

Numerical Simulation of Ship Collision with Rafted Ice Based on Cohesive Element Method

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Abstract

The gradual increase in shipping and drilling activities in the Arctic regions has resulted in the increased importance of studying the structural safety of polar ships in various ice conditions. Rafted ice refers to a type of accumulated and overlapped sea ice; it is driven by external forces, such as wind and waves, and may exert high loads on ships and threaten their structural safety. Therefore, the properties of rafted ice and the construction of numerical models should be studied before exploring the interaction and collision between ships and rafted ice. Based on the nonlinear finite-element method, this paper introduces the cohesive element model for the simulation of rafted ice. The interaction between ships and rafted ice is studied, and the ice force of the hull is obtained. Numerical simulation results are compared with model test findings, and the effectiveness of the cohesive element method in the construction of the model of rafted ice materials is verified. On this basis, a multilayer rafted ice model is constructed, and its interaction with the ship is studied. The research unveils that rafted ice parts impede crack generation and slow down crack propagation to a certain extent.

Keywords Cohesive element method; Rafted ice; Rafting length; Ship-ice collisions; Finite element model; Numerical simulation

1 Introduction

The existence of rafted ice in polar natural ice conditions cannot be ignored. Driven by external forces, such as wind and waves, sea ice continually breaks and overlaps to form widespread rafted ice in the ice zone (Figure 1). Scholars have conducted a series of studies on this type of ice. On the one hand, concerns regarding the structure of rafted ice, including single-layer thickness, the number of layers, rafting length, etc., have emerged. Kovacs (1970) observed that rafted ice is likely to form in two-level ice with the same thickness and may exist in level ice of different thicknesses. Parmeter (1974) developed a mechanical rafted ice model and observed that the extreme ice thickness of

rafted ice without fracture was approximately 0.17 m. The overlap thickness of the Bohai Sea is usually less than 1 m (Yang et al., 1991). Melling et al. (1993) surveyed sea ice at 120 km of Tuktoyaktuk Peninsula southeast of the Arctic Polt Sea and observed rafted ice with up to four layers of overlap and measuring approximately 6 m thick in total. Worby et al. (1996) revealed that the average thickness of single-layer rafted ice can reach 0.9 m, and up to eight rafted layers can form. According to Ji et al. (2001), the buckling conditions of sea ice determine the rafting length of rafted ice. Under the same ice thickness, the rafting length of one-dimensional (1D) rafted ice is approximately twice that of finger-shaped rafted ice.

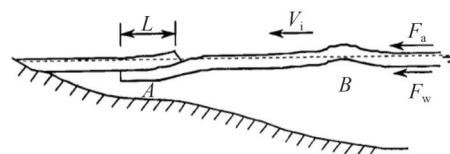


Figure 1 Schematic map of rafted ice formation (Ji et al., 2001)

Based on physical forms, experts further focus on the mechanical properties of rafted ice, including secondary frozen strength, average strength, etc. A field study conducted by Frederking and Timco (1984) indicated the mostly particle structure of ice crystals at the secondary freezing of rafted ice. Poplin and Wang (1994) observed a higher

Article Highlights

- Ship collision with rafted ice was simulated by using cohesive element method.
- Rafted ice material model was validated against model test.
- Crack propagation and failure process of rafted ice were obtained in the simulations.

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average strength of rafted ice than the shore ice samples. Under pure shear load, the shear strength of rafted ice is lower than that of level ice with a mostly cylindrical structure. At the University Centre in the Svalbard laboratory, Shafrova and Høyland (2007) performed a uniaxial compression experiment on frozen ice. The ice sample was precut in a 45° direction to the axis and submerged in water with secondary freezing to simulate the freezing bond between ice blocks. As the loading direction was 45° from the secondary freezing layer, the model ice broke along the freezing face. Since the precut frozen layer was parallel to the laboratory made layered freshwater ice, the freeze bond strength measured by the uniaxial compressive strength was the strength between the superposition of two flat ices. Bailey et al. (2010) developed a 1D thermal consolidation model of rafted sea ice; the model predicts the time that ice level forms rafted ice in a continuous ice layer. Chen (2019) investigated the failure mode and physical properties of rafted ice by testing sea ice from a site in Liaodong Bay of the Bohai Sea. Experiments showed that compared with level ice, columnar ice crystals caused a decrease in the compression strength and elastic–brittle transformation rate of rafted ice. Studies on the mechanical properties of rafted ice mostly focused on experiments on either real ice samples obtained from the field or refrozen ice samples in the laboratory. Numerical modeling of rafted ice and its interaction with ocean structures are insufficient and require further studies, not only to gain information on the behaviors of rafted ice but also to provide insights into potential ice-breaking methods (Yuan et al., 2022; Zhang et al., 2023; Zhou et al., 2023).

To simulate the secondary freezing strength and crack propagation behavior of rafted ice, one needs must apply an effective numerical method to simulate the fracture behavior of sea ice. The cohesive element method (CEM) has been developed over a long period and applied to fracture simulation of concrete and composite materials. CEM was initially applied to 2D crack simulation and has been extended to 3D conditions. As cohesive modeling that uses traction–separation relations (cohesive laws) can be used to describe line-like (2D) or surface-like (3D) cohesive zones, 2D and 3D studies, whose difference mainly lies between lines and surfaces, can be realized. CEM was gradually applied to the fracture and destruction simulation of 3D ice materials. Most scholars studied the collision between different ice models and various structures based on CEM, and the results show the feasibility of applying CEM in the simulation of crumbling ice accumulation and secondary destruction (Zou et al., 1996; Konuk et al., 2009; Määttä et al., 2011; Lu et al., 2012; Wang et al., 2018; Wang et al., 2019; Chen et al., 2021; Ni et al., 2022; Liu et al., 2023b).

CEM is based on finite elements and replaces the failure of the body cell with that of cohesive elements. Therefore, a numerical model of rafted ice can be built using CEM.

Based on the nonlinear finite-element numerical method and cohesive element model, in this paper, a numerical model of rafted ice is built, and the validity of rafted ice materials is verified. Numerical simulation of the collision between a ship and rafted ice is performed in consideration of the effect of freezing strength and porosity of sea ice.

2 Rafting length of rafted ice

The rafting length of rafted ice is important in the study of its mechanical properties. Ji et al. (2001) analyzed the formation process of a semi-infinite long 1D rafted ice and obtained the calculation formula for the rafting length. Given the rafting lengths of sea ice in the processing of rafted extrusion damage and bending damage ($L_{\max}^{(c)}$ and $L_{\max}^{(f)}$), respectively, the calculation formulas are obtained as follows:

$$L_{\max}^{(c)} = \frac{\sigma_c}{\mu g \rho_i h_i} \quad (1)$$

$$L_{\max}^{(f)} = \frac{1}{\mu \rho_i} \left(\frac{\rho_w E h_i}{3g(1 - \nu^2)} \right)^{1/2} \quad (2)$$

In consideration of the extrusion and bending damage of sea ice, its maximum rafting length should be the minimum of $L_{\max}^{(c)}$ and $L_{\max}^{(f)}$:

$$L_{\max} = \min(L_{\max}^{(c)}, L_{\max}^{(f)}) \quad (3)$$

where σ_c refers to the uniaxial compression strength of level ice, μ indicates the friction coefficient, ρ_w corresponds to the seawater density, ρ_i represents the sea ice density, g means the gravity acceleration, E stands for the elastic modulus of sea ice, h_i is the thickness of sea ice, ν represents the Poisson's ratio of sea ice.

Based on the field test data on Bohai Sea Ice (Li et al., 2006), the proposed value for E is 1.9 GPa. According to sea ice measurements from ice stations in the Arctic in 2010–2016, the maximum vertical uniaxial compression strength of ice σ_c ranges between 2.07–3.83 MPa (Wang, 2019). The proposed value of σ_c in this paper is 2.63 MPa, which is the average of the maximum vertical uniaxial compression strength of ice in each ice station. The relationship between Poisson's ratio and the temperature of T sea ice is computed as follows (Wang, 2019):

$$\nu = 0.333 + 0.061 5e^{(T/5.48)} \quad (4)$$

where T has a value of -2.7 °C, which is the minimum temperature of ice in the central Arctic Ocean. Determined by calculations, ν has a value of 0.371. Table 1 lists all the parameters of sea ice used in this paper.

Table 1 Sea ice parameters required for rafted ice structures

Parameter	Value
Uniaxial compressive strength (MPa)	2.63
Young's modulus (GPa)	1.9
Poisson's ratio	0.371
Seawater density (kg/m ³)	1.025×10 ³
Sea ice density (kg/m ³)	0.88×10 ³
Static friction coefficient between sea ice	0.1

Previous works reported the maximum thickness of rafted sea ice. Kovacs and Sodhi (1980) predicted the maximum ice thickness in the bending damage of sea ice as follows:

$$h_{\max} \leq \frac{12\sigma_c^2(1-\nu^2)}{C_b^2\rho wgE} \quad (5)$$

where C_b refers to the boundary correction coefficient for ice displacement under different boundary conditions. C_b is also related to the ratio of the length and characteristic length of the elastic beam, which ranges between 1 and 2 under various boundary conditions. Similarly, based on elastic plate shell theory, Li et al. (2006) predicted the extreme thickness of single-layer level ice composed of multiple layers of rafted ice. When cracks are present in ice, the approximate conditions for elastic bending of a single layer of maximum ice thickness are calculated using the following equation:

$$h_{\max} < \frac{\sigma_c^2(1-\nu^2)}{0.59\rho wgE} \quad (6)$$

Meanwhile, in the absence of cracks in the ice, the approximate conditions for elastic bending of a single layer of ice having a maximum thickness are computed as follows:

$$h_{\max} < \frac{\sigma_c^2(1-\nu^2)}{5.33\rho wgE} \quad (7)$$

The maximum thickness under different conditions is obtained through the substitution of the parameters in Table 1 into the abovementioned equations. If we take C_b as 2, $h_{\max}$ from Eq. (5) has a value of 0.938 m, and the values of $h_{\max}$ from Equations (6) and (7) reach 0.53 and 0.059 m, respectively, for level ice with and without cracks. Therefore, the value of $h_{\max}$ varies widely when using different equations, and thus, the actual situation of the problem must be considered.

3 Numerical model of rafted ice

3.1 Numerical modeling

CEM is a crack simulation method that combines the

cohesion model theory and finite-element method (FEM). This method not only involves the effective crack initiation and propagation evolution of materials or structures but also avoids the problem of infinite stress at the crack tip. The cohesive force model is suitable for the study and analysis of large-scale yield deformation of materials or structures because it was developed based on the theory of elastic–plastic fracture mechanics. The model is convenient to use in the calculation of fracture problems without presetting the initial crack. In the process of fracture failure of a material or structure, despite the gradually stretching crack interface in the cohesive region, the kinematic equation of the cohesive force model shows high compatibility with the finite elements connected next to each other. Thus, CEM is an adapted method of FEM achieved via the inclusion of cohesive elements.

The cohesion model comprises two unit types: the body unit and the cohesive element, where the constitutive relationship of the former is represented by stress–strain relationship, and the constitutive relationship of the cohesive element follows the traction–separation criterion (Sun et al., 2016). The bilinear traction–separation criterion is widely applied, given its simplicity and effectiveness in general. In the bilinear tension displacement relationship, the maximum stress, critical fracture energy, and slope K of the stress rise stage are given. The value of K is generally consistent with Young's modulus (E) of the material; however, the stiffness of the original material is affected because the cohesive force element is embedded in the unit (Fan and Tadmor, 2019). The stiffness of the cohesive force element can be enhanced through the increased value of K , which reduces the loss of material stiffness in contact. The maximum stress value, fracture energy release rate, and crack cracking maximum displacement are all important parameters for describing the mechanical state of the cohesion region; the basic properties of materials can be obtained through calculations and uniaxial compression tests, etc. (Suo et al., 1992; Yang and Cox, 2005). In addition to traction law parameters on cohesion, structural thickness affects the length of the cohesive zone. With the increase in thickness, a gradual decrease occurs in the change rate of the cohesive zone length versus the increase in thickness. After the thickness has been increased to a certain value, the cohesive zone length no longer changes (Huang, 2022).

During numerical simulation, when the external force of the cohesive element reaches the maximum traction that it can withstand, the cohesive element begins to develop along the descending segment of the traction–separation criterion curve until it reaches maximum failure separation. The cohesive element is then removed from the grid.

Figure 2 shows the form of connection between the body and cohesive element in the cohesion model. Numerical simulation of the fracture process of composite materials, such as concrete and other materials, commonly uses cohesive

elements with a certain thickness. Meanwhile, in the fracture simulation of ice materials, given the lack of material of a certain thickness between the body units, the cohesive element in the level-ice cohesion model has a zero-thickness unit (Lu et al., 2014).

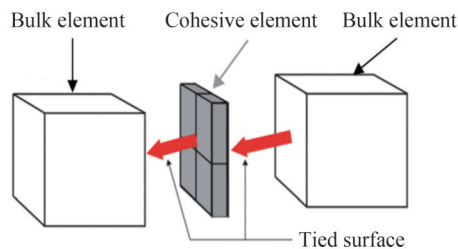


Figure 2 Connection method between the cohesive element and body unit

The cohesive element is inserted into the rafted ice numerical model to simulate ice crack expansion. Figure 3 displays the process of modeling rafted ice. First, two-level ice blocks overlap with each other, as shown in Figure 3(a), and cohesive elements are inserted between ice elements and ice layers simultaneously. Different parts possess various cohesive element parameters, which are distinguished using varied colors. In Figure 3(b), the purple cohesive element stands for the layer cohesive element, and the yellow one represents the interlayer cohesive element. The cohesive element acts as a “bonding function.” The bonding strength between ice elements and ice layers can be varied by changing the strength of various cohesive elements depending on the actual situation.

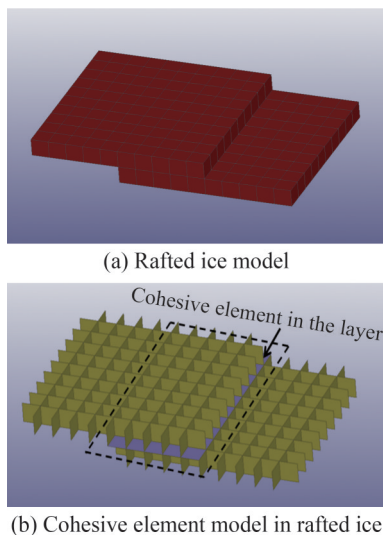


Figure 3 Construction process of rafted ice using the cohesive element model

Natural sea ice contains randomly distributed cracks, pores, and other defects. In addition, cracks are most likely to expand along the defect area, which affects the mechanical

properties and damage characteristics of level ice. The ice model with porosity aids in the simulation of the behaviors of natural sea ice. In this paper, the porosity of ice is simulated through the removal of cohesive elements rather than bulk elements. According to related studies, porosity is 2% (Li et al., 2010), and 2% cohesive elements are randomly removed. Figure 4 illustrates the deletion of partial cohesive elements in the random porosity model.

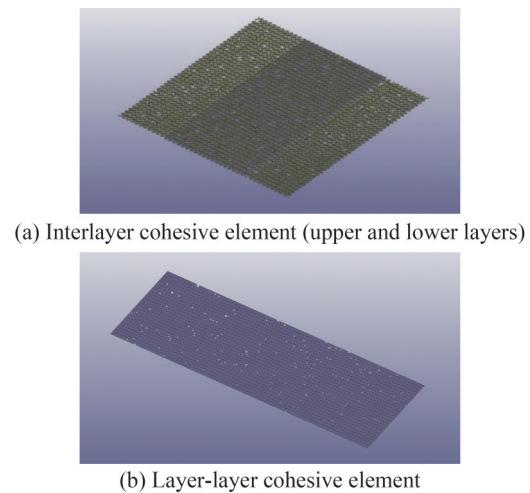


Figure 4 Cohesive element with random porosity

3.2 Validation

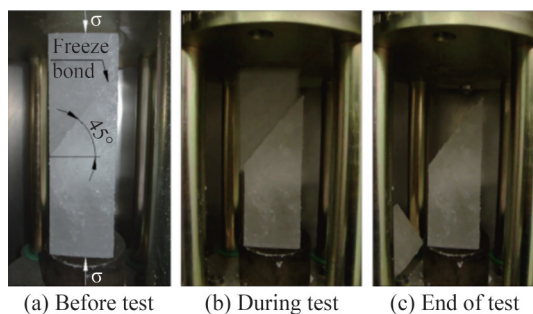
In this paper, a simulation of the mechanical properties of ice material is performed using the isotropic elastoplastic model. Table 2 shows the parameters of the ice model needed for finite element model. To validate the rafted ice model used in this paper, we compare the numerical results with experimental data from the work of Shafrova and Høyland (2007). Shafrova and Høyland (2007) conducted ice freezing strength experiment at Svalbard University Laboratory (Figure 5), in which a freshwater ice cube was cut into two parts along the 45° direction versus the axis, submerged in water, and frozen again at an average temperature of -10°C at different freezing times before the uniaxial compression test. Based on their results, we set up finite element and cohesive element numerical models with the same size as the experimental one (62 mm×62 mm×175 mm) and compare the numerical freezing strengths with experimental ones along the freezing surface after three secondary freezing time (24 h, 48 h and 60 h, respectively).

After secondary freezing, the contact surface shows a considerably lower freezing strength than the ice itself. As a result, the ice sample inevitably produces large cracks on the freezing surface when it bears the load down along the z -axis (Figure 5). Therefore, the numerical model only involves setting up the cohesive element on the freezing surface to simulate the fracture of the ice sample. The parameters of the finite element of the ice material can follow those in

Table 2 Ice material parameters

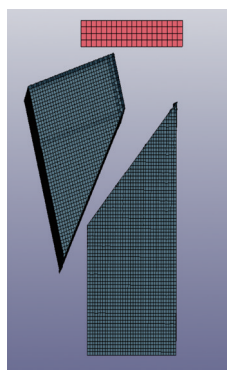
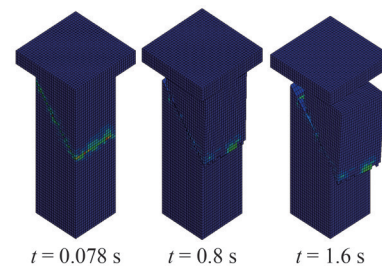
Density (kg/m ³)	Shear modulus of elasticity (GPa)	Yield stress (MPa)	Hardening modulus (GPa)	Bulk modulus (GPa)	Plastic failure strain	Cut off the pressure (MPa)
895	2.2	2.12	4.26	5.26	0.002	−4

Table 2 used in the nonlinear finite element software. In addition, for the cohesive element along the bonding surface, the energy release rate between the tangential and normal is a dominating factor that should be determined carefully, especially at different freezing periods. Through multiple groups of axial compression simulation, the parameters of the cohesive element are adjusted, and their specific values, which correspond to the working conditions of the experiment, are shown in Table 3.

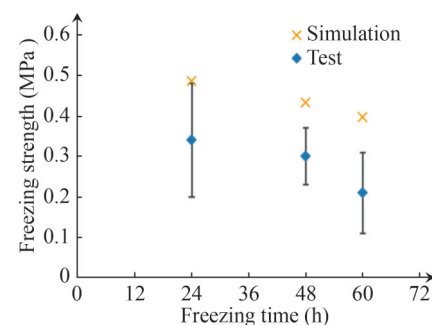
**Figure 5** Freezing strength experiment (Shafrova and Høyland 2007)**Table 3** Parameters of cohesive elements corresponding to simulated experiments

Secondary freezing time (h)	Energy release rate tangential/normal (J/m ²)	Peak load (kN)
24	6/30	65
48	10/30	65
60	12/30	65

Figure 6 provides the fractured state of the ice sample, which matches the experimental phenomenon well at the end of the numerical simulation. As displayed in Figure 7, the ice body is continuously squeezed, and stress on the slit site accumulates constantly. Then, stress reaches the allowable fracture stress value before the ice body separates and finally breaks into two sections.

**Figure 6** Schematic of ice samples during fracture**Figure 7** Diagram of ice failure stress structure

On this basis, we compare the freezing strength between numerical simulation results and experimental data (Figure 8). The numerical simulation results agree generally with experimental data and some numerical results are slightly higher than experimental findings. This outcome may be due to experimental microscopic defects, such as microcracks in secondary freezing, that easily break and lower the freezing strength. However, the simulation of micro behaviors of ice damage in numerical simulation is notably difficult.

**Figure 8** Comparison of freezing strength from simulation results and experimental data

The simulation reproduces the basic mechanical behaviors of rafted ice under external forces, which lays a foundation for the real-life collision between ships and rafted ice.

Further verification is possible through numerical simulations of the fracture generated by hydraulic pressure (Detournay, 2004; Liu et al., 2022), which will not be considered in this paper.

4 Calculation and analysis of collision between an icebreaker and rafted ice

4.1 Case study

The interaction between ice and icebreaker must be considered for the actual ice zone navigation (Sazonov and

Dobrodeev 2021; Zheng et al., 2022; Li, 2023; Liu et al., 2023a). Therefore, the collision between an icebreaker hull and rafted ice is established and studied in this paper. The ship hull is modeled using shell elements (Figure 9), and the main parameters of the icebreaker are shown in Table 4. The hull is considered a rigid body without elastic–plastic deformation. Table 5 lists the material parameters of the rigid body.

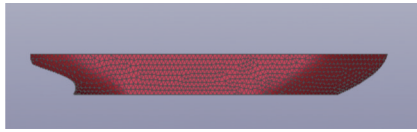


Figure 9 Finite-element model of an icebreaker

Table 4 Main parameters of the icebreaker model

Parameter	Numeric value
Overall length (m)	166
Length between perpendiculars (m)	147.2
Molded breadth (m)	22.6
Molded depth (m)	13.5
Designed draft (m)	8
Scantling Draft (m)	9
Designed displacement (t)	18 102.4
Total displacement (t)	21 025

Table 5 Parameters of rigid body materials

Density (kg/m ³)	Elastic modulus (GPa)	Poisson's ratio
7 850	210	0.3

The width of the rafted ice is nearly four times that of the ship, and its length is no less than three times the bow length, which is sufficient to cover the collision-affected area (Zhang, 2015). The width of the selected icebreaker type is 22.6 m, and that of the rafted ice is set as 80 m. The rafted ice has a total length of 80 m, of which the length of the rafting area is 40 m. The single-layer ice thickness and rafting area thickness measure 0.66 and 1.32 m, respectively. All of these dimensions follow the rules in Section 2. Figure 10 shows the schematic of rafted ice. The rafted ice is discretized in three prismatic meshes with dimensions of 1.414 m×1.414 m×2 m and a thickness of 0.66 m.

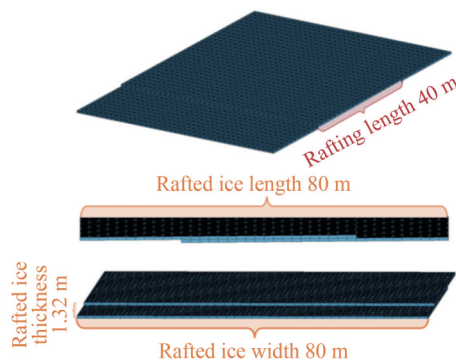


Figure 10 Schematic of rafted ice numerical model

Cohesive elements in rafted ice are constructed through the establishment of a general numerical model (Section 3.1). In detail, the generation of cohesive elements occurs during the modeling of crack propagation. Additional cohesive elements are further generated by shell-forming elements, and the original shell units are deleted. The cohesive elements exhibit a density consistent with that of ice.

As discussed in Section 3, the secondary freezing strength between rafting areas is usually lower than that within ice. The freezing strength in this rafted ice model is approximately 30% weaker than the original level of ice (Bailey et al., 2012; Zhang et al., 2023). The energy release rate of cohesion between ice sheets and ice elements varies, and the capacity release rate is an important parameter affecting the mechanical properties of cohesion (Table 6).

Table 6 Cohesive element parameters

Parameter	Interlayer	Layer–layer
Density (kg/m ³)	895	895
Energy release rate (J/m ²)	80/101.25	52/52
Tensile strength (MPa)	0.8	0.8
Shear strength (MPa)	0.9	0.9
Law of traction	Bilinear type	Bilinear type

The minimum ice-breaking capability of PC6 ice-class polar ships used in this paper can continuously break 0.7 m thick ice at a speed of at least 4 kn. To study the effect of rafting ice on ice loads and ice breaking, we consider the 4 kn icebreaker speed in the case study. For the boundary conditions of rafted ice, the edge near the icebreaker is treated as a free end, and the other three boundaries are fixed and set as nonreflecting boundary conditions. Figure 11 shows the schematic of the ship and rafted ice. In addition, a single surface erosion contact between the ship and rafted ice is considered. The dynamic friction coefficient of collision between the structure and rafted ice is set as 0.04, the static friction coefficient as 0.14, and the friction between ice elements as 0.05 (Timco and Weeks, 2010). The friction coefficient affects the friction force between ice and structure, but it has minimal influence on the cohesion model inside.



Figure 11 Schematic of the collision scenarios and boundary conditions between ships and rafted ice

The ice element is damaged during the collision between the ship and rafted ice (Figure 12). At $t = 3$ s, the icebreaker produces a distinct radial crack region close to the ship hull

during its contact with rafted ice. During the subsequent collision, the ship side continuously squeezes the rafted ice, and some broken ice pieces start to fall off from the main body of rafted ice. Then, at around $t = 11$ s, the icebreaker sails to the overlapping region, and from the effective stress of the cohesive element of ice shown in Figure 12(b), stress concentration, which is marked in circles, occurs along the lateral front edge just before the overlapping region on the rafted ice. Crack expansion continues along with the extrusion of the icebreaker into the ice. When $t = 33$ s, the ship passes through the overlap completely. The overlapping region features slightly narrower cracks than the single-layer region, which denotes that the rafting parts hinder crack generation and decrease the rate of crack propagation to a certain extent. Furthermore, ice damage is more severe along the lateral edges of overlapping regions than on other parts, which results from stress concentration in these regions, as marked by circles in Figure 12(c).

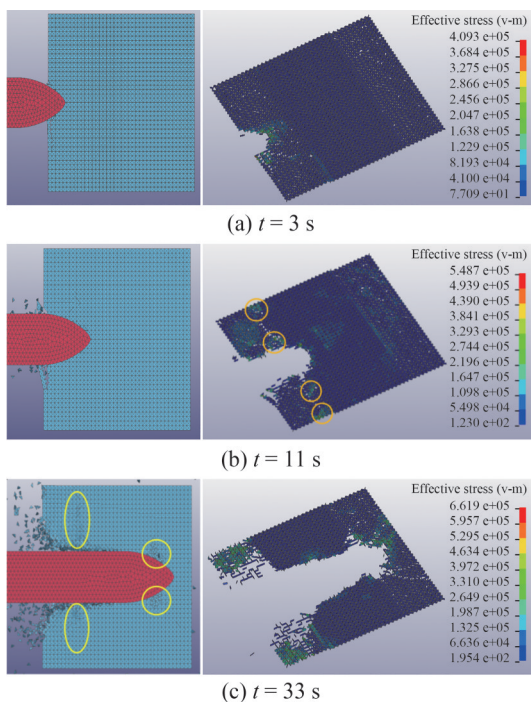


Figure 12 Collision process of an icebreaker and rafted ice, with the ship and finite element of ice in the left column and effective stress of cohesive element of ice in the right column

Figure 13 shows the plot of the time–history curve of the ice force of the ship in the x -direction. The minus sign denotes the force direction opposite the moving direction of the ship. The average ice load in the x -direction reaches 0.2 MN. Combined with the result illustrated in Figure 12, at around $t = 11$ s, the ship first comes into contact with the rafting part of the rafted ice. As a result, ice force increases sharply until the hull completely passes through the rafting parts at approximately 25 s, when the ice force peaks. Then, the curve drops suddenly within a short period

with the sharp decrease in ice thickness. Next, the ice force oscillates with several peaks along with the accumulation of crushed ice.

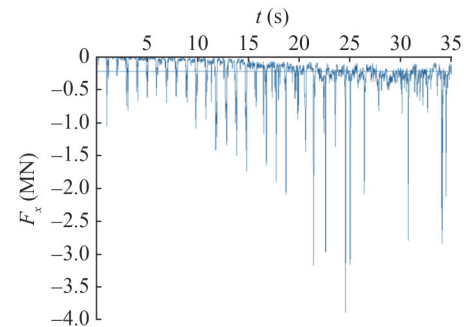


Figure 13 Time history of the force of ship–rafted ice collision

To study the influence of ship speed on the ice load of icebreaker–rafted ice collision, in combination with the actual ice-breaking speed of icebreakers, this paper uses three ship speeds: 3, 4, and 5 kn. Figure 14 shows the calculation results at two different displacements, namely 25 (left) and 40 m (right). During sailing, the faster the ship speed, the faster the crack propagation expansion and the larger the expansion range, and these conditions are likely to produce large pieces of broken ice.

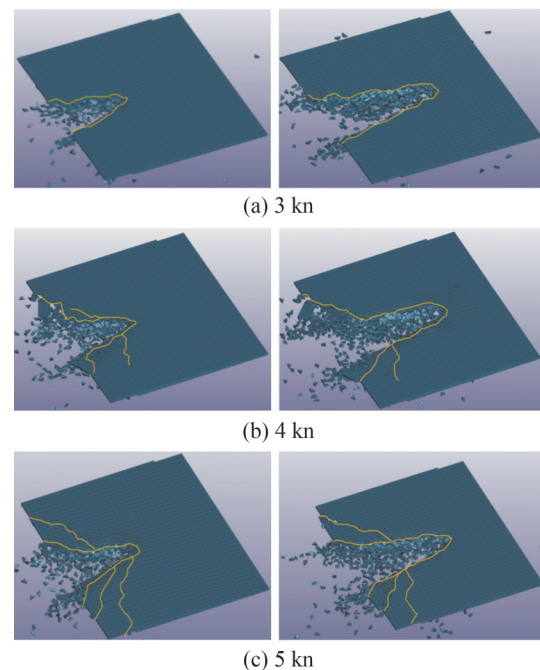


Figure 14 Time history of the force of ship–rafted ice collision

4.2 Comparison of results on single- and double-layer ice

For comparison, we also calculate the collisions of the icebreaker with single- and double-layer ice at the same

speed of 4 kn. The length and width of the ice are kept constant at 80 m. The single- and double-layer ice have thicknesses of 0.66 and 1.32 m, respectively. All other settings, including the grid size, ice material parameters, contact settings, and boundary conditions, are the same as those of the collision of the ship and rafted ice. The cohesive parameter values between the ice elements of the single-layer ice are the same as those of the single-layer part, and those between the ice elements of the double-layer ice are the same as those of the rafting parts of rafted ice in Section 4.1.

Figures 15 and 16 provide the collision results of single- and double-layer ice, respectively. For the single-layer ice, cracks expand along the pore mostly without the hindrance of rafted ice. On the other hand, for the double-layer ice, random pores of the two layers make up each other through the bonding of layer–layer cohesive elements, which lessens the effect of pores on crack propagation. Given the absence of abrupt thickness change in the double-layer ice, stress concentration along the edge of rafting parts in Figures 12(b) and 12(c) disappears. The ice thickness increases, and thus, the collision force increases, and more broken ice pieces fall off from the main ice body during collision.

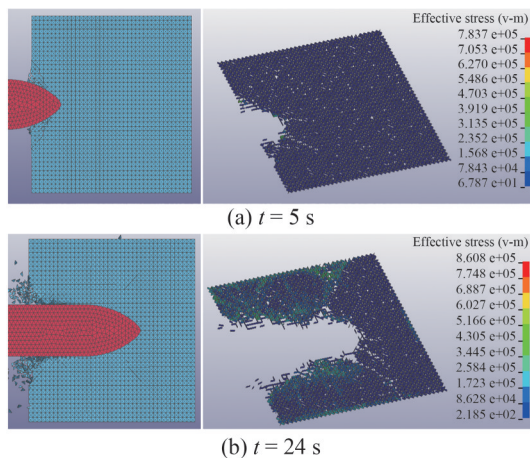


Figure 15 Collision between icebreaker and a single-layer ice

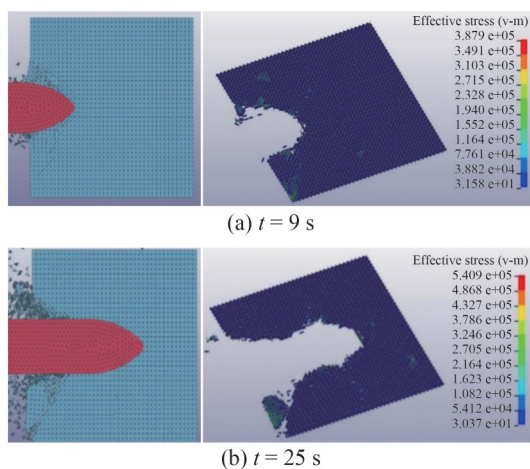


Figure 16 Collision of icebreaker and double-layer ice

Table 7 provides the comparison of the average ice force in the x -direction and peak ice force in the direction of three cases. From single-layer ice to rafted ice and then to double-layer ice, given the increase in thickness and length of rafting parts, the average ice force and force peak in the x -direction increase gradually. The force peak of rafted ice is close to that of double-layer ice, which indicates that in the actual navigation process, rafted ice may cause a large ice force in the rafting parts and threaten the structural safety of the ship.

Table 7 Ice forces under different working conditions unit: MN

Working condition	Single-layer ice	Rafted ice	Double-layer ice
Absolute value of average ice force	0.11	0.18	0.21
Absolute value of ice force peak	2.22	3.01	3.15

5 Conclusions

A numerical model of rafted ice is built based on nonlinear finite elements and CEMs. Comparison is conducted between numerical results and previous experimental data for validation. On this basis, a numerical simulation of the collision between an icebreaker and rafted ice is performed. The collision results for the icebreaker with rafted ice, single-layer ice, and double-layer ice are compared. The main conclusions include the following:

(1) The CEM can simulate ice cracks well. Through the insertion of a zero-thickness cohesive element into the finite element of ice, this paper proposes a rafted ice model. The freezing strength between rafting areas can be varied from that inside the ice by changing the parameters, such as the energy release rate between tangential and normal, of cohesive elements in and between the layers.

(2) The porosity of natural ice can be simulated through the random removal of cohesive elements from this model. This step is easier than the removal of finite elements of ice and can be used to simulate crack propagation along the pores in a realistic manner.

(3) Comparison of the ice-breaking results on rafted ice, single-layer ice, and double-layer ice reveals that given the bonding of layer–layer cohesive elements, rafting parts hinder crack generation and decrease crack propagation rate to some extent. Stress concentration occurs along the edges of rafting parts, and severe damage is generated. The rafting ice region exhibits large ice forces, with peak ice force close to that of the double-layer ice having the same thickness. Thus, the ice loads and structural safety of icebreakers should be checked in rafting ice areas.

In the future, the model proposed in this paper can be applied to more complicated ice conditions, such as ice ridges.

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