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Study on ship-ice interaction based on improved ice constitutive model

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Abstract: The interaction between ship and sea ice is one of the important problems in the field of ship collision, and the simulation of sea ice is the difficulty and focus of ship-ice collision. An elastoplastic constitutive model considering the temperature gradient of the ice layer is proposed, and the stress is updated by using the fully implicit graph return algorithm. Tsai-Wu yield criterion and empirical failure criterion are used to describe the yield and failure of the ice, which are embedded in the VUMAT subroutine of the finite element software ABAQUS, and the accuracy of ice material is verified. The ship-ice collision behavior under different collision speeds and bow column angles is studied, and the change of collision force, hull damage and deformation, and failure behavior of sea ice during the collision process are summarized. The results show that the collision force increases non linearly with the increase of ship speed, and the extent of ice damage and hull damage increases, and the collision force on the hull increases with the increase of the bow column inclination. The research results can provide a reference for the structural design of ships sailing in ice area.

Keywords: sea ice constitutive model, Ship-ice collision, Bow post inclination, temperature gradient

1. Introduction

The development of polar resources is one of the hot spots in the world today. The Arctic is rich in natural resources. Studies have shown that the reserves of oil, natural gas and other resources in the Arctic account for about 25% of the global oil and gas resources [1]. In recent years, the global climate is gradually warming, leading to the continuous melting of the ice layer in the Arctic, and the development and scientific research activities of polar resources in various countries are becoming more and more frequent. Ships sailing or operating in the polar regions often collide with sea ice, and sometimes it is necessary to actively collide with ice in order to open a channel. The safety of navigation should be taken as the primary premise when the ship is sailing. Therefore, it is of great significance to study the ice load and hull damage and deformation when the ship collides with the sea ice in the ice area.

The establishment of ice material is the key factor to study ship-ice collision. In order to study the interaction between ship ice as comprehensively and accurately as possible, a suitable constitutive model of ice material is very important. At present, researchers at home and abroad have done a lot of research work on this. The constitutive model of sea ice proposed mainly includes elasticity, elastoplasticity, viscoelasticity and plasticity [2]. Gao established an elastic-plastic sea ice material model through secondary development [3]. The numerical simulation results are in good agreement with the existing pressure-area curve, which verifies the accuracy of the sea ice model, and applies it to the process of ship ice collision to obtain better results. He [4] used the isotropic elastic fracture model to simulate the sea ice, and carried out the numerical simulation of ice and rigid wall. The results were in good agreement with the sea ice collision pressure area curve recommended by ISO, which verified the feasibility of the selected model of ice material. Based on the nonlinear finite element method, Wang [5] used the linear softening elastoplastic constitutive model to simulate the flat ice-layer, and introduced the cohesive element. The simulation results are in good agreement with the actually observed failure mode of the ice layer impacting the lighthouse.

Research on ship-ice interaction is in its infancy. In the field of ship ice collision research, numerical simulation is the main research method used at present. Yan and Zhu [6] studied the dynamic response of hull plate structure in the process of ship ice collision by numerical simulation method, and verified the effectiveness of numerical simulation by carrying out model tests. On this basis, they studied the influence law of floating ice quality, speed and plate thickness on the dynamic response and plastic deformation of hull plate. Hu [7] used LS-DYNA software to simulate the collision process between the FRP ship and the ice raft, and analyzed its influence on the dynamic response of the hull and the ice raft structure in the collision process from the perspective of the lay of FRP and the ship speed. Liu [8] used ANSYS and LSDYNA software to study the resistance during the ice breaking of ships in ice area, and analyzed the influence of friction coefficient, collision speed, ice thickness and so on on the ship ice collision force.

Using only one constitutive model can not reflect all the properties of sea ice because the physical and mechanical properties of sea ice are extremely complex. So it is necessary to select an appropriate constitutive model according to the specific situation and research purpose. Aiming at the problem that there is a temperature gradient from the upper surface to the lower surface of the ice layer, based on the ideal elastic-plastic sea ice constitutive model, this paper uses the finite element software ABAQUS to simulate the collision process between the ship and the flat ice- layer in different situations, and studies the mechanical properties of the ice, so as to provide a reference basis for the study of the load during the ice breaking of ice breakers.

2. Sea ice material model

The properties of ice are very complex, which are related to time, salinity, porosity and other factors. The selection of ice constitutive model is the key and difficult point in numerical simulation. Relevant studies have shown that the strain rate has a non negligible effect on the mechanical behavior of sea ice, which shows viscosity at low strain rate (less than $10^{-3}s^{-1}$) and brittleness at high strain rate (greater than $10^{-3}s^{-1}$) [9]. In this paper, the ideal elastoplastic constitutive model considering the influence of layer ice temperature gradient is used to simulate the mechanical properties of sea ice, and it is applied to the simulation of ship ice collision to study the collision results under different collision scenarios.

2.1 Theoretical formula of sea ice constitutive model

The ideal elastoplastic model does not harden in the plastic stage. In the initial stage of collision, the ice first experiences the elastic stage, and the stress-strain relationship satisfies Hooke's law [10].

After experiencing the elastic stage, ice materials continue to be compressed and enter the plastic stage. The yield criterion is a sign to judge whether the material is in the elastic or plastic state. Whether the yield criterion is accurate is very important to simulate ice materials.

In the process of collision, the ice element at the collision is under three-dimensional stress. Jones [11] and Rist [12] found that hydro-static pressure has a non negligible effect on the yield of ice materials. Therefore, the unified polyhedral yield criterion of isotropic fresh water ice, iceberg ice and columnar ice given by Derradji Aouat [13] on the basis of triaxial test is selected, which can be summarized as following form [14]:

$$f\left(p, J_2\right) = J_2 - \left(a_0 + a_1 p + a_2 p^2\right) = 0 \qquad (1)$$

Where a_0, a_1 and a_2 are constants obtained by fitting triaxial test data. The above form is Tsai-Wu yield function [13].

For layer ice, considering that there is a temperature gradient from the upper surface to the lower surface of sea ice [15], and temperature has a non negligible influence on the determination of constants in the yield function. Therefore, the yield criterion can be converted into a function of temperature:

$$f\left(p, J_2, T\right) = J_2 - \left(a_0(T) + a_1(T) p + a_2(T) p^2\right) = 0 \qquad (2)$$

Where T is the temperature.

Ahmed A. Derradji [13] obtained the yield surface of iceberg ice at a series of different temperatures (-1, -6, -11 and -16 ℃), as shown in the figure below.

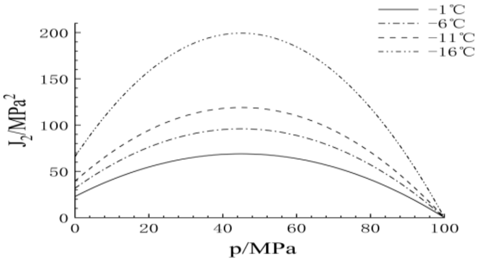


Fig. 1 Yield function curves at different temperatures

When the temperature is between -1 ℃ and -11 ℃, the yield surface increases linearly with temperature, that is, the ice strength increases linearly with temperature. When the temperature decreases from -11 ℃ to -16 ℃, the yield surface expands sharply, which is much higher than most data points. The parameters in the common formula (1) corresponding to these four groups of curves are shown in the table below.

Table 1 Values of a_0, a_1 and a_2 at different temperatures

temperature(℃)	a_0（MPa^2）	a_1（MPa）	a_2
-1	22.794	2.051	-0.02279
-6	31.736	2.856	-0.03174
-11	39.366	3.542	-0.03937
-16	65.921	5.932	-0.06592

In order to determine the parameters corresponding to the temperature (such as -8 ℃) between the experimental temperature points (-1 ℃, -6 ℃, -11 ℃, -16 ℃), it is necessary to first judge which of the -1 ℃ ~-16 ℃ range the temperature falls in, and then carry out linear interpolation in the corresponding range.

The strain in the plastic stage is divided into elastic and plastic strain, and the constitutive relationship is expressed by the incremental theory [10].In addition to the yield criterion, a reasonable failure criterion should be established to simulate the failure characteristics of ice materials. In this paper, the empirical failure criterion proposed by Liu [16] is adopted. When the equivalent plastic strain is greater than the failure strain, the material reaches failure and is deleted.

The following table shows the ice material parameters adopted in the text [17] .

Table 2 Ice material parameters

Parameter	Value	Parameter	Value
Density	900kg/m^3	Poisson's ratio υ	0.3
Elastic modulus	9500MPa	Initial failure strain ε_0	0.01

In the plastic stage, the fully implicit graph return algorithm is used to solve iteratively to update the stress. The algorithm can be divided into two steps, including elastic prediction and the plastic adjustment. In the elastic prediction step, the trial stress is calculated according to Hooke's law [10].

In the plastic adjustment step, the increment of plastic consistency parameter is solved by iterative methods, so as to obtain the real stress. This algorithm calculates the plastic strain increment at the end of the increment step.

The first step of the program is to solve the trial stress and substitute the yield function for discrimination. If in the elastic stage, the test stress is equal to the real stress. If it is in the plastic stage, the test stress will return to the yield surface through the plastic adjustment.

2.2 Verification of constitutive model of ice material

Under the four temperatures in Table 1, round ice and rigid plate are selected for collision simulation, and the numerical simulation results are compared with the pressure contact area curve $p=7.4A^{-74}$ proposed by Masterson et al. [18] in 2007, which is adopted by ISO specification [19]. Through this simulation, the accuracy and rationality of the above sea ice constitutive model are verified. The radius of one end of the round ice is 5m, the other end is 0.5m, and the height is 5m. The section size of rigid plate is 12m × 12m, 50mm thick, rigidly fixed around. The cone ice impacts the rigid plate at the speed of 10m/s, and the friction coefficient is set to 0.15. The following figure shows the finite element model of circular ice and rigid plate.

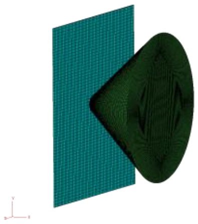


Fig. 2 Collision model of cone ice and rigid plate

According to the collision force time curve obtained by numerical simulation, the contact area-time curve can be obtained, and then the pressure-contact area curve can be solved.

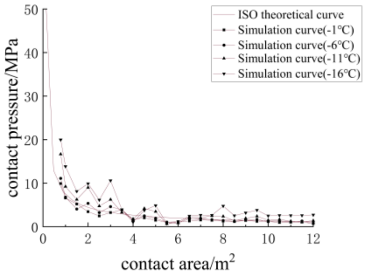


Fig. 3 Pressure area curve

By comparing the pressure-area curve, it can be seen that the change trend of the pressure-area curve of the simulation results is relatively consistent with the ISO recommended curve, which can be applied to the study of ship ice collision to obtain relatively reliable results.

3. Numerical simulation of ship-ice collision

Based on the above numerical simulation of spherical ice rigid plate collision, the ice model has been verified. Now the ice model is further applied to the numerical simulation of the continuous ice-breaking process of ships in the ice layer.

3.1 Effects of ship-ice collision velocity on ice-breaking process

3.1.1 Ship-ice collision model

This section takes an ice breaker [20] as the research object. The main parameters of the hull structure are shown in the table below, and the profile diagram is shown in the figure below.

Table 3 Main parameters of ship

Parameter	Value	Parameter	Value	Parameter	Value
Length/m	167	Waterline/m	9	Displacement/t	21025
Width/m	22.6	Waterline	26°	Length between perpendiculars/m	147.2
Height/m	13.5	Water plane	0.8276	Bow angle/°	24

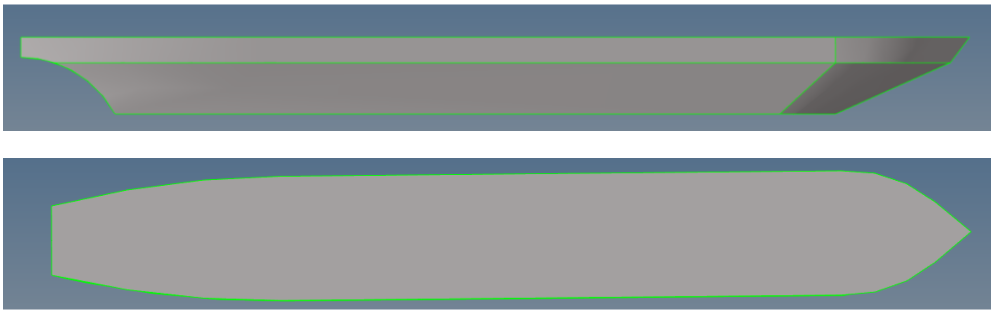


Fig. 4 Pressure area curve

In case of ship ice collision, the speed of ship has a great influence on the collision results. In order to study the influence of navigation speed on the ice-breaking process, four ice breaking speeds are set, which are 4m/s, 6m/s, 8m/s and 10m/s respectively, keeping other conditions consistent. The ice thickness is 2m, the temperature of upper surface is -10 ℃, the lower surface temperature is -2 ℃, and the temperature increases linearly with the increase of depth, which is a typical feature of cold sea ice in winter. The hull is simulated by shell elements with a thickness of 50mm, and the ice is solid element. The ice layer is 100m long and 50m wide. The three sides away from the hull are rigidly fixed. The initial velocity in the x direction is applied to the hull to make it hit the ice layer, and the friction coefficient is 0.15.

The hull material is a kind of high-strength steel [21], and the elastic-plastic model is adopted. The material properties are shown in the table below.

Table 4 Ship material parameters

Parameter	Value
Density/ (kg/m^3)	7850
Yield stress/MPa	335
Elastic modulus/GPa	206
Hardening modulus /GPa	1.18
Failure strain	0.2

The following figure shows the ship ice collision finite element model.

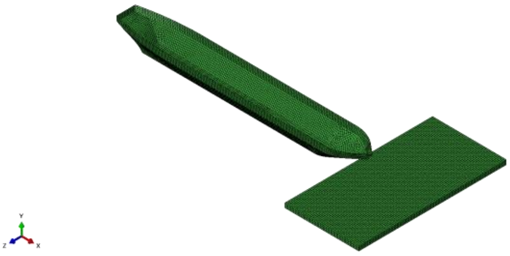
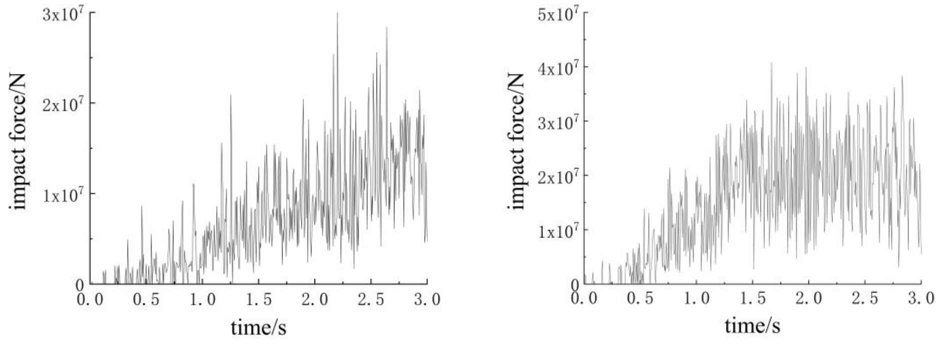


Fig.5 Finite element model of ship ice collision

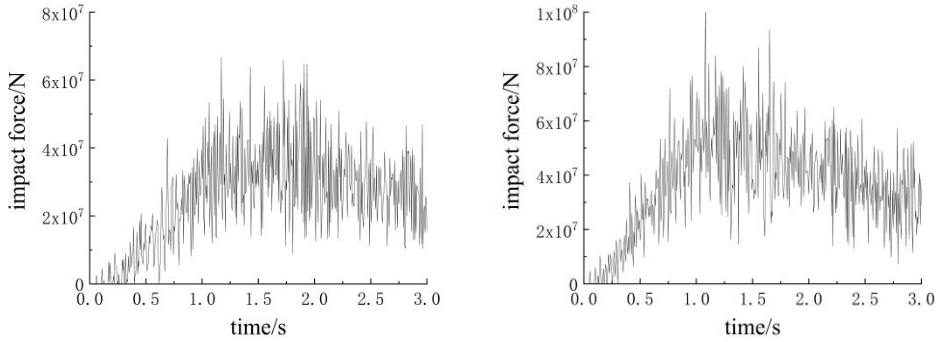
3.1.2 Analysis of impact force

The following figure shows the impact-force curve in the x direction at different speeds during the collision, with the abscissa unit of s and the ordinate unit of N.

In the process of ship ice collision, the ice is deleted due to the failure of collision and extrusion, so the process of "contacting-ice breaking-contacting-ice breaking" will continue to occur, and the collision force curve shows a constantly fluctuating state. It can be seen from the figure that as the ship moves, the contact area between the hull and sea ice continues to increase, and the collision force rapidly rises to a certain value, and then fluctuates in the range near a certain value. Then, as the sea ice continues to fail and delete, the collision force shows a downward trend. The figure shows that the impact force is positively correlated with the velocity, but it does not increase nonlinearly. The peak values of impact force at different speeds are 30MN, 40MN, 65MN and 100MN respectively. It can be seen from the comparison that when the ship speed is small, the collision force increases slowly, and when the ship speed is large, the peak collision force will increase nonlinearly and rapidly.



(a) 4m/s (b) 6m/s

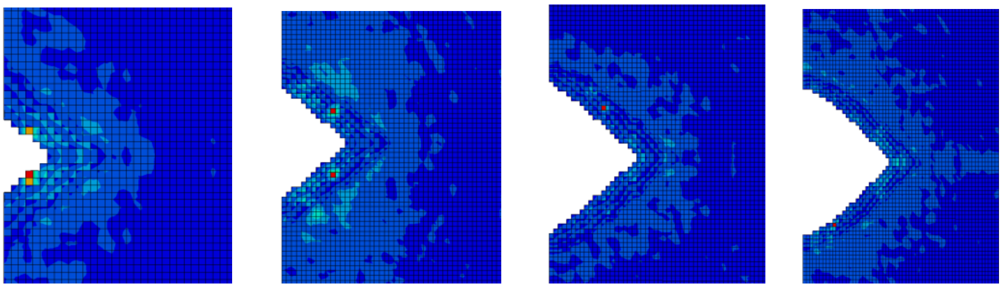


(c) 8m/s (d) 10m/s

Fig. 6 Impact force curve in X direction at different speeds

3.1.3 Analysis of ice damage

Figure 8 shows the damage and damage of ice layer after ship ice collision at different speeds, and the time is 1.5 s after the collision. It can be seen from the figure that as the ship advances, the sea ice in contact with the bow is squeezed and deleted after reaching the failure strain, resulting in a gap in the contact area of ship and ice , which continues to increase as the ship advances. It can be seen from the figure that the larger the speed of the ship, the larger the gap of the ice layer, and the greater the damage to the ice layer. Similarly, it can be seen that the greater the damage to the ship. It can be seen from the ice damage that the failed elements are mainly the ice unit in direct contact with the hull, and the outer unit rarely fails. Therefore, the ice close to the hull is under the greatest pressure, and the plastic strain soon reaches the failure strain and is deleted, while the outer element has less deformation due to the constraints of other elements.

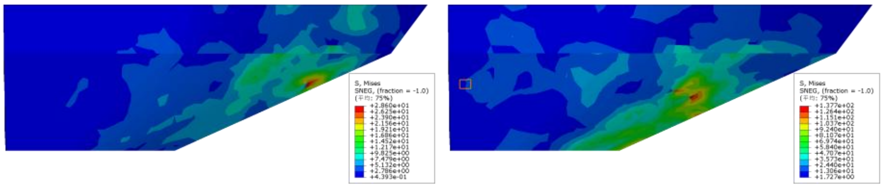


(a) 4m/s (b) 6m/s (c) 8m/s (d) 10m/s

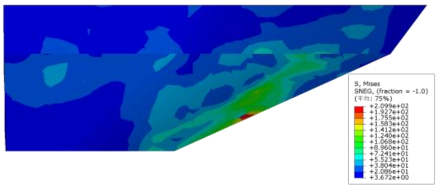
Fig. 7 Comparison of failure stress nephogram of ice layer at t=1.5s

3.1.4 Analysis of hull deformation and damage

Figures 9, 10, 11 and 12 show the stress nephogram of the hull at different speeds during the collision. It can be seen from the figure that the maximum stress of the hull occurs at the contact part of the ship ice collision. During the whole process, the stress is below the yield stress for most of the time. Comparing the damage and deformation of the hull at different speeds, it can be seen that when the ship speed is 4m/s and 6m/s, the ultimate stress of the hull is below the yield stress, indicating that the hull deformation is within the range of elastic deformation, when the ship speed is 8m/s, a small amount of plastic deformation occurs at the collision site with the increase of time ,and when the ship speed is 10m/s, plastic deformation is more serious. Therefore, for the hull materials used in this section, the speed of ship should be controlled within a reasonable range as far as possible during the driving process, so as to reduce the damage to the hull. At the same time, as the waterline area of the hull is stressed area, damage and deformation are easy to occur, so the strength of the structure here should be strengthened, or high-strength materials should be used.

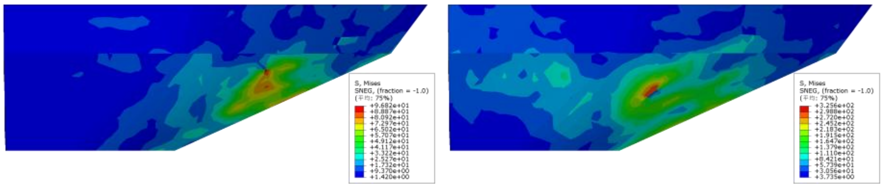


(a) t=1s (b) t=2s

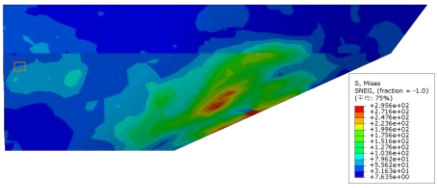


(c) t=3s

Fig. 8 Stress nephogram of bow at different times at 4m/s speed

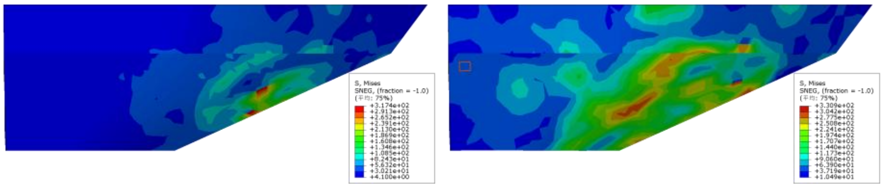


(a) t=1s (b) t=2s

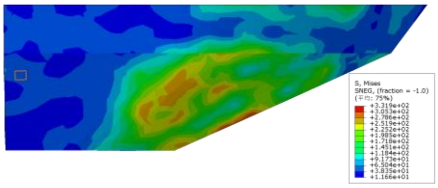


(c) t=3s

Fig. 9 Stress nephogram of bow at different times at 6m/s speed

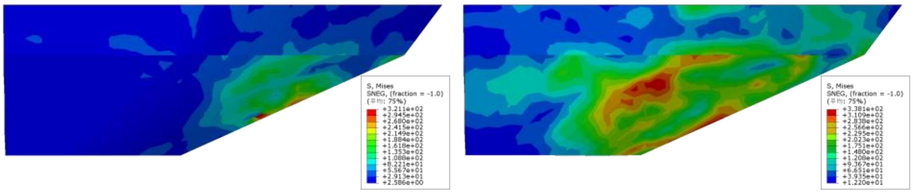


(a) t=1s (b) t=2s

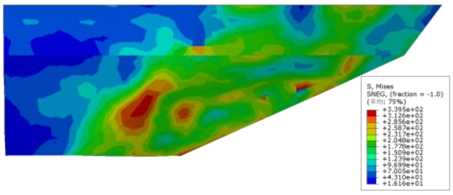


(c) t=3s

Fig. 10 Stress nephogram of bow at different times at 8m/s speed



(a) t=1s (b)t=2s



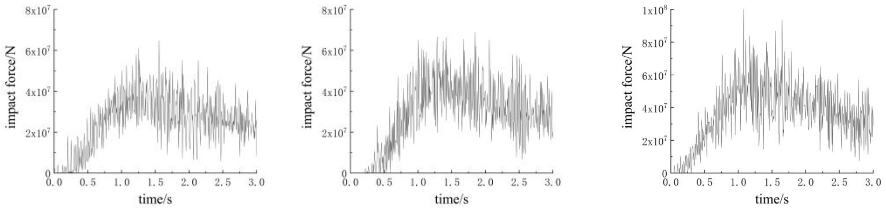
(c) t=3s

Fig. 11 Stress nephogram of bow at different times at 10m/s speed

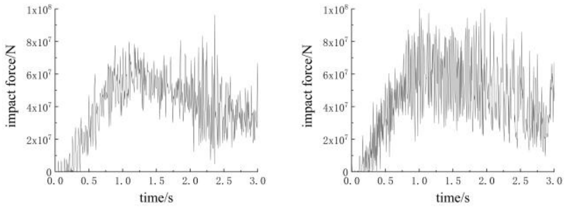
3.2 Effects of bow column inclination on hull structure

This section studies the influence of the inclination of the bow column on the collision, mainly analyzing the influence of the inclination of the bow on the hull structure. Therefore, the hull is simplified as a rigid body, and the change of the collision force on the bow under different inclination is observed. The collision model is the same as that in section 3.1, and four kinds of bow column inclination angles are set to study their influence on the ice-breaking process. The angles are 20 °, 22 °, 24 °, 26 ° and 28 ° respectively. Set the ship speed to 10m/s, and other conditions remain the same.

Figure 16 shows the time-dependent curve of the impact force in the x direction. It can be seen from the figure that the horizontal collision force on the bow increases with the increase of the inclination of bow. The change trend of collision force curve with time under different angles is similar, which first rises from zero to a peak, and then fluctuates in a certain range. When the inclination angle is 20° ~24 °, the impact force increases slowly. The impact force increases significantly at 24° ~28 °. Therefore, within the scope of design requirements, reducing the inclination of the bow column of the small boat will help to reduce the collision force on the bow, so as to reduce the hull damage. The best angle can be selected in combination with the ice-breaking effect in the design.



(a) 20° (b) 22° (c) 24°



(d) 26° (e) 28°

Fig. 12 Collision force curve in X direction under different bow column inclination

4. Conclusions

In this paper, an ideal elastic-plastic ice material considering temperature is proposed and written as a VUMAT user subroutine. The model is verified based on the finite element software ABAQUS. The model is applied to the numerical simulation of studying the ice load and ice damage during ship-ice collision. The main conclusions are as follows:

(1). The ice material model proposed in this paper is simulated by spherical ice collision, and its results are in good agreement with the ISO theoretical curve. It can reasonably describe the mechanical behavior of ice, and can be applied to the numerical simulation of ship ice collision.

(2). When the ship collides with ice, the higher the speed of the ship, the greater the collision force between the ship and ice. When the speed of the ship is higher, the peak value of the collision force increases nonlinearly and rapidly, and the damage and deformation of the ship hull and the destruction and failure of ice are also more serious. Therefore, in order to effectively break the ice and protect the hull structure at the same time, the speed of ship should be controlled within a certain range and the strength of the structure at the collision contact should be strengthened.

(3). The horizontal collision force on the bow increases with the increase of the bow angle. While ensuring the ice-breaking effect, the bow angle should be controlled within a certain range, so as to protect the hull structure.

Acknowledgments

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