Suggestion of a design load equation for ice-ship impacts

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ABSTRACT: *In this paper, a method to estimate ice loads as a function of the buttock angle of an icebreaker is presented with respect to polycrystalline freshwater ice. Ice model tests for different buttock angles and impact velocities are carried out to investigate ice pressure loads and tendencies of ice pressure loads in terms of failure modes. Experimental devices were fabricated with an idealized icebreaker bow shape, and medium-scale ice specimens were used. A dry-drop machine with a freefall system was used, and four pressure sensors were installed at the bottom to estimate ice pressure loads. An estimation equation was suggested on the basis of the test results. We analyzed the estimation equation for design ice loads of the International Association of Classification Societies (IACS) classification rules. We suggest an estimation equation considering the relation between ice load, buttock angle, and velocity by modifying the equations given in the IACS classification rules.*

KEY WORDS: Medium-scale ice; Polycrystalline freshwater ice; Buttock angle; Ice load; Estimate equation.

INTRODUCTION

The most important factor in designing icebreakers and Arctic voyage vessels is the precise estimation of ice loads. This is because of the need to understand the ice-failure mode, which is determined by impact velocity, bow shape, buttock angle, contact area, and ice thickness (Jordaan, 2001).

In general, it is not an easy task to estimate the ice load because it exhibits very complex characteristics. The failure of ice is strongly dependent on its dimension and grain size, as well as on environmental factors, such as temperature, strain rate, etc. (McKenna et al., 1996; Karna and Rim, 1996; Blanchet, 1998). Although the estimation of critical ice loads corresponding to ice failure is recognized to be very difficult, much research based on laboratory-scale experimental studies has been carried out.

Previous studies show that two types of research activities have been conducted: one is experimental studies (Hawkes and Mellor, 1972) on the estimation of material characteristics, and the other (Blanchet, 1998; Jordaan, 2001) is tests conducted to understand the ice-structure interaction. From the viewpoint of ice-load estimation, Sodhi et al. (1998) and Daley et al. (1998) carried out ice-structure indentation tests in order to estimate ice pressure and observe the contact area during an impact. However, their studies considered ice pressure under static or quasistatic velocities only.

Jordaan reported very important information about the nature of high-pressure zones on the basis of experimental results from medium-scale impact tests (Jordaan, 2001). He has conducted high strain rate experiments (0.1–100 mm/s) to provide quantitative data for the force or pressure characteristics of the high-pressure zones.

Meaney et al. (1996) in their research paper summarized medium-scale ice indentation test results, including

uniaxial compression tests under a constant strain rate. When the test velocities for indentation were fixed as 12 and 20 mm/s only, they could show that damage appears to have a greater influence on creep rate than on elastic modulus.

Peyton (1966) and Blenkarn (1970) have both shown a well-known extremely brittle event at very high homologous temperatures in the ice-structure interaction test. The test results for a similar load are governed by the sequential flaking of the ice edge. We are going to address this phenomenon in this study. The compressive failure of ice during an indentation event was also reported from medium-scale test programs conducted in the field (Frederking et al., 1990; Masterson and Frederking, 1993; Masterson et al., 1999).

The current method to determine ice interaction pressure with an offshore structure employs the aspect ratio, contact area, and ice thickness. These factors become significant factors for interactions between structures and ice floes (Masterson and Spencer, 2000).

There are many studies on the ice-offshore structure interaction. On the other hand, there are very few relevant studies on ice-ship impact tests and ships ramming on ice. The study of the sudden interaction between ships and ice floes, such as a ship ramming into ice, is required from the viewpoint of the increasing operation of vessels in the Arctic Ocean.

Ice pressure loads that impacted with an icebreaker were reported as a function of velocity by Frederking (2003) and Lubbad and Loset (2011). They reported ice pressure loads estimated by pressure sensors that were installed on the hulls of the icebreakers. The test results show an average ice pressure decrease with increasing contact area. Riska (1987) also demonstrated that an assumed contact area can be determined as a function of time with knowledge of the geometry of the bow, ice edge, and ship motion.

Although local ice pressure from real icebreakers or ships had been estimated, laboratory-scale ice model tests were employed due to the various difficulties encountered in full-scale testing. There are many constraints such as weather, accuracy, and repetition. Medium-scale tests provide a good way to study impact failure and forces and to characterize the ice during testing. We carried out ice-impact laboratory tests using medium-scale freshwater ice and found the tendency of the test results for ice loads. It is noted that freshwater ice was used in the impact test as a preliminary study for the evaluation of the sea ice impact load. We have considered the buttock angle as a significant parameter when the icebreaker is crushing the ice floe. Laboratory impact tests of the interaction between ship bow and ice floe were conducted as scenario tests.

Ice class rules and IACS Polar class rules were analyzed, and a modified ice load equation was suggested based on the results of ice impact tests. The modified equation was also verified by test results.

EXPERIMENTAL INVESTIGATION

Impact testing, which can provide useful information on ice-ship structure impact incidents, is generally known to be very difficult to perform. The main reason for those difficulties can be regarded as too many uncertainties such as variances in ice specimen geometry, chemical composition of ice, test velocity etc., during the impact test. Although no standard methodology for impact testing of ice is available yet, the demand to understand ice-ship structure impacts is increasing.

In this regard, over the past decades, two types of ice-ship structure impact test methods have been adopted. One is a crushing test between a full-scale icebreaker and ice, the other is a laboratory-scale impact test.

In order to investigate the ice-ship interaction, Frederking (1999) investigated the effect of impact velocity on the forces acting on the ice during voyages by the Oden in 1991 and the St. Laurent in 1994. He reported the relationship between the duration time of impact forces and impact velocity, as well as the contact area and average ice pressure.

The thickness of ice also affects ice loads. Blanchet (1998) carried out ice-structure interaction experiments with first-year sea ice on an offshore structure. For first-year-level sea ice, there is a decrease from about 0.9 MPa for an ice thickness of 0.4 m to about 0.7 MPa for an ice thickness of 1.8 m. These results are valid for cold water ice, a structure width of 162 m, and interaction velocities between 0.01 and 1 m/s. Based on these results, the ice load is not linearly proportional to ice thickness.

In the present study, in order to investigate the strength of ice under impact loading, we carried out laboratory-scale ice impact tests using a drop tower testing facility. Note that the strength of ice will be referred to as the ice load in this paper.

It is well known that the ice load varies widely according to the failure mode, temperature, salinity, impact velocity, contact area, size of ice specimen, etc. (Sanderson, 1988). This is the main obstacle in deriving the design load for ice impact on a ship. In other words, it is not an easy task to provide a unified formulation that considers the abovementioned parameters sufficiently.

Since the impact induced by a ship-ice interaction may occur on an Arctic route, the reference ice characteristics have to be of multi-year sea ice. According to previous research, it has been reported that freshwater ice can give similar strength characteristics to multi-year sea ice (Sanderson, 1988). Therefore, when considering significant parameters, the effect of salinity was not included in this study.

On the other hand, it is also well recognized that the crystallinity of ice affects its strength characteristics (Schulson, 1990). As a practical method for preventing change in the crystallinity of the ice, it is recommended that a temperature of -15°C be considered as the optimum condition (Schwarz et al., 1981). In this study, although an investigation of the crystallinity of ice was not conducted for the specimens used in this study, the test specimens were stored at -15°C prior to impact testing to prevent any change in the ice crystalline structure.

When considering ice-ship structure impact incidents, as well as the abovementioned specific features, it is concluded that at least two parameters (velocity and ship structure details) should be regarded as the key factors in developing a formulation. In this study, we developed a formulation for ice loads as a function of velocity, ship structure details, and contact area. It is noted that temperature, salinity, and ice specimen size are maintained constant.

Fig. 1 shows the relative angle definition of the ice-ship structure contact, which is identified for the impact incident. The main parameter for the contact condition is the buttock angle, which indicates the angle between the ice and the ship's bow structure. The buttock angle refers to the angle of the buttock line measured from the horizontal at the upper ice waterline.

Fig. 1 The relative angle definition according to the relationship of the ship's bow structure and the ice (Det Norske Veritas, 2009, p.51).

Fig. 2 A schematic view of the experimental setup (left) and drop tower facilities (right).

Fig. 2 shows the drop tower test facility used in this study. Originally, this drop tower was constructed to conduct impact tests for the insulation panel system of Liquefied Natural Gas (LNG) carriers (Chun et al., 2009). The impact condition can be

generated by a free-fall type mass system with weights of 260–300 *kgf* and heights of 0.1–1.3 *m*. With the free fall drop mass, an impact velocity of up to 8.5 *m/s* can be generated. As aforementioned, in order to create the impact condition of the ship's bow structure and ice, four types of test jigs were used according to the test scenario (buttock angles: 20°, 25°, 30°, and 40°). Table 1 summarizes the test scenarios. In this study, using a reference value (for the case of 90°), the effect of the buttock angle on the ice load was investigated. Specimen Impact Reference (IR) indicates the impact test for the case of 90° buttock angle. It is noted that the reference strength of ice impact is measured by the IR specimen. Specimen Impact Buttock (IB) is used for investigating the effect of buttock angle.

Table 1 Ice impact test scenarios.

Test Specimen	Impact velocity	Buttock angle
IR	1.5 <i>m/s</i> ~5 <i>m/s</i>	90
IB	1.5 <i>m/s</i> ~5 <i>m/s</i>	20, 25, 30, 40

The most important issue for deriving the design load of ice impact is the precise measurement of the impact load during the impact incident. In this study, the ice loads were measured by a precise reaction force measuring system. As a data acquisition system, four load sensors with 64,000 *frame/s* resolution were embedded under the drop tower. Fig. 3 shows a photograph of the reaction force measuring system as well as the experimental setup of a specimen (for the case of 40° buttock angle).

Fig. 3 (a) A photograph the of reaction-force measuring system and (b) a photograph of the experimental setup (buttock angle 40°).

RESULTS OF THE IMPACT TEST

Case IR

Fig. 4 illustrates the time history of ice loads as a function of the impact velocity for the case of the IR specimen. The ice load is the average value of reaction force obtained for each test scenario. It can be concluded that the ice load increases linearly with increasing impact velocity, although some discrepancies exist. As shown in the figure, it was found that the maximum load value remains almost the same above an impact velocity of 3 *m/s*. We found that the impact-velocity-dependent ice load shows a critical point. This is somewhat meaningful data for analyzing the ice load in terms of the impact velocity.

According to previous research, a typical and important feature of the mechanical behavior of ice is the transition between

ductile and brittle failure in the case of the time-variant failure problem. Batto and Schulson (1993) have shown that the strength of ice is reduced when the failure pattern changes from ductile to brittle. Therefore, the evaluation of critical strength, which refers to the maximum value at the point of transition, is very important.

From this viewpoint, we investigated the effect of failure pattern on the ice load. Fig. 5 demonstrates the failure pattern for each scenario. As is clearly seen in the figure, brittle failure patterns are observed above the 3 m/s impact velocity range. In other words, owing to the relatively wider portion of (micro-) brittle failure, overall failure occurred more easily in the specimen without any remarkable load increase. This indicates that critical ice load depends not only on the impact velocity, but also on the failure pattern.

Fig. 4 Time history of ice loads according to impact velocities for case IR.

Fig. 5 Observed failure pattern for each scenario: (a) 1.5 m/s, (b) 2.0 m/s, (c) 2.5 m/s, (d) 3.0 m/s, and (e) 5 m/s.

From the obtained results, the following conclusions can be drawn: (1) ice load increases with increasing impact velocity but the relationship is not linearly proportional to impact velocity (2) however, the maximum value of ice load is limited by a critical value that corresponds to the velocity for transition of failure pattern; and (3) therefore, it is crucial to measure the critical value when varying the impact velocity.

Case IB

It is expected that the ice load depends on the angle of impact. As mentioned above, we set up a test scenario for varying the impact angle using the defined buttock angle.

In contrast to the test results of IR (without buttock angle), a critical load value was not shown in results corresponding to a velocity of 1.5–3.0 m/s (see Fig. 6). The brittle failure mode has been especially investigated for a buttock angle of 40° at 5 m/s. In the case of IR, the brittle failure pattern was observed at a velocity of 3 m/s, but in the case of IB, this pattern was observed at a velocity of 5 m/s.

Fig. 6 The time history of the ice load for each scenario for case IB.

A possible way to explain these differences is to consider the effect of flaking. Further research (Daley et al., 1996) showed the flaking phenomenon in the ice-impact problem. When a specific angle exists between the impact structure and ice specimen, prior cracks are created on the contact surface of the ice specimen. Daley et al. (1996) identified the phenomena where multi-level flakes break off from the ice specimen as flaking. According to his assumption, the ice load is governed by the formation of flakes. The flakes, or spalls, remove parts of the ice edge, decreasing the area of ice in contact with the structure. This causes a drop in the ice load (Croasdale et al., 1977).

The force required to cause flaking becomes a local force peak (see Fig. 7). It is obviously observed as a flaking phenomenon and sequential failure under a velocity of 3 m/s. As all the local force peak is repeated during the impact on each of angles, sequential failure occurs from the surface. In conclusion, the final failure pattern becomes non-brittle (ductile).

It can be seen that ice loads increase as the impact velocity increases. It is also found that several load drops due to flaking are obtained for all test cases.

Fig. 7 Typical flaking sequence and time history of the ice load (Daley et al., 1998).

Flaking was observed for impact tests with buttock angles of 20° and 30° in Fig. 6(a) and (c). However, the results for buttock angles of 25° and 40° and an impact velocity of 1.5-3.0 m/s indicate that the load drops with flaking and the specimen is broken in the brittle mode at a velocity of 5 m/s, as shown in Fig. 6(b) and (d).

Photographs of ice fracture with a buttock angle of 40° are shown in Fig. 8. The ice fracture phenomenon was captured for various velocities. It is also found that several load drops due to flaking, ductile failure (local fracture and sequential failure) characteristics, as seen Fig. 6, are clearly obtained.

Fig. 8 Photographs of ice fracture phenomenon with a buttock angle of 40° and impact velocities of (a) 1.5 m/s, (b) 2.0 m/s, (c) 2.5 m/s, (d) 3.0 m/s, and (e) 5 m/s.

As mentioned above, since the test condition of IB generates a line load, the global failure of ice appears the same as in the test of the research (Daley et al., 1998). Daley et al. (1998) considered ice floe impact on structures such as plant installed in the Arctic and Antarctic seas. In this study, we investigated the flaking phenomenon related to the ice-structure impact test depending on buttock angle.

Table 2 The duration time and total force with various buttock angles.

	20°		25°		30°		40°		90°	
	Max.total force (kN)	Duration time(s)	Max.total force (kN)	Duration time(s)	Max.total force (kN)	Duration time(s)	Max.total force (kN)	Duration time(s)	Max.total force (kN)	Duration time(s)
1.5m/s	11.823	0.1796	12.694	0.1404	11.84	0.1224	13.471	0.0566	110.351	0.0156
2.0m/s	14.991	0.1406	16.268	0.1408	--*	--*	25.275	0.0846	157.414	0.016
2.5m/s	15.375	0.0686	21.689	0.1412	24.081	0.1046	30.102	0.0546	162.909	0.016
3.0m/s	17.876	0.148	24.852	0.1042	30.411	0.1046	42.377	0.0516	187.054	0.0154
5.0m/s	47.072	0.0702	32.078	0.063	38.303	0.1046	91.624	0.034	183.504	0.0238

Note: * means experimental error

In Table 2, the test results of IB (with buttock angle) show that the duration time is longer and the maximum force is lower than the results of IR (without buttock angle). Moreover, the overall test results with buttock angle indicated that ice loads tend to increase as velocity increases.

The maximum total force of the impact test with buttock angle 40° is higher than that in the case of other angles. On the other hand, the duration time is shorter than the other buttock angles.

Fig. 9 (a) The time history of ice loads at 40° buttock angle and (b) the time history of ice loads at 3 m/s.

Fig. 9(a) shows the time history of ice loads with buttock angles of 40° at velocities of 2 m/s, 3 m/s, and 5 m/s. Fig. 9(a) shows the graphs for comparing duration times and shows that the duration time is inversely proportional to velocity increases. Fig. 9(b) shows that the maximum ice loads become higher as the buttock angle increases.

Fig. 10 (a) The brittle behavior of ice impact with a buttock angle of 40° at 5 m/s and (b) the ductile behavior of ice impact with a buttock angle of 40° at 1.5 m/s.

Fig. 10 shows two types of representative graphs for the ice impact test. Brittle behavior of ice impact was observed frequently at a velocity of 5 m/s, and ductile behavior was observed from a velocity of 1.5 m/s to a velocity of 3.0 m/s. Fig. 10(b) expresses the flaking phenomenon of the ice impact test as reported by Daley et al. (1998).

Fig. 11 Ice force as a function of the buttock angle.

Fig. 11 represents the relationship of total forces and buttock angle for each impact velocity. Total force increases with increasing buttock angle, except for the case of 5 m/s velocity. The total force also increases with increasing velocity at each of angles.

Whole crack propagation by impact load was recorded using a high-speed camera with a sampling rate of 500 Hz. A representative photo of crack propagation, sequentially captured crack at buttock angle of 25° and velocity of 2.5 m/s, is shown in Fig. 12.

Fig.12 The failure of ice at a velocity of 2.5 m/s with a buttock angle of 25°.

DEVELOPMENT OF DESIGN LOAD EQUATION FOR ICE IMPACT

Discussion of as-is design load equation

Development of an ice-load expression is crucial for selecting an appropriate propulsion system and designing the ship's dimensions from the perspective of safe design. In this context, several ice class rules have been provided by the activities of the

International Association of Classification Societies (2011). In this study, as-is ice class rules are investigated prior to developing a practical design formula. American Bureau of Shipping (ABS, 2008), Russian Maritime Register of Shipping (RS, 2003), Det Norske Veritas (DNV, 2009), and Finnish-Swedish (Swedish Maritime Administration, 2009) rules were selected as references. The ABS ice rule for ice load estimation is based on finite element analyses, where ice load is analyzed using a pressured ice belt around the hull according to load height.

Typically, the extreme ice pressure, $P_{\max}$, given by the model is calculated from the following formula:

$$P_{\max} = 3.37c_d c_i p_0 (1.059 - 0.175L) \quad (1)$$

$$Q = P_{\max} h \quad (2)$$

where c_d is a factor which takes account of the influence of the size and engine output of the ship. c_i is a factor which takes account of the probability that the design ice pressure occurs in a certain region of the hull for the ice class in question. p_0 is Ice nominal pressure. Q is Line load. h is load height which is applied to the side shell longitudinal along the model length.

Eq. (1) and (2) show the expression of ice load for the ABS (2008) ice rule. The details of each component of Eq. (1) and (2) can be found in reference.

The factors c_d , c_i , p_0 of Eq. (1) are defined by the Finnish-Swedish Ice Class Rule (FEM Guideline). The distinguishing point about the ABS rule is that it considers ice loads on the hull side from an ice belt and refers to the Finnish-Swedish Ice Class Rule. However, effects of the buttock angle are not included.

The main aspect of the RS ice rule for ice load estimation is the application of various factors that can consider different effects induced by seasonal environments. RS (2003) suggests calculating the ice load with regard to ice thickness, ship type, weather, or waves using corresponding affecting factors (see Eq. (3)~(14)). While it can be seen that RS can ensure precise estimation of the ice load, its direct application is somewhat difficult because all of the ice-ship impact conditions and/or ship design details should be provided.

$$c_w = 0.0856L \quad \text{for } L \leq 90\text{m} \quad (3)$$

$$c_w = 10.75 - \left(\frac{300-L}{100} \right)^2 \quad \text{for } 90 < L < 300\text{m} \quad (4)$$

$$c_w = 10.75 \quad \text{for } 300 \leq L \leq 350\text{m} \quad (5)$$

$$p = p_{st} + p_w \quad (6)$$

$$p_{st} = \text{static pressure} \quad (7)$$

Summer load waterline

$$p = p_w \quad (8)$$

$$p_{st} = 10z_i \quad (9)$$

where c_w is a wave factor, and p_w is a design pressure.

z_i is the distance from the point of application of the load to the summer load waterline, in m .

$$p_w = p_{w_0} - 1.5c_w \frac{z_i}{d} \quad (10)$$

$$p_w = p_{w_0} - 7.5a_x z_i \quad (11)$$

$$\text{where } p_{w_0} = 5c_w a_v a_x \quad (12)$$

$$a_v = 0.8 \frac{v_0}{\sqrt{L}} \left(\frac{L}{10^3} + 0.4 \right) + 1.5 \quad (13)$$

$$a_x = k_x \left(1 - \frac{2x_i}{L} \right) \geq 0.267 \quad (14)$$

where a_v and a_x are a factor is not to be taken as less than 0.6. v_0 is a initial velocity. k_x is a factor equal to 0.8 and 0.5 for hull sections forward and aft of the midship section, respectively. x_i is the distance of the considered section from the nearest fore or aft perpendicular, in m (RS, 2003).

The ice class rule of the Russian Maritime Register of Shipping (2003) suggests designing ice loads depending on summer and winter seasons, as expressed in Eq. (3)~(14). There are advantages to using detailed factors that are affected by the bow form and wave in the RS rule, because these factors can consider the environmental condition of a vessel route in frozen sea to estimate ice loads. In addition, there are factors, such as engine power and waves, for estimating design ice loads depending on buttock angle.

As for the Finnish-Swedish (Swedish Maritime Administration, 2009) ice class rule, it proposes a design equation of ice loads considering the bulb shape of arctic operating vessels. Compared to RS, the main distinguishing feature of Finnish-Swedish is the use of engine output as the key factor in estimating design ice loads (see Eq. (15)).

The design ice pressure is determined by the following formula:

$$p = c_d \cdot c_1 \cdot c_a \cdot P_0 \quad (15)$$

$$C_d = \frac{a \cdot k + b}{1000} \quad (16)$$

where a and b are a coefficient decided according to value 'k'. c_d is a factor that takes account of the influence of the size and engine output of the ship. c_1 is a factor that takes account of the probability that design ice pressure occurs in a certain region of the hull for the ice class in question. c_a is a factor that takes account of the probability that the full length of the area under consideration will be under pressure at the same time. P_0 is the nominal ice pressure (SMA, 2009).

$$k = \frac{\sqrt{\Delta \cdot P}}{1000} \quad (17)$$

where Δ is the displacement of the ship at maximum ice class draught. P is the actual continuous engine output of the ship.

The Finnish-Swedish rule suggests designing ice loads as in Eq. (15)~(17). The design ice loads of the Finnish-Swedish (Swedish Maritime Administration, 2009) rule consider engine power, ship size, and bow and stern shape. Moreover, many ice class rules of classification suggest design ice loads with reference to the Finnish-Swedish rule. However, as we do not consider

engine power in the ice impact test, this rule was not suitable for modifying the design ice load rule.

On the other hand, DNV (2009) gives the ice load formula as an ice class rule under the consideration of the effect of ship bow structure and the buttock angle. Considering that the most important factor on ship-ice impact during the voyage is the arbitrary inclination of the outer plating (ship-bow-hull system) with the ice, the expression of impact incidents (i.e., impact angle and impact energy) is a very critical issue. In this regard, we selected DNV as a reference for developing a new design formula.

A brief introduction to the DNV rule is given below. The design ice load component affecting the ship head is given by

$$P_{ZR} = P_R F_{EL} \quad (18)$$

$$P_R = 28 \left(\frac{C_R E_{IMP}}{\tan \gamma} \right)^{0.6} (\sigma_{ice} \tan \alpha)^{0.4} \quad \text{in general} \quad (19)$$

$$E_{IMP} = E_{KE} \frac{\tan^2 \gamma}{\tan^2 \gamma + 2.5} \quad (20)$$

$$F_{EL} = \sqrt{\frac{E_{IMP}}{E_{IMP} + C_L P_R^2}} \quad (21)$$

$$C_L = \frac{L^3}{3 \cdot 10^{10} I_V} \quad (22)$$

$$E_{KE} = \frac{1}{2} V (V_{RAM})^2 \quad (23)$$

$$V_{RAM} = V_B + V_H \quad (24)$$

where, P_{ZR} is a vertical ramming design load. $C_R = 1$ for the class notation Polar only, $C_R = 2$ for the class notation icebreaker. E_{KE} is vessel's kinetic energy before ramming. V_{RAM} is the design speed in m/s when ramming may occur V_B is the specified continuous speed when breaking a maximum average ice thickness, V_H is the increase in speed in thinner ice and I_V is the moment of inertia in m^4 about the horizontal neutral axis of the midship section. L is a rule length and rule breadth.

Suggestion of design ice load equation

Based on the intensive investigation of various possible formulae, we propose a new design formula in this study based on the correlation function of ice load as shown below:

$$P = f(\sin \gamma)^a (n E_{impact})^{\frac{2}{3}} \sigma_{ice}^{\frac{1}{3}} \quad (25)$$

$$E_{impact} = \frac{1}{2} m v^2 \quad (26)$$

where γ is the buttock angle and E_{impact} is the kinetic energy induced by impact. σ_{ice} is the nominal stress of the ice. m is the impact mass (unit: 1000 kg) and v indicates impact velocity in $m \cdot s^{-1}$. f , a , and n are constants of the correlation function.

According to Eq. (25), ice load increases with the increase of impact kinetic energy and is related to buttock angle by the term $\sin\gamma$. This is the same basis as the IACS (2011) Polar class rule.

The weight of the experimental device for varying buttock angle is 260-300 kg. σ_{ice} is the nominal strength of the ice.

The nominal strength is defined by Frederking and Gold (1975)

$$\sigma_{ice} = \frac{P_{max}}{T_c B_c} \quad (27)$$

where P_{max} is the maximum total force, T_c is the ice contact thickness; and B_c is the ice contact breadth. The average contact thickness and contact breadth of the ice specimens T_c and B_c are 260 mm and 610 mm, respectively. P_{max} is 187 kN and was estimated when the impact mass plate was dropped at 3 m/s. Therefore, the calculated nominal strength of the ice impact is 1.18 MPa. The nominal ice strength is estimated differently for buttock angles, as shown in Fig. 11. The maximum force is divided by contact area, where the contact area A' depending on buttock angle has a relation with area A that is adopted in the equation of nominal ice strength, written in Eq. (27).

$$A' = \frac{A}{\sin\gamma} \quad (28)$$

$$\sigma_{ice} = \frac{P}{A'} = \frac{P \sin\gamma}{A} \quad (29)$$

Accordingly, the nominal ice strength has a relation with $\sin\gamma$ as written in Eq. (29).

Fig. 13 The idealized feature of contact area by considering the buttock angle.

To compare with the DNV rule of design ice load, we calculated roughly the design ice load by the DNV rule using the dimensions of the experimental device, although the DNV ice class rule was established for arctic operating vessels and icebreakers, and the shape of the dry drop tower and impact mass are unlike the shape of ships. Table 1 lists the dimensions of the dry-drop tower and impact mass.

The constants of the correlation function, f , a , and n , are defined using a regression curve based on experimental data. The results of the fits to the data in Fig. 14 are summarized in Table 4. MATLAB was used for obtaining the regression curve. Fig. 14 shows the suggested equation has a better agreement with experimental results than the DNV ice class rule. Note that the data of Fig. 14 and the best fit curves are presented here only for illustration.

Table 3 Dimensions of the dry-drop tower (DDT) and impact mass.

	M (1,000 kg)	B (m)	L (m)	$I_V (m^4)$
Dimension of DDT	0.3	1.1	3	0.021681

Fig. 14 Comparison of results of experiment and suggested ice load rule and DNV with buttack angles of (a) 20°, (b) 25°, (c) 30°, and (d) 40°.

Table 4 The constants f , a , and n of the developed ice load equation depending on the buttack angle.

	20°	25°	30°	40°
f	4.268	3.889	5.347	10.6
a	0.1041	0.04184	0.03752	0.01032
n	9.868	9.847	6.219	5.882

We considered the relationship with constants f , a , and n , and variable $\sin \gamma$ from ice load measurements. The constants f , a , and n of the developed ice load equation depending on buttack angle can be calculated by MATLAB. Eq. (30) is derived from cubic polynomial plots and written as shown below:

$$f(x) = qx^3 + rx^2 + sx + t \quad (30)$$

where $f(x)$ is total force, and x is velocity.

Table 5 The constants of Eq. (30).

	q	r	s	t
20°	-0.03939	0.9288	5.56	-1.313
25°	-0.03866	0.9115	5.457	-1.289
30°	-0.03952	0.9318	5.578	-1.317
40°	-0.07713	1.819	10.89	-2.571

Eq. (30) is suggested using the regression method. The constants q, r, s, and t are available on the conditions related the buttock angles and the variable x. The variable x is velocity from 1.5 m/s to 5.0 m/s.

In the process of regression curve, the errors were found 0 %, meaning $R^2=1.00$. R^2 , correlation coefficient, is used in the context of statistical models whose main purpose is the prediction of future outcomes on the basis of other related information. It provides a measure of how well future outcomes are likely to be predicted by the model. Therefore, the suggested design ice load equation can be useful in estimating ice load when considering the buttock angle of the ship if only the impact reference of ice is known.

CONCLUDING REMARKS

We described medium-scale impact tests conducted with freshwater ice. The medium-scale tests provided invaluable information on the failure processes in impact tests.

During the tests, we estimated the reaction force of ice using four pressure sensing load cells under the ice specimen. The ice impact test was carried out for various velocities (1.5-5 m/s) and buttock angles. The idealized buttock angle represents the bow of an icebreaker. We observed the failure mode of ice, contact area, and reaction force for four buttock angles. The results from the load cell are presented. Ice loads could be explained by the conclusions summarized below.

- (1) The results of ice impact tests indicate that ice loads are prone to increase with increasing velocity of the impact mass and an increasing buttock angle.
- (2) A high velocity leads to stress concentrations and consequently, more spalls.
- (3) The sequential flaking phenomenon was observed under a velocity of 3 m/s.
- (4) Ice loads are dependent on kinetic energy, related to impact velocity, and are related to the sine of the buttock angle.
- (5) We suggest a design equation of ice loads on the basis of experimental results. The design equation of ice loads is modified using the DNV ice class rules and IACS Polar class rules. It is compared with the original DNV ice class rules and is verified.
- (6) Based on the laboratory impact test and modification of DNV rule, useful formulae for evaluating the ice impact load were developed. While the validity of the proposed formulae was verified by comparing the experimental results, the range of application is not verified for the sea ice case. Further studies on the sea ice problem should be carried out to extend the results of this study.

There are a few differences between freshwater and sea ice, such as strength, density, and salinity. However, the characteristics of freshwater ice load behavior upon impact seem to be similar with those of sea ice (Sodhi et al., 1998). The multi-year ice in the arctic has similar characteristics with freshwater ice (Sanderson, 1988). Consequently, we expect that a relational equation for ice-ship impact can be developed, as significant factors are analyzed and the design equation of ice load is suggested in this study.

ACKNOWLEDGEMENTS

Research funds provided by the Ministry of Knowledge and Economy, Korea, through the Industrial Strategic Technology Development Program (Grant No.10033640) are acknowledged and greatly appreciated. This work was also supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) through GCRC-SOP (Grant No. 2011-0030667).

REFERENCES

- American Bureau of Shipping, 2008. *Guidance notes on Ice class: October 2008 consolidation includes: March 2005 version plus Corrigenda/Editorials*. New York: ABS.
- Batto, R.A. and Schulson, E.M., 1993. On the ductile-to-brittle transition in ice under compression. *Acta Metallurgica et Materialia*, 41(7), pp.2219-2225.
- Blanchet, D., 1998. Ice loads from first-year ice ridges and rubble fields. *Canadian Journal of Civil Engineering*, 25(2), pp. 206-219.
- Blenkarn, K.A., 1970. Measurement and analysis of ice forces on Cook Inlet Structures. *2nd annual Offshore Technology Conference*. Houston, Texas: OTC.
- Chun, M.S., Kim, M.H., Kim, W.S., Kim, S.H. and Lee, J.M., 2009. Experimental investigation on the impact behavior of membrane type LNG carrier insulation system. *Journal of Loss Prevention in the Process Industries*, 22(6), pp.901-907.
- Croasdale, K.R., Morgenstern, N.R. and Nuttall, J.B., 1977. Indentation tests to investigate ice pressures on vertical piers. *Journal of Glaciology*, 19(81), pp.301-312.
- Daley, C., Tuhkuri, J. and Riska, K., 1996. *Discrete Chaotic Ice Failure Model Incorporating Extrusion Effects*. Calgary: National Energy Board.
- Daley, C., Tuhkuri, J. and Riska, K., 1998. The role of discrete failures in local ice loads. *Cold Regions Science and Technology*, 27(3), pp.197-211.
- Det Norske Veritas, 2009. *Ships for navigation in ice*. Norway: DNV.
- Frederking, R., 1999. The Local Pressure-Area Relation in Ship Impact with Ice. In: NRC (National Research Council Canada), *15th International Conference on Port and Ocean Engineering under Arctic Conditions, POAC'99*. Helsinki, Finland 23-27 August 1999, Ottawa: NRC.
- Frederking, R., 2003. Determination of local ice pressures from ship transits in ice. In: NRC (National Research Council Canada), *the Thirteenth (2003) International Offshore and Polar Engineering Conference. ISOPE'03*. Honolulu, Hawaii, USA 25-30 May 2003. Ottawa: NRC.
- Frederking, R.M.W. and Gold, L.W., 1975. Experimental study of edge loading of ice plates. *Canadian Geotechnical Journal*, 12(4), pp.456-463.
- Frederking, R.M.W., Jordaan, I.J. and McCallum, J.S., 1990. Field tests of ice indentation at medium scale: Hobson's choice ice island, 1989. In: IAHR (The International Association for Hydro-Environment Engineering and Research), *10th International Symposium on Ice*. Espoo, Finland 20-23 August 1990, Madrid: IAHR.
- Hawkes, I. and Mellor, M., 1972. Deformation and fracture of ice under uniaxial stress. *Journal of Glaciology*, 11(61), pp. 103-131.
- International Association of Classification Societies, 2011. *IACS UR-I Requirements concerning POLAR CLASS*. London: IACS.
- Jordaan, I.J., 2001. Mechanics of ice-structure interaction. *Engineering Fracture Mechanics*, 68(17-18), pp.1923-1960.
- Karna, T. and Rim, C.W., 1996. *Model for global first-year ice loads*. Finland: VTT Building Technology.
- Lubbard, R. and Løset, S., 2011. A numerical model for real-time simulation of ship-ice interaction. *Cold Regions Science and Technology*, 65(2), pp.111-127.
- Masterson, D.M. and Frederking, R.M.W., 1993. Local contact pressures in ship/ice and structure/ice interaction. *Cold Regions Science and Technology*, 21(2), pp.169-185.
- Masterson, D.M. and Spencer, P.A., 2000. *Ice force versus aspect ratio*. In: *International Union of Theoretical and Applied Mechanics (IUTAM) Symposium: Scaling laws in ice mechanics and ice dynamics*. Fairbanks, Alaska USA 13-16 June 2000, Netherlands: Kluwer Academic Publisher.
- Masterson, D.M., Spencer, P.A., Nevel, D.E. and Nordgren, R.P., 1999. Velocity effects from multi-year ice tests. In: ASME (American Society of Mechanical Engineers), *18th International Conference on Offshore Mechanics and Arctic Engineering, OMAE'99*. Newfoundland, Canada 11-14 July 1999, New York, ASME.
- McKenna, R.F., Bruneau, S.E. and Williams, F.M., 1996. *In-Situ Shear Strength Measurements of Model Ice Rubble Using a Punch Technique*. Ontario: Canadian Geotechnical Society.
- Meaney, R., Jordaan, I.J. and Xiao, J., 1996. Analysis of medium scale ice-indentation tests. *Cold Regions Science and Technology*, 24(3), pp.279-287.

- Peyton, H.R., 1966. *Sea ice strength, Annual report*. Alaska: Geophysical Institute, University of Alaska.
- Riska, K., 1987. *On the mechanics of the ramming interaction between a ship and a massive ice floe*. PhD. Helsinki University of Technology.
- Russian Maritime Register of Shipping, 2003. *Rules for the classification and construction of sea-going ships, edition 2003*. St. Petersburg: RS.
- Sanderson, T.J.O., 1988. *Ice mechanics and risks to offshore structures*. Norwell: Kluwer Academic Publishers.
- Schulson, E.M., 1990. The brittle compressive fracture of ice. *Acta Metallurgica et Materialia*, 38(10), pp.1963-1976.
- Schwarz, J., Frederking, R.M.W., Gavrilov, V.P., Petrov, I.G., Hirayama, K.-I., Mellor, M., Tryde, P. and Vaudrey, K.D., 1981. Standardized testing methods for measuring mechanical properties of ice. *Cold Regions Science and Technology*, 4(3), pp.245-253.
- Sodhi, D.S., Takeuchi, T., Nakazawa, N., Akagawa, S. and Saeki, S., 1998. Medium-scale indentation tests on sea ice at various speeds. *Cold Regions Science and Technology*, 28(3), pp.161-182.
- Swedish Maritime Administration, 2009. *The structural design and engine output required of ships for navigation in ice: Finnish-Swedish Ice Class Rules*. Norrköping: SMA.