METHOD

Motion Equation

PD discretizes the research objectives in the computational domain into a finite number of material points. The interaction between these material points is not limited to directly adjacent points, but also forms material point pairs that interact with other material points within a specific neighborhood range, which is called horizon ($R = \delta$). Each material point has a certain volume and mass. In the theory of BB-PD, the equations of motions for any material point pairs within the horizon can be written as follows:

$$\rho\ddot{\boldsymbol{u}}(\boldsymbol{x},t) = \int_{H_x} \boldsymbol{f}(\boldsymbol{u}(\boldsymbol{x}',t)-\boldsymbol{u}(\boldsymbol{x},t),\boldsymbol{x}'-\boldsymbol{x})dV_{x'} + \boldsymbol{b}(\boldsymbol{x},t) \tag{1}$$

where, ρ represents the density; H_x represents the collection of other material points within the horizon of the material point $\boldsymbol{x}$, $H_x = \{\boldsymbol{x}' \in R : \|\boldsymbol{x}'-\boldsymbol{x}\| < \delta\}$, δ is the radius of the horizon; $\ddot{\boldsymbol{u}}$ represents the acceleration vector; $\boldsymbol{u}$ represents the displacement vector; $\boldsymbol{f}$ denotes the constitutive force of the material points $\boldsymbol{x}$ and $\boldsymbol{x}'$ at time t; $V_{x'}$ is the volume of the material point $\boldsymbol{x}'$; $\boldsymbol{b}$ is the external force.

Constitutive Relation

To describe the constitutive relations between material points within the horizon, $\boldsymbol{\xi} = \boldsymbol{x}'-\boldsymbol{x}$ and $\boldsymbol{\eta} = \boldsymbol{u}(\boldsymbol{x}',t)-\boldsymbol{u}(\boldsymbol{x},t)$ are defined as the relative position and the relative displacement vector of the material points $\boldsymbol{x}$ and $\boldsymbol{x}'$ at time t, where $\boldsymbol{u}$ represents the position vector. In the present work, the prototype microelastic brittle (PMB) model proposed by Silling et al. (2005) is adpoted to describe the constitutive relationship of ice sheet, which is considered to be isotropic in the initial state. the pairwise force function between material point pairs can be expressed as follows:

$$\boldsymbol{f}(\boldsymbol{\eta},\boldsymbol{\xi}) = g(\boldsymbol{\eta},\boldsymbol{\xi})\frac{\boldsymbol{\eta}+\boldsymbol{\xi}}{|\boldsymbol{\eta}+\boldsymbol{\xi}|} \tag{2}$$

$$g(\boldsymbol{\eta},\boldsymbol{\xi}) = \begin{cases} cs\mu(t,\boldsymbol{\eta},\boldsymbol{\xi}), & |\boldsymbol{\xi}| < \delta \\ 0, & |\boldsymbol{\xi}| > \delta \end{cases} \tag{3}$$

where c represents the bond constant; s represents the bond stretch between the material points. They can be expressed as follows:

$$c = \frac{18k}{\pi\delta^4} = \frac{6E}{\pi\delta^4(1-2\nu)} \tag{4}$$

$$s = \frac{|\boldsymbol{\eta}+\boldsymbol{\xi}|-|\boldsymbol{\xi}|}{|\boldsymbol{\xi}|} \tag{5}$$

where k represents the bulk modulus; E represents the elastic modulus; ν represents the Poisson's ratio, which is 0.25 in the three-dimensional simulation of BB-PD.

Breaking Criterion

To describe the ice breaking process caused by ice-ship interaction, the time-dependent breaking criterion function introduced in Eq. 3 can be expressed as follows:

$$\mu(t,\boldsymbol{\eta},\boldsymbol{\xi}) = \begin{cases} 1 & \text{if } s(t',\boldsymbol{\xi}) < s_0 \quad \text{for all} \quad 0 \le t' \le t, \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

where s_0 represents the critical stretch for bond breaking, which means that when the bond between any pair of material points is stretched beyond a critical value, there is no bond force between this pair of material points. The critical stretch s_0 can be written as follows:

$$s_0 = \sqrt{\frac{10G_0}{\pi c\delta^5}} = \sqrt{\frac{5G_0}{9k\delta}} \tag{7}$$

where G_0 is the critical energy release rate of ice, also known as fracture energy.

In view of the feature of the bond breaking, the following damage index is introduced to describe the local damage degree of the material point:

$$\varphi(\boldsymbol{x},t)=1-\frac{\int_{H_x}\mu(\boldsymbol{x},t,\boldsymbol{\xi})dV_{\xi}}{\int_{H_x}dV_{\xi}} \tag{8}$$

where $\varphi\in[0,1]$. Clearly, the above damage index indicates the ratio of the breaking bond to all the bonds of material point within the horizon range.

RESULTS AND DISCUSSIONS

Three-point Bending Test of Ice Beam

To demonstrate the accuracy of the present BB-PD model in simulating the breaking process of ice, the simulation of the three-point bending test of an ice beam is performed. The present results are compared with the numerical and experimental results obtained by Xue et al (2018).

The size settings in the experiment are used to establish the numerical model, which are shown in Fig.1. The size parameters of ice beam are L = 0.65 m, W = 0.07 m and H = 0.07 m, respectively. Located in the center of the ice beam, the upper support moves downward at a constant speed of 0.005 m/s, providing continuous force. Two lower supports are symmetrically distributed relative to ice beam, which are fixed and regarded as rigid bodies. The spacing between lower supports is L_0 = 0.65 m. The parameters of ice beam in this simulation are set as shown in Table 1. The time step is set to 1.0×10^{-6} s. The particle spacing is dx = 0.005 m. The radius of the horizon $\delta = 3.015dx$, which will be used in the simulation later in this paper.

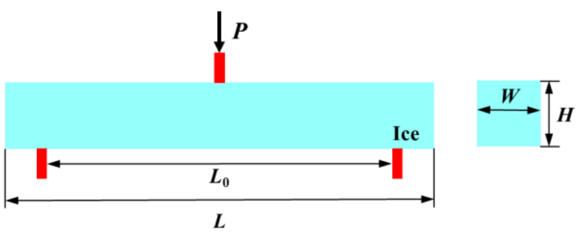
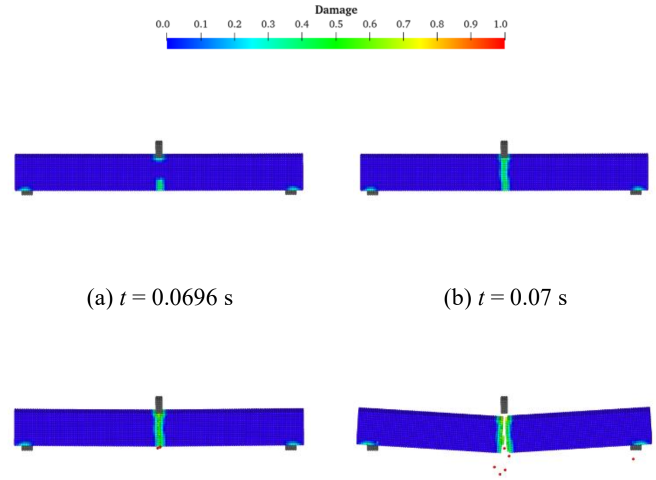


Fig.1 Schematic diagram of the three-point bending test

Table 1. Parameters of ice beam in simulation

Young 's Modulus	Density	Critical Stretch	Critical Energy Release Rate
6.83 GPa	900 kg/m^3	0.00039	19 J/m^2

In the numerical simulation, due to the continuous movement of the upper support, the ice beam shows a state where the bottom is stretched and the top is compressed. When the breaking occurs, the crack first occurs on the lower surface and forms a cross section in a short time. The whole breaking process is shown in Fig.2. It can be seen that cracks initiate from the bottom at the midspan of the ice, and the ice is eventually split into two parts. The time history curves of ice load obtained by different methods are presented in Fig.3. The horizontal axis is the displacement of the upper support in the vertical direction. The current PD result is in good agreement with the results obtained by the other two methods, while the peak load 1168 N obtained by present BB-PD is also very close to the experimental value 1128 N.



(a) t = 0.0696 s (b) t = 0.07 s

(c) t = 0.08 s (d) t = 0.12 s

Fig.2 Breaking process of ice beam

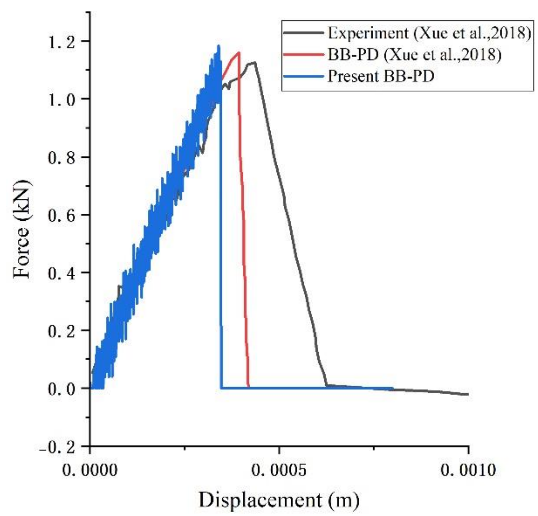


Fig.3 Time history curves of ice load

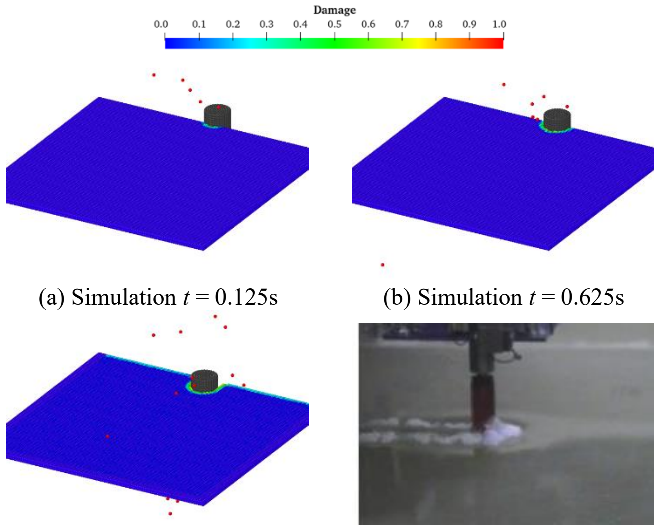
Interaction between Ice and Cylindrical Structure

On the basis of the above validation, the numerical simulation of horizontal ice breaking of cylindrical structure is carried out in this section. The cylinder is regarded as a rigid structure with a diameter of 0.05. The size parameters of ice sheet are L = 0.5 m, W = 0.5 m and H = 0.005 m, respectively. The parameters of ice sheet are set as shown in Table 2. The cylinder is continuously in contact with the ice sheet at a speed of 0.05 m/s. In order to restore the laboratory ice pool conditions, the left and right ends and the distal end of the ice sheet are fixed. Hydrodynamic force is not considered in this simulation. The particle spacing is dx = 0.005 m, while the time step is set to 1.25×10^{-6} s.

Table 2. Parameters of ice beam in simulation

Young 's Modulus	Density	Critical Stretch	Critical Energy Release Rate
1.8 GPa	900 kg/m^3	0.00075	19 J/m^2

As is shown in Fig.4, in the process of ice-structure interaction, an ice channel is opened up in the middle of the ice sheet, which is similar to the phenomenon observed in the experiment (Sodhi and Morris, 1984). Spattered particles represent the broken ice particles under the action of the structure. The time history curve of ice load in this process is presented in Fig.5. It can be seen that the curve presents the characteristics of violent oscillation as a whole. This is because under the uniform collision of the structure, the ice in the direction of motion will cause local damage, and the next small part of the time will not hinder the structure movement. Here only the force parallel to the direction of motion is given, and the force in other directions is relatively negligible.



(a) Simulation t = 0.125s (b) Simulation t = 0.625s

(c) Simulation t = 1.25s (d) Experiment

Fig.4 Icebreaking process of cylindrical structure

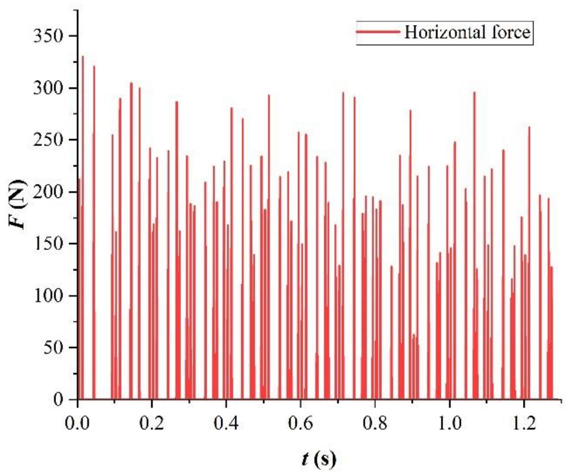


Fig.5 Ice load curve of cylindrical structure

Full-scale Icebreaker Sailing Through the Level Ice Region

The accuracy and feasibility of the PD model have been verified through above simulations. In this section, the PD model will be used to simulate the ice-breaking process of a full-scale icebreaker sailing through the level ice region, focusing on the characteristics of ice cracks and ice load. The prototype of the icebreaker is Russian Arktika, with the length overall of 173.3 m and the moulded breadth of 34.0 m.

As is shown in Fig.6. the numerical model is simplified as the interaction between the icebreaker and the ice sheet. The size parameters of ice sheet are L = 200 m, W = 130 m and H = 1 m, respectively. The sailing velocity of the icebreaker is set to v = 2.572 m/s. The particle spacing is dx = 0.5 m, while the time step is set to 5×10^{-4} s. The boundary conditions are the same as the previous simulation of cylinder. Other parameters in simulation are given in Table.3.

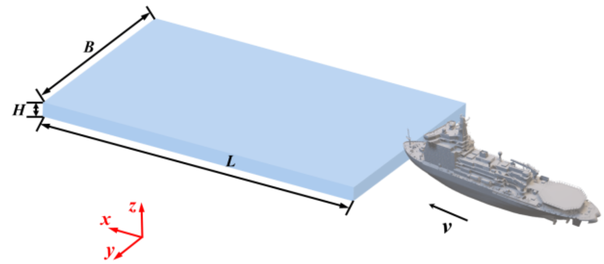
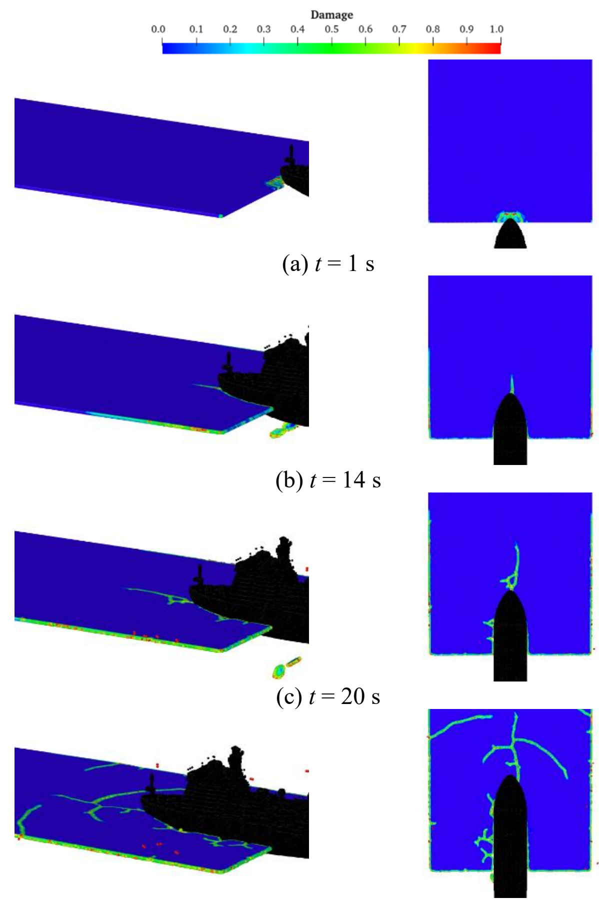


Fig.6 Schematic diagram of icebreaker sailing through the level ice region

Table 3. Parameters of ice sheet

Young 's Modulus	Density	Critical Stretch	Critical Energy Release Rate
5 GPa	900 kg/m^3	0.00006	33 J/m^2



(a) t = 1 s

(b) t = 14 s

(c) t = 20 s

(d) t = 30 s

Fig.7 Icebreaking process of icebreaker

The simulation of the icebreaker sailing through the level ice region is shown in Fig.7, which is divided into two forms: three-dimensional view and the top view. The formation of radial cracks is mainly along the direction of ship motion, and circumferential cracks will be formed in the collision area. The phenomenon that the crack extends to the boundary is also due to the limitation of the calculation area. Time history curve of ice load in icebreaking process is presented in Fig.8. It can be seen that the ice load in the process of ice-ship contact can be divided into three stages. In the first stage, the bow hits the horizontal ice, and the load peak appears at this time, accompanied by local damage. During the second stage, the bow continued to break the ice, accompanied by the oscillation of the load, similar to the interaction between the cylinder and ice mentioned above. In the third stage, most of the hull entered the ice area, causing large-scale damage.

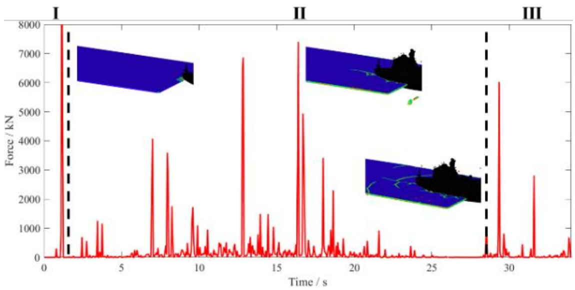
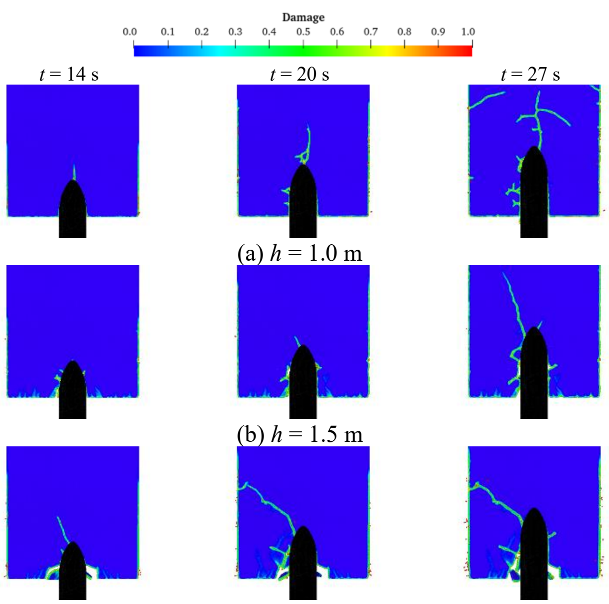


Fig.8 Ice load curve of icebreaker

Influence of ice thickness

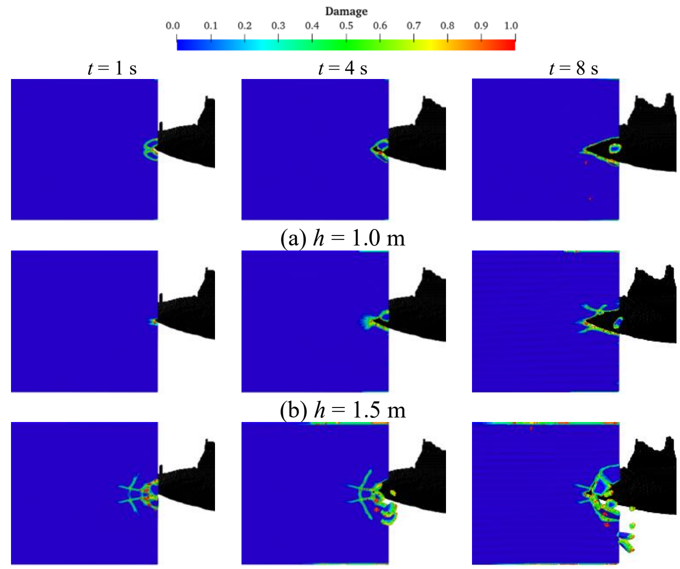
The thickness of ice has a great influence on the ice load and crack characteristics. The numerical results of icebreaking process from the perspective of top-down view and low-angle view are shown in Figs.9 and Figs.10, respectively. As is shown in Fig.9, the cracks formed in the thin ice area are mainly distributed along the movement direction of the icebreaker, and rarely extend to the boundary. When the ice has thickened, the ice sheet becomes more difficult to break and tends to be locally damaged, and the cracks in front of the bow are more likely to extend to the ice boundary.



(c) h = 2.0 m

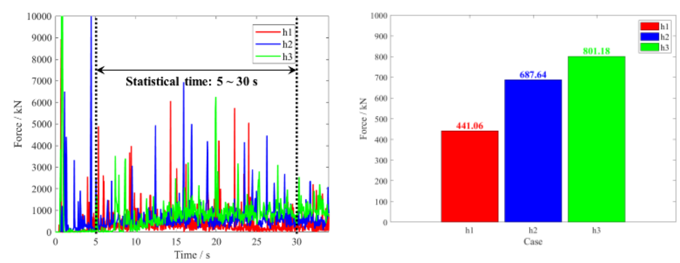
Fig.9 Icebreaking process with different ice thickness (top-down view)

In the early stage of the interaction between the icebreaker and the ice, when the icebreaker sails through the thicker ice area, due to the collision and extrusion of the bow and the ice plate, there will be many shedding ice under the bow. The occurrence of broken ice is related to the thickness of flat ice. The thicker the ice layer, the more obvious the phenomenon of broken ice. The characteristics of ice load curve are given in Fig.11, in which h1, h2 and h3 are equal to the ice thickness of 1 m, 2 m and 3 m respectively. The average ice load under different ice thickness is calculated by taking the statistical time of 5 - 30 s. It is certain that the ice resistance increases with the increase of ice thickness.



(c) h = 2.0 m

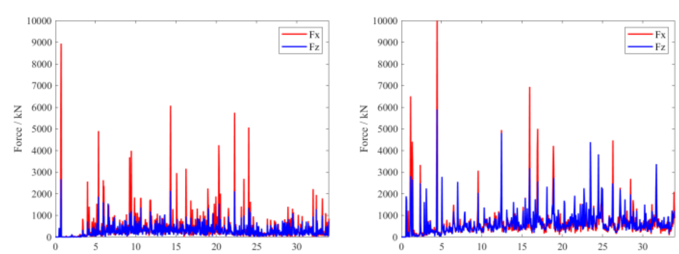
Fig.10 Icebreaking process with different ice thickness (low-angle view)



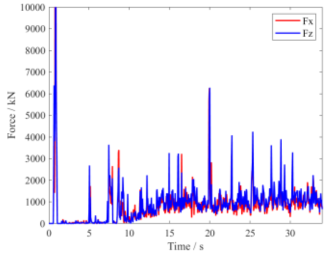
(a) Time history of ice load (b) Average ice load

Fig.11 The characteristics of ice load curve of icebreaker

Fig.12 also shows the comparison of ice load components. It can be seen that as the ice layer thickens, the proportion of vertical load on the ship will increase. This is because if the thick ice is destroyed, the ship needs more vertical force to crush the ice. Table 4 confirms this phenomenon more intuitively by the ratio of vertical load to horizontal load.



(a) h = 1.0 m (b) h = 1.5 m



(c) $h = 2.0$ m

Fig.12 Comparison of ice load components with different ice thickness

Table 4. Ratio of vertical load relative to horizontal load

Case	Ratio
$h = 1.0$ m	0.7224
$h = 1.5$ m	0.9926
$h = 2.0$ m	1.0996

CONCLUSIONS

In this paper, a numerical solution of the BB-PD method is established for the problem of ice-ship interaction as well as ice-structure interaction. The whole ice-breaking process is restored by numerical simulation, focusing on the generation and propagation of cracks and the calculation and characteristics of ice load. The following main conclusions can be drawn:

Through comparison with the experiment or previous numerical results in the simulation of three-point bending test of an ice beam, the accuracy of the numerical model based on the BBPD method is validated. The BB-PD numerical model is further extended to the application of the interaction between cylinder and ice, in which the icebreaking process is similar to that in the experiment.

The present BB-PD model is capable to simulate the icebreaking process of icebreaker. The fracture behavior of the icebreaker during navigation is reasonable. In this study, the icebreaking process can be roughly divided into three stages: bow icebreaking stage, continuous icebreaking stage and extreme large-scale damage. The ice thickness has a dramatic effect on the ice load. The thin ice area is more likely to form large-scale damage, and the cracks in the thick ice area are easy to extend to the boundary. When sailing in the thick ice area, the falling of broken ice can be observed. The increase of ice thickness increases the proportion of average ice load and vertical load.

This study is helpful to understand the breaking process of ice and the characteristics of ice load during the ice-ship interaction. However, there are still many deficiencies in the research, such as ignoring the hydrodynamic effect, ignoring the change of boundary conditions, limiting the degree of freedom of ship motion, etc. Future research will focus on and try to solve complex ice-water-structure coupling problems.

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