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Recent Work on Dynamic Inelastic Response of Polar Ship Structure Subjected to Ice Floe Impact

ZHU Ling[1,2], *GUO Zhi−han*[1,2], *CAI Wei*[3]

(1. Key Laboratory of High Performance Ship Technology (Wuhan University of Technology), Ministry of Education, Wuhan 430063, China; 2. School of Naval Architecture, Ocean and Energy Power Engineering, Wuhan University of Technology, Wuhan 430063, China; 3. State Key Laboratory of Advanced Technology for Materials Synthesis and Processing, Wuhan University of Technology, Wuhan 430070, China)

Abstract: Extreme ice floe impact events on polar ship structures are very common in ice regions. The inelastic deformation of structures under ice impact loadings reflects directly the damage states of the structures and is thus an important and convenient parameter in structural strength assessment and design. Therefore, the aim of this paper is to review the recent research progress on dynamic inelastic response of polar ship structure subjected to ice floe impact. Some important experimental, numerical and theoretical work was introduced to study dynamic plastic responses of ship plates under single and repeated ice impact loadings. The effects of ice deformation and damage characteristics on the plastic energy absorption of ship plates were evaluated in this paper by comparing with rigid mass impact responses. In addition, the plastic deformation accumulation, energy-sharing mechanisms and pseudo-shakedown phenomenon of ship plates subjected to identical repeated ice impacts were explored. Based on the analytical solutions for inelastic response of ship plates under ice impact, some plastic design formulae and curves were proposed to determine the thickness of ship plates under ice impact loading, which can provide useful references for the structural design of ice-going ships.

Key words: polar ship structure; ice floe impact; inelastic response; plastic design

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0 Introduction

The Arctic region has abundant oil and gas resources and acts as a lifeline for many communities with the increasing exploitation of the Arctic channel. More voyages across the Arctic waters will be possible in the future due to global warming and declining extent of sea ice. However, the increased ship traffic and resources exploitation activities in these waters may increase the probability of impacts between ice floes/icebergs and ships and offshore structures, which necessitates safety assessment of such events. Thus, the assessment of the dynamic structural behaviour of ship plates subjected to ice impacts is of paramount

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Biography：ZHU Ling (1962−), male, professor, Ph.D. supervisor; GUO Zhi-han (1998–), male, Ph.D. student; CAI Wei (1996–), male, associate research professor. corresponding author, E-mail: caiwei199696@whut.edu.cn.

importance to improving the safety of ships and offshore structures operating in the Arctic region.

The structural design against ice impact has been commonly carried out using the limit state design approaches, such as the Ultimate Limit State (ULS) and Accidental Limit State (ALS). In this regard, the loads from rare iceberg or huge ice floe impacts can be described as an Abnormal Level Ice Event (ALIE), as seen in International Organization for Standardization (ISO) standards[1], which is in accordance with the Accidental Limit State (ALS) in the current standard codes for ship and offshore structures. In the ALS design method, the annual probability of occurrence is typically 10^{-4}, and the allowable structural damage due to ice impact loading can be determined based upon the fact that the structure has enough residual strength to prevent progressive collapse and that the safety of the crew and environment can be maintained. Based on the limit state design approaches, there are three design strategies for ship structures, namely the ductility design, shared-energy design and strength design, as shown in Fig.1. The shared-energy design method is widely used in the design of general ice-strengthened ships, by which the plastic deformations are inevitable in ship operations. This method implies that both the ship structure and the ice dissipate energies by undergoing significant deformations or damage. The whole collision energy is shared by both colliding bodies, as indicated in Fig.2. For this design method, the degree of structural deformation or damage depends on their relative strength. When the ice is stiff enough or can even be assumed as an idealized rigid body, the impact energies are mainly dissipated by the ship structures, which corresponds to the ductile design method. Therefore, it is of great significance to study the plastic deformation and energy absorption mechanisms arising from the impacts between the ship plates and ice floes or icebergs.

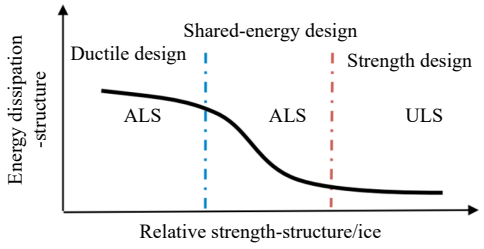


Fig.1 Characterization of design principles in terms of the share of energy dissipation versus relative strength of structure and ice[2]

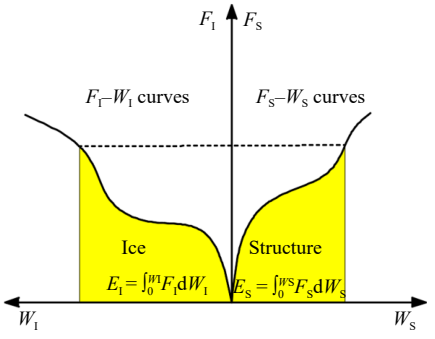


Fig.2 Energy components absorbed by ice and the marine structure

Much research work has been conducted to investigate the dynamic responses of marine structures under ice collision using experimental and numerical methods. Some full-scale or model-scale ice-structure interaction tests have been reported, such as full-scale collision tests between ice bergy bit and the CCGS Terry Fox icebreaker[3−4], full-scale ice crushing tests conducted in Aker Arctic test basin[5], full-scale ice load measurement tests of Xue Long icebreaker[6], the quasi-static laboratory model tests in which an ice cone was slowly pushed against a large scale steel stiffened plate[7], the laboratory collision tests between a floating steel structure in a tank and freshwater ice blocks[8], the ice drop impact tests[9−10], the ship-ice glancing impact test in ice tank[11], the large double-pendulum ice impact tests[12], and the horizontal impact tests[13−15]. From these scaled and full-scale tests, the dynamic responses of ice-structure interaction were obtained, such as permanent deformations of structures, impact forces, and ice loading pressures.

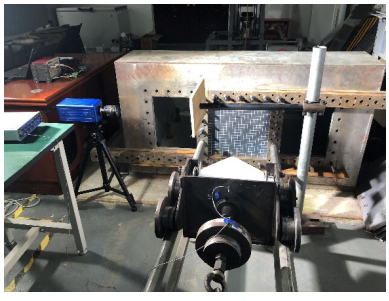
In recent years, numerical methods for predicting the plastic damage of ship structure under ice impact are widely used by the Nonlinear Finite Element Method (NFEM). The mechanical behaviour of ice during

impact is very complicated, and a mature ice material model comprehensively describing the behaviours is still lacking due to the complexity of ice constitutive model. A few material models are available in the literature for ice modelling, such as the isotropic elastic failure constitutive model, crushable foam model[16−17], the elastic-plastic and pressure dependent constitutive model[10,18−22], the rate-sensitive constitutive model[10,23] and the damage model[15,24]. These numerical models of ice material are employed in the finite element simulations to model the ice failure in ship-ice collision.

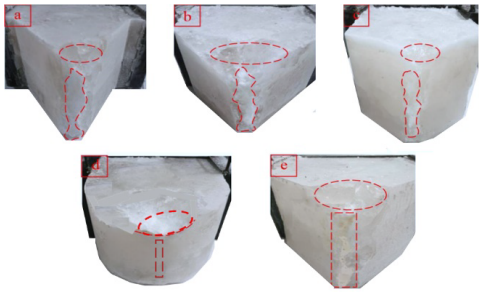
This paper aims to review the recent research progress on dynamic inelastic response of polar ship structures subjected to ice floe impact. The recent research work on laboratory ice impact tests, numerical simulations and theoretical solutions to study dynamic plastic responses of ship plates under single and repeated ice impact loadings was summarized. The plastic deformation accumulation, energy-sharing mechanisms and pseudo-shakedown phenomenon of ship plates subjected to identical repeated ice impacts were revealed. Moreover, the plastic design method to determine the plate thickness of ship plates under ice impact loading is introduced in this paper, which can provide useful references for the structural design of ice-going ships.

1 Recent research work on laboratory fresh-water ice impact tests of ship plates

A series of single and repeated freshwater ice impact tests on steel plates were carried out to study the dynamic responses of ice-plate impact[13−15,25]. The experimental set-up details, measuring devices, and testing procedures introduced by Cai et al[15] are shown in Fig.3. In the tests, the ice slid down along the steel rail to obtain an initial impact velocity and hit the fully clamped plate specimen at its centre and at the same point during the repeated impact event. The specimen boundaries were fully clamped by the double-layer clamps, and the specimen as well as the clamps were bolted to the support structures in the tests. The impact force-time histories, deflection-time histories of plate and ice impact damage process were obtained in the impact tests, which can provide some useful data for validating the numerical and theoretical method.



(a) Experimental equipment[15]

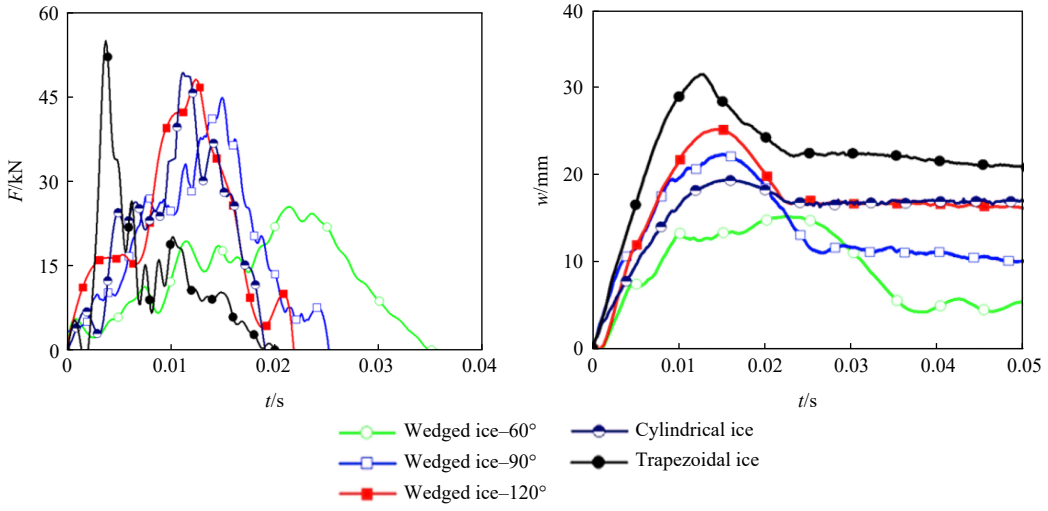


(b) Damaged ices after impact[14]

Fig.3 Ice impact tests on full-clamped steel plates

Fig.4 shows the time histories of ice impact force and displacement at the central point of plates impacted by ice specimens with different geometries. It can be found that the maximal collision force of the wedge-shaped ice with 60° front angle is the smallest in all collision force responses, while the maximal collision force of the trapezoid-shaped ice is the largest in all collision force responses. Moreover, with the increase of the front angle of wedge-shaped ice, the impact force peak and plastic deformation of plate gradually increase while the collision time becomes shorter. The wedge-shaped ice with 60° front angle is the sharpest and is easier to break with large crushed ice, so its strength is the weakest compared to other ice models due to its fragile characteristics. It can be concluded that, when the ice floe is very sharp, it is easier to

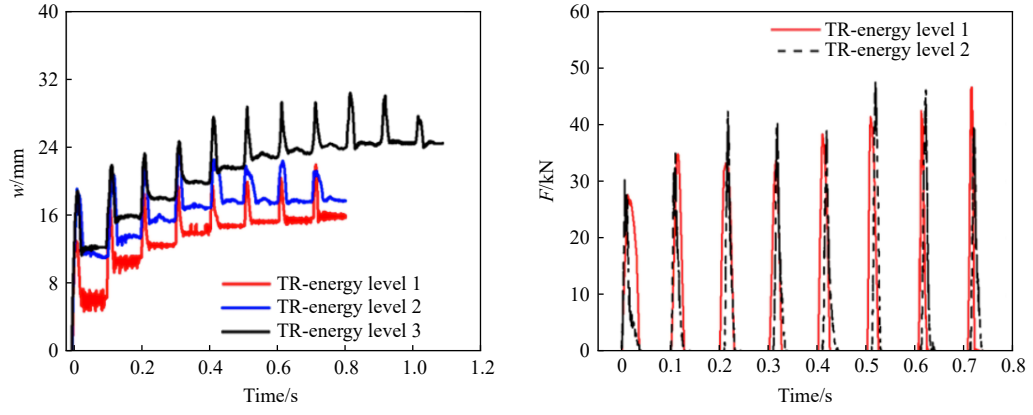
break and crush in the impact process. Under such circumstances, a large part of impact kinetic energy will be dissipated due to ice failure, the permanent plastic deformation of the plate and the impact force will be smaller than those of the flat or smooth front end of the ice. Besides, the impact time will be longer due to the continuous breaking of ice.



(a) Impact force time histories (b) Displacement-time curves at central point of the plate specimen

Fig.4 Impact test results of ship plates under a single ice impact with different ice geometries[15]

In repeated ice impact events, with the number of ice impact increases, the maximum permanent deformation of a plate is gradually increasing while the increment of permanent deformation of the plate is gradually decreasing, as shown in Fig.5(a). Besides, the smallest peak impact force appears at the first impact, and the peak impact force is gradually increasing with the number of impact, as shown in Fig.5(b). After repeated identical ice impacts, the plates have large accumulated plastic deformations, which will gradually stabilize and no longer increase. This phenomenon is called pseudo-shakedown, and its occurrence is related to the elastic strain energy. Zhu et al[26] obtained the empirical equations to estimate the elastic strain energies corresponding to the permanent deflections of plates by applying dimensional analysis to experimental data. Using rigid indenters of different geometries, the number of impacts required to reach the pseudo-shakedown status was predicted successfully.



(a) Displacement-time curves at central point of the plate specimen (b) Impact force time histories

Fig.5 Repeated impact test results of ship plates under repeated ice impact with different impact energy levels[25]

Ice impact tests using a large double-pendulum apparatus were conducted by Gagnon et al[12], as shown in Fig.6(a). In this study, the high spatial resolution pressure-pattern images were recorded to analyze the pressure distribution from ice impact tests. A significant observation was that in the earlier stage of tests, the crushed ice generated during the impacts could maintain strength and extend the actual contact area beyond the nominal contact area. Jiang et al[27] designed an experimental setup to study the collision pressure exerted on structures due to ice impacts, as seen in Fig.6(b). Both the strain experienced by a steel plate and the pressure due to the ice collision were measured. The pressure distribution on the steel plate surface was recorded by pressure-sensitive film. It was observed that the collision force increased in proportion to collision energy when plotted on a logarithmic scale.



(a) Ice holder pendulum (left) and impact module pendulum (right)[12]　　(b) Pendulum setup holding ice and steel plate specimens[27]

Fig.6 Ice impact tests using a large double-pendulum apparatus

In addition, some scholars have also carried out ice drop impact tests on the structures. As shown in Fig.7(a), Ince et al[9] made a comparison of drop hammer tests on a steel plate impacted by an ice body and a steel body. The ice body and steel body with the same shape were dropped from the same height onto a steel plate. During the experiment, the impact force and the permanent deformation of the steel plate were measured. The comparisons revealed that the impact plastic damage of the steel plate caused by the actual ice was less than that caused by the rigid body. Fig.7(b) shows the laboratory ice drop impact test conducted by Yu et al[10], in which the behavior of stiffened panels subject to the impact of a wedge-shaped ice was studied. An acceleration sensor was mounted on the holder to record the impact force. The experiment showed that



(a) A steel plate impacted by a steel body and an ice body respectively[9]　　(b) A stiffened plate impacted by a wedge-shaped ice[10]

Fig.7 Ice drop impact test

the stiffened steel panels sustained large plastic deformation without rupture, demonstrating a strong capacity against large ice loads.

For ice impact tests in a water tank, Kim et al[8] conducted a collision test between an ice block and a floating structure in water, as shown in Fig.8(a). The impact force was measured by a tactile pressure sensor. The impacts of ice blocks at speeds of 1–2 m/s with panels of different stiffness produced various plastic deformations, ranging from 3 mm to 5 mm dents in 2 mm and 4 mm thick plates to no visible marks in a 12 mm thick plate. Zhang et al[28] used a real ship's side shell processed by the scale ratio of 1:10 as the research object to verify the rationality of the numerical simulation method of ship-water-ice coupling collision, as shown in Fig.8(b). The strains of the structure and the deformations of the plates were measured at different speeds. The result showed that the peak stress in the collision region gradually decreases towards the surroundings, consistent with the overall distribution pattern of the plate deformation. Besides, Sun et al[11] conducted a series of model tests to investigate the spatial and temporal variations of the impact loads by simulating the glancing impact events between a polar research vessel and giant ice floes in an ice tank. The ship-ice impact loads were recorded by a grid-based tactile sensor attached on the bow area of the model ship. It was found that the initial impact location near the stem was more effective to generate the downward flexural deformation of ice.



(a) Model experiments of ice impact with a floating stiffened structure[8]

(b) Ice-plate impact in water medium[28]

(c) Model tests of ship-ice impact in an ice water tank[11]

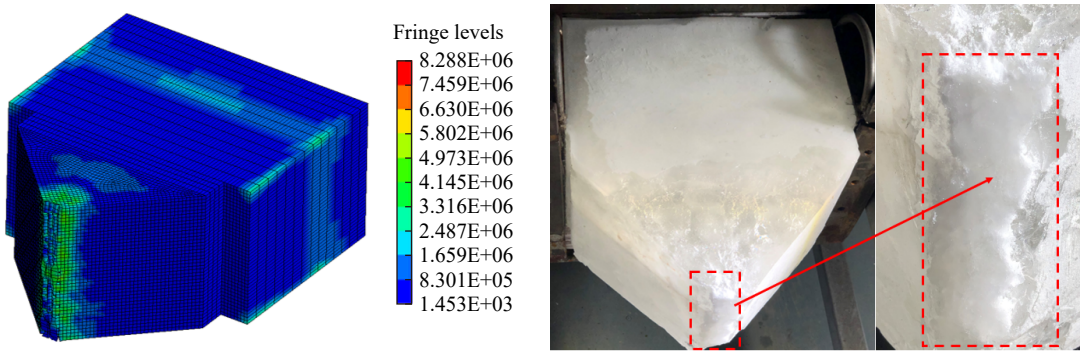
Fig.8 Water tank tests

2 Numerical analysis on ship plates under ice impact

In recent years, finite element methods for predicting the plastic damage of ship structures under ice impact have been widely developed by using commercial software, such as ABAQUS and ANSYS/LS-DYNA. In the ice-structure impact scenario, the ice modelling in numerical simulation is fairly challenging. Ice is a natural and complex material consisting of brine, solid ice, gas and other impurities, containing many internal pores, flaws and initial cracks in its interior. Moreover, the ice material characteristics in the ice-structure impact interaction are influenced by some factors, such as strain rate, temperature, years of formation, grain size, internal friction, imperfections, cracks, and failure modes. Fig.9 shows experimental and numerical ice damage in the impact process[15]. The impact causes ice particles of various sizes to break off and produces large quantities of small ice pieces. The ice crushing and spalling process is difficult to simulate by FE method, especially ice spalling rate. In reality, developing an ice material model considering all factors remains challenging to fit all ice impact tests due to random variations in the ice properties.

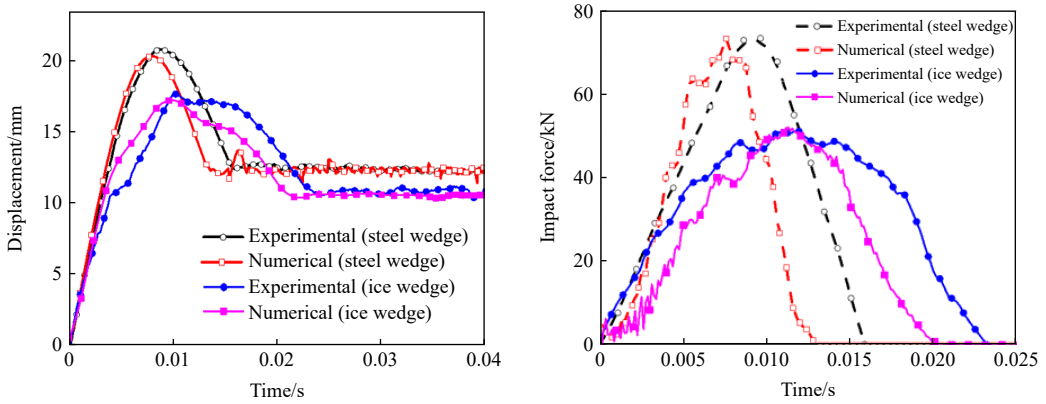
Some numerical constitutive models for ice material modelling were developed in the past ten years, such as the isotropic elastic failure constitutive model, crushable foam model, the elastic-plastic constitutive model and some simple damage models. These numerical models of ice material are employed in the FE

simulations to simulate the ice failure in ship-ice collision. An ice material model based on a soil and concrete material model (MAT_SOIL_CONCRETE) with user-defined ice material curves was used by Cai et al[15] to simulate the ice mechanical behaviour in an ice-plate impact. Fig.10 shows the experimental and numerical results for plate specimens subjected to ice and steel wedge impacts with the same impact energy[13]. Though there are some small differences in the collision time between experimental and numerical results, good agreement between numerical and experimental results is obtained in terms of the plate deformations and collision forces based on the above-mentioned ice material model. The numerical method with the proposed ice material model Cai et al[15] can accurately and efficiently predict the dynamic responses of plates under ice impact. The comparisons between ice wedge-plate impact and steel wedge-plate impact in Fig.10 show that assuming ice as a rigid material leads of unrealistic and inaccurate predicted responses. Besides, it is noted that when the collision energy and geometric dimensions of the wedge are the same, the plastic deformations and absorbed energies of plates, and the collision forces based on the ice wedge-plate impact model are smaller than those based on the steel wedge-plate impact model under the same impact conditions.



(a) Numerical ice damage　　(b) Experimental ice damage[15]

Fig.9 Comparison of ice damage after impact



(a) Displacement-time curves at central point of the plate specimen　　(b) Impact force time histories

Fig.10 Comparisons between experimental and numerical results[15]

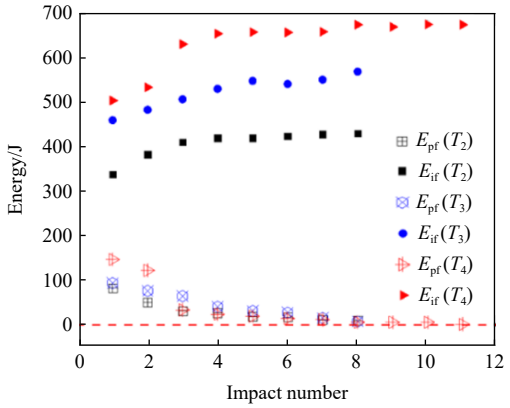
In order to investigate the differences of the absorbed energy of a plate under ice/steel wedge impact and the influences of the dissipated energy of ice wedge due to ice crushing, the energy absorption reduction factor (EARF) of the plate is defined as:

$$EARF = E_{pi}/E_{ps} \tag{1}$$

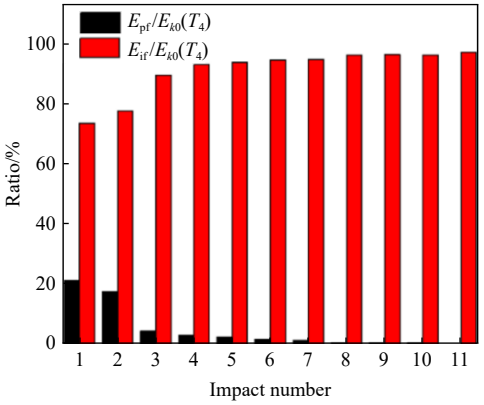
where E_{ps} represents the final total absorbed energy of plate after the steel wedge impact, and E_{pi} represents the final total absorbed energy of plate after ice wedge impact. The side structure of the midship is

longitudinally framed, with a framing spacing of 0.4 m and a plate height of 0.4 m. The numerically obtained EARF value is in the range of 0.2~0.3. The EARF is has a strong correlation with plate dimensions.

The numerical simulations for plates subjected to repeated ice impacts were also conducted by Cai et al[25]. With the number of a finite impact increases, the plastic strain energy of the structure in each impact gradually decreases while the energy dissipation of ice gradually increases. Besides, both the increment of E_{if} and the decrement of E_{pf} for each ice impact are gradually decreasing with the increase of impact numbers, as shown in Fig.11(a). Fig.11(b) illustrates energy dissipation ratios of the plate and ice against the number of impacts. It is noted that most of the impact energies are dissipated by the ice failure during the ice-plate impact, and the final absorbed energy of the plate E_{pf} only occupies a very small proportion of the total impact kinetic energy in the repeated ice impacts.



(a) Energy dissipation of the ice and the plate against the number of impacts (T_2, T_3, T_4)[25]



(b) Energy dissipation ratios (E_{if}/E_{k0}, E_{pf}/E_{k0}) against the number of impacts, where E_{if} is the final dissipated energy of ice and E_{pf} is the final absorbed energy of plate which is also the total plastic strain energy of plate[25]

Fig.11 Energy dissipation of the ice and energy dissipation ratios against the number of impacts

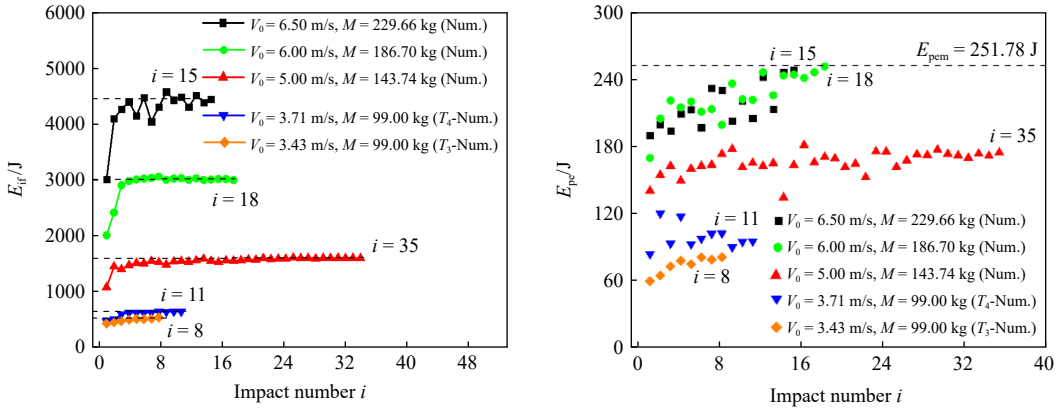
For the structures under repeated rigid ice impacts, since the ice will dissipate the impact energy by deformations and damage during impact, the energy criterion for the achievement of pseudo-shakedown of the structure subjected to repeated ice impacts was proposed by Cai et al[25] as follows

$$E_{k0} \leqslant E_{iRm} + E_{pem} \tag{2}$$

where E_{k0} is the initial impact energy, E_{pem} is the maximal elastic strain energy which the deformed structure can store before rupture and E_{iRm} is the finally stable value of dissipated energy of ice in repeated impacts, which depends on the initial impact energy and the relative strength of plate and ice. Some numerical studies on the steel plates subject to repeated ice impact were conducted by Cai et al[25] to obtain the approximate values of E_{iRm} and E_{pem}, as shown in Fig.12. Through a series of numerical simulations for the ice-structure impact with larger initial impact energies, the approximate elastic strain energy of the structure can be obtained. Due to energy dissipation of ice, it is easier for the structure under repeated ice impacts to reach a pseudo-shakedown state than that under repeated rigid mass impacts under the same impact conditions.

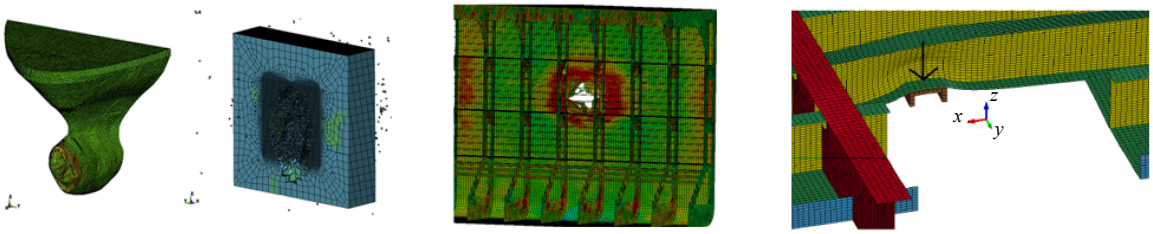
In the past 10 years, several significant numerical works for the ice-structure collision have been reported. For example, Liu et al[18] simulated the collision between ship bow and iceberg, as shown in Fig.13(a). During the collision, the ship bow and iceberg shared the total dissipated energy, and the iceberg dissipated most of the energy. Gao et al[19] also conducted numerical simulations on a side structure of a tanker impacted with an iceberg, as shown in Fig.13(b). Li et al[29] investigated the responses of LNGC's cargo containment system (CCS) under iceberg collision, as shown in Fig 13(d). The displacement of CCS

was mainly rigid body displacement caused by inner hull structure, while some local deformations appeared at the cleat and intersection area. An elastic-plastic ice model was implemented in a user-defined subroutine VUMAT and used the cohesive element in a numerical solution by Yu et al[10] to study the behavior of stiffened plate subject to the impact of a wedge-shaped ice. It was shown that the stiffened steel panels sustained large plastic deformation without rupture, demonstrating a strong capacity against large ice loads, as seen in Fig.13(e).

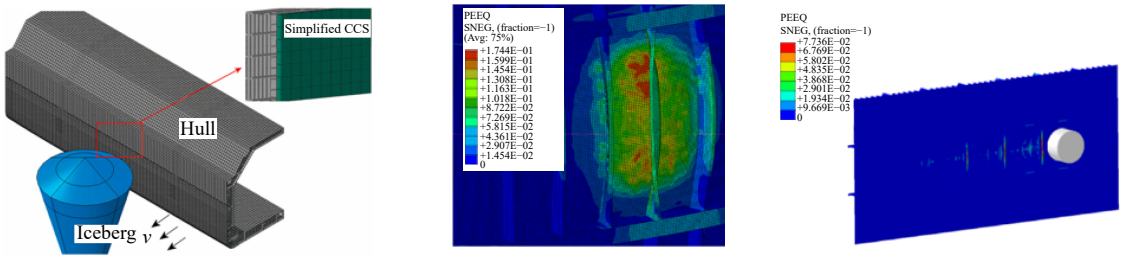


(a) Final dissipated energy of ice　　(b) Elastic strain energy of plate[25]

Fig.12 Final dissipated energy of ice and elastic strain energy of plate obtained numerically



(a) Bow and iceberg deformation[18]　　(b) Impact damage of side structures[19]　　(c) Simulation of sliding ice loads on the grillage structure by using a rigid indenter[30]



(d) Numerical model of LNGC's cargo containment system (CCS) under iceberg collision[29]　　(e) Plastic strain distribution of stiffened plate under ice impact[10]　　(f) Simulation of sliding ice loads on ship structure[21]

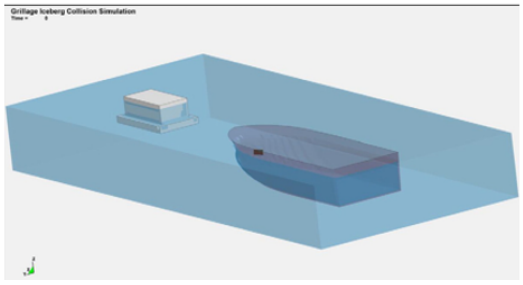
Fig.13 Numerical simulations of ice-structure collision

Ship structures will be impacted by ice floes at the vicinity of the waterline. In this case, the ice impacts tended to move along the hull due to relative motions between the ship and the ice floes. Quinton et al[30] simulated the response of the grillage under sliding ice loads by using a rigid indenter instead of an ice body, as shown in Fig.13(c). It appeared that moving loads may cause significantly more severe structural damage than the purely normal loads. In order to take the realistic ice load into account, a dynamic 4D pressure

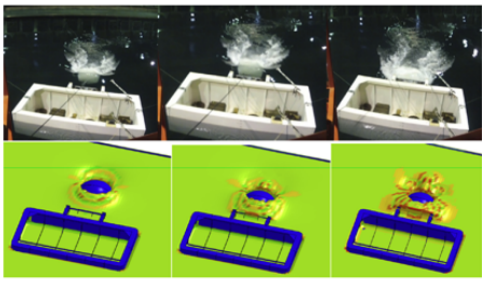
model, and a "crushable foam" ice model were adopted by Quinton et al[31] in subsequent studies. Results from simulations using these realistic models agreed with the findings of the previous work. Moreover, Zhang et al[21] used the subroutine VUMAT to simulate the sliding impact between an ice floe and a ship hull structure in ABAQUS, as shown in Fig.13(f). The effects of static structure-to-structure friction coefficient and the relative stiffness between ice and structure were studied. It was found that the deformation of structures would increase the total friction coefficient, which was defined as the ratio of the friction force (the tangential contact force) to the normal contact force. From the above studies, it can be inferred that the ice loads induced by the sliding impact can cause greater damage to structures compared to normal loads. Therefore, the sliding ice load should be given due consideration in the structural design process of polar ships under ice floe impacts.

Numerical simulations of ship-ice collision that considers structure-ice-fluid interactions have always been challenging. Numerical simulations of a collision between a tanker and a bergy bit considering hydrodynamics were conducted by Gagnon et al[32], as shown in Fig.14(a). Realistic movement of the bergy bit due to the vessel's bow wave prior to contact with the ice was observed and the damage to the grillage resembled the published results from actual grillage damage tests. Song et al[33] used fluid-structure interaction (FSI) method to simulate the experiment of ship-ice collisions in a water tank conducted by Kim et al[8], as shown in Fig.14(b). In the experiment, the bow wave accelerated the floater prior to impact and reduced the relative velocity between the floater and the ice mass at the instant of contact. This reduced the demand for energy dissipation in the ice mass and the structure. The FSI method simulates this interaction effect quite well. Yu et al[34] proposed a numerical solver for coupled simulation of glacial ice impacts accounting for the effects of hydrodynamic-ice-structure interaction. Fig.14(c) show snapshots of the ice cube motions in water during and after collisions. The solver enables more realistic simulation of structural damage to ships and offshore structures under combined indentation and sliding ice loads. Besides, Feng et al[35] developed a coupled SPH-FEM model of a stiffened panel structure on a ship side subjected to a massive ice floe in water, as shown in Fig.14(d). The coupled SPH-FEM method integrated with an elastoplastic constitutive model is implemented to simulate the fracture failure of ice. The hydrodynamic effect of the surrounding water is considered based on the SPH model. The impact force and the wave disturbance phenomena of the numerical simulation show similarities with those of the documented experimental results.

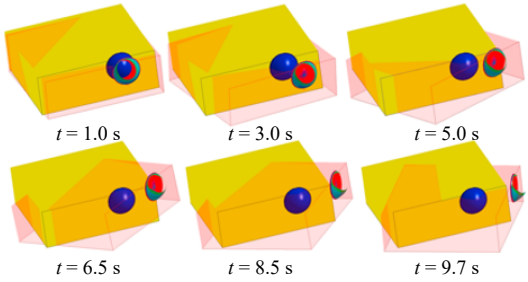
Among numerical methods, the discrete element method has been acknowledged as a valid numerical tool for ice load prediction. Coupling the discrete element method (DEM) and finite element method (FEM) to study the interaction between ice and structures is adopted by some scholars. A strong coupled DEM-FEM model was adopted by Ji et al[36] to investigate the impact of ice load and ice-induced vibration on the monopile foundation of OWT (Offshore Wind Turbine) during the crushing process of sea ice, as shown in Fig.15(a). It was found that the time series of ice force at a higher velocity of ice indicates strong randomness, whereas the time series of ice force at lower velocity presented a sawtooth shape including the periodic loading and unloading processes. Yang et al[37] developed a coupled DEM-FEM model to investigate the interaction between an ice block and a propeller, as shown in Fig.15(b). The ice and propeller were simulated using the sphere-based DEM and hexahedral solid elements of the FEM, respectively. During ice-propeller milling, the thrust, torque, displacement, and stress of the propeller change periodically with the blade frequency, and the amplitude changes were small. The maximum stress and displacement of each blade were located on the leading edge.



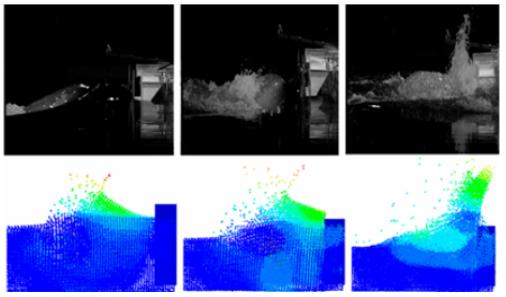
(a) Collision between the bergy bit and a tanker submerged in the water[32]



(b) Simulation of ship-ice collisions in the water tank by FSI method[33]

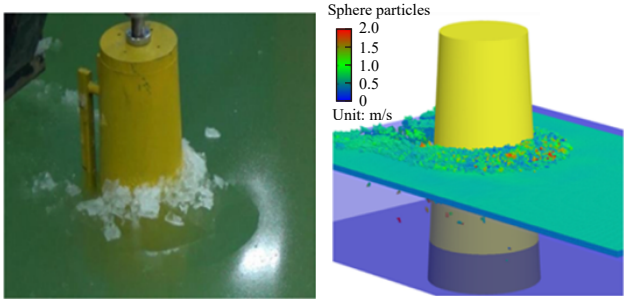


(c) Snapshots of ice motions during and after collisions[34]

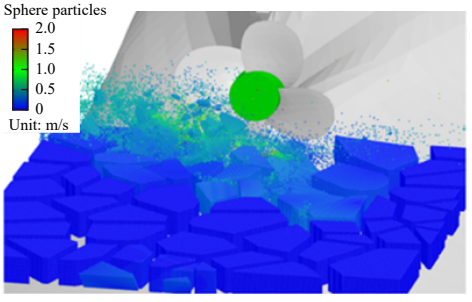


(d) Simulation of ship-ice collisions in the water tank by coupled SPH-FEM method[35]

Fig.14 Numerical simulations for ice-structure collision in a water tank



(a) Model test and numerical simulation on the dynamic responses of the monopile foundation of OWT during the crushing process of sea ice[36]

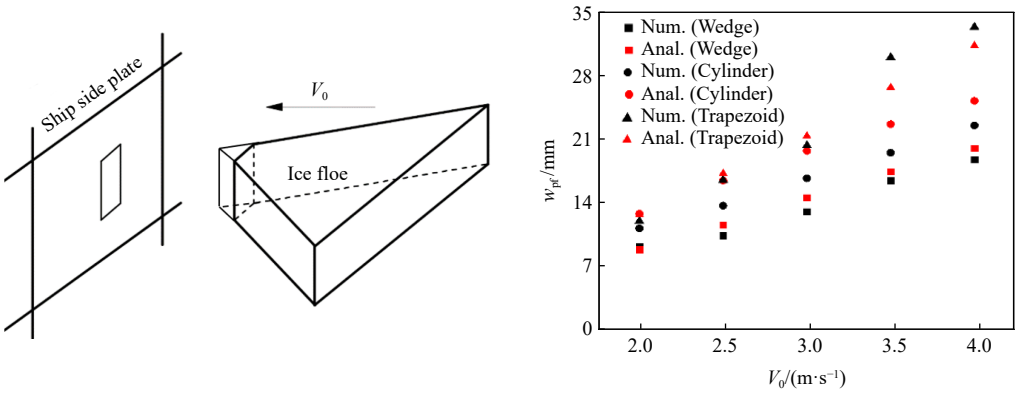


(b) Simulation of interaction process between ice and propeller[37]

Fig.15 DEM-FEM model

3 Theoretical work on large plastic deformation prediction of ship side plate under ice impact loading

An approximate theoretical method based on the rigid-plastic solutions and the energy approach of ice crushing was developed by Cai et al[38] to predict the large plastic deformation of ship plates subjected to ice impact loading using assumed impact scenarios between ship plates and ice floes, as shown in Fig.16(a). The ice-plate impact scenario assumes a head-on collision between a vertical side structure and an ice floe, ignoring the effect of ship motion and ice rotation during impact. The plate under the extreme ice floe impact will generate some significant plastic deformations. In this case, both the colliding bodies of ship plate and ice floe will dissipate the impact energy by forming significant deformations or damages. The analysis process of the developed theoretical model for ice-plate impact responses is illustrated in Fig.17[38].



(a) Simplified ice-plate impact scenario

(b) Comparisons of numerical and theoretical obtained plastic deformations of plates[38]

Fig.16 Simplified ice-plate impact scenario and comparisons of numerical and theoretical obtained plastic deformations of plates[38]

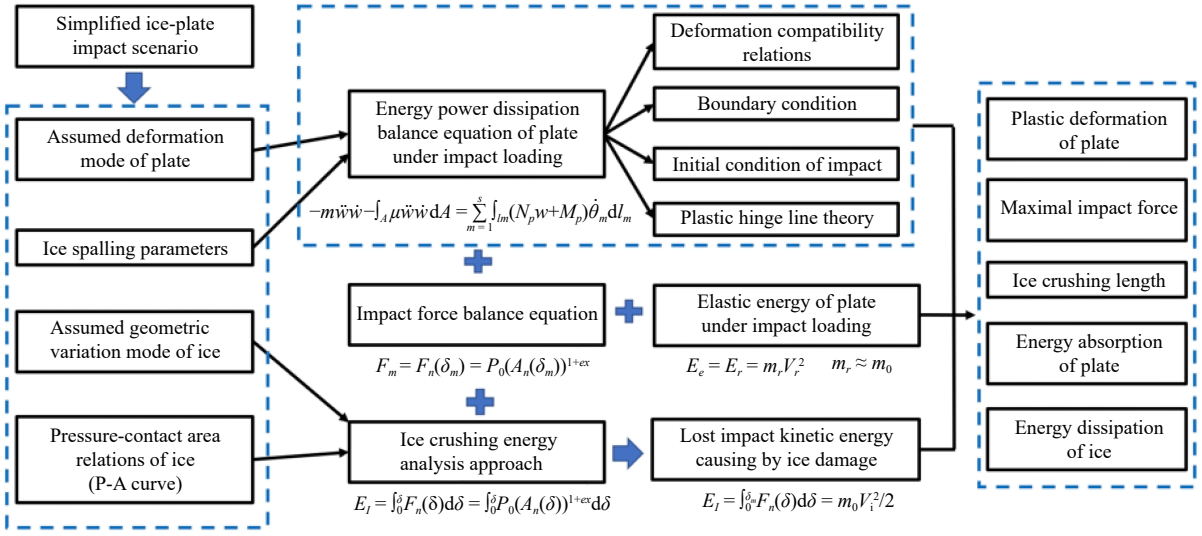


Fig.17 Introduction of the developed theoretical model for predicting ice-plate impact responses

Based on the developed analytical method, the maximal impact force, plastic deformation of plate, ice crushing length and energy dissipation of ice and plate can be obtained. The comparisons of numerical and theoretical obtained plastic deformations of plates shown in Fig.16(b) indicate that the developed analytical method has a high accuracy to predict the dynamic responses of ship plates under ice floe impact loading.

The applicable range of the proposed analytical model is summarized as follows:

-Head-on collisions of an ice floe with a vertical plate structure;

-Ignoring the effect of ship motion and ice rotation during impact;

-The assumed boundary condition of plate structure is fully clamped.

The proposed analytical formulations can provide a useful tool for quick assessment of the plastic damage extent of ship plate under ice floe impact loading.

4 Plastic design method for ship structures under ice floe impact

Elastic theory is only applicable to structure design under the premise that the material does not yield, but local loads that cause yielding cannot represent the maximum load a structure can support. Besides, using

elastic design method leads to a large structural thickness, resulting in heavy weight and high cost. Generally, structures can withstand a local load several times greater than the elastic limit load before they can be considered to fail in any significant way. Considering that a structure with small permanent deformations caused by local loading still has a carrying capacity, the plastic design method introduced can be applied in the structural design under ice impact loading by defining an allowable permanent set. The rigid-plastic analytical method for metal structure subjected to repeated mass impacts can provide a useful tool in structural plastic design. Zhu et al[39] proposed a new method to design the polar ship plates which are frequently subjected to repeated impact from ice floes. They utilized an illustrative design example to illustrate the plastic design method for ship plates under repeated impacts and gave some related design formulae and curves to determine thicknesses of ship plates under repeated ice impacts based on rigid-plastic analytical solutions for repeated impacts as reported in Ref. [40]. Under the given design requirements for allowable permanent deformations, the plate thickness can be determined according to two design curves as shown in Fig.18, where W_{2f} is the maximum permanent deflection for second impact, H is the thickness of plate, and B_0 is the width of short side of plate.

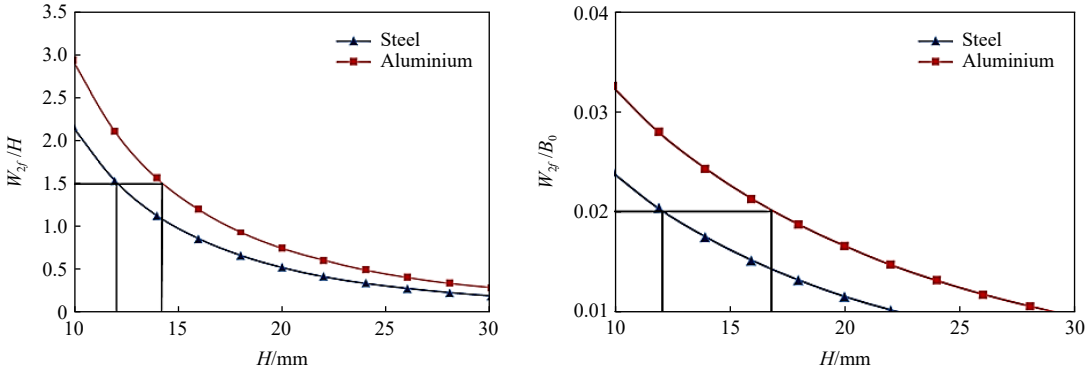


Fig.18 Plate thickness design curves for repeated impact loadings under two design requirements[39]

Until now, the repeated ice impact loading effects on the structural response have not yet been explicitly considered in relevant classification societies' rules, but more attention needs to be paid by designers to the hazard of the large permanent deformations caused by repeated impacts.

5 Conclusions

This paper mainly reviews the recent research progress on dynamic inelastic response of polar ship structures subjected to ice floe impact. A series of laboratory ice impact tests, numerical simulations and theoretical solutions to study plastic behavior of ship plates under single and repeated ice impacts were conducted in the past 10 years. It is worth noting that, we carried out a large number of original experiments on scaled steel plate specimens repeatedly impacted by laboratory-made freshwater ice to study and reveal the plastic deformation accumulation mechanisms, energy-sharing mechanisms and pseudo-shakedown phenomenon of ship plates. Moreover, we extended the rigid-plastic method in ship collision to ship-ice collision considering the energy dissipation caused by ice failure in the impact process. Combining the energy approach of ice crushing with a simplified rigid-plastic theoretical solution, an approximate analytical method was proposed to predict the plastic damage of a ship plate against an ice floe impact, which can provide a useful and convenient tool for the estimation of plastic damage of ship plates subjected to ice floe impact.

Based on the analytical solutions for inelastic response of ship plates under ice impact, some plastic design formulae and curves were derived to determine the plate thickness of ship plates under ice impact loading, which can provide useful references for the structural design of ice-going ships.

References

[1] International Standard. International Standardization Organization. Petroleum and natural gas industries-Arctic offshore structures, ISOTC67/SC7/WG 8, Final draft: ISO/CD 19906[S]. 2010.

[2] Amdahl J. Impact from ice floes and icebergs on ships and offshore structures in polar regions[C]//IOP Conference Series: Materials Science and Engineering. IOP Publishing, 2019, 700(1): 012039.

[3] Gagnon R E. Analysis of data from bergy bit impacts using a novel hull-mounted external impact panel[J]. Cold Regions Science and Technology, 2008, 52: 50–66.

[4] Ritch R, Frederking R, Johnston M, et al. Local ice pressures measured on a strain gauge panel during the CCGS Terry Fox bergy bit impact study[J]. Cold Regions Science and Technology, 2008, 52(1): 29–49.

[5] Määttänen M, Marjavaara P, Saarinen S, et al. Ice crushing tests with variable structural flexibility[J]. Cold Regions Science and Technology, 2011, 67(3): 120–128.

[6] Wu G, Kong S, Tang W, et al. Statistical analysis of ice loads on ship hull measured during Arctic navigations[J]. Ocean Engineering, 2021, 223: 108642.

[7] Manuel M, Gudimetla P S R, Daley C, et al. Controlled plastic deformation of a grillage using artificial freshwater ice at large scale[C]//Proceedings of the 22nd International Conference on Port and Ocean Engineering under Arctic Conditions (POAC 2013). Espoo (Finland), 2013.

[8] Kim E, Storheim M, Amdahl J, et al. Laboratory experiments on shared-energy collisions between freshwater ice blocks and a floating steel structure[J]. Ships and Offshore Structures, 2017, 12(4): 530–544.

[9] Ince S T, Kumar A, Park D K, et al. An advanced technology for structural crashworthiness analysis of a ship colliding with an ice-ridge: Numerical modelling and experiments[J]. International Journal of Impact Engineering, 2017, 110: 112–122.

[10] Yu T, Liu K, Wang G, et al. A tri-axial ice model for simulating ice-stiffened panel impact: Experiments and numerical modeling[J]. Marine Structures, 2023, 88: 103358.

[11] Sun J, Huang Y. Investigations on the ship-ice impact: Part 1. Experimental methodologies[J]. Marine Structures, 2020, 72: 102772.

[12] Gagnon R E, Andrade S L, Quinton B, et al. Pressure distribution data from large double-pendulum ice impact tests[J]. Cold Regions Science and Technology, 2020, 175: 103033.

[13] Zhu L, Cai W, Chen M, et al. Experimental and numerical analysis of elastic-plastic response of ship plates under ice floe impacts[J]. Ocean Engineering, 2020, 218: 106174.

[14] Bi L, Zhu L, Cai W. Effect of ice crushing characteristics on plastic deformation of ship plate under ice impact[C]//31st International Ocean and Polar Engineering Conference, International Society of Offshore and Polar Engineers (ISOPE), 2021.

[15] Cai W, Zhu L, Yu T X, et al. Numerical simulations for plates under ice impact based on a concrete constitutive ice model[J]. International Journal of Impact Engineering, 2020, 143: 103594.

[16] Gagnon R E. A numerical model of ice crushing using a foam analogue[J]. Cold Regions Science and Technology, 2011, 65(3): 335–350.

[17] Kim H, Daley C, Colbourne B. A numerical model for ice crushing on concave surfaces[J]. Ocean Engineering, 2015, 106: 289–297.

[18] Liu Z, Amdahl J, Løset S. Plasticity based material modelling of ice and its application to ship-iceberg impacts[J]. Cold Regions Science and Technology, 2011, 65: 326–334.

[19] Gao Y, Hu Z, Ringsberg J W, et al. An elastic–plastic ice material model for ship-iceberg collision simulations[J]. Ocean Engineering, 2015, 102: 27–39.

[20] Yu Z, Amdahl J. A numerical solver for coupled dynamic simulation of glacial ice impacts considering hydrodynamic-ice-structure interaction[J]. Ocean Engineering, 2021, 226: 108827.

[21] Zhang J, Liu Z, Ong M C, et al. Numerical simulations of the sliding impact between an ice floe and a ship hull structure in ABAQUS[J]. Engineering Structures, 2022, 273: 115057.

[22] Mokhtari M, Kim E, Amdahl J. Pressure-dependent plasticity models with convex yield loci for explicit ice crushing simulations[J]. Marine Structures, 2022, 84: 103233.

[23] Ma D, Li X, Manes A, et al. Numerical modelling of ice: Mechanical behaviour of ice under high strain rates[J]. International Journal of Impact Engineering, 2022, 172: 104375.

[24] Polach R B, Ehlers S. Model scale ice—Part B: Numerical model[J]. Cold Regions Science and Technology, 2013, 94: 53–60.

[25] Cai W, Zhu L, Qian X D. Dynamic responses of steel plates under repeated ice impacts[J]. International Journal of Impact Engineering, 2022, 162: 104129.

[26] Zhu L, Wang X, Guo K, et al. Effects of indenter geometry on pseudo-shakedown of steel plates under repeated mass impacts[J]. International Journal of Impact Engineering, 2024, 185: 104865.

[27] Jang H, Hwang S, Lee J. Experimental evaluation and validation of pressure distributions in ice-structure collisions using a pendulum apparatus[J]. Journal of Marine Science and Engineering, 2023, 11(9): 1761.

[28] Zhang J, Huang F, Liu H, et al. Experimental study on collision of hull plate model and ice in water medium[J]. Journal of Ship Mechanics, 2020, 24(4): 492–500.

[29] Li M, Wan Z, Yuan Y, et al. A numerical method for analysing the responses of cargo containment system of an LNGC under iceberg collision[J]. Ships and Offshore Structures, 2023, 18(6): 1–14.

[30] Quinton B, Daley C, Gagnon R. Effect of moving ice loads on the plastic capacity of a ship's structure[C]//International Conference and Exhibition on Performance of Ships and Structures in Ice. Anchorage, Alaska, 2010.

[31] Quinton B, Daley C, Gagnon R. Realistic moving ice loads and ship structural response[C]//International Society of Offshore and Polar Engineers (ISOPE), Rhodes, Greece, 2012.

[32] Gagnon R E, Wang J. Numerical simulations of a tanker collision with a bergy bit incorporating hydrodynamics, a validated ice model and damage to the vessel[J]. Cold Regions Science and Technology, 2012, 81: 26–35.

[33] Song M, Kim E, Amdahl J, et al. A comparative analysis of the fluid-structure interaction method and the constant added mass method for ice-structure collisions[J]. Marine Structures, 2016, 49: 58–75.

[34] Yu Z, Lu W, Van den Berg M, et al. Glacial ice impacts: Part II: Damage assessment and ice-structure interactions in accidental limit states (ALS)[J]. Marine Structures, 2021, 75: 102889.

[35] Feng Y, Li H, Ong M C, et al. Numerical investigation of collision between massive ice floe and marine structure using coupled SPH-FEM method[J]. Ships and Offshore Structures, 2023, 18(3): 380–390.

[36] Ji S, Yang D. Ice loads and ice-induced vibrations of offshore wind turbine based on coupled DEM-FEM simulations[J]. Ocean Engineering, 2022, 243: 110197.

[37] Yang D, Liu L, Ji S. Numerical analysis of interaction between sea ice and propeller based on coupled DEM-FEM model[J]. Ocean Engineering, 2023, 268: 113469.

[38] Cai W, Zhu L, Gudmestad O T, et al. Application of rigid-plastic theory method in ship-ice collision[J]. Ocean Engineering, 2022, 253: 111237.

[39] Zhu L, Shi S, Yu T X. A new ice load-response model for structural design of ice classed ships[C]//The Twenty-fifth International Ocean and Polar Engineering Conference, OnePetro, 2015.

[40] Zhu L, Faulkner D. Damage estimate for plating of ships and platforms under repeated impacts[J]. Marine Structures, 1995, 9(7): 697–720.

极地船舶结构在浮冰冲击下动态非弹性响应研究进展

朱　凌[1,2], 郭志涵[1,2], 蔡　伟[3]

（1. 高性能舰船技术教育部重点实验室(武汉理工大学), 武汉 430063; 2. 武汉理工大学 船海与能源动力工程学院, 武汉 430063; 3. 武汉理工大学 材料复合新技术全国重点实验室, 武汉 430070）

摘要: 极地船舶结构遭受极端浮冰撞击事件在冰区是非常常见的, 冰体冲击载荷下结构的非弹性变形直接反映了结构的损伤状态, 是结构强度评估和设计中一个重要而方便的参数。因此, 本文旨在回顾极地船舶结构在浮冰冲击下动态非弹性响应的最新研究进展, 介绍一些关于研究船体板在单次和重复冰体冲击载荷下动态塑性响应的重要实验、数值和理论工作。通过比较冰体和刚性质量块冲击下的结构响应, 评估冰体变形和损伤特性对船体板塑性变形能量吸收的影响。此外, 还探讨船体板在相同重复冰体冲击下的塑性变形累积和能量共享机制以及伪安定现象。基于冰体冲击下船体板非弹性响应的解析解, 提出一些可确定冰体冲击载荷下船体板厚塑性设计公式和曲线, 可为冰上航行船舶结构设计提供有用的参考。

关键词: 极地船舶结构; 浮冰冲击; 非弹性响应; 塑性设计

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作者简介: 朱　凌(1962−), 男, 武汉理工大学教授, 博士生导师;

郭志涵(1998−), 男, 武汉理工大学博士研究生;

蔡　伟(1996–), 男, 武汉理工大学副研究员, 通讯作者, E-mail: caiwei199696@whut.edu.cn。