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Estimation of the fatigue damage for an ice class vessel under broken ice condition using a simplified method

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ABSTRACT

In this study, a simplified analysis method was developed to evaluate the fatigue damage of an ice class vessel under broken ice condition. The ice resistance, which is essentially calculated at the design stage of the ice class vessel, and the hull form information were used to estimate the local ice load acting on the outer-shell of the ship. The local ice load was applied to the finite element analysis model, and the Weibull parameters for the target fatigue point were derived. Finally, fatigue damage was evaluated by applying the S-N curve and the Palmgren-Miner rule. For the verification of the proposed simplified method, numerical analyses using direct approach were performed for the same conditions. A numerical model that implements the interaction between ice and structure was introduced to verify the local ice load calculated from the simplified method. Finally, the fatigue analyses of the Baltic Sea for actual ice conditions were performed, and the results of the simplified method, the direct analysis method, and the LR method were compared.

KEY WORDS: Simplified analysis method; Fatigue damage; Ice class; Broken ice condition.

INTRODUCTION

As vessels become larger and larger, the fatigue problem of the vessel due to the wave load is still attracting great interest from researchers and ship owners. Numerous studies on theories and analysis methods are being actively carried out, and related evaluation procedures are well developed, so designers have no difficulty in applying them to design. On the other hand, the research on the problem of the ice-induced fatigue is still insufficient. Since the Arctic region is very sensitive to environmental pollution and any form of oil spill is not allowed (Muizis, 2013), fatigue damage evaluation of ship structural members due to ice load is required in the design of an ice-going vessel.

In case of fatigue caused by wave load, many simplified methods have already been developed. In particular, most of the classification societies have their own procedures based on solid theoretical backgrounds (American Bureau of Shipping, 2012, Bureau Veritas, 2016, Det Norske Veritas, 2014, Lloyd's Register. 2015). Likewise, it is necessary to develop a method for efficiently evaluating the fatigue damage by ice load. Such a procedure should be applicable to initial design stage or repair process through simple and quick application.

In this study, a simplified analysis method was developed to evaluate the fatigue damage of an ice-going ship subjected to ice loads in broken ice fields. Using the ice resistance and the hull form information, which are essential for the ice-going ship design, the local ice loads acting on the shell plate were estimated. The finite element method was used to calculate the stress of the target fatigue through the local ice load, and the Weibull parameters were derived from the calculated stress and environmental conditions. Finally, fatigue damage was evaluated by applying the S-N curve and the Palmgren-Miner rule based on the derived Weibull parameters. For the verification of the proposed method, the local ice loads on the outer-shell, which were calculated by the direct analysis method using a numerical model and the simplified method, were compared. For the numerical analysis, a simulation model developed by Kim and Kim (2019) that implements the interaction between ice and structure was introduced. Finally, the fatigue analyses of the Baltic Sea for actual ice conditions were performed, and the results of the simplified method, the direct analysis method, and the LR method were compared.

ANALYSIS METHODOLOGY

The ice-induced fatigue analysis method using the simplified model developed in this study consists of five steps as shown in Figure 1. Given the ice resistance, the hull form at the waterline, the environmental conditions and the corresponding finite element analysis model, the fatigue damage for the specific condition can be simply calculated.

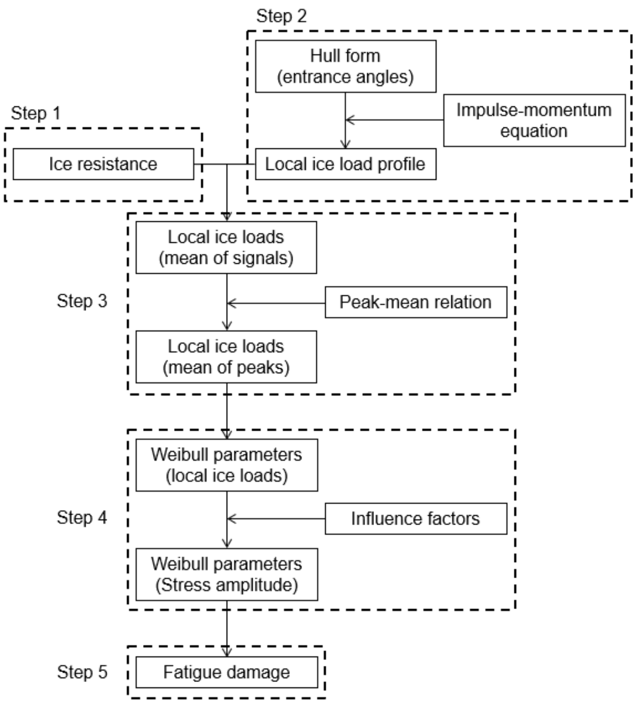


Figure 1. Calculation procedure for simplified ice-induced fatigue analysis

Calculation of the ice resistance

The calculation method developed in this study starts from the calculation of ice resistance.

The local ice load is estimated from the ice resistance, which is an essential element in the design of the ice going ship. Since the ice resistance is calculated based on the average ice condition, the local ice load estimated from the ice resistance is applicable to fatigue analysis. According to Jones (1987), the total ice resistance (R_t) can be divided into four components as Eq. (1).

$$R_t = R_{br} + R_c + R_b + R_o \tag{1}$$

where R_{br} is the ice breaking resistance and R_c is the ice clearing resistance. R_b is the ice buoyancy resistance and R_o is the open-water resistance.

In case of the broken ice condition, the clearing resistance and the buoyancy resistance are unknown variables. Each component can be calculated by various empirical formulas introduced in Kim et al (2017) or by numerical simulations.

Derivation of the local ice load profile

The impact between an ice floe and a ship at the entrance can be illustrated as shown in Figure 2. For simplicity, it was assumed that the ship impacts have been restricted to the waterline plane. Assuming that the ship advances at a speed V in the x-direction, the ship collides with an ice with mass m and ship velocity v. Then, the impact impulses of the normal component N_n and the tangential component N_t can be calculated as Eq. (2), (3) and (4). Here, the incident angle θ is the slope of the ship at the point of impact, and the angle θ_1 is the reflected angle of the ice after impact.

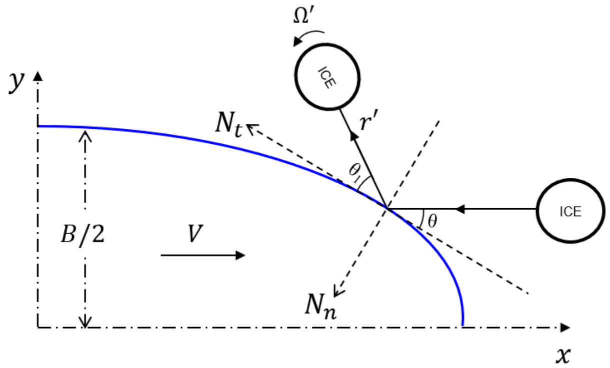


Figure 2. Ice floe impact with ship's entrance (Aboulazm, 1989)

$$-mVsin\theta + N_n = mv'sin\theta_1 \tag{2}$$

$$mVcos\theta - N_t = mv'cos\theta_1 \tag{3}$$

$$N_t r' = \Omega' I \tag{4}$$

where v' and Ω' are the linear and rotational velocity of the ice floe after impact, respectively. I is the polar mass moment of inertia of the ice.

The coefficient of restitution e, which means the ratio of the relative velocity between two objects before and after collision, can be defied as Eq. (5). In this study, 0.1 was taken for the coefficient according to Aboulazm (1989). The friction coefficient τ can be expressed as Eq. (6).

$$e = v'sin\theta_1 \,/\, Vsin\theta \tag{5}$$

$$\tau = N_t \,/\, N_n \tag{6}$$

Aboulazm (1989) derived an equation for calculating the ice resistance R in broken or pack ice condition based on the above five equations.

$$R = (CmV^2 sin^2\theta(B + d))/(2kd^2)\{csc^2\theta - [(cot\theta - \tau(1 + e))^2 + e^2] - (mr^2/\mathrm{I})[\tau(1 + e)]^2\} \tag{7}$$

where C is the ice concentration. d is the diameter of the ice floe. k is the shape factor of the ice floe.

Assuming that there is no friction in this equation, Eq. (7) can be changed to Eq. (8). Since Eqn. (8) is a function of the incident angle θ, it is possible to estimate the ice load at an arbitrary collision position, and thus to predict the ice load distribution along the outer-shell.

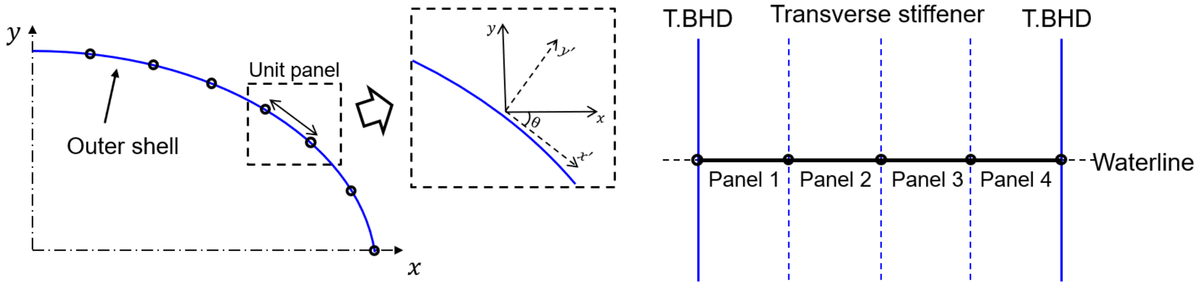
$$R = (CmV^2 sin^2\theta(B + d))/(2kd^2)(csc^2\theta - cot^2\theta - e^2) \tag{8}$$

Since the sum of the local ice loads is the same as the global ice load, the local ice load at the specific location can be obtained from Eq. (9) if the ice load distribution is known.

$$\overline{G_x} = \sum_i^n \overline{L_{\iota x}} \tag{9}$$

where $\overline{G_x}$ is the mean of the longitudinal component of the global ice load. n means the number of the panel. $\overline{L_{\iota x}}$ is the mean of the longitudinal component of the local ice load calculated on the i-th panel.

Since ice resistance has the same meaning as the mean of the longitudinal component of the global ice load, it is possible to directly use the ice resistance calculated from Eq. (8) in Eq. (9). In this study, an arbitrary number of panels are generated on the outer-shell of the ship for efficient calculation the local ice load as shown in Fig. 3.



(a) Plan view (b) Elevation view

Figure 3. Example of panel discretization

Derivation of local ice load peaks

Assuming that linear transformation is possible between ice load and the resulting stress as Suyuthi et al. (2013), the calculated load for a panel, which is a mean value of measured signals, should be converted to the mean of the ice load peaks for the application to fatigue analysis. Therefore, the next step is to convert the mean of the signals to the mean of the peaks. Assuming that the local ice loads show a triangular time series pattern (Suyuthi et. al, 2013, Lee et. al, 2016), the correlation between the average of the signals and the average of the peaks can be approximated. In this study, the correlations between the average of the signals and the average of the peaks for each impact were analyzed, and the local ice load peaks were derived through the relation.

Derivation of the Weibull parameters

In this study, a two-parameter Weibull model was applied to express the probability distribution of peaks in ice loads. Therefore, it is required to derive the Weibull parameters based on the calculated average ice load peak.

According to Olkin et al. (1980), the mean value ρ of the 2-parameter Weibull distribution can be expressed as Eq. (10).

$$\rho = q\Gamma(1+\frac{1}{h}) \tag{10}$$

where q and h are the Weibull scale parameter and shape parameter, respectively. Γ() is the gamma function.

In case of the shape parameter for the ice load, it is possible to calculate using a simple equation developed by Zhang et al. (2011) as Eq. (11). Then, since the shape parameter and the average ice load peak are known, the scale parameter corresponding to each panel can be calculated using Eq. (10).

$$h = 0.8{h_{eq}}^{-0.6} \tag{11}$$

where h_{eq} is the equivalent ice thickness (Kujala, 1994).

Since the probability density function of stress amplitude is needed for the fatigue analysis (Suyuthi et al, 2013), it is necessary to convert the parameters for the ice load in each panel to parameters for the stress amplitude. Assuming that the same shape parameter can be used for both ice load and stress amplitude, only the scale parameter needs to be changed. In addition, assuming that the ice load and the stress amplitude are linear, the scale parameter for the local ice load can be converted into the value for the stress by using the influence coefficient γ derived by the static analysis as Eq. (12).

$$Q_i = \gamma_i \times q_i \tag{12}$$

where Q and q are the Weibull scale parameters for the stress and the local ice load, respectively. i means the panel number.

Calculation of the fatigue damage

In case of using the 2-parameter Weibull model, the probability density function of stress amplitude can be expressed as Eq. (13), and the fatigue damage D using the model can be expressed as Eq. (14). Here, the mean stress effect was not considered.

$$f_s(S) = \frac{h}{Q}\left(\frac{S}{Q}\right)^{h-1} exp\left\{-\left(\frac{S}{Q}\right)^{h}\right\} \tag{13}$$

$$D = \frac{N_T}{K}\int_0^\infty S^m \frac{h}{Q}\left(\frac{S}{Q}\right)^{h-1} exp\left\{-\left(\frac{S}{Q}\right)^{h}\right\} dS \tag{14}$$

where $f_s(S)$ is the probability density function of the stress amplitude S. h is the Weibull shape parameter, and Q is the Weibull scale parameter. where K and m are parameters defining the S-N curve. N_T is the total number of stress cycles expressed as the product of the impact frequency v_d and the travel distance d as Eq. (15).

$$N_T = v_d d \tag{15}$$

In this study, for calculating the impact frequency, the equation developed by Zhang et al. (2011) was used as Eq. (16).

$$v_d = \frac{1}{10.4{h_{eq}}^{0.75} - 2.0h_{eq} + 1.18} \tag{16}$$

Assuming m is an integer, using the Binomial theorem and gamma function, Eqn. (14) can be converted to Eq. (17).

$$D = \frac{N_T}{K} \sum_{k=0}^{m} \frac{m!}{(m-k)!k!} q^k \Gamma(1 + \frac{k}{h}) \quad (17)$$

Since each panel is assumed to be independent of each other, the total fatigue damage of the target location can be calculated by adding up the fatigue damage calculated from each panel as Eq. (18).

$$D_{total} = \sum_i^n D_i \quad (18)$$

where n is the total number of panels, and D_i means the fatigue damage calculated for the i-th panel.

VERIFICATION OF THE SIMPLIFIED METHOD USING A NUMERICAL MODEL

The verification of the simplified method was performed by the direct analysis using a numerical analysis model developed by Kim and Kim (2019) that implements the interaction between ice and structure using the finite element method. The local ice loads on the outer-shell derived by the direct analysis model and the simplified method were compared under same conditions. The target vessel used for verification analysis is Araon, which is the Korean icebreaking research vessel (IBRV), and the main particulars of the vessel are described in Kim et al. (2017). Analysis cases for the verification test are presented in Table 1. For the ice thickness, the equivalent ice thickness (h_{eq}) was applied, and the thicknesses used for the fatigue analysis were set to 0.3, 0.6 and 0.9m. In case of the ice concentration, the case studies for a 40%, 60% and 80% ice concentration were considered. Ship speed was fixed to 4 knots.

Table 1. Analysis cases for the verification test

Case	Ice thickness (m)	Concentration (%)	Ship velocity (knot)
1	0.3	40	4
2	0.3	60	4
3	0.6	40	4
4	0.6	60	4
5	0.9	40	4
6	0.9	60	4

Comparison of the local ice load

The local ice loads on the outer-shell of the ship calculated by the simplified analysis method and the direct analysis method were compared. For calculation of ice load, panels were created along the outer-shell at the waterline as shown in Figure 4. To obtain local ice load distribution according to location, the panel-specific ice loads calculated by the direct analysis for each condition are shown in Fig. 5. Each point of Fig. 5 represents the dimensionless local ice load at the center point of the panel. The load on each panel is the average of the load time series derived from the direct calculation. As a result, it is found that the distribution of local ice loads is a function of distance from F.P.

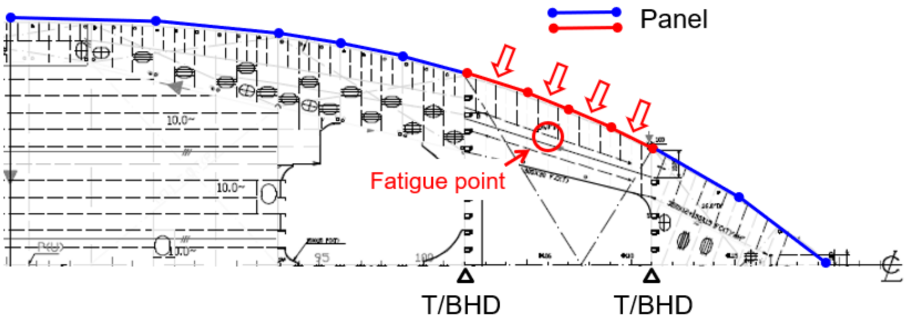


Figure 4. Panels for the calculation of the local ice loads

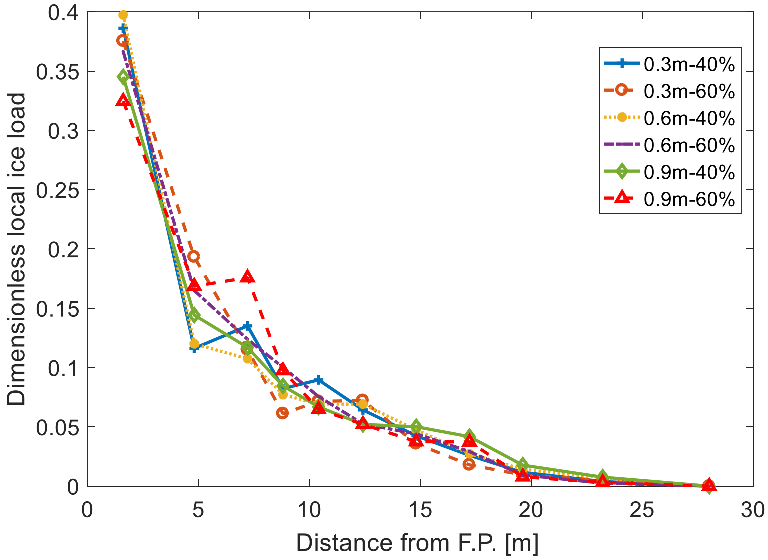
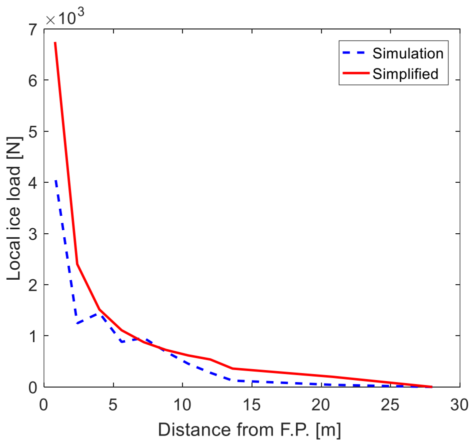
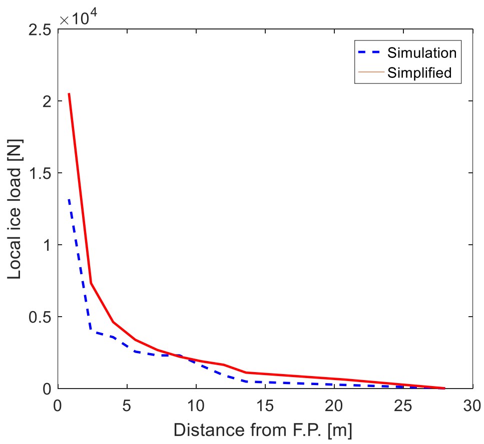


Figure 5. Distribution of the dimensionless local ice loads with respect to the distance from F.P.

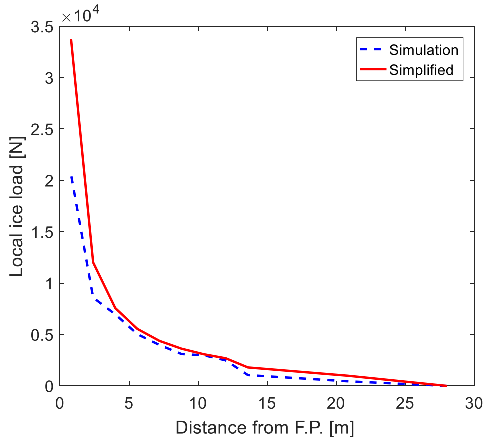
In Figure 6, local ice load distributions using direct analysis method ('Simulation') and simplified analysis method ('Simplified') were compared at each condition. The ice resistance used in the simple analysis was derived through direct analysis. Although the results of the simplified analysis tend to be larger overall, it can be seen that the two results are well matched.



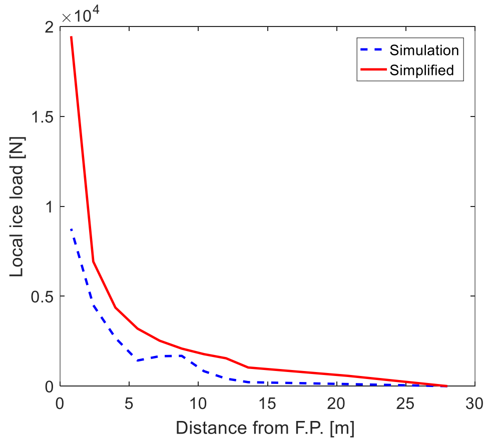
(a) 0.3m / 40% / 4knots



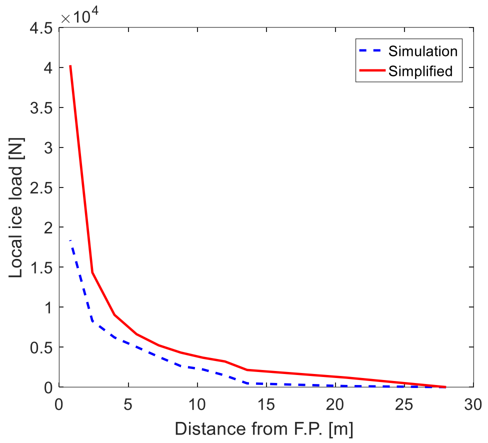
(b) 0.6m / 40% / 4knots



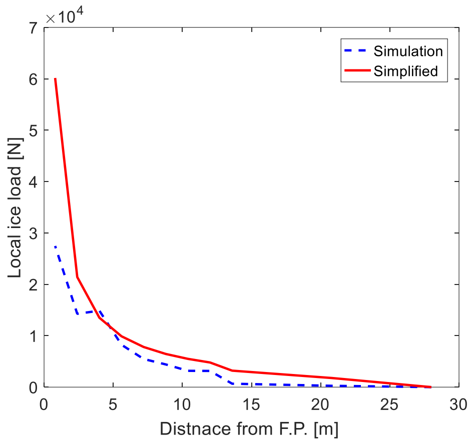
(c) 0.9m / 40% / 4knots



(d) 0.3m / 60% / 4knots



(e) 0.6m / 60% / 4knots



(f) 0.9m / 60% / 4knots

Figure 6. Comparison of local ice load distribution for different ice conditions

FATIGUE DAMAGE ASSESSMENT ON THE ACTUAL ENVIRONMENTAL CONDITION

The fatigue damage assessment of the ship has been performed based on the actual environmental conditions using the proposed simplified method. The environmental conditions considered in the analysis are presented in Table 2. It was assumed that the route is the Kemi route of the Baltic Sea, and the vessel visits the Kemi port 3.5 times each winter month in the 25-year service life (Lloyd's Resister, 2014). The monthly sailed distance is described in Lloyd's Resister (2014). Considering the wave-induced fatigue damage, the acceptance criterion 0.5 was used for the final fatigue damage ratio (Lloyd's Resister, 2014).

Table 2. Environmental conditions for the fatigue analysis

Items	Value
Trading route	Kemi route
Ice concentration (%)	100
Ship speed (knots)	8
Acceptance criteria	0.5

The fatigue damages calculated using three different methods, which are the direct analysis method, the simplified analysis method and the LR method were compared. Table 3 compares the final fatigue damage ratios obtained by each method. Here, D_{DI}, D_{SI} and D_{LR} mean the damage ratios by the direct method, the simplified method and the LR method, respectively. As a result, it can be found that the fatigue damage ratio calculated by the simplified analysis method is three times larger than that calculated by the direct method. In addition, the difference between the results by the simplified method and the LR method is less than 30%.

Table 3. Comparison of the total fatigue damage ratios

Methods	Fatigue damage ratio
Direct analysis	0.18
Simplified analysis	0.52
LR method	0.45

CONCLUSIONS

This paper proposed a novel ice-induced fatigue assessment method using a simplified analysis that can be applied in broken ice condition. This method has been developed for situations requiring rapid computation such as initial design.

The ice resistance, which is essentially calculated at the design stage of the ice class vessel, and the hull form information were used to estimate the local ice load acting on the outer-shell of the ship. The local ice load was applied to the finite element analysis model, and the Weibull parameters for the target fatigue point were derived. Finally, fatigue damage was evaluated by applying the S-N curve and the Palmgren-Miner rule. For the verification of the proposed method, numerical analyses using direct approach were performed for the same conditions. A numerical model that implements the interaction between ice and structure was introduced to verify the local ice load from the proposed method. Finally, the fatigue damage assessment for the actual conditions of the Baltic Sea was performed through the proposed method, and the result was compared to the results by the direct analysis using the numerical simulation and by the LR method. As a result, the proposed method yielded about 3 times more conservative results than the direct analysis method. Also, when compared with the LR method, the result was as high as 30%.

ACKNOWLEDGEMENTS

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