Numerical Study of Ice Loads on Ship Hulls in Ridged Ice Fields

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Summary

A numerical model is introduced to investigate both global and local ice-induced loads on ship hulls in first-year ridged ice fields. Probabilistic ice fields are generated according to the statistical distributions of ridge height and spacing. Based on a semi-empirical method, the cycles of contact, crushing, and bending constitute continuous icebreaking processes by which a numerical model of ship-ice interaction in level ice and consolidated layer in ice ridges can be developed. The ridge keel is regarded as a floating, homogeneous and isotropic granular solid. Keel resistance can be predicted based on ideas borrowed from soil mechanics: the bow component is calculated as an integral of resistance per unit width with a modified Rankine's plasticity model, including consideration of the effect of ship movement and inertia force of ice accumulation in front of ship bow. The computation in this simulation is time-saving compared to DEM model used to simulate ship and ridge keel interaction in recent years. The numerical global and local ice loads are discussed through results of a case study conducted in a series of different ice conditions. Ship performance and statistics of ice-induced frame loads are analyzed. Comparisons are made of the simulated results against published results of model tests and field measurements in ridged ice fields.

1. Introduction

Ice ridges are common ice features, appearing especially in dynamic ice conditions. It is believed that 40% of all sea ice is ridged ice¹⁾, formed when level ice floes are compressed and sheared by environmental driving forces such as wind and currents. An idealized first-year ice ridge is presented in Fig. 1. Piling up of broken ice rubble occurs above and below the parent ice sheet, which represents the hydrostatic equilibrium. Consequently, the keel formed of rubble under the waterline has a much larger volume than the sail formed of rubble over the waterline. The keel is usually 5–7 times thicker than the sail. Water filling the pores between ice pieces often refreezes, forming a consolidated layer downward. Its growth rate is higher than that of the surrounding level ice.

Ice ridges constitute a significant obstacle and often control the design load levels for ships operating in ice-covered waters. Sometimes the keel depth can exceed the ship draft. In such cases, much energy is consumed by displacing ice blocks. For that reason, it is important to predict the ice-induced loads on ice-going ships in ridged ice fields in terms of structural safety and overall operation. Most analytical models of ridge failure divide a ridge into three components: the sail, keel, and consolidated layer. Total loads are obtained as a summation of

them because of each section of the ridge. In practical calculations, the ice loads caused by the sail section are much smaller than those arising from the keel section and consolidated layer, and are therefore usually ignored.

Fig. 1 Idealized first-year ice ridge.

The methods of calculating the ice resistance induced by ridge keels have been based largely on ideas borrowed from soil mechanics theory such as Coulomb's theory and Rankine's theory. Keinonen²⁾ considered ridges as unconsolidated with a constant thickness and proposed an analytical method to calculate the pure ridge resistance based on Coulomb's method. Mellor³⁾ employed Rankine's theory to find the ship resistance in thick brash ice, which is similar to the unconsolidated ridge considered by Keinonen²⁾. In addition, the resistance formula derived by Malmberg⁴⁾ is used extensively in ridged ice section of transit models, which simulates the ship's performance in various ice conditions along specific routes. These analytical methods are used widely to obtain the global ice resistance caused by ridge keels. Moreover, discrete element method (DEM) is applied to model the interaction between ships and ice ridge in some studies. In fact, the DEM is useful to obtain both global and local ice

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loads. Hisette et al.⁵⁾ and Gong et al.⁶⁾ simulated the ship-keel interaction using a three-dimensional DEM with ice pieces represented by polyhedral particles, but such computations can be time consuming even for a single ice ridge. Based on the background presented above, it remains a very difficult task, both numerically and experimentally, to estimate the local ice load on ship hulls in ice fields containing multiple ridges.

Generally speaking, ice loads caused by breaking the consolidated layer are assumed to be the same as level ice loads in the same ice thickness. In most transit models in ridged ice fields, the resistance component attributable to the level ice stretches and consolidated layers is calculated using an empirical level ice resistance formula. Kuuliala et al.⁷⁾ applied the method proposed by Riska et al.⁸⁾, by which the level ice resistance is assumed to be linearly dependent on the ship speed. Lindqvist⁹⁾ divided ice resistance into three terms of crushing, bending, and submergence, and proposed an ice resistance formula, which is widely used as well. Furthermore, a semi-empirical method proposed by Su et al.¹⁰⁾ makes it more realistic to investigate the problem from a time domain perspective in which icebreaking process is idealized as successive contact-crushing-bending cycles; using it, the three degree-of-freedom (DOF) rigid body equations of surge, sway, and yaw are solved. Tan et al.¹¹⁾ extended the planar model of Su et al.¹⁰⁾ to a 6-DOF model, including the effects of ship heave, roll, and pitch motions. This numerical procedure can be a good candidate to calculate ice-induced loads in level ice and a consolidated layer instead of the empirical resistance formula.

In this paper, ice resistance arising from ridge keels are calculated with a modified Rankine's plasticity model as an integral of resistance per unit width, taking account of the effects of ship movement and the inertial force of ice accumulation in front of the ship bow. A semi-empirical time domain solution is introduced to develop a numerical model of ship-ice interaction in level ice and the consolidated layer in ice ridges. A combination of the two numerical approaches above is useful to calculate the time histories of global and local loads in ridged ice fields. Probabilistic modelling of ridged ice fields is used with ridge sails and keels represented as triangles according to the statistical distributions of ridge height and spacing, as presented by La Prairie et al.¹²⁾. The ice-induced loads in different ice thickness can be determined from a series of numerical simulation. Global ice loads and ship performance in different ice conditions are investigated.

Statistics related to ice-induced frame loads are analyzed herein. In earlier work examining statistics of ice loads, Suominen and Kujala¹³⁾ found that the Weibull distribution was the most suitable to describe measurement data on board MS Kemira if the shape parameter equals 0.75. Suyuthi et al.¹⁴⁾ reported that the best fit to the data on the coast guard vessel KV Svalbard was provided by a Weibull distribution with the shape parameter located in the range of 0.7–1.0. In the present study, a Weibull statistical model is applied to represent the ice-induced frame load process obtained from numerical simulation. The statistical results are compared to data measured in the field.

2. Modelling of Ship-Ice Interaction

2.1 Generating Ridged Ice Fields

Ridges are complex structures with wide variation in shape and size, comprising sails, keels, and consolidated layers. For simplification, ice ridges are modelled using triangular sails and keels, separated by stretches of level ice sections. Generally, the consolidated layer has varying thickness, which is 40–70% greater than that of surrounding level ice. Strub-Klein and Sudom¹⁵⁾ report the slope angle for keel α_k presented in Fig. 1 as constant with an average value of 22° . Both the sail height and keel spacing of ice ridges can be modelled as exponential distributions^{16) 17)}. Therefore, Monte Carlo method is used to generate a probabilistic model of ridged ice fields.

The distribution of ridge sail heights¹⁶⁾ can be expressed as

$$p(h_s; h_c, \lambda) = \lambda \exp(-\lambda(h_s - h_c)) \quad (1)$$

where h_s represents sail heights, h_c denotes a cut-off height of sail heights, and λ stands for the shape factor of the distribution i.e. the inverse of mean height of sails higher than h_c . Presumably, the ridge keel depth is, on average, proportional to sail height, i.e., $h_k = ch_s$. Therefore, the probability distribution of keel depths can be written as $p(h_k; h_c, \lambda) = \lambda \exp(-\lambda(h_k/c - h_c))$ based on Eq. (1). As described herein, the ratio c of keel depth to sail height is set as 5¹⁸⁾.

Similarly, keel spacings, i.e. distance between two adjacent ridges can be modelled as an exponential distribution¹⁷⁾.

$$p(d; \mu(h_c)) = \mu(h_c) \exp(-\mu(h_c)d) \quad (2)$$

Therein, d signifies keel spacing, μ is the shape parameter i.e. the expected number of keels per kilometer.

2.2 Motion Equations

Motion equations of ship are described by the equations of motion in 6 DOF. They can be written as

$$(\mathbf{M} + \mathbf{A})\ddot{\mathbf{r}}(t) + \mathbf{B}\dot{\mathbf{r}}(t) + \mathbf{C}\mathbf{r}(t) = \mathbf{F}(t) \quad (3)$$

where $\mathbf{M}$, $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$ respectively represent the mass, added mass, damping and restoring force matrices, $\mathbf{F}$ represents the excitation forces and moments, and $\mathbf{r}$ is the displacement vector of ship. No damping term is included in this simulation.

According to Newmark method and an assumption of linear acceleration in Su et al.¹⁰⁾, three equations can be derived from the motion equation.

$$\dot{\mathbf{r}}(t_{k+1}) = \dot{\mathbf{r}}(t_k) + \frac{1}{2}\ddot{\mathbf{r}}(t_k)\delta t + \frac{1}{2}\ddot{\mathbf{r}}(t_{k+1})\delta t \quad (4)$$

$$\mathbf{r}(t_{k+1}) = \mathbf{r}(t_k) + \dot{\mathbf{r}}(t_k)\delta t + \frac{1}{3}\ddot{\mathbf{r}}(t_k)\delta t^2 + \frac{1}{6}\ddot{\mathbf{r}}(t_{k+1})\delta t^2 \quad (5)$$

$$\mathbf{r}(t_{k+1}) = \left(\frac{6}{\delta t^2}(\mathbf{M} + \mathbf{A}) + \mathbf{C}\right)^{-1}(\mathbf{F}(t_{k+1}) + (\mathbf{M} + \mathbf{A})\left(\frac{6}{\delta t^2}\mathbf{r}(t_k) + \frac{6}{\delta t}\dot{\mathbf{r}}(t_k) + 2\ddot{\mathbf{r}}(t_k)\right)) \quad (6)$$

In those equations, δt stands for the time interval of numerical integration; t_k represents the k th time step. The excitation forces and moments can be decomposed into five components as

$$\mathbf{F} = \mathbf{F}^{\text{level}} + \mathbf{F}^{\text{ridge}} + \mathbf{F}^{\text{p}} + \mathbf{F}^{\text{ow}} + \mathbf{F}^{\text{Euler}} \quad (7)$$

where the superscripts 'level', 'ridge', 'p', 'ow', and 'Euler' respectively refer to ice force due to level ice and ice ridges, propeller and rudder, open water, and a fictitious force induced

using a non-uniformly rotating body-fixed frame. Furthermore, $\mathbf{F}^{\text{ow}}$ can be ascertained using the cross-flow theory¹⁹⁾. The lift and drag coefficients of the rudder can be determined in wind tunnel tests or computations²⁰⁾. The net thrust available to overcome ice resistance can be estimated as

$$T_{\text{net}} = T_B \left(1 - \frac{1}{3} \cdot \frac{u}{v_{\text{ow}}} - \frac{2}{3} \cdot \left(\frac{u}{v_{\text{ow}}} \right)^2 \right) \quad (8)$$

where T_B denotes the bollard pull, u is the forward velocity component, v_{ow} stands for the open water speed. The open water resistance in surge direction has been incorporated in Eq (8).

2.3 Ice-induced Loads in Level Ice

A semi-empirical method is used to develop a numerical model of interaction between a ship and level ice. The cycles of contact, crushing, and bending constitute a continuous icebreaking process.

2.3.1 Contact forces

As the hull contacts with ice edge in level ice sheet, as presented in Fig. 2, local crushing occurs at the contact zones until the ice edge is broken by the bending moment. In each contact zone, a crushing force F_{cr} acts on the ship hull, which is normal to the contact surface. In addition, F_{cr} [kN] can be determined by the contact pressure p_{av} [MPa] and the contact area A_{cr} [m²].

$$F_{\text{cr}} = p_{\text{av}} A_{\text{cr}} \quad (9)$$

A large amount of in-service data demonstrates a decrease of average pressure with increasing contact area²¹⁾. A mathematical model proposed by Palmer²²⁾ gives $p_{\text{av}} = 1.7 A_{\text{cr}}^{0.25}$.

Aside from the crushing force, the hull is also subjected to vertical and horizontal frictional forces. Presumably, no vertical (bending) displacement of the ice wedge exists during crushing. The direction of frictional force is opposite to that of velocity. Therefore, frictional forces are proportional to the relative velocity components based on the resolutions of forces and velocities. These resolutions are dependent on hull angles that include waterline angle and frame angle. The global ice load is an integrated effect of local ice loads over the hull area. For a particular frame, the local line load [kN/m] is calculated by dividing the ice force on this frame by the frame spacing.

Fig. 2 Local contact zones between a ship and a level ice edge.

2.3.2 Bending failure

The vertical force component F_z increases as the ship continues to penetrate into the ice plate. When it exceeds the bearing capacity of the ice edge, P_f , bending failure will occur and a circular ice floe will be broken from the ice plate. Subsequently, a new ice edge develops and the icebreaking process cycle repeats

as the ship travels further.

Bearing capacity P_f is calculable with Kashtelian's method²³⁾.

$$P_f = C_f \left(\frac{\varphi}{\pi} \right)^2 \sigma_f h_i^2 \quad (10)$$

In that equation, φ denotes the open angle of the ideal wedge, σ_f is the flexural strength of ice plate, h_i represents the ice thickness, and C_f is an empirical coefficient. The broken ice floe radius R_i is determined using the formula presented by Wang²⁴⁾ as

$$R_i = C_l l (1.0 + C_v v_n^{\text{rel}}) \quad (11)$$

where $v_{n,2}$ is the velocity component normal to the contact surface, C_l and C_v are empirical parameters, and l is the characteristic length of ice plate given as

$$l = \left(\frac{E h_i^3}{12(1-\nu^2) \rho_w g} \right)^{1/4} \quad (12)$$

where E represents the Young's modulus of ice, ν stands for Poisson's ratio, and ρ_w expresses the density of seawater. For the present study, empirical constant C_f is set as 3.1, which is chosen in Su et al.¹⁰⁾ by comparing the numerical icebreaking force to Lindqvist's ice resistance at different ice thickness. Also, C_l and C_v as referred from Wang are, respectively, 0.32 and 0.25²⁴⁾.

2.4 Ice-induced Loads in Ice Ridges

Ice ridge loads are usually divided into components corresponding to the ridge structure make-ups, including sails, keels, and consolidated layers. The effects of ridge sails on ship resistance are neglected because they are assumed to be much smaller than the forces related to breakage of the consolidated layer and displacement of the keel rubble.

2.4.1 Force attributable to the consolidated layer

The consolidated layer sometimes exerts the greatest forces on structures during ridge-structure interaction. Timco et al.²⁵⁾ reported that, during a ridge interaction, the consolidated layer is usually assumed to fail in a manner similar to a level ice sheet (i.e. the influence of the sail and keel on the behavior are ignored). Therefore, modelling of interaction between the ship and the consolidated layer resembles that in level ice stated as above. The consolidated layer of ridges h_{cl} is assumed to be 1.5 times²⁶⁾ the thickness of the surrounding level ice.

2.4.2 Keel resistance

Keel resistance include two components, respectively due to friction at the mid-ship and displacement of the ice blocks at the bow, which are obtainable by some analytical models based on ideas borrowed from soil mechanics. The keel is regarded as a floating granular solid that is homogeneous and isotropic. The calculations of these two components are presented as following.

The mid-ship resistance component R_m caused by friction is given according to Malmberg⁴⁾, as shown below.

$$R_m = C_m T \int_{L_m} \left(h_r(x) + \left(\frac{h_r(x)}{T} - 0.5 \right) B \right) dx \quad (13)$$

In that equation, L_m stands for the length of parallel mid-ship, C_m is a constant dependent on the Poisson's ratio, which is set as 45.9 kg/m²s² in the simulation according to La Prairie et al.¹²⁾. Also, $h_r(x)$ represents the ridge depth beneath a point along the mid-ship at any moment, T denotes the draught, and B is the breadth at waterline. Factor $(h_r(x)/T - 0.5)$ is non-negative, i.e. taken as zero

when $h_r(x) < 0.5T$. This formula is useful to calculate global loads as an integral along the whole mid-ship part, and to calculate the local loads as an integral on a specified frame at mid-ship.

The resistance component because of displacement of the ridge keel at the bow can be found using Rankine's theory. The Rankine theory is limited to the conditions of a vertical pushing plate and a horizontal or semi-infinite sloping surface. However, 1) for this study, the keel opening angle and the waterline half-angle are not large (keel angle $\alpha_k = 22^\circ$, and waterline half-angle $\beta = 23.6^\circ$ are set in the simulation). Therefore, the slope angle of ridge surface normal to cross sections (A-A plane) is less than 10° . Consequently, it presumably does not introduce too much inaccuracy to treat the ridge surface normal to A-A plane as horizontal. In addition, 2) undertaking the ship bow as a slender wedge, the ice will simply pile up against the ship bow until the resistance reaches the value for a vertical plate, and thus frame angle is not included in bow-keel interaction. Based on those two reasons above, it is reasonable to assume that Rankine's plasticity model can be available for the interaction of each A-A plane and the ice ridge surface.

The bow-keel interactions can be divided into two cases, i.e. the ridge height at a certain point is smaller than and larger than the draught. In the case that the ridge height at a certain point is less than the draught, based on Rankine theory, as depicted in Fig. 3, the bottom figure shows the cross-section view of A-A plane. A rupture plane forms at each A-A plane in the ridge when the ship moves forward. Mellor³⁾ derived the bow resistance per unit width R attributable to normal force, which is expressed as shown below.

$$R = \frac{1}{2}(1-p)(\rho_w - \rho_i)g \frac{1 + \sin \phi}{1 - \sin \phi} h_r(x)^2 \quad (14)$$

Therein, p signifies the porosity of ridges, ϕ stands for the internal friction angle, and ρ_w and ρ_i respectively express the densities of seawater and sea ice.

Fig. 3 Rupture plane when the ridge height at a certain point is smaller than the draught.

When the ridge height at a certain point is larger than the draught, a second lower rupture plane is introduced. That fact was

demonstrated by Keinonen²⁾, who applied Coulomb model, i.e. limit equilibrium analysis to calculate the resistance, as portrayed in Fig. 4. Although the ridge height in contact with ship bow is the draught, from the perspective of Coulomb model, resistance results from the volume of ice wedge block, which is subjected to buoyancy and to forces from the ship bow and rupture planes. This area is approximately proportional to the draught and the ridge height. Therefore, for simplification, a modification is made on Eq. (13): the bow resistance because of normal force at a certain point with height greater than the draught can be expressed as

$$R = \frac{1}{2}(1-p)(\rho_w - \rho_i)g \frac{1 + \sin \phi}{1 - \sin \phi} h_r(x)T \quad (15)$$

Aside from the normal crushing force, friction occurs as a result of the relative lateral motion of the ship bow and ice blocks. The friction runs tangential to the bow. The ridge keel is triangular. Therefore, the ridge height in contact with each A-A plane is varied gradually along the ship bow. Considering the tangential frictional force additionally, the global resistance on the bow R_b can be expressed as an integral along the ship bow.

$$R_b = \int_{L_{bow}} R(\tan \beta + \mu_i) / \tan \alpha_k dh_r \quad (16)$$

In that equation, L_{bow} represents the length of ship bow, β stands for the waterline half-angle, and μ_i is the frictional coefficient.

Regarding local loads on a specified frame, for any point at depth z , the vertical component of normal stress is $(1-p)(\rho_w - \rho_i)g(h_r - z)$. Therefore, according to Rankine theory, the horizontal stress can be ascertained as the coefficient of passive stress $(1 + \sin \phi) / (1 - \sin \phi)$ times the normal stress. The ice loads on the specified frame at A-A plane are calculable as an integral of horizontal stress along the contact height with ice ridge. The resultant local ice loads are an accumulation of the A-A plane along the frame spacing.

Myland²⁷⁾ reported that an increase of resistance with growing penetration velocity can be assumed to be proportional based on the model test results of ridge penetration. Therefore, the total keel resistance R_k can be expressed as shown below.

$$R_k = \frac{k_{pen} v_{pen}}{\sqrt{gh_r(x)}} R_b + \left(\frac{R_{m_max}}{R_{b_max}} \right) \frac{k_{pen} v_{pen}}{\sqrt{gh_r(x)}} R_m \quad (17)$$

Therein, k_{pen} is a factor that depends on the ship model's ridge breaking capability and the number of back repetitions necessary to break the ridge. It is 1.3–2.0; also, v_{pen} is the penetration velocity.

Fig. 4 Rupture planes when the ridge height at a certain point is larger than the draught

Aside from the resistance R_m and R_b introduced above, the inertia force of ice accumulation in front of each A–A plane can be considered. Two parts of the ice blocks contribute to the total inertia force: the ice pile below ridge surface in front of A–A plane and the ice wedge block between A–A plane and rupture plane. In fact, the ice pile acceleration is the same as the ship acceleration. For the ice wedge block, the acceleration varies at different points. A reasonable assumption of inertia distribution is required. However, the ice pile shape is difficult to predict using analytical method. For that reason, a simplified ice pile edge parallel to the A–A plane is introduced in this study, by which the inertia force of the ice pile can be compensated with that of ice blocks between the rupture plane and the simplified ice pile edge. Moreover, the acceleration is assumed to vary linearly from zero at the edge in contact with the unmoved ridge to ship acceleration at the edge in contact with the A–A plane. The total global or local inertia force is calculable as an integral at each A–A plane along the ship bow or frame spacing.

3. Numerical Results of Ice Loads

3.1 Global Ice Loads and Ship Performance

Numerical simulations are conducted in different ice conditions with level ice thicknesses of 0.2–1.0 m. The ridge porosity was 0.25–0.4. The internal friction angle varied: 47°–58°. For this study, 0.3 and 52.5° were used as the porosity and internal friction angle, as referred from a report by Kuuliala et al.⁷⁾. In transit simulations, the values of cut-off height and the inverse of shape parameter of sails height distribution were set respectively as 0.4 and 0.2. The expected number of keels per kilometer was set as 11¹⁶⁾. Characterized by the mean ridge keel depth, ridge density, and level ice thickness, random ridged ice fields can be modeled according to Eq. (1) and Eq. (2). If the generated ridges overlap, then the union of the overlapping keels is used. An example of the keel distribution in a ridged ice field for 1 km is portrayed in Fig. 5. Sea ice ridges are difficult, impediments to navigation in ice. Ships are usually unable to pass through them in a continuous mode. If the ship stops in the ridge, then it backs out into its own broken channel for one ship length and penetrates into the ridge again until the ship has passed through the ridge. Thrust astern is set the same to thrust forward at full power. In such cases, keel resistance along the mid-ship because of friction are the only resistance term considered. An icebreaker is used as the ship model in simulations. The main characteristics of the calculated ship are presented in Table 1. The material properties of ice are defined by the constants in Table 2.

In numerical simulations, the ship model is driven by constant power. The initial velocity of a ship transiting through ridged ice fields is set as the mean velocity in level ice of equal thickness. Under the keel conditions shown in Fig. 5, simulated time histories of global ice loads and ship speeds in level ice thicknesses of 0.2 m and 1.0 m are shown respectively in Fig. 6. It is apparent that the ice-induced load resembles a sequence of spikes. For 0.2 m ice thickness, the keel resistance dominates. For 1.0 m ice thickness, the ice load induced by breaking the consolidated layer dominates. That result is explainable from two factors, 1) according to Eq. (9), the ice plate bearing capacity is proportional to the square of level ice thickness. Thus, the

consolidation loads in 1.0 m level ice thickness are much higher than those in 0.2 m thickness. 2) Based on Eq. (16), the keel resistance is proportional to the penetration velocity. Because the transiting speed in lower ice thickness is higher, even in the same keel distribution, the keel resistance in the case of 0.2 m ice thickness is larger than the other one. This phenomenon has also been observed in field trials. Based on field measurement data, Keinenon²⁸⁾ found that resistance attributable to consolidation might be the major resistance component for small ridges and for heavily consolidated ridges.

Fig. 5 Keel distribution in a ridged ice field model.

Table 1 Ship characteristics

Length between perpendiculars	149.26 m
Breadth	22.36 m
Draught	8 m
Displacement	21000 t
Bollard pull	90 t
Moment of inertia I_{xx}	$1.39 \times 10^8 \text{ kg m}^2$
Moment of inertia I_{yy}	$2.44 \times 10^9 \text{ kg m}^2$
Moment of inertia I_{zz}	$2.57 \times 10^9 \text{ kg m}^2$
Waterline entrance angle	23.6°
Stem angle	21.8°

Table 2 Ice properties

Young's modulus E	3500 MPa
Poisson ratio ν	0.3
Flexural strength σ_f	0.55 MPa
Frictional coefficient μ_f	0.15
Density of sea water ρ_w	1025 kg/m ³
Density of sea ice ρ_i	900 kg/m ³
Porosity of ridges p	0.3
Internal friction angle ϕ	52.5°

Furthermore, the ship forward speed drops sharply from the initial velocity, i.e. the mean velocity in level ice of the same thickness, because of the high loads caused by the consolidated layer and ridge keels. In the case of 0.2 m ice thickness, the ship transits the ridged ice field continuously without going astern. By contrast, six backs must be used to pass through an ice field with 1 m level ice thickness, when the ship speed value turns negative. The value of the global ice loads during the backing period are nearly zero because the ship backs into level ice stretches that have already been broken. For that reason, no contact with the ice

edge occurs. Only friction between the mid-ship and ice ridges might occur. Nine ridges exist in all in this realization of ridge fields. The segment ends in Fig. 6 represent time points at which the ship bow begins to penetrate into and has completely gone through each ridge. It is apparent that in the case of 1 m level ice thickness, backs are necessary for transiting the large ridges. Sometimes backs even happen in level ice sections such as that behind the third ridge or in small ridges such as the sixth ridge because the ship slows dramatically after passing through the previous large ridge. It cannot maintain forward speed.

To validate the numerical calculation method of ice loads in ridged ice fields presented in this paper, simulations of transiting a single ice ridge were conducted and were compared to results of ridge penetrating model tests with systematically varied keel depths performed in an earlier study using HSVA's ice model basin²⁷⁾. Several ice conditions resembling model tests were simulated using a numerical model, for example, in the No. 3010 test run of that earlier study by Myland, the keel depth scaled to full scale was 7.6 m. The level ice thickness of 0.05 m was tested with a scale factor equal to 22. A similar case of 7.6 m ridge keel depth and 1.1 m level ice thickness was set in the numerical simulation. The full scale maximum load value in the model test is about 2.6 MN²⁷⁾, whereas the numerical result is 6 MN. This nearly twice larger value in numerical simulation may be attributed to the different ship dimensions, ridge models, propulsion powers and other ice properties between simulations and model tests. For example, the larger scale of the numerical ship model than that in model test (the length between perpendiculars of the ship model in the No. 3010 test run was 126.6 m) is one of the possible reasons, which could cause higher ice loads. Moreover, many parameters, such as the porosity of ridges, internal friction angle, engine powers, ice flexural strength, etc., have significant effect on ice loads, however, the values of

these parameters cannot be found in Myland²⁷⁾. Also, many assumptions are made in the numerical model of ship-ridge interaction as stated previously, which may be different from model test. Therefore, the results of ice loads would show disparities, if these conditions are different, even though the level ice thickness and ridge depth are set the same.

Ice resistance is defined as the time average of all longitudinal forces due to ice acting on the ship. Fig. 7 and Fig. 8 show that the ice resistance and mean speed are also calculated for variable ice conditions. Considering the random nature of ridged ice, 50 simulations were performed for each ice condition in this study. Fig. 7 presents the numerical ice resistance in ridge ice and level ice generally increasing concomitantly with the increasing level ice thickness for constant ship speed of 5 m/s. Some disparities can be observed, for instance, in the case of 0.7 m thick ice. It is due to changes in the nature of icebreaking pattern. Contact zones mainly occur at the parallel midbody in 0.7 m thick ice, where the frame angle is nearly vertical, and consequently, the vertical component of contact force is not sufficient to induce a bending failure. The crushing area could progressively increase, which leads to severe icebreaking force. When crushing dominates, higher loads might be caused in thinner ice. The fitted line of numerical resistance in level ice is quite consistent to Lindqvist results. The present resistance caused by ice ridges is higher and it increases faster than Lindqvist's ice resistance at the same speed because of the effects of keels and consolidated layers. Fig. 8 shows mean speeds driven by constant power obtained in this paper and in Kuuliala's transit simulation model⁷⁾. The ridge density is set the same in the two simulations. The mean ridge thickness in Kuuliala's model is 3 m, whereas the same value of 3 m and a larger value of 6.67 m are used for this study for

Fig. 6 Simulated global ice loads and ship speeds (top, level ice thickness = 0.2 m; bottom, level ice thickness = 1.0 m).

comparison with Kuuliala's results. Consequently, an obviously lower mean speed is obtained with 6.67 m mean ridge depth in the same level ice thickness. For 0.3 m level ice thickness, the speed value with 3 m mean ridge depth in the present simulation closely approximates Kuuliala's numerical value, but the mean speed decreases faster as the level ice thickness increases in this study. Kuuliala's numerical results show that the expected values of mean speed decrease almost linearly with increasing ice thickness. An approximately linear relation between mean speeds and level ice thickness is also observed in cases of 6.67 m and 3 m mean ridge depth in this study. Moreover, the slopes of these two cases are quite consistent. They are larger than that in Kuuliala's simulation. This might be attributed to the different dimensions of these two numerical ship models. As a result, the present numerical results are comparable with those found from Kuuliala's study, with some slight differences.

Fig. 7 Ice resistance in various ice thicknesses.

3.2 Local Ice-induced Loads and Statistical Analysis

3.2.1 Local Ice-induced Loads

Aside from global ice loads, the line load on a specified frame can be obtained from the numerical simulation. Because the ice sheet is crushed continuously by bow shoulders, the icebreaking forces become more severe at these areas. Therefore, a frame on the bow shoulder area is selected for this study. Its location is marked as presented in Fig. 2. Fig. 9 shows the simulated time histories of local ice loads on this frame with the keel distribution in Fig. 5 in level ice thickness of 0.2 m and 1.0 m. The maximum numerical load peaks in 1 m ice thickness can reach 1400 KN/m, which is comparable to measurements published in the final report of the ARCDEV project²⁹). In this ARCDEV report, a duration of 10 min time history when the ice tanker M/T Uikku went through an ice ridge is recorded during measurement No. 35. The level ice thickness samples consist of four tenths in the

interval of 0.3 m–0.7 m, five tenths in the interval of 0.7 m–1.2 m, and one-tenth in the interval greater than 1.2 m. The ridge depth distribution is one-half in the range of 1.0 m–1.5 m and another half in the range of 1.5 m–2.0 m. The scale of M/T Uikku is close to the numerical ship model, of which the length between perpendiculars is as long as 150 m. The maximum signal value from bow shoulder area is up to 1000 KN/m.

From Fig. 9, it is apparent that in the case of 0.2 m ice thickness, contacts between the frame and ice edge of level ice or consolidated layer rarely occur. The only occurrence is emphasized in the box. Compared to that, the impulse caused by the keel resistance lasts for a longer duration required for a ship to pass through the present ridge. Load values of these two kinds are in the same level. However, for 1.0 m ice thickness, the frame loads caused by displacing keel blocks are much smaller than those because of the breaking level ice and the consolidated layer. That is true because that 1) the frame spacing is only 0.35 m in the simulations, less than one percent of the ship bow length, and ridge keels are treated as homogeneous and isotropic. Therefore, the frame keel resistance accounts for a very small share of the global keel resistance. 2) ship-level ice or ship-consolidated layer interaction happens at local contact zones as presented in Fig. 2. Therefore, if contact occurs on the specified frame, it will cause a high local load. Consequently, even though both the keel component and level/consolidation component contribute greatly to global ice loads, the keel effect is not important for local frame loads. It can be ignored in high level ice thickness. In ARCDEV research, instantaneous impulses rising from the nearly zero value are dominant, which means that the local loads induced by keels are quite small and nearly negligible.

Fig. 8 Simulated mean speeds in various ice thicknesses.

Fig. 9 Simulated time histories of local ice loads in level ice thickness of 0.2 m and 1.0 m
(top, level ice thickness = 0.2 m; bottom, level ice thickness = 1.0 m).

3. 2. 2 Statistical Analysis

Individual ice loads must be separated when studying ice load statistics. Before probability plotting, a Rayleigh separation is applied to identify load peak values $x_1, x_2, \dots, x_n$, as introduced into Kujala et al.³⁰⁾. A proper value of the separator is chosen initially. The Rayleigh separation method seeks the first peak value of the time history. The next peak value cannot be found until the time history signal decreases below the value of the Rayleigh separator chosen previously. If the time series signal does not decrease below this limit, but instead later increases above the first value, the first value is abandoned and a new value is selected as the first peak value. Fig. 10 shows how the Rayleigh method operates when the separator value is set as 1/4. Circles show the peak values of Rayleigh-separated ice loads.

Fig. 10 Peak values according to Rayleigh method.

The same 50 numerical simulations of ice-induced frame load

processes for each ice condition deal with Rayleigh separation. Generally, the distribution of local ice load peaks might be described approximately using a Weibull distribution based on statistical analysis of field measurement data of ice loads^{13) 14)}. Its cumulative density function can be expressed as

$$F(x) = 1 - \exp\left\{-\left(\frac{x}{\theta}\right)^k\right\} \quad (18)$$

where θ represents the scale parameter and k stands for the shape parameter of the ice load distribution. To ascertain the proper values for the parameters of the Weibull distribution underlying the ice load process, a probability paper can be employed. According to the empirical cumulative distribution function, the parameters of Weibull distribution can be estimated by fitting using least squares method.

Fig. 11 shows that the ice load peaks on a specified frame are presented in the Weibull distribution. The cumulative distributions of ice load peak area shown as a function of the load level on the logarithmic axis $[\ln(x)]$ and cumulative occurrence probability on the twice logarithmic axis $[-\ln(-\ln(1-F))]$. With high ice thickness of 1 m, peak values are observed to form nearly a straight line, which means that the ice load peaks of the numerical simulation fit the Weibull distribution well, whereas in the low ice thickness of 0.2 m, some deviations from the straight line occur in upper tail because in this case the loads attributable to the level ice section are low and the ridge keel effect might be more readily apparent, but it is still acceptable to model it using a Weibull distribution.

The statistical distribution parameters of numerical load peaks

are shown in Table 3 in different ice conditions. From statistical analysis of field measurement data, the shape parameter is found to be generally $0.7 < k < 1.0^{(4)}$. By comparison, the shape parameter value of the simulated peak distribution, i.e. the slope of the fitted line, is reasonable.

Table 3 Distribution parameters of the Weibull model for load peaks of various ice thicknesses

h_i	Shape parameter k	Scale parameter θ
0.2 m	1.182637213	22.20314394
0.3 m	0.837363066	37.79190118
0.4 m	0.761759073	117.6023794
0.5 m	0.887733865	179.1000669
0.6 m	0.914366998	244.3113063
0.7 m	1.013852295	294.7142815
0.8 m	0.994764758	338.8530354
0.9 m	0.839885362	411.8339793
1.0 m	0.874790836	475.7855868

Fig. 11 The calculated load peak distribution and fitted line of Weibull distribution (top, level ice thickness = 0.2 m; bottom, level ice thickness = 1.0 m).

4. Conclusions

A numerical model is developed to calculate both global and local ice loads in first-year ridged ice fields, in which a semi-empirical method is introduced to develop a numerical model of ship-ice interaction in level ice and the consolidated layer in ice ridges. A modified Rankine's plasticity model is

applied to calculate ice loads caused by ridge keels, considering effects of ship movement and inertia force of ice accumulation in front of the ship bow. Multiple simulations of ship transiting ridged ice in different ice conditions are conducted under randomly generated ridge-field profiles. Ship performance can be well reproduced using the numerical method. Computed results confirm that ice ridges can engender high load levels, causing the ship speed to slow dramatically when sometimes backs might have to be required. Although the ridge keel factor contributes much to global ice loads, the keel effect is not great for local frame loads: in fact, it is negligible in cases of high level ice thickness. The simulated global and local ice-induced loads compare well with published results of model tests and field measurements in ridged ice fields. The local load peaks can be modeled as a Weibull distribution, although some deviations exist in cases of low ice thickness. The shape parameters of the Weibull model representing numerical ice loads process agree well with statistical results of field measurement data. This agreement makes it possible to apply the model for practical use for route planning in ice or for evaluating a ship's operability and structural safety in given ice conditions.

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