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Fatigue Damage Estimation of a Sloped Offshore Structure in Level Ice

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ABSTRACT

Ice loads repetitively acting on a structure during continuous breaking may cause fatigue cracks potentially leading to catastrophic structural failure. This paper proposes a fatigue assessment procedure for a sloped offshore structure operating in drifting level ice. Fluctuation of local ice load acting on the external surface of structure was statistically modelled and used for fatigue life estimation of a critical hot spot point within the structure. Due to the complexity induced by ice rubble piling up during ice action, the situation was idealized in such a way that only breaking induced repetitive local ice load was considered. This also allows the method to be applied to both upward and downward ice actions. Breaking local ice load was calculated using ISO 19906 and other statistical parameters were derived using empirical formulas. To check the validity of the proposed analysis procedure, direct analysis using finite element method, with which ice continuous breaking phenomenon was successfully captured (in prior work), was carried out for all different combinations of ice thickness and speed. Then, the fatigue damage was calculated based on the obtained local ice loads and compared with the results obtained by the proposed simplified methodology.

KEY WORDS: Level Ice; Probability distribution; Fatigue; Sloped structure; Breaking; Finite element.

INTRODUCTION

Prediction of long-term ice induced fatigue damage starts with modeling the probability distribution of ice loads. During the ice interaction, the behavior of the ice is very complex depending on the ice type, properties, and the hull form, so most previous studies have depended on field measurements to obtain ice loads. However, field measurements require time and are costly. Limited ice conditions inevitably restrict the extended application of the data for the design of arctic vessels exposed to a wider range of conditions. Recently, numerical simulations have been applied to overcome these limitations of field measurements. Yue et al. (2017) published a procedure for evaluating the fatigue damage in pack ice. Kim & Kim (2019) proposed a procedure to estimate the fatigue damage for an ice-going vessel due to ice floes. This procedure uses the ISO 19906 method for calculating ice loads on sloping faces which makes it easy to cope with various hull forms and ice conditions.

This paper introduces the fatigue analysis procedure for the sloping structures operating in level ice fields. Assuming simplified ice action, the stochastic model for the local ice load acting on the designated panels on the hull surface was fitted with a 2-parameters Weibull distribution. Applying the ice load distribution to the FE model of the structure, the Weibull parameters of stress amplitudes were derived. Finally, fatigue damage was assessed according to Palmgren-Miner's rule. To verify this procedure, direct analysis using numerical simulation, with which continuous ice breaking mechanism was successfully captured, was carried out for all different combinations of ice thickness and speed. The interactions between ice sheet and structure were modeled and damage-based erosion model (Jeon & Kim. (2021)) was employed to simulate cracks in ice. Then, the fatigue damage was calculated based on the obtained local ice loads and compared with the results obtained by the proposed methodology.

SIMPLIFIED ANALYSIS

Local ice load

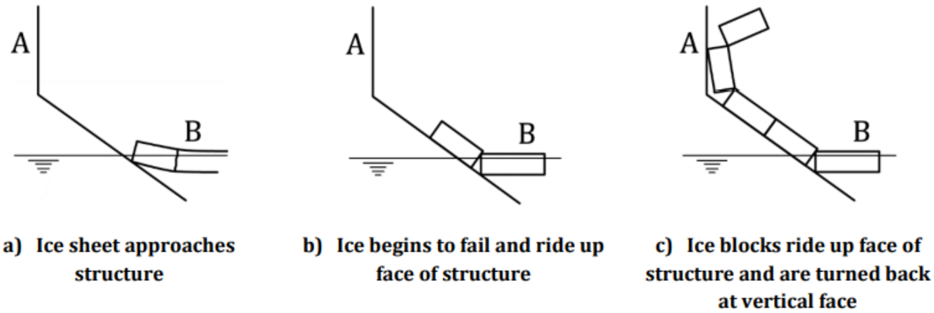

Figure 1. Ice breaking mechanism (ISO 19906)

Figure 1 demonstrates the mechanism by which upward sloping structures interacts with level ice. Along the slope of the structure, bending failure of the ice sheet, ice ride up and accumulation of rubble are observed.

The level ice-induced load can be represented by the sum of the 'breaking force' due to bending failure and the 'rubble force' due to the influence of the rubble. Rubble action is considered to diminish the magnitude of fluctuating ice load due to the potential damping effect against the load fluctuation induced by breaking. This leads to the idea that the removal of rubble action may provide some conservatism in fatigue life estimation. In line with this, only the breaking force was considered in the fatigue life estimation for simplicity purpose.

According to ISO 19906, the horizontal and vertical components of ice load can be expressed as follow (1), (2).

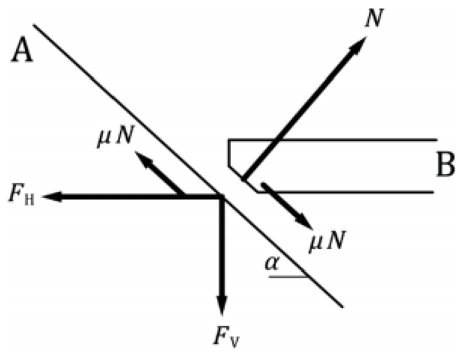

Figure 2. Ice action components (ISO 19906)

$$F_V = Ncos(\alpha) - \mu Nsin(\alpha) \tag{1}$$

$$F_H = Nsin(\alpha) - \mu Ncos(\alpha) \tag{2}$$

where N is normal component of the ice load, α is the sloping angle and μ is the friction coefficient between ice and structure.

The vertical component of breaking force also can be expressed using the theory for the bending of a beam on an elastic foundation.

$$F_V = 0.68\sigma_f w_B \left(\frac{\rho_w g h^5}{E}\right)^{0.25} \tag{3}$$

By inserting (3) into (1), The normal component of breaking force is as shown as (4).

$$N_{load} = \frac{0.68\sigma_f w_B}{\cos(\alpha) - \mu\sin(\alpha)}\left(\frac{\rho_w g h^5}{E}\right)^{0.25} \tag{4}$$

where σ_f is flexural strength, ρ_w is density of water, h is ice thickness, E is young's modulus and w_B is effective width which can be expressed as:

$$w_B = \left(\frac{\pi^2}{4}\right)L_c \tag{5}$$

with the conditions

$$L_c = \left(\frac{Eh^3}{12\rho_w g(1-v^2)}\right)^{0.25} \tag{6}$$

where v is Poisson's ratio

These equations, which are for breaking only, can be applied to both upward and downward breaking. If ride-up and rubble loads were to be calculated they would have to be adjusted by substituting buoyancy for gravity forces in the methodology described by ISO 19906.

Probability Distribution of Ice Load

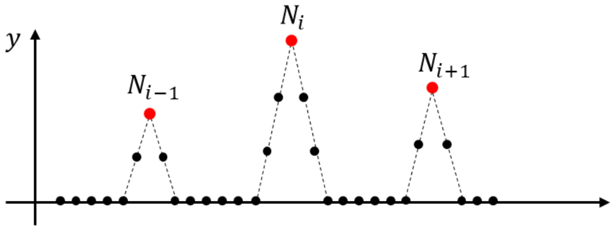

Figure 3. Ice load peak

Because ice is a natural material, there can be variability in ice properties for each breaking failure. Therefore, for the actual load action, the peak of the breaking force would vary, as shown in Figure 3. In the previous studies, exponential, gamma and Weibull distribution were introduced as representative statistical model of the ice load. In Zhang et al. (2011), the distribution of ice load amplitude x was described by a 2-parameters Weibull distribution. Its probability density function is:

$$f(x) = \frac{\zeta}{q}\left(\frac{x}{q}\right)^{\zeta-1} \exp\left\{-\left(\frac{x}{q}\right)^{\zeta}\right\} \tag{7}$$

where the shape parameter ζ is:

$$\zeta = 0.8h_{eq}^{-0.6} \tag{8}$$

The scale parameter can be led by inserting (4) into (9) which is the definition of the expected value of Weibull distribution. (9) can be rewritten as (10)

$$E[x] = q\Gamma(1 + \frac{1}{\zeta}) \tag{9}$$

$$q = \frac{1}{N_{load}}\Gamma\left(1 + \frac{1}{\zeta}\right) \tag{10}$$

Stress at the target point

Since the fatigue damage is usually evaluated using hotspot stress, the Weibull parameters of ice load must be converted to that of the stress in the structure. Duration of ice load is generally far smaller than the natural period of the steel structure, it is reasonable assumption that the structure responds in quasi-static way under ice load. Therefore, conversion of ice load to local stress can be done by simply introducing the influence factor, as (11).

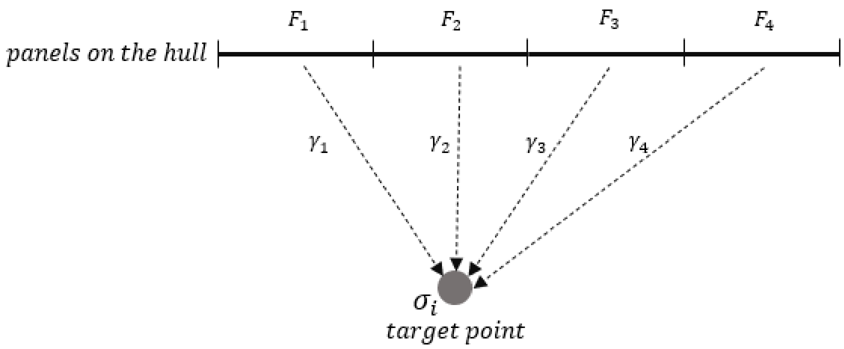

Figure 4. Relation between external force and stress

$$\sigma_i(t) = \gamma_i F_i(t) \tag{11}$$

where the subscript i stands for the panel number, $\sigma(t)$ is stress at the target point, γ is an influence factor and $F(t)$ is ice load.

By inserting (4) into (11), the mean of stress amplitude $N_{stress,i}$ is expressed as:

$$N_{stress,i} = \gamma_i N_{load,i} = \gamma_i q_i \Gamma(1 + \frac{1}{\zeta}) \tag{12}$$

When the Weibull distribution of the stress amplitude is expressed as (13), the scale and shape parameters are:

$$f_i(X) = \frac{\xi}{Q_i}\left(\frac{X}{Q_i}\right)^{\xi-1} \exp\{-\left(\frac{X}{Q_i}\right)^{\xi}\} \tag{13}$$

$$Q_i = \gamma_i q_i \tag{14}$$

$$\xi = \zeta \tag{15}$$

Fatigue Damage

The closed form expression of the fatigue damage for the 2-parameter Weibull distribution could be derived by applying the Weibull parameters and S-N curve to the Palmgren-Miner's rule (Suyuthi et al. (2013)). When the S-N curve is as shown (17), basic fatigue damage D is:

$$D_i = \frac{N_0}{K} Q_i^m \Gamma(1 + \frac{\mathrm{m}}{\xi}) \tag{16}$$

$$\log N = \log K - \log \Delta S^{m} \tag{17}$$

where m is negative inverse slope of the S-N curve, and $\log K$ is intercept of the $\log N$-axis by the S-N curve. N_0 is predicted number of impacts until failure for stress amplitude ΔS which is expressed as:

$$N_0 = N_{unit} * Distance \tag{18}$$

the number of impacts in unit length N_{unit} is terms of characteristic length which is expressed as:

$$N_{unit} = \left(\frac{\pi}{4} L_c\right)^{-1} \tag{19}$$

DIRECT ANALYSIS

In order to verify the proposed procedure, direct analysis using finite element method was performed, whose procedure is summarized in Figure 5. It is named 'direct analysis' because the probability distribution of the stress is obtained by counting peaks directly from the stress in time domain. To obtain the time series, numerical simulations on level ice structure interaction using finite element method were carried out. The numerical method proposed by Jeon and Kim (2021) was used in this study to simulate complicated interactions between level ice and structure. They used damage-based erosion model to realize the ice fracture, and successfully implemented the continuous crack propagation of the level ice.

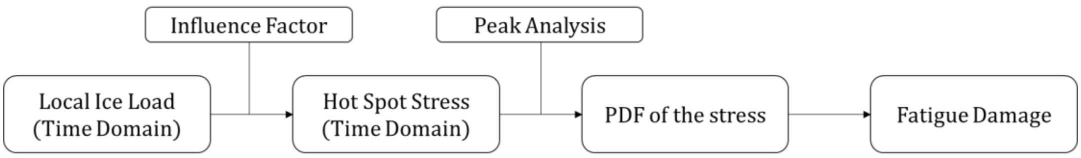

Figure 5. Procedure of direct analysis

Finite Element Model

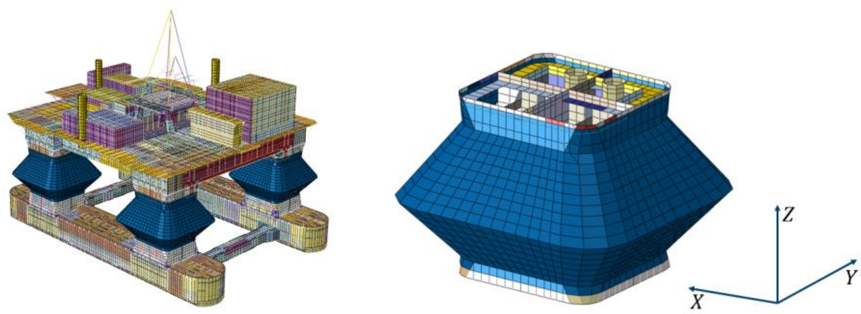

Figure 6. FE model of semi-submersible drilling rig

The target structure is the ice belt of a semi-submersible drilling vessel shown in Figure 6. Ice belt zone was selected out of the global model and meshed with rigid element. Rigid element was used for the ice load calculation because ice load was calculated and statistically processed independent of stress. This separate ice load calculation is done for the purpose of load comparison between direct analysis and simplified analysis. Moreover, direct calculation of stress is very time consuming due to very small time interval required for the explicit time integration. The details of the structure are shown in Table 1. As a description of the table, the dimensions of the structure are information about the 'PLANE' section of the structure, and 'height T' and 'height B' are the distance from the end of the slope to the top and bottom.

Table 1. Details of the structure

Dimensions of the structure							
PLANE	slope angle [°]	middle width $[m]$	top/bottom width $[m]$	waterline width $[m]$	height $[m]$	height T $[m]$	height B $[m]$
XZ	55	29.18	17.66	26.38	19.5	3	1
ZY	55	30.46	18.56	27.66	19.5	3	1

The material properties used to apply damage-based erosion model are shown in Table 2. The properties from 'Density of ice' to 'Damping coefficient' are not used in the simplified analysis, but are used only to realize the crack propagation in the FE simulation of the direct analysis.

Table 2. Material properties

Material properties	Values	Units
Flexural strength	539	kPa
Young's modulus	0.35	GPa
Poisson's ratio	0.3	-
Dynamic friction coefficient	0.03	-
Density of water	1040	kg/m^3
Density of ice	909	kg/m^3
Angle of friction	36	°
Fracture energy	15	J/m^2
Damage initiation strain	1E-10	-
Compressive strength	1	MPa
Dilation angle	12	-
Damping coefficient	5	1/s

APPLICATION

The ice thickness-velocity conditions used in the verification are shown in Table 3. In direct analysis, selected 12 conditions, denoted as bold character in Table 3, were analyzed to minimize the computational cost and the remaining conditions were covered by linear interpolation of calculated results. Fatigue cracks were assumed to occur at the weld toe of the stiffener of the outer shell. As shown in Figure 7, ice loads were extracted and processed on the selected 2 panels, which are considered to be most influential to the fatigue at the hot spot location inside the hull.

Table 3. Thickness-velocity conditions.

	case 1	case 2	case 3	case 4	case 5
thickness [cm]	**29.6**	59.2	**88.8**	118.4	**148**
velocity [cm/sec]	**9.18** , 18.36 , 27.55 , **36.73** , 45.91 , 55.09 , 64.27 , **73.45** , 82.64 , 91.82 , **101**				

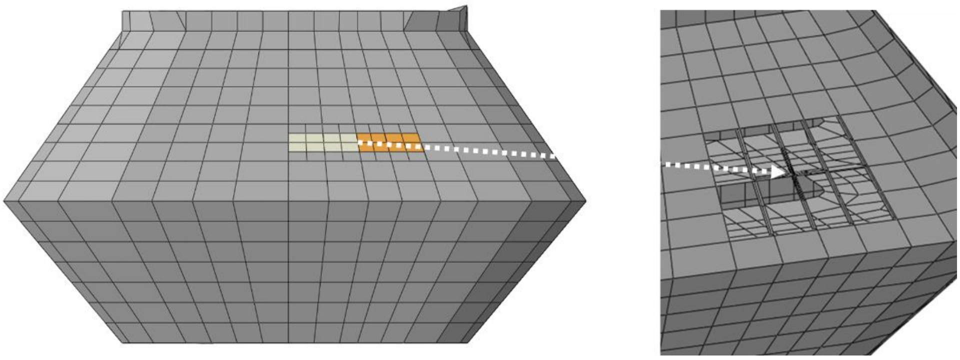

Figure 7. Fatigue target point & panels

Ice Load

Figure 8 shows the cumulative probability distribution function of ice load for the case 1, case 3, case 5. Unlike direct analysis, the ice load of the simplified analysis exhibits one probability distribution per ice thickness. This is because the dynamic effect of the velocity is not considered in the ice load calculation of simplified analysis.

The ratio of the average ice load to the simplified and direct analysis is as shown in Table 4. Compared to the results of simplified analysis, the results of direct analysis at the 101 cm/sec which has maximum value are between 17% and 55%.

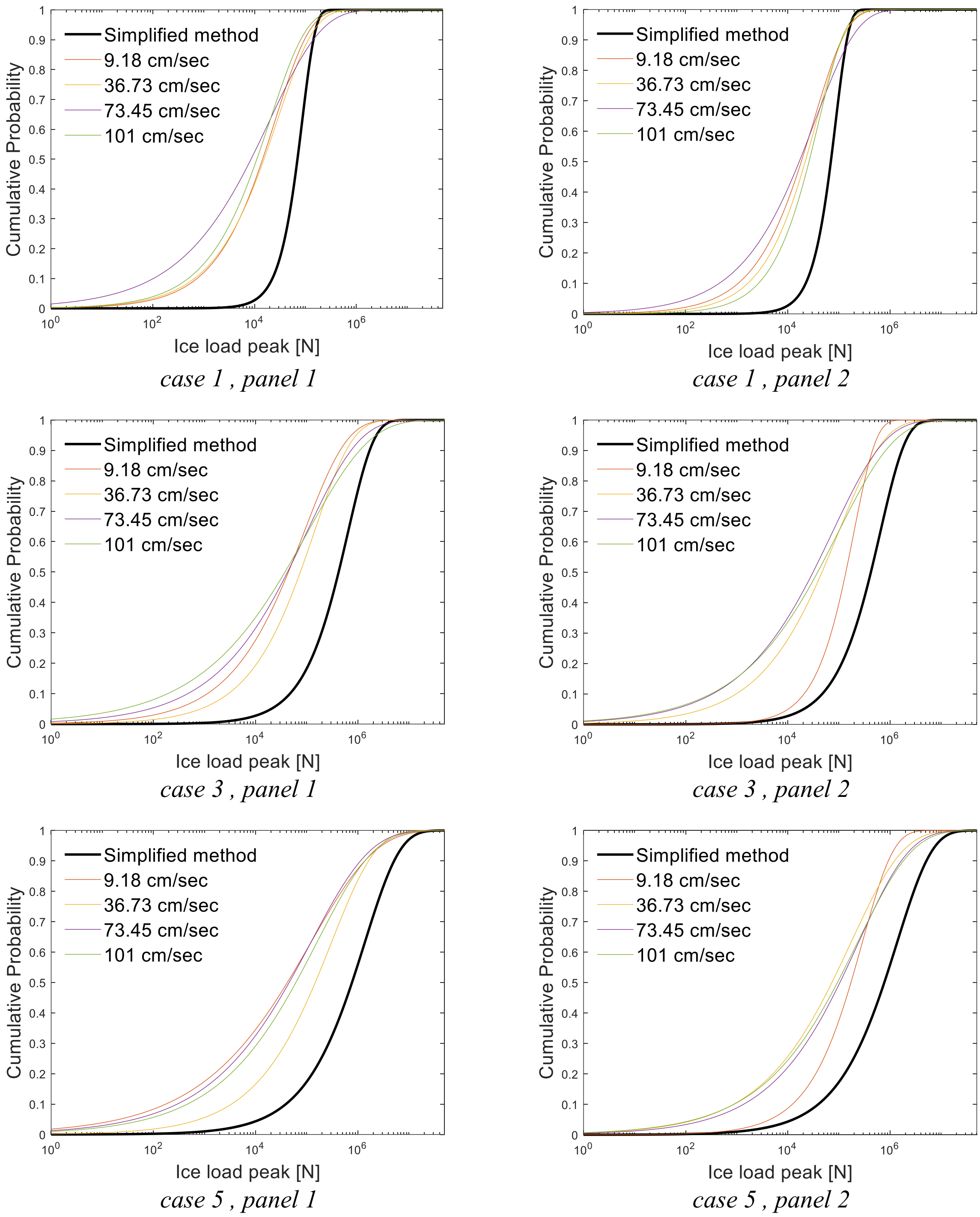

Figure 8. Cumulative probability distribution for the ice conditions.

Table 4. Ratio of the average ice load peak

	case 1	case 2	case 3
panel 1	36.65%	31.47%	17.76%
panel 2	55.61%	30.34%	22.98%

Fatigue Damage

After the load-stress transformation with the influence factors, fatigue damage for the unit ice travel distance were assessed. As stated before, the fatigue damage during the unit ice travel distance for all the other thickness-velocity conditions was calculated by linear interpolation. Finally, total damage was derived by considering the actual ice travel distance for every condition.

Both simplified and direct analysis are applied with design S-N curve of welded joint proposed by Det Norske Veritas (2010).

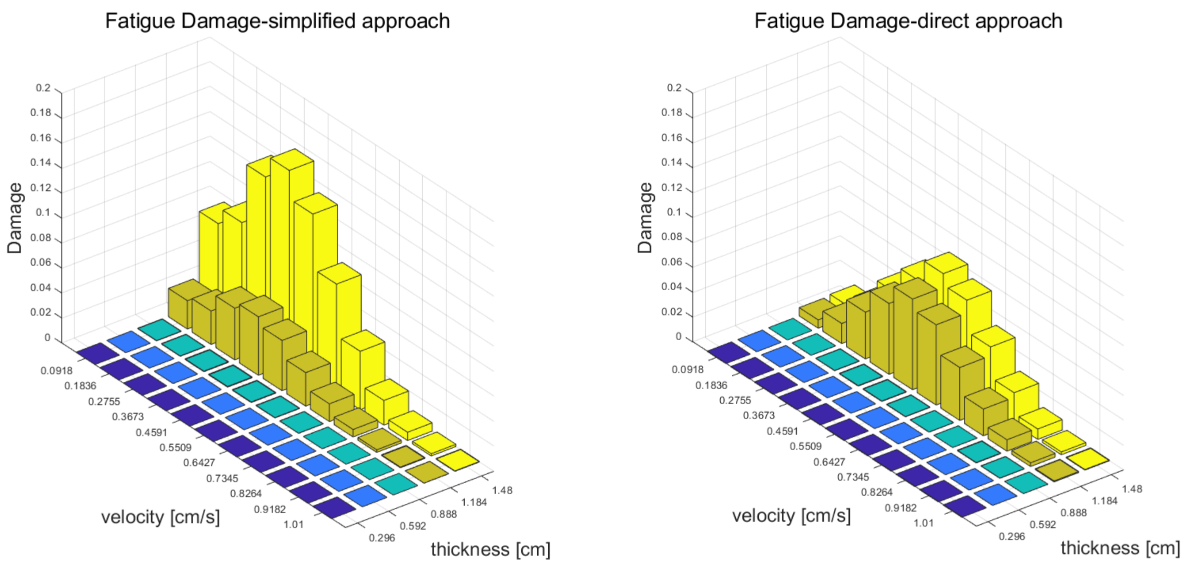

Figure 9. Fatigue damage for the thickness-velocity conditions

The results of fatigue damage against thickness shown in Table 5. In the simplified analysis, a constant load frequency is calculated regardless of the size of the panel. This means that if the panel size is too large for the ice thickness, the load frequency will be too small on each panel. Also, the smaller the thickness of ice, the greater the dynamic effect of the velocity, which increases the load frequency. It was easily observed that ice breaks into crushing immediately after collision at small thicknesses in the simulations of direct analysis. These are why the results of simplified analysis at 29.6, 59.2 cm thickness were very small compared to direct analysis.

Table 5. Fatigue damage for the various ice thickness.

Ice thickness [cm]	Damage (simplified analysis)	Damage (direct analysis)	Damage ratio (simplified/direct)
29.6	3.8232 E-007	3.5111 E-006	0.1089
59.2	5.0845 E-007	3.7336 E-006	0.1362
88.8	0.0026	0.0024	1.0833
118.4	0.2278	0.3314	0.6874
148	0.7506	0.3793	1.9773

CONCLUSION

This paper proposes a simplified fatigue analysis procedure for the sloped structure colliding with level ice, and comparison has been made with direct analysis results for the validation purpose. Even though actual situation taking place during the collision process is quite complicated, especially due to the rubble compilation, only breaking forces induced by the bending of level ice were considered for the fatigue analysis. Due to this, local ice load calculated by simplified method turned out to be larger than that of direct calculation. However, total fatigue damage calculated by simplified method does not always stay on the conservative side, because the frequency of bending failure in simplified analysis is larger than that of direct calculation results. This is mainly due to the constant frequency of the ice load regardless of the size of the panel, so the criteria for panel size should be established for proper assessment.

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