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Fatigue Damage Calculation for Ship Hulls Operating in Pack Ice

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ABSTRACT

Fatigue damage induced by ice loads is an important issue for ships operating in ice-covered waters. This paper shows the fatigue damage calculation of a ship structure navigating in pack ice fields due to ice loads based on a numerical simulation. A discrete element method (DEM) is employed to simulate the interaction between drifting ice floes and a moving ship. The simulation domain contains hundreds of circular ice floes with random size and distribution. A Weibull model can be used to describe the ice load peaks. The cumulative density functions of ice load peaks in different ice conditions (ice thickness and ice concentration) can be determined from a series of numerical simulation. The structural fatigue stress is determined using structural beam theory. According to the joint probability distribution of ice thickness and ice concentration and a proper S-N curve, fatigue damage can be estimated based on the Palmgren–Miner's rule. An example of fatigue damage calculation is presented in this paper, and the calculated result reflects the fatigue damage due to ice-induced loads in pack ice is rather small.

KEY WORDS: Fatigue damage; Pack ice; Numerical simulation; Ice loads.

INTRODUCTION

Fatigue damage can be important for ships operating in ice-covered waters due to the harsh environment, which may lead to oil leaks, or even cause a catastrophic failure, threatening the overall safety of the structures. However, the research of fatigue damage due to ice action has not been developed well compared with wave action. At present, most studies on fatigue damage due to ice-induced loads are conducted by field measurements. Zhang and Bridges (2011) introduced a deterministic fatigue assessment procedure, the Ship Right FDA ICE Procedure, proposed by Lloyd's Register to assess fatigue damage of ship structure induced by ice loads. Suyuthi. A, et al. (2013) derived closed form expressions of the fatigue damage for several different statistical models of the stress amplitudes. However, the field measurements are usually quite limited and incomplete, so it is difficult to evaluate the fatigue damage correctly and to provide a guide for the design of new structural components or new ship routes. Compared to the field measurements, the ice conditions and ship hull can be easily varied in the numerical simulation, which can be used to complement the lack of data in some regions, or to predict the fatigue life for new structures. The numerical method seems quite promising to evaluate the fatigue damage.

Ships navigating in ice-covered waters can encounter a wide range of different ice conditions, including pack ice, level ice, ridged ice, ice in wave and so on. Therefore, the cases of fatigue damage calculation should also contain all kinds of ice conditions. In the authors' previous research (Han and Sawamura, 2016), fatigue damage calculation of ship operating in level ice has been proposed based on a numerical simulation. While in certain cases, such as managed ice fields and marginal ice zones, where a continuous ice sheet has been broken into smaller ice floes by icebreakers or wave actions, ships mainly operate in broken ice fields. In broken ice, occasional ship-ice collisions may occur, rather than continuous icebreaking process in level ice. Therefore, the fatigue damage in these pack ice cases will be studied in this paper.

Several numerical methods have been developed to simulate the interaction between ships and pack ice floes. Hansen and Løset (1999) proposed a DEM model for theoretical investigation of behavior of a mooring turret in broken ice. Daley et al. (2012) used a GPU-Event-Mechanics (GEM) approach to assess vessel performance in pack ice, in which the ice floes were all represented as convex polygons. Ji et al. (2012) modelled the ice floes with three-dimensional (3D) dilated disk elements, and the ship hull was modelled with 3D disks with overlaps.

In this paper, a 2D DEM numerical model is developed, with the ice floes represented as hundreds of circular disks, to produce ice loads data for fatigue damage calculation, instead of field measurement data. The ice loads in different ice conditions (ice thickness and ice concentration) can be determined from a series of numerical simulation. A Weibull statistical model is applied to represent the ice load process. Based on the structural beam theory, the distribution of ice load peaks can be converted into the distribution of stress amplitudes. The Palmgren-Miner cumulative damage rule is applied to calculate the fatigue damage. The calculated fatigue damage in broken ice is rather small, compared to the one in level ice.

MODELLING OF ICE-SHIP INTERACTION

Motion Equations

Motion of the Ship

Motion equations of ship are described by the equations of motion in three degrees of freedom and can be written as below:

$$(\mathbf{M}+\mathbf{A})\ddot{\mathbf{r}}(t)+\mathbf{B}\dot{\mathbf{r}}(t)+\mathbf{C}\mathbf{r}(t)=\mathbf{F}(t) \tag{1}$$

where **M**, **A**, **B**, and **C** are the mass, added mass, damping and restoring force matrices respectively, **F** is the excitation forces and moments, **r** is the displacement vector of ship. The damping term is not included in this simulation.

According to Newmark method and an assumption of linear acceleration (Su et al., 2011), three equations can be derived from the motion equation:

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

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

$$\mathbf{r}(t_{k+1}) = (\frac{6}{\delta t^2}(\mathbf{M}+\mathbf{A}) + \mathbf{C})^{-1}(\mathbf{F}(t_{k+1}) + (\mathbf{M}+\mathbf{A})(\frac{6}{\delta t^2}\mathbf{r}(t_k) + \frac{6}{\delta t}\dot{\mathbf{r}}(t_k) + 2\ddot{\mathbf{r}}(t_k))) \quad (4)$$

where δt is the time interval of numerical integration, t_k represents the *kth* time step. The excitation forces and moments can be decomposed into four components:

$$\mathbf{F} = \mathbf{F}^{\text{ice}} + \mathbf{F}^{\text{p}} + \mathbf{F}^{\text{ow}} + \mathbf{F}^{\text{Euler}} \quad (5)$$

where the superscripts 'ice', 'p' , 'ow' and 'Euler' refer to ice-ship collision, propeller and rudder, open water, and a fictitious force induced by a non-uniformly rotating body-fixed frame respectively.

Motion of Ice Floes

Ice floes in this paper are modeled as hundreds of circular discs with random size and distribution. In each time step, the motion of every ice floe needs to be solved. The motions of ice floes follow the Newton's second law, and are solved by the assumption of linear acceleration as well. For the ice floes in the simulation domain, besides the ice-ice collision force and ship-ice collision force, they are also subjected to the water drag force. The added mass of ice floes should be taken into account (Ji et al., 2012):

$$M_{\text{a}} = C_{\text{m}}\rho_{\text{w}}V_{\text{sub}}\frac{d(|\boldsymbol{V}_i - \boldsymbol{V}_w|)}{dt} \quad (6)$$

where M_a is the added mass of floe ice, C_m is the added mass coefficient, ρ_w is the water density, V_{sub} is the submerged area of the floe, $\boldsymbol{V}_i$ and $\boldsymbol{V}_w$ are the velocity vectors of ice floe and water respectively. Here, for a circular disc the added mass is not included in the calculation of the moment of inertia, and it is also assumed that the water drag force act through the center of the disc and do hence not contribute to the torque of the disc floes.

Ice-Ice Contact Force and Ship-Ice Contact Force

The contact between two circular ice floes is presented in Figure 1. It is supposed that there are two components of contact force on the contact zone, i.e. the normal force and the tangential force. The **n-t** coordinate system with the origin O_i is defined as below:

$$\vec{n} = \frac{\overrightarrow{O_iO_j}}{|O_iO_j|} = (\cos\theta, \sin\theta) \quad (7)$$

$$\vec{t} = (-\sin\theta, \cos\theta) \quad (8)$$

where O_i and O_j are the centers of the two contact discs, $\vec{n}$ and $\vec{t}$ are the unit vectors of the normal axis and tangential axis respectively, θ is the angle from x-axis to the vector $\vec{n}$.

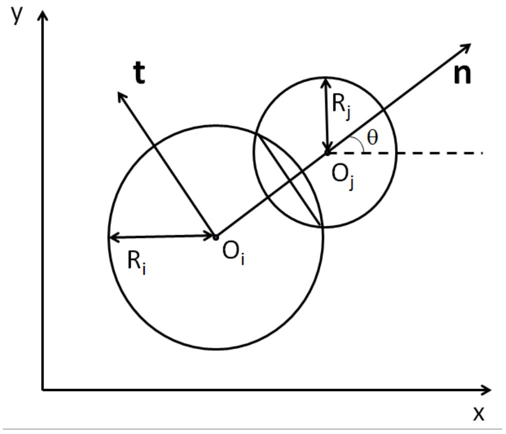


Figure 1. Collision between two circular ice floes.

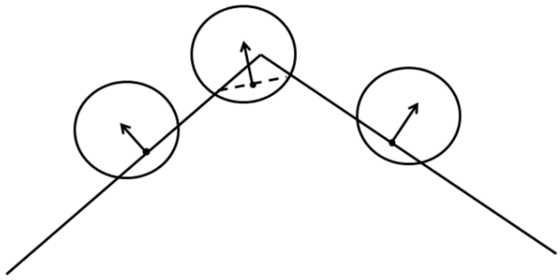


Figure 2. Collision between ship and ice floe.

The normal force is represented as a sum of elastic and damping terms:

$$F_{\mathrm{n}}^{i} = -K_{\mathrm{ne}}\delta_{\mathrm{n}}^{i} - K_{\mathrm{nv}}\dot{\delta}_{\mathrm{n}}^{i} \tag{9}$$

where the subscript n denotes the normal direction, the superscript i denotes the current time step, K_{ne} is the normal contact stiffness, K_{nv} is the normal contact viscosity, δ_n^i is the normal indentation of overlap, $\dot{\delta}_n^i$ is the relative velocity of the two disks at normal direction.

The tangential force is treated as linear-elastic:

$$F_{\mathrm{t}}^{i*} = F_{\mathrm{t}}^{i-1} - K_{\mathrm{te}}\dot{\delta}_{\mathrm{t}}^{i}\Delta t \tag{10}$$

where the subscript t denotes the tangential direction, the superscript i-1 denotes the previous time step, K_{te} is the tangential contact stiffness, $\dot{\delta}_t^i$ is the relative velocity of the two disks at tangential direction, Δt is the time interval.

However, the upper limit of the tangential force is the Coulomb friction limit, so the tangential force can be expressed as:

$$F_{\mathrm{t}}^{i} = \min(F_{\mathrm{t}}^{i*}, \mathrm{sign}(F_{\mathrm{t}}^{i*})\mu F_{\mathrm{n}}^{i}) \tag{11}$$

where μ is the ice–ice friction coefficient.

For ship-ice collision, the calculation method of the contact force is similar to the one of ice-ice collision. The ship waterline is represented as a polygon, including nodes and line segments. In the simulation, each segment has to be checked for contact with the discs. A case of collision between ship and ice floe is illustrated in Figure 2. In this paper, the middle point of the contact line is the reference contact point, and the contact normal direction is defined as perpendicular to the line that passes through the two intersecting points between the ship waterline and ice floe (Feng and Owen, 2004), by which no directional jump occurs at the corner when the ice floe continuously moves from the left position to the right. The total contact forces acting on ship hull and each ice floe are calculated as a sum of contact force induced by all the ship-ice collisions and ice-ice collisions.

FATIGUE DAMAGE CALCULATION

During operation in pack ice fields, a ship is expected to travel in a range of different stationary ice conditions (ice thickness and ice concentration), so the total fatigue damage D can be calculated by accumulating the fatigue damage contributions D_j in each stationary condition.

Ice-induced Loads Distribution

In each stationary ice condition, the time series of ice loads can be obtained from the numerical simulation. Generally, the distribution of load peaks may be approximately described by a Weibull distribution based on statistical analysis of field measurements data of ice loads. Its cumulative density function can be expressed as:

$$F(x) = 1 - \exp\left\{ \left(\frac{x}{\theta}\right)^k \right\} \tag{12}$$

where θ is the scale parameter, k is the shape parameter of ice loads distribution. In order to determine the proper values for the parameters of Weibull distribution which is underlying the ice loads process, a probability paper can be employed.

Prior to the probability plotting, a proper separator is chosen and a Rayleigh separation is applied to identify the load peak values x_1, x_2,⋯, x_n (Kujala et al., 2009). According to the empirical cumulative distribution function, the parameters of Weibull distribution can be estimated by fitting by means of the least square method.

Structural Response

The structural fatigue stress, which is induced by the ice loads, is determined using structural beam theory. As to transverse frame, the conversion from loads into the stress is a sort of linear transformation. Referring to Finnish Swedish Ice Class Rules (2010), the relationship between loads and stress is expressed as:

$$S = \gamma P_{\mathrm{ice}} = \frac{P_{\mathrm{ice}} s l}{m_{\mathrm{t}} Z} \times 10^3 \tag{13}$$

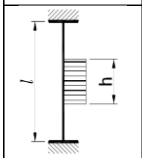
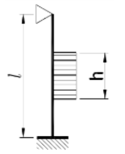
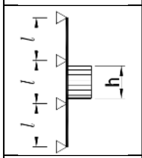
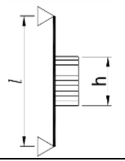
where P_{ice} is the ice loads [kN/m], s is frame spacing [m], l is span of the frame [m] , Z is the section modulus [cm^3].

$$m_{\mathrm{t}} = \frac{7 m_0}{7 - 5h/l} \tag{14}$$

where h is height of load area [m], m_0 takes the boundary conditions into account. The values of m_0 are given in the following table.

From the linear transformation, we can conclude that the ice-induced stress also follows the Weibull distribution, and the shape parameter p and the scale parameter q of stress distribution can be determined by $p = k$ and $q = \gamma\theta$.

Table 1. Boundary Conditions of the structural beam (Finnish Swedish Ice Class Rules, 2010).

Boundary Condition	m_0	Example
	7.0	Frames in a bulk carrier with top wing tanks
	6.0	Frames extending from the tank top to a single deck
	5.7	Continuous frames between several decks or stringers
	5.0	Frames extending between two decks only

Distribution of Ice Thickness and Ice Concentration

The thickness and concentration of the ice cover is highly variable, due to thermal and mechanical factors. In this paper, we use the ice conditions data, i.e. the mean value and standard deviation of ice thickness and ice concentration of Weddell region in Antarctic Sea as a calculation example (Worby et al., 2008). Worby et al. (2008) provides the histogram of ice thickness distribution, which is quite closed to lognormal model. Therefore, this study represents the ice thickness with a lognormal distribution. Worby et al. (2008) gives the mean value and standard deviation of ice concentration, but does not provide the statistic distribution. Here, the distribution of ice concentration is also assumed to follow a lognormal distribution in the calculation. A random variable of ice thickness or concentration is denoted as *X*, which follows a lognormal distribution, then $Y = ln(X)$ follows a normal distribution, i.e. $Y \sim N(\mu,\sigma)$. The relationship between the mean value and the variance of *X* and *Y* is:

$$E(X) = e^{\mu+\sigma^2/2} \tag{15}$$

$$D(X) = (e^{\sigma^2} - 1)e^{2\mu+\sigma^2} \tag{16}$$

The logarithmic function is a monotonic function, therefore the possibility of ice thickness or concentration *P(x)* equals to the possibility of their logarithmic value, which can be determined by integration of the probability density function of the normal distribution between $ln(x-\Delta x/2)$ and $ln(x+\Delta x/2)$:

$$P_X(x) = P_Y(\ln(x)) = \int_{\ln(x-\frac{\Delta x}{2})}^{\ln(x+\frac{\Delta x}{2})} \frac{1}{\sqrt{2\pi}\sigma} \exp(-\frac{(y-\mu)^2}{2\sigma^2})dy \tag{17}$$

In the calculation of ice thickness probability, Δx is set as 0.1m, and in the calculation of ice concentration probability, Δx is set as a percentage of 10%. It is assumed that the random variables of ice thickness and ice concentration are independent of each other in this paper.

Fatigue Damage Expression

The Palmgren–Miner's linear damage hypothesis is applied for fatigue damage calculation in a particular stationary condition, D_j:

$$D_j = \sum_{i=1}^{n_s} \frac{n_i}{N_i} \tag{18}$$

where n_i is the number of stress amplitudes, N_i is number of amplitudes to failure for a constant stress S_i, n_s is the number of stress magnitudes.

S-N Curve

The relationship between S_i and N_i is given by a S-N curve, which can be expressed as:

$$N_i S_i^m = K \tag{19}$$

where K and m are the constants of S-N curve. The probability of the stress magnitude S_i can be written in the following two forms:

$$P(S_i) = \frac{n_i}{N_0} = f(S_i)\Delta S \tag{20}$$

where N_0 is the total number of stress amplitudes in each stationary condition, $f(S)$ is the probability density function of Weibull distribution of stress amplitudes:

$$f(S) = \frac{p}{q}\left(\frac{S}{q}\right)^{p-1} \exp\left\{-\left(\frac{S}{q}\right)^p\right\} \tag{21}$$

Insert Eqs.(19) , (20) and (21) into Eq.(18), the fatigue damage in a particular stationary condition can be translated as:

$$D_j = \frac{N_0}{K} q^m \Gamma\left(1+\frac{m}{p}\right) \tag{22}$$

where $\Gamma(\cdot)$ is the gamma function.

Impact Frequency

The number of ice impacts N_0 is variable and related to ice thickness and ice concentration. It can be determined by impact frequency per unit distance times sailed distance in each condition. Suyuthi. A, et al. (2013) proposed that the impact frequency in level ice can be estimated based on the inverse of the characteristic length of the ice plate:

$$\upsilon_d = \frac{1852}{13.3617 h_i^{3/4}} \tag{23}$$

where υ_d is the number of events per nautical mile. It should be noted that this estimation of the impact number is applied for the whole ship hull, so the impact frequency should be lower for a frame. The employment of Eq.(23) is over-estimated. The number of ice impacts N_0 in pack ice is determined by the calculated number in level ice times the percentage of ice concentration.

NUMERICAL CALCULATION RESULTS

Numerical Result of Ice Loads

A rectangular simulation domain is used to model the pack ice field with a dimension of 600 m×250 m. The radius of ice floes is set to be in the range from 2m to 10m randomly, with a specified ice concentration. Considering the effect of random position of ice floes on the ice-induced loads on a certain frame, five different random position distributions of ice floes with the same ice concentration are employed here. An example of random calculation domin with ice concentration of 60% is shown in Figure 3. In this paper, periodic boundary conditions are adopted, in case of which the discs leaving the ice domain will be re-introduced on the opposite boundary with their momentum unchanged, so as to ensure the ice concentration in the simulation domain constant. Ship navigates with a constant thrust, and its main characteristics is given in Table 2. Some computational parameters about ice properties are presented in Table 3.

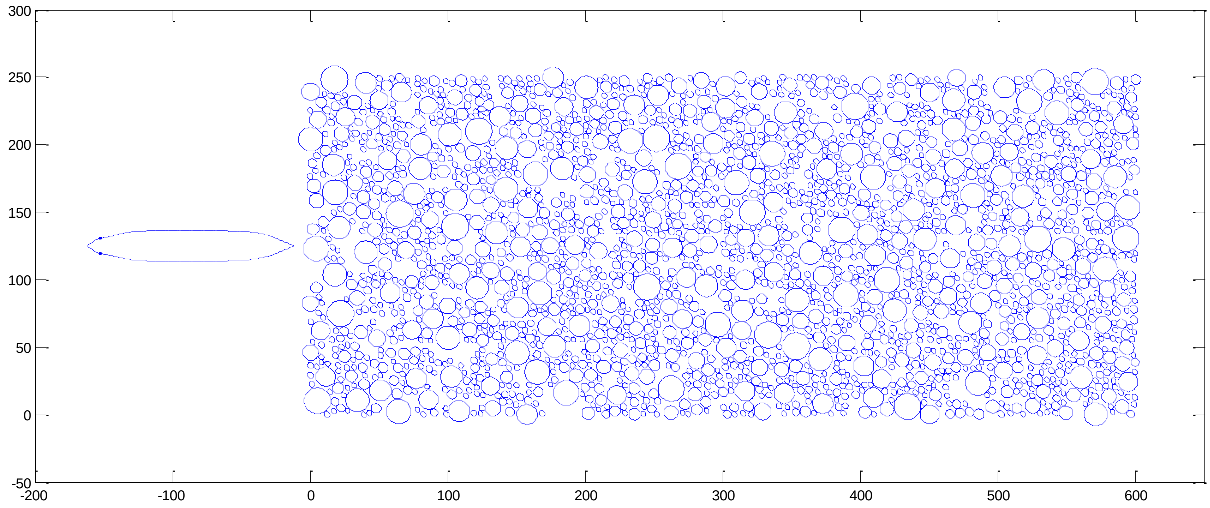


Figure 3. A random calculation domain with ice concentration of 60%

Table 2. Ship Characteristics

Length between perpendiculars	Breadth	Draught	Displacement	Moment of inertia I_{zz}
96.0m	18.4m	5.16m	4890.13t	2.57×10^{9}kg m^{2}

Table.3 Ice Properties

Normal contact stiffness K_{ne}	Tangential contact stiffness K_{te}	Normal contact viscosity K_{nv}	Friction coefficient μ	Added mass coefficient C_m	Water density ρ_w	Ice density ρ_i	Ice concentration Mean(std)	Ice thickness Mean(std)

587 KN/m	352 KN/m	5.87 KN·s/m	0.35	0.15	1000 kg/m^3	900 kg/m^3	38% (36%)	0.58m (0.55m)

An example of the time series of ice resistance obtained from numerical simulation is shown in Figure 4. The ice-induced load looks like a sequence of spikes, and the maximum ice load in this case is 1167 KN. Ji et al. (2012) simulated the ice loads of ship operating with a speed of 4.0 m/s under ice concentration of 60%, and the numerical maximum value was 1479KN. Daley et al. (2012) calculated the ice loads of a vessel with constant thrust under 35% ice coverage, and the simulated maximum value was about 1500KN. Compared to numerical results of ice loads in pack ice in these reference papers, the simulation values in this paper are in the same order of magnitude.

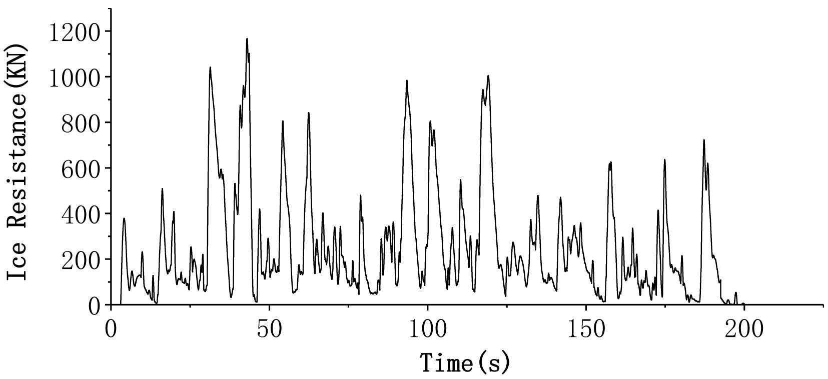


Figure 4. Example of the time history of ice load peaks calculated by the numerical simulation (Ice thickness = 0.5m, Ice concentration = 40%)

The ice load peaks on a specified frame are plotted in the Weibull distribution, as shown in Figure 5. The cumulative distributions of ice load peaks area plotted as a functions of the load level in logarithmic axis [ln(*x*)] and cumulative occurrence probability in twice logarithmic axis [-ln(-ln(1-F))]. The peak values forms nearly a straight line is observed, which means ice load peaks of the numerical simulation fits the Weibull distribution well.

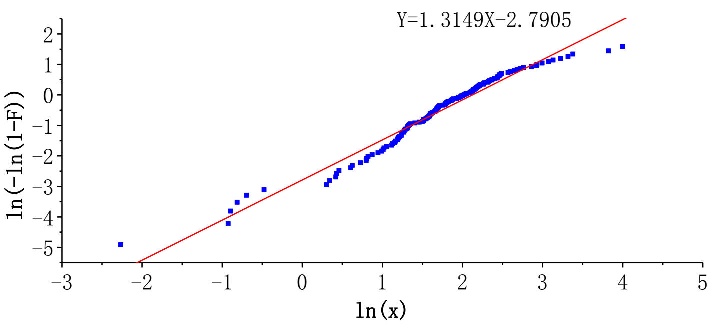


Figure 5. Example of the calculated local load peak distribution on a certain frame and fitted line of Weibull distribution (Ice thickness = 0.5m, Ice concentration = 40%).

Because nearly all the statistical results of ice-induced loads come from the field measurement data, and the field experiments contain all kinds of different ice conditions, including pack ice, level ice, ridged ice, etc. However, the ice condition studied in this paper is only pack ice, therefore, it is unreasonable to compare the statistical result of ice loads in this numerical simulation to those results in field measurements. Here, the global ice loads around the whole ship hull are plotted in the Weibull distribution as well, shown in Figure 6, in order to compare with the statistical result of Daley et al. (2014), which also focuses the study on pack ice, but with the ice floes represented as convex polygons. The case of Daley et al. (2014) is 40% ice coverage with different combination of ice thickness. The statistical result shows the shape parameter mainly concentrates in the range between 0.5 and 0.6. From the comparison, the shape parameter, i.e. the slope of the fitted line in this paper is 0.5929 (Ice thickness = 0.5m, Ice concentration = 40%), which is in the same range.

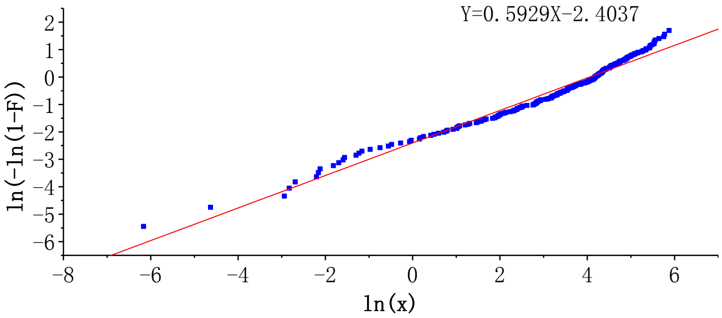


Figure 6. Example of the calculated global load peak distribution on a certain frame and fitted line of Weibull distribution (Ice thickness = 0.5m, Ice concentration = 40%).

Fatigue Calculation Result

The fatigue damage accumulates D_j in ice thickness from 0.2m to 1.0m and ice concentration from 10% to 60%. The constants which are needed in the fatigue calculation are shown in Table 4. The travelling distance per year is assumed to be 2500 nm. An example of fatigue damage calculation process for ice concentration 10%, 40% and 60% are presented in Table 5.

Table.4 Fatigue Calculation Constants

Frame Spacing *s*	Span of Frame *l*	Section Modulus *Z*	Height of Load Area *h*	Boundary Condition m_0	S-N curve parameter, *K*	S-N curve parameter, *m*
0.35m	1.5m	267cm^3	1.0m	5.0	1.0E+15.117	4.0

The total fatigue damage *D* of the calculated frame per year can be calculated by accumulating D_j in different ice conditions (ice thickness and ice concentration). The accumulation value is 1.788×10^{-4}, which is rather small, compared to the value in level ice in the authors' previous study (Han and Sawamura, 2016), which is 5.617×10^{-3}. It may be attributed to two factors: first, in pack ice fields, the distribution of ice floes is quite scattered, which will result in a remarkable decrease in the number of impacts between ship and sea ice. Then ice floes in pack ice field can be pushed away when the ship navigates through, therefore the magnitude of ice-induced loads is relatively lower. And the fatigue results based on numerical simulation seem reasonable preliminarily when compared to the fatigue damage value of Suyuthi. A, et al. (2013), which applied the field measurement data, although the ice data is not exactly the same, as shown in Table 6. The value of Suyuthi. A, et al. (2013) is 5.836×10^{-4}, which is between the above two values in pack ice and level ice based on numerical simulation respectively. It can be explained that the field measurements include all different kinds of ice conditions.

Table.5 Fatigue Damage Calculation

(1) Ice concentration = 10%

h_i	$P(h_i)$	N_0/year	p	q	D_j
0.2	0.158327347	7588.308373	2.6496	9.7441	6.99371E-08
0.3	0.151581688	5366.373432	2.4839	9.6343	5.08826E-08
0.4	0.124953085	3569.966254	1.5500	11.7473	1.88839E-07
0.5	0.098136737	2366.985408	1.8752	11.228	6.52014E-08
0.6	0.075940523	1595.797085	1.9527	10.5157	3.11866E-08
0.7	0.058670606	1099.277135	1.9790	10.328	1.94872E-08
0.8	0.045513197	772.6614357	1.8584	10.3881	1.58917E-08
0.9	0.035538153	551.8158333	1.8754	11.2128	1.51158E-08
1.0	0.027958931	402.2938638	1.4700	11.3122	2.15123E-08

(2) Ice concentration = 40%

h_i	$P(h_i)$	N_0/year	p	q	D_j
0.2	0.158327347	36520.56928	1.2338	8.7038	1.31244E-06
0.3	0.151581688	25826.97001	1.1166	10.5967	3.24644E-06
0.4	0.124953085	17181.326	0.911	9.5782	4.85455E-06
0.5	0.098136737	11391.68973	1.3149	8.3494	2.67554E-07
0.6	0.075940523	7680.159417	1.0518	8.427	5.30045E-07
0.7	0.058670606	5290.537072	1.4227	8.7389	1.12178E-07
0.8	0.045513197	3718.620028	1.1923	10.2582	2.99859E-07
0.9	0.035538153	2655.747155	1.1228	9.74613	2.32318E-07
1.0	0.027958931	1936.136515	1.0891	10.0265	2.21805E-07

(3) Ice concentration = 60%

h_i	$P(h_i)$	N_0/year	p	q	D_j
0.2	0.158327347	12679.82534	0.9966	22.0372	5.59571E-05
0.3	0.151581688	8967.041731	1.0621	19.458	1.66705E-05
0.4	0.124953085	5965.301666	1.0571	18.622	9.54759E-06
0.5	0.098136737	3955.158394	1.056	15.5344	3.08269E-06
0.6	0.075940523	2666.526889	1.068	17.346	3.03701E-06
0.7	0.058670606	1836.857622	1.0399	18.0731	2.8589E-06

0.8	0.045513197	1291.09303	0.936	19.1623	4.85725E-06
0.9	0.035538153	922.066954	0.9284	18.1544	2.95297E-06
1.0	0.027958931	672.2204316	0.9896	17.086	1.11888E-06

Table.6 Comparison of Fatigue Damage.

Published by	Sea are	Ice condition	Duration	Ship type	Fatigue damage
Suyuthi. A, et al. (2013)	Baltic Sea	Real sea ice (Pack ice + level ice + Ridge ice)	1 year (2500 nm)	Ice breaker	5.836×10^{-4}
Han and Sawamura, (2016)	Baltic Sea	Level ice	1 year (2500 nm)	Ice breaker	5.617×10^{-3}
Present paper	Antarctic Sea (Worby et al., 2008)	Pack ice	1 year (2500 nm)	Ice breaker	1.788×10^{-4}

CONCLUSIONS

A fatigue damage calculation method based on a numerical simulation has been introduced. The numerical simulation with a DEM model has been performed to obtain the time series of ice-induced loads in pack ice fields. The numerical result of ice loads has been compared with the existing numerical data preliminarily. Although the simulation model and the ship hull structure are not exactly the same, the magnitude of ice load and shape parameter of statistical Weibull model are quite consistent. The total fatigue damage can be an accumulation of damages in different ice conditions, according to the joint probability distribution of ice thickness and ice concentration and a proper S-N curve. The calculated fatigue result is much smaller than the one in level ice. The ice conditions and ship hull can be easily varied in numerical simulation, compared to field measurement, so the numerical method can be promising to calculate the fatigue damage. In order to evaluate the fatigue damage in real sea ice trial, the numerical method as a combination of simulation models in different ice conditions such as level ice, pack ice, ridge ice and also wave is needed. The proper ice conditions data, S-N data and structural response under ice load are also needed.

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