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Interaction between sea ice/iceberg and ship structures: A review

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Abstract For ship structural design and good maneuverability in an ice-covered sea, the local and global load of ice cover on ships should be well understood. This paper reviews the extensive work done on ice loads on ships, including: (a) Ice pressure and local load determination based on field and model tests; (b) Global ice loads on ships from full-scale field observations, model tests and numerical models under different ice conditions (level ice and pack ice) and ship operations (maneuvering and mooring). Special attention is paid to the discrete element simulation of global ice loads on ships; and (c) Analytical solutions and numerical models of impact loads of icebergs on ships for polar navigation. Finally, research potential in these areas is discussed.

Keywords **sea ice, iceberg, local ice load, global ice load, ship hull, experiment, numerical simulation**

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0 Introduction

Structural design and maneuvering performance of ships have been comprehensively studied as polar expeditions, oil-and-gas exploitation and feasibility studies of Arctic navigation have been carried out in recent years[1-2]. Currently, only limited research activities on the ice-ship interaction is carried out in China, and this hinders future Chinese research activities and navigation in polar regions.

The satisfactory determination of local ice load and ice pressure on ship structures is important for the design of ship structures. Recently, the relationship between ice pressure on hull and contact area was validated with measured data[3-6]. Local impact and global resistance of sea ice or icebergs on ships are the two major issues in ship's design and navigation in ice-covered waters. Ships may mainly encounter four types of ice conditions, namely, level ice, broken ice, ice ridges and icebergs. Work on ice ridge-ship interaction is still limited. Ice resistance is closely related to ship's maneuvering performance, and computation of this resistance is different for mooring, straight-forward transit, turning and zig-zag maneuvers[7-11]. Moreover, ice loads are influenced by ice failure modes, marine dynamic characteristics, sea ice mechanical properties and ship's structure.

Ice loads on ships have been extensively studied through measurements in the field, model tests in ice basin and numerical simulations. In numerical simulations of ice-ship interaction, the finite element method (FEM) was commonly adopted[11-14]. However, much attention has recently been paid to the discrete element method (DEM) for efficient simulation of broken ice dynamics during ice-ship interaction. DEM used in conjunction with the FEM has strong advantages in describing the ice structure at micro-scale, and reasonably modeling the ice breaking and ice clearing dynamics at macro-scale, and thus obtaining a representation of the whole ice loading process.

Therefore, this paper aims at providing a state-of-the-art literature review on the area of ice loads on ships. It consists of the following sections on local ice loads, global ice loads and iceberg loads on ships.

1 Ice pressure and local ice load on ships

Ice pressure and local ice load on ship hull is one of the

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most important factor for determining ship hull's scantling strength. Ice class rules provide design ice loads for different ice classes and use these design ice loads to determine the scantling design requirements. There are many ice class rules issued by maritime authorities and classification societies, using different methods to define design ice loads. Among these rules, the most used ice class rules are the Finnish and Swedish Ice Class Rules (FSICR) issued by Finnish and Swedish maritime authorities[15]. In FSICR, the design ice loads are based on measurement experience and historic statistical data for ships traveling in first-year ice conditions in Baltic Sea. The design ice loads in FSICR have very short return period to match the elastic requirements for hull structures. There is no specific ship/ice interaction scenarios are considered. In FSICR, many important factors affecting actual ice loads on the hull are not considered, such as hull form angles, ice strength in different regions etc. FSICR design loads can not be used for multi-year ice which is common in Arctic area. The Unified Requirements for Polar Class (Polar UR) issued by International Association of Classification Societies (IACS) provide design ice loads for ships traveling in both first-year and multi-year ice conditions[16]. The design ice loads in Polar UR are based on glancing ship/ice interaction scenario in which hull and ice floe have tangent impact to each other, using the energy-balance theory and calibrated with historical measurement data. The design ice loads in Polar UR depends on ship hull form angles (waterplane and frame angles), ship speed, ice crushing and flexural strength, etc. To check hull strength under ice loads for polar ships with scenarios other than glancing, industry need to use different ice load models to calculate proper ice loads[17].

While ice class rules provide design ice loads for scantling design, the design ice loads from ice class rules are far from enough to assess hull strength under ice loads with many different operational conditions, since ice loads on a ship's hull are complicated process that involves failure of ice in various modes. Research works are performed not only to improve design ice loads in existing ice class rules, but also to provide ice load assessment for situations not covered by rules. These works include both experimental measurement and simulations.

Local pressure data collected from instrumented panels installed on ship hulls are important sources of information to assist in the estimation of global ice loads for ship design. Based on fracture mechanics, the ice impact load on ship structures is a function of the size of the loaded area[18]. The understanding of the relationship between ice load, ice pressure and area of contact is of importance.

Model tests on two ship models were carried out in the Aalto ice tank, and the statistical characteristics of ice crushing pressure during impact were studied[6]. Local peak loads were analyzed for each time step, yielding information on maximum load measured on a tactile sensor. Peak pressure profiles along the ship's waterline were calculated from four sensor sheets located at different positions on the hull. For the general cargo ship, the sensors were placed in bow shoulder, midship, aft shoulder and aft locations. Line loads, q, decrease as a function of increasing load width, and the relationship can be written as

$$q = C\left(\frac{L_C}{S}\right)^{-a} \tag{1}$$

where q is the line load (unit: $\mathrm{N \cdot m^{-1}}$); C is the mean and mean plus two times the standard deviation of the line load with the smallest load width (unit: $\mathrm{N \cdot m^{-1}}$), s is a constant, having the value of 11.0 mm, L_C is the load width, and a is also a constant. The line load data obtained from the model tests were scaled to full-scale by multiplying a geometrical scale factor to allow for the comparison with full-scale field data.

Field measurement is the most commonly used method to study the problem since ice pressure can be obtained without influence of scale effect. Taylor et al.[4] and Li et al.[5] performed probabilistic analyses of local ice loads measured at the full-scale trials. Taylor et al. used the event-maximum method to analyze the local pressure[4], while Li et al. adopted the up-crossing rate method[6]. Both of them determined the local ice pressure as

$$F_z(z) = \exp\left\{-\exp\left[-\frac{z - x_0 - x_1}{a}\right]\right\} \tag{2}$$

where z is the maximum pressure per unit time. Initially, the variable x_0 was found to be close to zero. For the parameter x_1, there are a few functions which can be used depending on different field loading conditions.

- Based on the data of the Molikpaq structure in the Beaufort Sea, $x_1=\mathrm{a}\ln(\mathrm{m})$, where m is the expected number of events[19].
- Based on the data of the icebreaker Polar Sea in the Beaufort Sea, $x_1=\mathrm{a}\ln T_\mathrm{d}$, where $T_\mathrm{d} = \sum_{i=1}^{N} t_i\left(\frac{A}{A_\mathrm{L}}\right)$, where t_i is the duration of the i^th event, A and A_L are the instrumented area (or expected ice impacting area) and local area of interest in design, respectively[5].

The parameter a represents the functional relationship between pressure and area. From the analysis performed by Jordaan et al., it can be written as[3]

$$\mathrm{a}=1.25a^{-0.7} \tag{3}$$

where a is the nominal contact area. This relationship was also found to be appropriate for multi-year ice[19]. With the up-crossing rate method, the functional relationship for a and a was determined as $\mathrm{a}=0.363a^{-0.668}$ [5].

The measured crushing pressure–nominal contact area relationships were summarized based on the various ice crushing tests as shown in Figure 1. The measured bow pressures seem to be below the envelope curve represented by[6]

$$P=P_0A^{-\mathrm{b}} \tag{4}$$

where the pressure P is in MPa and the area A in $\mathrm{m^2}$. This relationship is called the pressure-area curve (PAC). Based on the comparison with full-scale measurements onboard MS Arcturus and IB Sisu, it was found P_0=0.42 and b = 0.52.

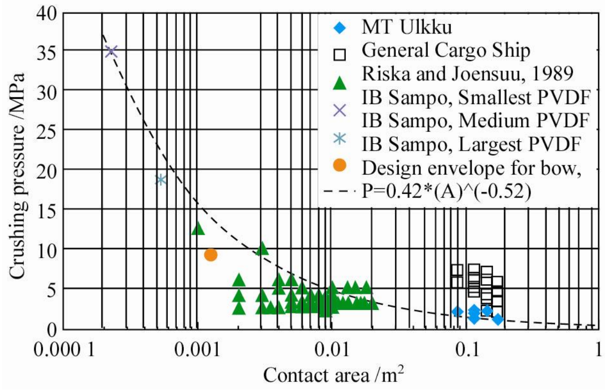

Figure 1 Pressure-area values obtained from crushing test results from IB Sampo, MT Uikku, a general cargo ship[6,20].

In order to take the experimental data into full consideration, two simultaneous processes during local crushing were considered: Ice crushing as a solid body in direct ship-ice contact, and the extrusion and dispersion of finely crushed ice particles. To describe the extrusion process, a hydrodynamic model of a solid body impacted by ice was modified to reconcile with field experimental data on the icebreaker CCGS *Louis S. St-Laurent* [21].

During full-scale ice-ship interaction in compression, most of the load is transmitted to a ship structure at high-pressure zones (HPZs) that are distributed in the interaction area. Wells et al. performed laboratory indentation tests to study the pressure distribution at the ice-indenter interface[22]. The center area was found to consist of isolated zones of very high pressure compared to the average pressures found during the tests. These peaks in pressure varied in intensity throughout the test, analogous to the behavior seen during medium and full-scale tests. Ulan-Kvitberg et al. also performed crushing tests to study ice pressure distributions on steel plate under different indentation speeds[23]. The force histories and pressure-area curves were determined with various shaped ice indenters. Besides the ice pressure on ship structures due to level ice, the local ice loads from rafted ice and ridged ice were also investigated for the polar regions[24-25].

2 Global ice load on ships

It is important to estimate both local and global ice loads on ships. The global ice load is an integration of local ice loads over the whole hull area that governs the ship’s overall performance in ice.

2.1 Full scale tests

Full-scale field measurements are considered as the most reliable basis for evaluating the magnitude of ice force on ships since ice loading on ship hulls is rather complicated, depending on a variety of factors including the ice conditions, hull geometry and the relative velocity between the ship and the ice. Chernov studied global ice loads on the icebreaker KIapitan Nikolaev with various types of ice features in the “Shtokman-2008” expedition[26]. In order to compute the vertical component of ice loads, stresses caused by longitudinal hull bending in vertical plane were measured. Frederking analyzed the influence of operational conditions (ship speed and power) and ice conditions (ice concentration, ice thickness and floe size) on ice impact load based on field ice data of the icebreaker CCGS *Louis S. St-Laurent* gathered in 1995[27]. Time series of measured loads were used to obtain the maximum force of each impact, as well as the impulse associated with it. The results show ice impact forces are related to the floe mass, ice concentration and ship speed, and the duration of an ice impact was directly related to the magnitude of the maximum force. The relationships between ice load and ice concentration, as well as ship speed are plotted in Figure 2.

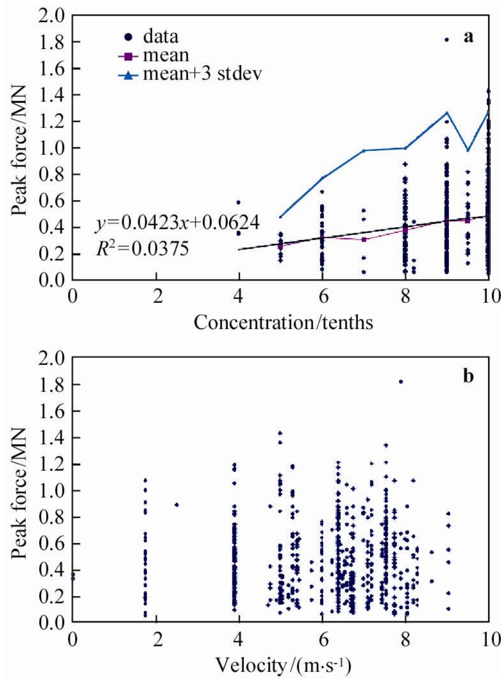

Figure 2 Impact force as a function of ice concentration (**a**) and ship velocity (**b**)[27].

Based on the full-scale measurement data obtained on board KV Svalbard in 2007, Suyuthi et al. presented results of ship resistance on first-year level ice in the Barent Sea[28]. Measurements were made of the ice thickness, ship speed and power setting. The ice thickness was measured by means of an electromagnetic device, which enables careful selection of the time sequences for which level ice was present. By utilizing Newton’s 2nd law and the conservation of energy, the relationship between the ship resistance and the ship speed was obtained and compared with Lindqvist’s ice resistance formulation. The formulation agrees well with ship resistance in thin ice; however, it overpredicts resistance in the thick ice cases. The reason for this discrepancy is not fully understood.

The ice loading process has a clear stochastic nature due to the variation in ice conditions and in the ice-breaking process. It is important to determine the main parameters that can be used as a basis for reliable probabilistic ice load models. Kujala et al. analyzed the short-term maximum values of ice-induced loads on MT Uikku, a typical cargo ship navigating in ice in the Baltic Sea[8]. The hull was instrumented to measure the ice-induced loads along the hull. The mean and standard deviations of the peak ice loads were related to the maximum ice thickness. The analysis reveals that Weibull distribution gives the best representation of the measured statistical distributions.

Probabilistic analysis of the short-term extreme ice loads acting on ship hull was investigated with data obtained from full-scale measurement onboard the Norwegian coast guard vessel KV Svalbard during the winter of 2007[29]. The available data include discrete peak amplitude time histories of estimated ice impact loads as well as corresponding ice thickness measurements in addition to ship speed and course. As an integral part of an Ice Loads Monitoring (ILM) system, the short-term prediction of ice load is very important in relation to the tactical navigation plan.

2.2 Model tests

A series of model tests of the USCGC *Healy* (WAGB-20) were carried out by NCR (National Research Council of Canada), and correlated with full-scale data. A complete set of resistance, propulsion and maneuvering model tests of the vessel were carried out for correlation with the full-scale data[30-32]. One of the objects of the model tests was to determine the effect of ice strength on the delivered power necessary for the Healy to meet her icebreaking specification.

Currently, model tests are deemed to be the best method to study ice actions on ships. In MOERI, ice model tests were carried out in 2009 to study ice resistance on an icebreaker[33]. The tests were conducted in level and pre-sawn ice. With increasing speed, the heave and pitch motions decrease, and the average resistance of a free model converges to the average resistance measured on the same model in constrained condition. The ice flexural strength and ice thickness are important factors influencing ice resistance. With these model tests, the ice resistance prediction formula was developed for this model.

Aksnes and Bonnemaire conducted model tests on a moored ship in level ice, and studied the response and mooring forces caused by changes in ice drift direction in three types of ice drift scenarios, straight drift, drift along circular arcs and sudden changes in drift direction[34]. The magnitude of the peak mooring force caused by drifting level ice was comparable to the peak mooring force caused by a relatively large first-year ice ridge. Woolgar and Colbourne studied the pack ice loading on moored ships by conducting scale model tests. Special interest was shown on the influence of the hull-ice friction coefficient[35]. The relationship between pack ice force and hull-ice friction coefficient was shown to be approximately a fourth root function. The model tests also considered the factors of ice floe size and ice concentration. The resulting non-dimensional equation provides insight on relationships between the predicted pack ice force and the variables under investigation. Applying the modified equation to the previous data sets showed the current analysis slightly improves the normalization of pack ice forces, as shown in Figure 3. The formulation provides a framework for pack ice force analysis, but test data are still required from individual vessels to enable full-scale predictions.

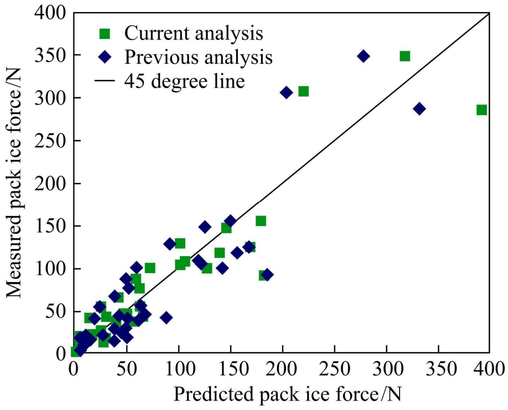

Figure 3 Measured pack ice force versus predicted pack ice force[35].

Aksnes developed a dynamic model of a moored ship in level ice to study the response and mooring forces with constant drift direction, based on the local ice forces formulation established with model tests[36-37]. The dynamic surge response of the ship was investigated by varying the ice drift speed and the surge natural period.

The ice-hull interaction load was separated into ice breaking, rotation and sliding components. Two treatments of ice forces based on measurements were introduced, one for the ice actions near the waterline, and one for ice actions on wet surfaces of the hull. A simplified formulation for forces near the waterline caused by breaking and rotation of ice floes was based on four random variables. An algorithm to extract these variables from the measured data was given. Probability distributions were fitted to the random variables and the distributions were analyzed with respect to the mooring stiffness and the ice drift speed. This model can be extended to variable ice drift direction.

2.3 Numerical simulations

With respect to numerical simulations of global ice loads on maneuvering ships, Valanto computed ice loads on the design waterline (DWL) of several vessels with his program VENICE to obtain ice load distributions on ship hulls advancing straight ahead and turning in level ice[38]. The maximum forces on the design waterline of the Swedish

Coast Guard Ship *KBV-181* were computed and compared with ice load distributions measured in model scale. The computed distributions were also compared with the design line load distributions used in the Finnish-Swedish ice rules and in the Polar Class rules. The ice load distributions on the design of vessel *Aurora Borealis* were computed with the program VENICE in HSVA in 2008, giving useful information on the ice load distribution on the ship hull.

A numerical method to simulate ship maneuvering in ice regions was developed based on quasi-finite element model by Su et al.[10,13,39-40]. The ship hull and ice edge were discretized into a number of nodes, and the discretized ship hull was a closed polygon. At each time step, the program collected ice nodes which were inside this hull polygon, and every contact zone was found. The coupling between ice forces and ship motions was considered, and a system of three degree-of-freedom rigid body equations of surge, sway and yaw were solved by numerical integration. The instantaneous ice forces and ship motions in both straight ahead and turning operations were calculated. Figure 4 shows the ice forces computed for the turning operation. The ice resistance measured from ice trials was also recorded. The mean value of ice force was higher in the turning condition. The numerical analysis was validated by comparison with ship performance data from the full-scale ice trials data of icebreaker AHTS/IB Tor Viking Ⅱ showing good agreement. Su et al. then simulated a ship moving forward in either uniform or randomly varying ice conditions with the numerical model developed above[10,13]. The thickness and strength properties of ice encountered by the ship were assumed to be constant or randomly generated using the Monte Carlo method. To validate the numerical results, an icebreaking tanker, MT Uikku, was modeled in the simulation program. Three different steering angles (5°, 15° and 30°) were used for the simulation of turning operations. The ice loading process was stochastically reproduced and the calculated amplitude values of the ice-induced frame loads were compared with field measurements. With this numerical model, the global ice load on ice hull can be effectively simulated under maneuvering performances in level ice.

Recently, Sayed and Kubat studied ship transit through pressured ice conditions with particle in cell method[14]. The plastic yield of ice cover was based on a cohesive Mohr-Coulomb criterion with a tension cut-off. Pressured ice conditions were modeled by allowing a shear force (representing wind drag) to compress an ice cover of initial uniform thickness against a straight land boundary. A ship was then introduced and moved parallel to the land boundary at a constant velocity. The simulation results show that both the velocity of the ship and the magnitude of the confining pressure have significant effects on ice force. The study also examined the dependence of ice forces on ship velocity and ice thickness.

To simulate the process of ship-ice interaction in real-time, a real-time simulating model was developed by Lubbad et al.[41]. The simulator is divided into smaller subsystems that are coupled together and communicate through a network. The Mathematical Ice Model (MIM) calculates the ice forces. The Mathematical Ship Model (MSM) receives inputs and computes new states for position, forces, torques, velocities and accelerations. These updated states are displayed by the Visual System. The real-time simulator was validated with a model test (interaction between a downward conical structure and ice sheet performed in HSVA carried out in 2009) and full-scale test (the icebreaker KV *Svalbard* in the Norwegian Arctic carried out in 2007—2008), respectively[41]. The validation tests exhibited a satisfactory agreement between the model calculations and experimental measurements.

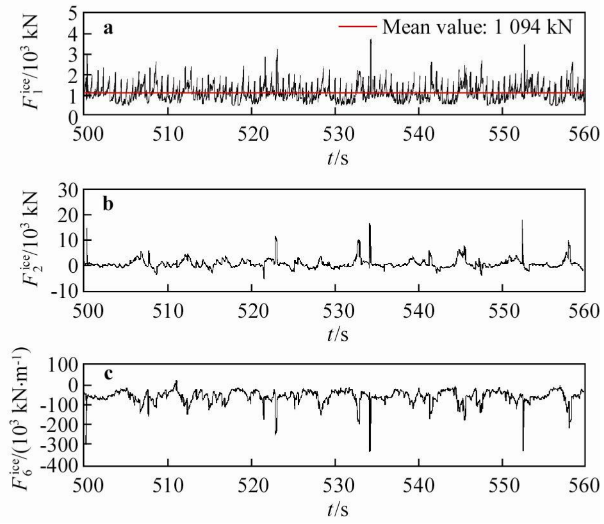

Figure 4 Ice forces in turning operation (in 0.6 m thick ice)[39]. **a**, Ice force in surge direction. **b**, Ice force in sway direction. **c**, Ice moment in yaw direction.

Regarding numerical simulations of global ice loads on moored ships, Aksnes established a 1-D model for the hands-on interaction between a moored ship and drifting level ice with the assumption that surge motion dominated the response[12]. The ice force was computed as a function of ship's penetration and relative velocity, utilizing both the elastic beam theory and friction theory. The ship was modeled with a single degree of freedom, with hydrodynamic and mooring forces in addition to the ice forces. A parametric study was performed for both the ice force model and the ice-ship interaction model. Comparisons with model tests showed that the numerical model predicted comparable load levels. The formulation for the penetration dependent part of the ice force was investigated to understand the relative significance of each parameter. The ice thickness, friction coefficient and ice density had a large influence on the mean force. This parametric study could be applied in planning of model basin tests.

Zhou et al. studied the dynamic ice forces on a moored icebreaking tanker induced by drifting level ice[42]. The mooring force and responses of the moored vessel were investigated through parametric studies with different ice thicknesses and ice drift speeds. Zhou et al. then modeled the ice-breaking process using a geometrical method that characterizes the contact zones between the hull of moored structure and the ice sheet[11]. Ice rotating and sliding forces were modeled semi-empirically using ship ice resistance formulations. The numerical model predicted the time history of both ice forces and global mooring forces as well as the dynamics of the floating structure. The simulation results obtained were compared with full-scale measurements and model test data on the Kulluk platform conducted in the Beaufort Sea during the 1980s. The simulated loads show fairly good agreement with the full-scale measurements as shown in Figure 5, although some scatter exists. The mean mooring force increases monotonically with ice thickness. This model was also used to study the influence of turret position on the stability of a moored icebreaking tanker (MT Uikku) under typical varying ice drift speeds and directions.

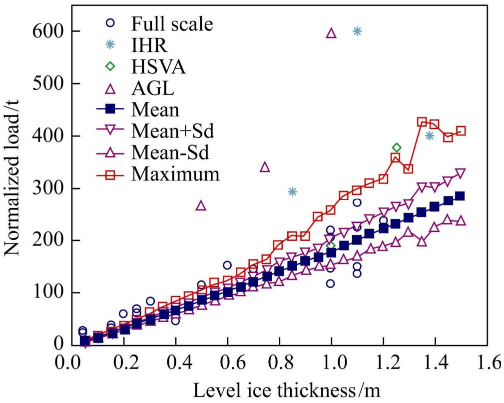

Figure 5 Comparison of simulated, full-scale and model test measured loads in level unbroken ice[11].

2.4 Discrete element simulations

Recently, the discrete element method (DEM) has been applied in the ice-ship interaction. Hansen and Loset first adopted 2-D disk DEM and studied ice loads on a ship in broken ice[43]. Konno and Konno et al. studied the ice resistance for ship navigating in a brash ice channel[44-45]. The sea ice floes were modeled with spherical and cubic particles, thus the ice cover can be modeled in one layer or two layers in regular packing, or random packing. With three different averaged ice sizes, the channel resistances were simulated. Results show that arrangement of ice pieces does not significantly affect the ship resistance. Effect of the ratio of spherical and cubic ice pieces in the channel was also investigated.

Zhan et al. simulated ship maneuvering in ice covered waters with the Ship Maneuvering Laboratory (SML) program and the DEM model (DECICE)[7]. The ship maneuvering performances (turning circle and zig-zag maneuvers) were simulated with the two programs. The comparisons with sea trial of Esso Osaka and numerical results from Seoul National University (SNU) were presented. Comparisons and discussion of the simulated results between cases with and without ice were also provided. NRC also conducted a variety of ice-ship and ice-structure interaction simulations using DECICE[46]. One of the simulations involves the Canadian icebreaker Terry-Fox moving forward and turning in level ice. The results show effects of ice conditions and ship motion on the computed forces and moments. The predictions were in good agreement with model test measurements obtained at NRC. The interaction of the ship hull and leading ice edge consisted of breaking of the ice followed by the submergence and subsequent clearing. These results were also typical of that observed in model tests. The predicted and measured moments were in good agreement. Moreover, Lau introduced the software OSIS-IHI (Ocean Structure Interaction Simulator—Ice-Hull Interaction) to model a ship maneuvering in a field of level ice. This software had been validated with extensive model and full-scale data, and was found satisfactory in marine simulator and ship design applications[47].

Sawamura et al. developed a 2-D model and a 3-D model to simulate the interaction between ice floe and ship[9]. The motions of the broken ice floes were described by the 3DOF rigid body motion in the 2-D simulation and 6DOF in the 3-D one. The ice pieces and the ship hull were represented by the small contact-spheres which were utilized to detect the contact point between two bodies. The contact force between the broken ice piece and the ship hull was dealt with by the impulsive response. The numerical results (Figure 6) show that the simulation can describe the mechanism of the rotating and sliding of the ice pieces qualitatively, and has high potential to satisfactorily estimate the submerging component in ice resistance.

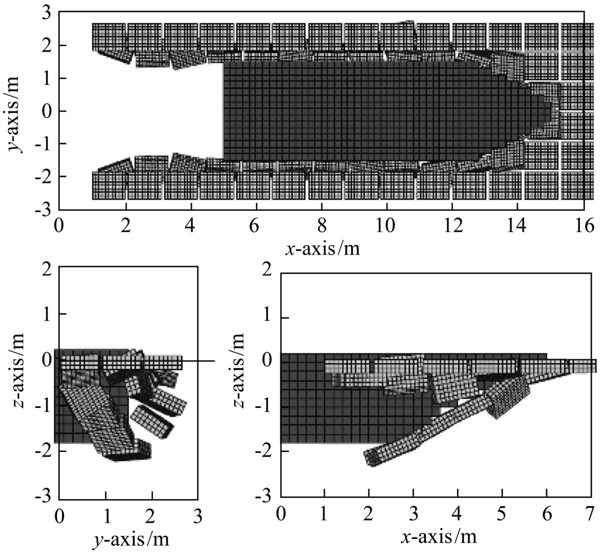

Figure 6 Ship advancing into the broken ice field simulated with 3-D model[9].

Karulin and Karulina investigated the behavior of a tanker moored to a point terminal under a change of ice drift direction using DEM simulation[48]. The broken ice was represented by a set of floating disks interacting with each other as viscous-elastic bodies. Model tests were carried out in the ice tank of the Krylov Institute, St. Petersburg. The mean dimension of ice floes was 100 mm× 100 mm. The disks' diameter was assigned 100 mm, the disk thickness 20 mm, and the ice concentration 80% similar to that used in the model tests. The results of numerical calculations were compared with experimental data. It shows that the numerical model may be used for analysis of moored tanker behavior in drifting ice.

3 Iceberg load on ships

The probability of collisions between ships and icebergs should be considered in Arctic and Antarctic regions. The assessment of loads caused by iceberg impacts is an important issue for ship designers. The knowledge about the iceberg shape and a continuum mechanics model of icebergs, in addition to iceberg mass and speed is required for a realistic design against an accidental iceberg impact.

In the analytical solution of ship-iceberg collision, the ship structure was assumed as a perfectly rigid body. Daley and Kim extended the standard approach by including the local plastic deformation[49]. This approach is more consistent with actual risk levels and consequences, and may provide a tool for regulation.

Liu and Amdahl developed a material model for iceberg ice based on the plasticity theory, and the "erosion" technique was employed to simulate the crushing of the iceberg[50]. The analysis was split into an assessment of external mechanics and internal mechanics. The result of external mechanics was the demand for energy dissipation. The separating of the external and internal mechanics of ship-iceberg collision problems simplified the numerical simulations significantly. Liu et al. further performed an integrated elasto-plastic analysis of ship-iceberg collisions based on continuum mechanics modeling of both bodies[51]. Liu et al. comprehensively studied the evolution of contact pressure and the distribution of damage to the foreship and crushing of the iceberg[52]. Moreover, considering the influences of iceberg shape, impact location on ice pressure, the temperature profile of icebergs and the failure criterion, based on effective plastic strain and hydrostatic pressure, both local and global contact pressures were investigated. The simulated results of iceberg-bow collision are shown in Figure 7. The numerical model and results can be applied to integrated analysis of iceberg impacts in the Accidental Limit State analysis.

Based on the simulated results of collision between a foreship structure and an iceberg with the nonlinear finite element method, Liu et al. further adopted the Bayesian Networks to estimate the iceberg impact loads on foreship and the corresponding damages[53]. The impact energy of ship-iceberg collisions and the damage originated in the ship's structures was assessed. The energy levels modeled are thereafter associated with extents of the damage in the ship.

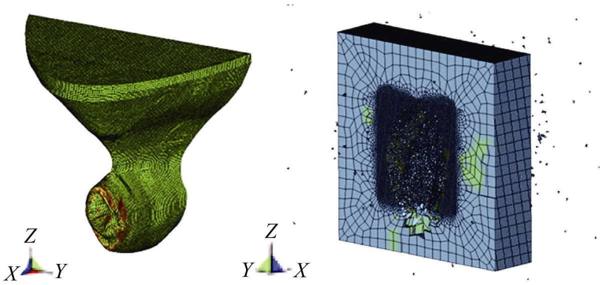

Figure 7 Bow and iceberg deformation[52].

Kim et al. studied collision between iceberg and side wall of LNG carrier ship using the nonlinear dynamic FE program LS-DYNA[54]. The simulated results were compared with collision experiments to verify the result of the simulation. In the collision, high stress areas were discussed based on numerical and experimental results. The safety and integrity of LNG carriers were assessed with the results. The comparative safety assessment of cargo containment systems for independent type (spherical and SPB) and membrane type (Mark-III and NO96) LNG carriers was performed through a numerical simulation and the related experimental work. Gagnon has done extensive research on numerical simulation of iceberg impacts. The so-called "crushable foam" material type was adopted to simulate ice crushing[55]. It is a promising method; however, it has not yet been applied to integrated analysis. Karlinsky and Chernetsov studied the impact of iceberg on floating production unit (FPU) with energy method[56]. Iceberg drifting velocity and mass dominated its kinetic energy, and the motion of the FPU impacted by an iceberg absorbed the energy. With the method, the impact force and absorbed energy of iceberg were calculated. It suggested that in case of unavoidable contact with a middle-sized iceberg or a large-sized hummock, it is advisable to reduce tension of the mooring lines, which will increase energy absorption of the mooring system during the first phase of interaction.

4 Conclusions

The state-of-the-art of sea ice loads on ships is reviewed based on published literature. Future works can be focused on the following points.

(1) Local ice pressure on a hull is a key issue to determine the global force on ships. With full-scale field tests and model tests, the relationship between ice pressure and contact area has been established. Further numerical models should be developed to describe the characteristics of ice pressure on a hull.

(2) Ice conditions are quite different in different field regions. Besides level ice, local and global loads on a hull should be established under actions of ice ridge, pancake ice, etc.

(3) During the impact process of ice cover on a ship hull, three stages of bending/breaking, rotating and sliding were identified, and the dynamic ice load function for each stage was established. However, the dynamic process for

the interaction between ice cover and the side of a ship is still an open problem.

(4) Different operation states of ships, maneuvering and mooring, should be further studied. For the maneuvering operation, ice loads on ships during transiting and turning operations should be studied. Moreover, for different operating states, global and local loads are different in different locations on the ship hull.

(5) In numerical simulations based on continuum mechanics, the ship structure can be treated as a rigid body or deformable body, and the sea ice as continuum media or discrete materials. In numerical simulations based on DEM, ice parameters, such as floe shapes, size, frictions, concentrations, etc., can be modeled appropriately. Moreover, DEM models can be applied for level ice or pancake ice. Nevertheless, effective numerical models should be developed with reliable computational parameters.

(6) The impact of iceberg on a ship hull is of interest for ship designs and operations. Numerical simulation is an effective approach to determine the impact load and the damage to a ship hull. It is necessary to consider the deformation of the ship structure in numerical modeling.

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References

1 Ibrahim R A, Chalhoub N G, Falzarano J. Interaction of ships and ocean structures with ice loads and stochastic ocean waves. Applied Mechanics Review, 2007, 60(5): 246-290.

2 Chircop A. Climate change and the prospects of increased navigation in the Canadian Arctic. Journal of Maritime Affairs, 2007, 6(2): 193-205.

3 Jordaan I J, Maes M A, Brown P W, et al. Probabilistic analysis of local ice pressures. Journal of Offshore Mechanics and Arctic Engineering, 1993, 115(1): 83-89.

4 Taylor R S, Jordaan I J, Li C, et al. Local design pressure for structures in ice: analysis of full-scale data. Journal of Offshore Mechanics and Arctic Engineering, 2010, 132(3): 031502-1-7.

5 Li C, Jordaan I J, Taylor R S. Estimation of local ice pressure using up-crossing rate. Journal of Offshore Mechanics and Arctic Engineering, 2010, 132(3): 031501.

6 Kujala P, Arughadhoss S. Statistical analysis of ice crushing pressures on a ship's hull during hull–ice interaction. Cold Regions Science and Technology, 2012, 70: 1-11.

7 Zhan D, Agar D, He M, et al. Numerical simulation of ship maneuvering in pack ice. Proceedings of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering, 2010, Shanghai, China, OMAE2010-21109.

8 Kujala P, Suominen K, Riska K. Statistics of ice loads measured on MT Uikku in the Baltic. Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions. 2009, Luleå, Sweden.

9 Sawamura J, Tachibana T. Development of a numerical simulation for rotating and sliding of the ice floes along a ship hull. Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions, 2011, Montréal, Canada, POAC11-036.

10 Su B, Riska K, Moan T. Numerical simulation of local ice loads in uniform and randomly varying ice conditions. Cold Regions Science and Technology, 2011, 65(2): 145-159.

11 Zhou L, Su B, Riska K, et al. Numerical simulation of moored structure station keeping in level ice. Cold Regions Science and Technology, 2012, 71: 54-66.

12 Aksnes V. A simplified interaction model for moored ships in level ice. Cold Regions Science and Technology, 2010, 63(1): 29-39.

13 Su B, Riska K, Moan T. Numerical study of ice-induced loads on ship hulls. Marine Structures, 2011, 24(2):132-152.

14 Sayed M, Kubat I. Forces on ships transiting pressured ice covers. Proceedings of the 21st International Offshore and Polar Engineering Conference. 2011, Hawaii, USA.

15 TraFi. Finnish and Swedish Ice Class Rules. Finnish Transport Safety Agency, 2010.

16 IACS. Unified Requirements for Polar Class. International Association of Classification Societies, 2010.

17 ABS. Guidance Notes on Ice Class. American Bureau of Shipping, 2012.

18 Kivisild H R, Blanche D, Revill C R. Ship/ice Intention pressures and energies during ship ramming. Journal of Offshore Mechanics and Arctic Engineering, 1989, 111: 361-368.

19 Jordaan I, Bruce J, Masterson D, et al. Local ice pressures for multiyear ice accounting for exposure. Cold Regions Science and Technology, 2010, 61(2): 97-106.

20 Riska K, Joensuu A. Ice-structure contact. Helsinki University of Technology. Report M-88. 1989, Otaniemi (in Finnish).

21 Appolonov E M, Didkovsky A V, Kuteinikov M A, et al. Improvement in design models for ice load evaluation under vessel impact against ice. Ships and Offshore Structures, 2011, 6(3): 249-256.

22 Wells J, Jordaan I, Derradji-Aouat A, et al. Small-scale laboratory experiments on the indentation failure of polycrystalline ice in compression: Main results and pressure distribution. Cold Regions Science and Technology, 2011, 65(3): 314-325.

23 Ulan-Kvitberg C, Kim H, Daley C. Comparison of pressure-area effects for various ice and steel indenters. Proceedings of the 21st International Offshore and Polar Engineering Conference Maui, Hawaii, USA, June 19-24, 2011

24 Daley C G. Oblique ice collision loads on ships based on energy methods. Oceanic Engineering International, 2001, 5(2): 67-72.

25 Daley C G. Re-analysis of Polar Sea ice pressure-area relationship. Marine Technology, 2007, 44(4): 234-244.

26 Chernov A V. Measuring total ship bending with a help of tensometry during the full-scale in situ ice impact study of icebreaker “kapitan nikolaev” . Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions, 2009, Luleå, Sweden, POAC09-027.

27 Frederking R. Ice loading on a ship in discontinuous ice. Proceedings of the 20th International Offshore and Polar Engineering Conference, 2010, Beijing, China.

28 Suyuthi A, Leira B J, Riska K. Full scale measurement on level ice resistance of icebreaker. Proceedings of the 30th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2011), 2011, Rotterdam, the Netherlands.

29 Suyuthi A, Leira B J, Riska K. Variation of the short term exterme ice loads along a ship hull. Proceedings of the 29th International Conference on Ocean, Offshore and Arctic Engineering, 2010, Shanghai, China. OMAE2010-20326.

30 Jones S J, Lau M. Propulsion and maneuvering model tests of the USCGC Healy in ice and correlation with full-scale. 7th International Conference and Exhibition on Performance of Ships and Structures in Ice, 2006, Banff, Alberta, IR-2006-04.

31 Jones S J, Moores C. Resistance tests in ice with the USCGC Healy. Ice in

the Environment: Proceedings of the 16th IAHR International Symposium on Ice Dunedin, New Zealand, 2nd—6th December 2002.

32 Johnston M, Timco G, Frederking R, et al. Whole-ship motions of USCGC Healy as applied to global ice impact forces. Proceedings of the 16th International Conference on Port and Ocean Engineering under Arctic Conditions POAC'01, 2001, Ottawa, Canada.

33 Jeong S, Lee C, Cho S. Ice resistance prediction for standard icebreaker model ship. Proceedings of the 20th International Offshore and Polar Engineering Conference,Beijing, China, 2010.

34 Aksnes V, Bonnemaire B. Analysis of the behaviour of a moored ship in variable ice drift. Proceedings of the 20th International Conference on Port and Ocean Engineering Under Arctic Conditions. 2009, Lule, Sweden, POAC09-25.

35 Woolgar R C, Colbourne D B. Effects of hull–ice friction coefficient on predictions of pack ice forces for moored offshore vessels. Ocean Engineering, 2010, 37(2): 296-303.

36 Aksnes V. A panel method for modelling level ice actions on moored ships. Part 1: Local ice force formulation. Cold Regions Science and Technology, 2011, 65(2): 128-136.

37 Aksnes V. A panel method for modelling level ice actions on moored ships. Part 2: Simulations. Cold Regions Science and Technology, 2011, 65(2): 137-144.

38 Valanto P. On computed ice load distributions, magnitudes and lengths on ship hulls moving in level ice. Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions. 2009, Lulea, Sweden. POAC09-60.

39 Su B, Riska K, Moan T. A numerical method for the prediction of ship performance in level ice. Cold Regions Science and Technology, 2010, 60: 177-188.

40 Su B, Riska K, Moan T. Numerical simulation of ship turning in level ice. Proceedings of the 29th International Conference on Ocean, Offshore and Arctic Engineering, 2010, Shanghai, China OMAE2010-20110.

41 Lubbad R, Loset S. A numerical model for real-time simulation of ship–ice interaction. Cold Regions Science and Technology, 2011, 65(2): 111-127.

42 Zhou L, Su B, Riska K, et al. Numerical simulation of moored ship in level ice. Proceedings of the 30th International Conference on Ocean, Offshore and Arctic Engineering, 2011, Rotterdam, The Netherlands, OMAE2011-49115.

43 Hansen E H, Loset S. Modelling floating offshore units moored in broken ice: comparing simulations with ice tank tests. Cold Regions Science and Technology, 1999, 29(2): 107-119.

44 Konno A. Resistance evaluation of ship navigation in brash ice channels with physically based modeling. Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions. 2009, Lulea, Sweden.

45 Konno A, Saitoh O, Watanabe Y. Numerical investigation of effect of channel condition against ship resistance in brash ice channels. Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions. 2011, Montréal, Canada.

46 Lau M, Lawrence K P, Rothenburg L. Discrete element analysis of ice loads on ships and structures. Ships and Offshore Structures, 2011, 6(3): 211-221.

47 Lau M. Ship manoeuvring-in-ice modeling software OSIS-IHI. Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions, 2011, Montréal, Canada, POAC11-138.

48 Karulin E B, Karulina M M. Numerical and physical simulations of moored tanker behaviour. Ships and Offshore Structures, 2011, 6(3): 179-184.

49 Daley C, Kim H. Ice collision forces considering structural deformation. Proceedings of the 29th International Conference on Ocean, Offshore and Arctic Engineering, 2010, Shanghai, China, OMAE2010-20657.

50 Liu Z, Amdahl J. A new formulation of the impact mechanics of ship collisions and its application to a ship–iceberg collision. Marine Structures, 2010, 23(3): 360-384.

51 Liu Z, Amdahl J, Loset S. Integrated numerical analysis of an iceberg collision with a foreship structure. Marine Structures, 2011, 24(4): 377-395.

52 Liu Z, Amdahl J, Loset S. Plasticity based material modelling of ice and its application to ship–iceberg impacts. Cold Regions Science and Technology, 2011, 65(3): 326-334.

53 Liu Z, Garee L, Amdahl J. Analysis of foreship and iceberg impact loads based on Bayesian networks. Proceedings of the 30th International Conference on Ocean, Offshore and Arctic Engineering, 2011, Rotterdam, the Netherlands, OMAE 50028.

54 Kim J, Oh H, Kim D. Safety assessment of cargo containment systems in LNG carriers under the impact of iceberg-ship collision. Proceedings of the 30th International Conference on Ocean, Offshore and Arctic Engineering. 2011, Rotterdam, The Netherlands.

55 Gagnon R E. A numerical model of ice crushing using a foam analogue. Cold Regions Science and Technology, 2011, 65(3): 335-50.

56 Karlinsky S L, Chernetsov V A. Production ship resistance to iceberg impact study. Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions, 2011, Montréal, Canada, POAC11-041.