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Uncertainty quantification in the ice-induced local damage assessment of a hull section

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ABSTRACT

For the northernmost ocean regions, where the ice is occasionally present, one must design a robust structure that can withstand rare ice events (i.e., a glacial ice impact). Despite existing engineering practice is well developed, many challenges remain. One of them is an understanding of local ice actions and action effects. The engineering community has adopted the limit-state design methodology for offshore structures, however, adequate guidance on how to design a structure against an accidental limit state (ALS) due to ice actions is lacking. The majority of existing experimental and full-scale ice data come from the structures that are virtually rigid and thus may not be representative for the scenarios where the structure deforms. Floating-ice impacts in which the structure sustains damage are in the shared-energy regime – both the ice and the structure dissipate energy through inelastic deformation. When analysts consider the shared-energy approach for assessment of the structure's capability to withstand glacial ice impacts, they should be aware of the variations in input data and of how they might affect their analysis. This study is a follow up of the response assessment of a hull structure under glacial ice impact loads. The paper examines the required information for application of the shared energy method, the variances in that information, and how these variances affect the assessment of structural performance. Results of analysis indicate that using the rule-based ice load models may be insufficient for damage assessment under the ALS caused by ice. It requires a case-tailored view on the energy absorption capacity of ice and ALS criteria.

KEY WORDS: Ice; Damage Assessment; Hull; Uncertainty

INTRODUCTION

Ice of glacial origin are of major importance for offshore structures located on the Grand Banks, the Labrador Shelf and the iceberg prone regions in the Barents Sea. Despite the difference in ice regimes between these geographical areas, there is a common element:

potential risk of impact with glacial ice features. On the Grand Banks, where glacial ice features are often present, the hull of the SeaRose FPSO is ice strengthened so as to meet the requirements of the DNV Baltic Ice Class 1A+. The hull can withstand an impact form a 100,000 tons iceberg at a speed of 0.5 m/s (Husky Oil Operations Limited, 2001). It is considered that icebergs with waterline lengths less than five meters do not pose a significant threat to this structure. In comparison to the SeaRose FPSO, frequency of ice interactions is very low at the location of the Johan Castberg FPSO (e.g., three impacts in 100 000 years, PSA (2018)), and thus the hull will not be strengthened to a specific ice class. Instead, the robustness of the structure has been checked for the case of sea ice or iceberg interactions with the hull; and the thickness of some structural elements have been increased by 25 %. To reduce ice risks further, the ice risk management system/ice management plan have been or (to be) implemented at both locations in the Grand Banks and in the Barents Sea.

It must be understood that the quality and quantity of the input data on threatening ice features are always limited, and interpretation of the available data is required. Historically, operators of marine vessels and offshore platforms have done everything to avoid severe or extreme ice conditions. A moving vessel can choose a different route through the ice, and an offshore structure may disconnect and move off location, or physical ice management procedures can be deployed to avoid the interaction. Once threatening ice conditions are encountered, no attempts are usually made to record the ice properties (e.g., underwater ice shape). Smaller ice features such as growlers and bergy bits having waterline length of approximately ten meters require a special consideration. This is because in high sea states, they may not be detected by the radar and could be difficult to manage. Furthermore, due to their motions in waves, they may strike above or below the ice-strengthened part or may even be thrown onto the deck of facilities.

In the existing engineering practice, there is no universally accepted procedure on how to design a structure against rare or extreme ice impact actions. The majority of the existing experimental and full-scale ice data comes from structures that are virtually rigid and thus may not be representative for the scenarios where the structure deforms. Floating ice impacts in which the structure sustains damage are in the shared-energy regime – both the ice and the structure dissipate energy through inelastic deformations. When analysts consider the shared-energy approach as a candidate for assessment of the structure's capability to withstand a glacial ice impact, they should be aware of the uncertainties involved in the procedure.

The purpose of this study is to develop an understanding on how the variations in input data for ice-induced damage assessment may affect the analysis. This work is a follow up of the response assessment of a hull structure under glacial ice impact loads; see Ekeberg et al. (2018) and Lu et al. (2018). This paper examines the information that the shared energy method needs, the variances in that information, how these variances affect the assessment of the structural performance and describes the issues found. Focus is placed on the local ice geometry, the local ice-load model and the acceptance criteria. We start by briefly discussing the approach adopted in ISO 19906 (2018), the shared energy approach and the associated uncertainties. Then we present a case study that addresses the outlined uncertainties and discuss the issues found.

Approach of the International Organization for Standardization (ISO)

The assessment of the resistance to ice impact should always be performed under the principle of the Ultimate Limit State (ULS) and further verified according to the requirements for the Accidental Limit State (ALS) (ISO 19906, 2018). The ULS ice impact event (annual probability of occurrence typically less than 10^{-2}) is important for the structural safety. This control ensures that all foreseen loads can be resisted with an adequate margin. In ALS design (annual probability typically less than 10^{-4}), damage to the structure is allowed as long as there is sufficient residual strength to prevent progressive collapse, and the safety of the crew and environment can be maintained. Regardless of the design principle adopted, the ice impact loads are often treated as pressure-area (p-A) relationships. The p-A relationship depends on the recurrence period and will typically be higher in the ALS than in the ULS, unless the p-A relationship corresponding to ULS does not exist.

In the ULS, local p-A curves are traditionally used to determine the required scantlings for plates, stiffeners, stringers and frames using relevant areas and associated pressures (i.e., $p=C\cdot A^{ex}$, where C and ex ($ex<0$) are the empirical coefficients). Structural resistance models may either be based on elastic theory or plastic methods of analysis. The latter approach gives generally better insight in the collapse pattern, which method that is most conservative depends on the partial safety factors used for the resistance.

In the ALS, the situation is different, especially if the ice action is limited by kinetic energy. It is not required that the structure shall resist the ice pressure. Considerable plastic (inelastic) behavior may be fully acceptable as long as the indentation level complies with the acceptance criteria, for example, no rupture of the outer shell that could cause flooding of two buoyancy compartments. Thus, it may happen that the structural resistance limits the contact pressures, while the ice does deform quite little. It is therefore not so obvious how traditional p-A relationships shall be handled for structures undergoing deep deformations. Consequently, in the ALS we are not so much concerned about the resistance to local, rapidly varying ice pressures, but rather the resistance to the global ice actions.

Shared energy approach

Analysis of an accidental limit state due to glacial ice impact is usually performed within the ductile domain and/or shared energy domain. If the ductile approach is used, the ice is treated as a rigid body, and the local geometry of the ice feature becomes critical. The approach can be conservative as well as untrustworthy, depending on the choice of the ice geometry. Knowledge on the site-specific ice shapes is needed for sound damage assessment within the context of ductile design. In this study, we focus on the shared energy approach. The following paragraphs briefly introduce the method and its steps.

The response of realistic ice-structure collisions are always in the shared-energy regime: both the ice and the structure will dissipate energy. From a physical point of view, when the ice hits the structure, the ice will always fail first locally. This is because the theoretical tensile ice strength ($0.1E$, where E is the elastic modulus of the material) is lower than that of steel. As the contact area between the ice and the structure increases, the structure may start to deform. With further increase of the contact area due to structural deformations, the structural resistance may become larger and ice resistance may become smaller due to softening. When the structural resistance exceeds that of the ice, the latter will deform. The process continues with the instantaneously weaker structure (ice/structure) undergoing deformation. The process stops when all available kinetic energy is dissipated. Mathematical/numerical modelling of such ice-structure interaction effects is associated with significant uncertainties and is thus often neglected in the engineering practice.

Steps of the method

As long as the impact and inertia forces predominate the response, the following procedure is typically used:

1. External mechanics analysis of the impact.
2. Internal mechanics analysis and assessment of damage using energy levels derived in Step 1.

The objective of the external mechanics analysis is to determine the demand for energy dissipation, i.e. how much of the kinetic impact energy must be dissipated by deformation of the structure and/or the ice feature and how much of that will remain as kinetic energy, possibly transferred to other rigid body motions. The demand for energy dissipation only specifies the total amount of deformation energy, not how this is distributed between the ice and the structure. The latter is determined by the internal mechanics analysis. The external mechanics can be solved by numerical simulation where both the local deformation and rigid body motion is modelled (e.g., as it was done in Lu et al. (2018)). Alternatively, it can be solved analytically (Yu et al., 2018 and Liu and Amdahl, 2019). In the internal mechanics analysis, force-deformation relationships for the ice and the structure are typically established by analyzing impacts of deformable ice against a rigid structure and rigid ice impacts against a deformable structure, respectively. The crushing of the ice and the structure damage is determined such that the total energy dissipation is equal to the demand for energy dissipation, as estimated by the external mechanics analysis in Step 1. Below we discuss the uncertainties associated with Step 2. Uncertainties associated with Step 1 have been addressed in Yu et al. (2018).

Ice Geometry

It is very important to distinguish between local and global geometry of the ice feature. The *global geometry* is decisive w.r.t. the mass of the feature as well as the exposure to impact of the various parts of the structure. The location of contact relative to the mass center including added mass is important w.r.t the demand for energy dissipation, which is expressed as a fraction of the total kinetic energy at the instant of impact. This concerns the so-called external mechanics; the aspects of this are not discussed herein. The *local geometry* is essential w.r.t. the resistance of the ice to deformation (crushing, extrusion etc.) at the contact point and the evolution of the load path geometry during the collision.

Models for ice load identification

Current international regulations and design practices prescribe two distinct methods for ice load identification; i.e., a probabilistic approach and a deterministic method. To identify ice actions the Norwegian petroleum industry standard NORSOK 003 requires that a probabilistic approach should be applied, however it allows using a deterministic method at an early stage. Independent of the method, ice actions are usually determined by using pressure-area curves as in ISO 19906, assuming that most of the deformation takes place in the ice and the structure is not deforming substantially. Table 1 below compares both methods in view of glacial ice impact loads leading to ALS.

In internal mechanics analysis, there is a need to establish a force-deformation curve for a given ice feature. If we use an ISO p-A to construct the force-deformation curve, we will be treating the ISO design curve as a process p-A curve. In ISO, the ice pressure-area relationships have been derived using force time histories and converting force values to pressures. These design curves are based on the peaks of the force/pressure data. In addition, in the deterministic approach, the pressure was based on the mean plus three times the standard deviation of pressure data for each contact area. The probability is low that during a rare event, the ice can develop those pressures for each contact area. Moreover, for contact areas larger than approximately one square meter, the pressure values drop so fast ($A^{-0.7}$) that it is questionable whether it can be used for calculations in the ALS. The local p-A curves in ISO should be treated as design curves for local design against ULS, i.e., for a given local design-area there is a corresponding ice ‘design-pressure’.

Table 1. Probabilistic versus deterministic approach; examples, pros and cons

<table>
<tr><th colspan="2">Probabilistic Approach ISO19906 (Sec. A 8.2.5.3)</th><th colspan="2">Deterministic approach ISO19906 (Sec. A.8.2.5.4)</th></tr>
<tr><td colspan="2">Used in offshore development projects (e.g. the White Rose)</td><td colspan="2">Used in Ekeberg, et al. (2018)</td></tr>
<tr><td colspan="2">ISO 19906 explicitly states that the method can be applied for short duration (order of seconds) bergy bit impacts</td><td colspan="2">Intended to provide local ice pressure associated with massive ice features having a thickness in excess of 1.5 m</td></tr>
<tr><td colspan="2">Considers time and the number of interactions in a year which is also recommended by ISO</td><td colspan="2">No extra input is required</td></tr>
<tr><td colspan="2">The effect of ice management operations can be considered by varying the expected number of impact events</td><td colspan="2">Simple to use</td></tr>
<tr><td colspan="2">Based on the ship impacts with MY ice (Kigoriak ramming trials with MY ice, etc.), thus on yesterday's designs, structures were not deforming, and thus datasets for specific regions and loading conditions</td><td colspan="2">Data have been derived from indentation tests in the Beaufort Sea (iceberg ice) and from measurements made on the ice pressure panels of the Molikpaq structure in the same area, structures were not deforming, and thus these datasets are for specific regions and loading conditions</td></tr>
<tr><td colspan="2">Resulting p-A curves are sensitive to the initial conditions: average impact duration, expected number of ramming/impact events per year, proportion of true hits on the design area</td><td colspan="2">The underlying pressure-area data is a mixture of different tests with different exposures, long and short duration events.
The pressure-area curve represent only exceedance probabilities on the pressure data and not values for AL actions
Analysis of the same data gives different p-A curves</td></tr>
<tr><td colspan="4">Some examples</td></tr>
<tr><td>PA-curve (10^{-4})</td><td>Source</td><td>PA-curve</td><td>Source</td></tr>
<tr><td>$p \approx 7.0A^{-0.7}$
$p=10$ MPa ($A \leq 0.6$ m^2)</td><td>For five, 3.5-seconds impacts per 1000 years, the proportion of true hits on the design area is 1 (Jordaan et al. 2014)</td><td>$p=7.4A^{-0.7}$</td><td>Data were divided into bins; a mean and standard deviation was determined for each bin. A linear least squares regression line was fitted to the average plus 3 times standard deviation points for the bins (Masterson et al., 2007)</td></tr>
<tr><td>$p=22.13A^{-0.7}$
$p=32$ MPa ($A \leq 0.6$ m^2)</td><td>For 1000, 5-seconds rams per year, the proportion of true hits on the design area is 0.7 (Ralph, 2016)</td><td>$p=9.6A^{-0.74}$</td><td>Linear quantile regression of log-log data, 0.99 quantile (Morrison and Spencer, 2014)</td></tr>
<tr><td>$p=14.9A^{-0.7}$
$p=22$ MPa ($A \leq 0.6$ m^2)</td><td>For three iceberg 3.5-seconds impacts per year, the proportion of true hits on the design area is 1.0 (ISO19906, Figure A.8-27, p. 238)</td><td></td><td></td></tr>
<tr><td>$p=2.01A^{-0.7}$
$p=2.9$ MPa ($A \leq 0.6$ m^2)</td><td>For one iceberg 3.5-seconds impacts per 10000 years, the proportion of true hits on the design area is 1.0 (this study)</td><td></td><td></td></tr>
<tr><td>$p=3.39A^{-0.7}$
$p=4.8$ MPa ($A \leq 0.6$ m^2)</td><td>For three 3.5-seconds impacts per 10000 years, the proportion of true hits on the design area is 1.0 (this study)</td><td></td><td></td></tr>
<tr><td colspan="4">The pressure will always drop off at the rate of approximately $A^{-0.7}$, that is part of the result, following the data.</td></tr>
</table>

Within the context of the internal mechanics analysis, the physical limits to the energy absorption capacity of ice become more important than the underlying pressure-area relationship. It may therefore be useful to consider the amount of energy spent on crushing a unit mass of ice (CSE). For fully confined iceberg ice at Pond Inlet (Masterson et al., 1992), when the effect of the sample size and boundaries are minimized, CSE is maximum 6.09 kJ/kg (average value being 2.96 kJ/kg). This value was derived using force-time history records obtained in the Pond inlet tests with 900, 1280 and 2300 mm radius indenters.

While the CSE value can be used to calculate the energy spent on ice crushing, the process p-A relationship during an ALS event could be also established. The question is: can we use the ISO curve with C=7.4 and ex=-0.7? The majority of the data for this curve come from the Pond Inlet tests on iceberg ice with 2300 mm radius indenter. The pressures obtained in the Pond Inlet test set are a series of maxima during individual tests (four tests in total), the data were binned according to the fully confined contact area and $p=7.4A^{-0.7}$ is the mean plus three standard deviations. Thus, it is questionable whether this curve can be used in the context of ALS. Instead, the process pressure-area relationship underlying the local ice-load calculations in IACS PC code (i.e., $p=3.2A^{-0.1}$) was found to better represent the physical value of the energy absorption of iceberg ice during crushing and spalling failure.

Acceptance criteria

Within the context of ALS checks of iceberg impacts, several different acceptance (and or fracture) criteria have been used in the past. In earlier works (Jordaan et al.), the localized value of 5% equivalent plastic strain in the shell plate was used as a serviceability/ALS condition in assessing the response of a hull section of a FPSO due to iceberg impacts. In addition, the depth of shell plate dent should not exceed half of the specified plate thickness. In damage assessment studies, Ekeberg et al. (2018) adopted a fracture criterion based on the 1st principal strain from the recommended practice (RP) DNV-GL-RP-C208 (2016). According to the RP, the limiting principal strain value is as a function of the mesh size, plate thickness and material quality. It was calculated to be 7% for the 355 MPa steel in Ekeberg et al. (2018). In the study by Lu et al. (2018), the fracture was assumed to occur at the onset of necking instability, thus neglecting the post-necking stage, and the principal strain prior to fracture was set to 16% for the 355 MPa steel material.

CASE STUDY

The objective of this study was to investigate how the variations in input data to internal mechanics analysis might affect the calculated damage and the conclusions on the integrity of the impacted structure. The case study considers uncertainties in ice geometry, ice load model and in acceptance criteria. The internal mechanics analysis has been performed for two different impact locations on a structure: on a stiffened bulkhead - location (a) and on a confined stiffened panel of the column front - location (b). The impact locations are shown in Figure 1, and model description and analysis setup is given in the following paragraphs.

Model setup

The structural response is calculated by NLFEM analysis in LS-DYNA. The impact structure is the Midgard column, that was modelled by Tavakoli and Amdahl (2010) for the assessment of structure strength against supply vessel impacts. Only the front part of one leg was modelled. The overall dimension of the column FE-model is 17200 mm × 308750 mm × 6100 mm (length × height × width). The finite element model of the column and impact locations are shown in Figure 1. The column outer shell thickness is in the range of 16-18 mm. The vertical stiffeners used in the column are HP320x12, HP300x11 and HP240x10.

Numerical simulations were carried out by using explicit NLFEM software LS-DYNA 971. The four node Belytschko-Lin-Tsay shell element with five integration points through the thickness and reduced integration was used. Hourglass stiffness is added using the stiffness based form (option 4 in LSDYNA). This is very efficient and gives less than 2-3% dissipation of spurious hourglass energy. The rear side, the top and the bottom of the column are constrained in all degrees of freedom (translation in direction of x-, y- and z-axis and rotation around x-, y- and z-axis).The rigid ice model is given a prescribed motion velocity of 3 m/s, and any strain rate effect is not taken into account. Two kinds of contacts are defined in this analysis, which are the self-contact and master-slave contact. For the rigid ice-column impact, the master-slave contact is used with the column being the slave part. Self-contacts are defined for the column model to detect possible contacts due to deformation. A static friction coefficient of 0.3 was used for all the contacts. These stiffeners were modelled as L-bars with dimensions 320 × 50 × 40 × 12 (mm), 300 × 50 × 50 × 11 (mm) and 240 × 40 × 30 × 10 (mm). This gives nearly the same height, width and the cross sectional area as the HPs. The column model was meshed using approximately 245,000 4-noded shell elements. The general element size is 120 mm.

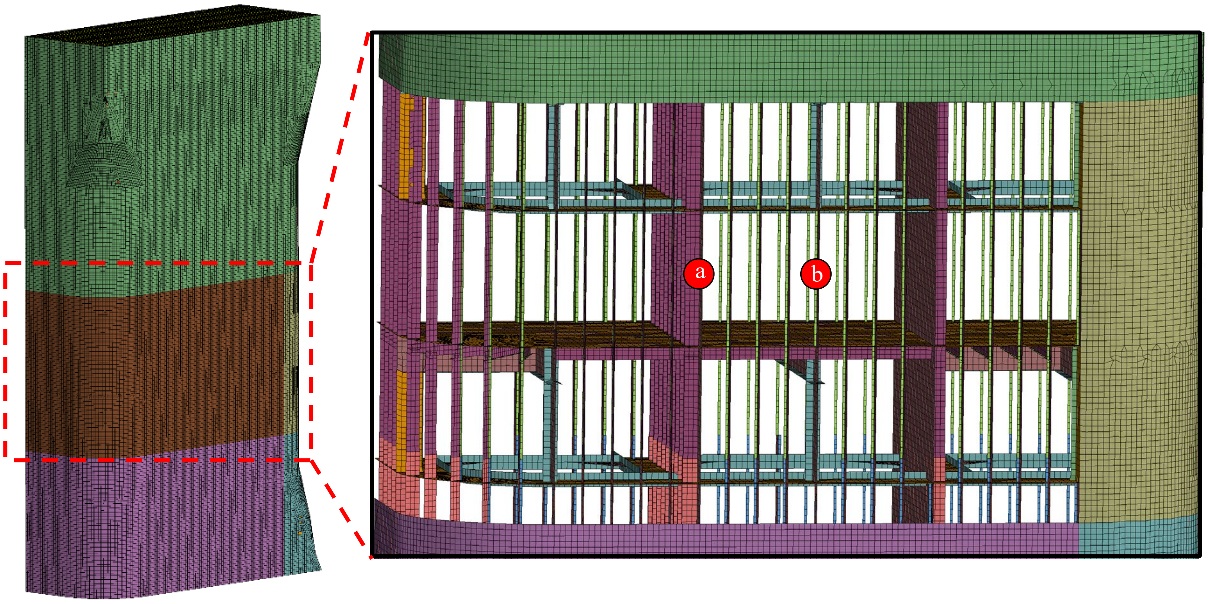


Figure 1. A finite element model of the Midgard column; Impact locations (a) stiffened bulkhead and (b) middle stiffener.

The power law hardening with a yield plateau model is used to model the material response. The BWH (Bressan-Williams-Hill) instability criterion is used to model fracture in the ice impact simulations. The BWH instability criterion was originally proposed by Alsos et al. (2008). The criterion combines Hill's local necking model (Hill, 1952) and the Bressan-Williams shear stress criterion (Bressan and Williams, 1983).

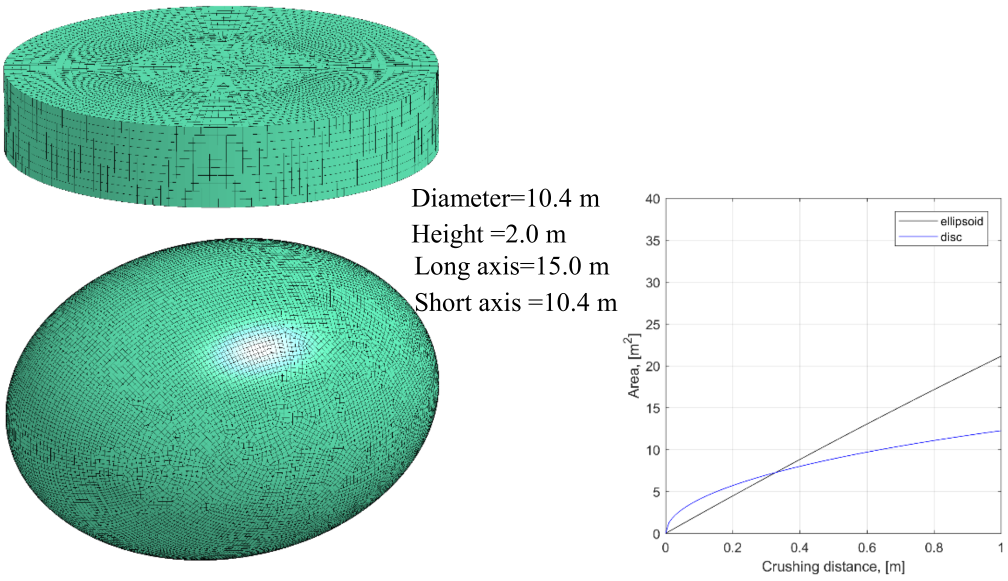
A through thickness integration point is failed by setting the stresses to zero once the failure criterion is satisfied. Final element erosion occurs once the middle integration point fails. This approach is preferred over requiring all integration points to fail prior to erosion because nodal fiber rotations in elements undergoing large strains may limit the strains in the remaining integration points, thus resulting in no erosion of the element.

Two kinds of steel material grades are used for the structure materials. The material properties are shown in Table 2. The outer shell material has a yield stress of 420 MPa, while the value for the stiffeners is 355 MPa.

At the impact location (a) the structure- and ice resistance is estimated for two different local ice geometries (shown in Figure 2a) corresponding to different evolution of the ice-structure contact area (Figure 2b). In addition, three different ice load models have been considered (Table 3) that correspond to different energy absorption capacity of ice or encounter frequency.

Table 2. Material properties

Steel grade	Young's Modulus	Yield Strength	Poisson Ratio	Power law hardening coefficient K	Power law hardening exponent n	epsilon_plateu
	MPa	MPa	[-]	MPa	[-]	[-]
Plate	$2.07\cdot10^5$	420	0.3	860	0.16	0.0
HP	$2.07\cdot10^5$	355	0.3	780	0.22	0.0



(a) (b)

Figure 2. Local ice shapes.

Table 3. Ice load models

#	Ice load model (MN)	Energy absorption capacity of ice (fully confined indentation with spherically-ended indenter) or encounter frequency	Ice Type
1	$F=3.2A^{0.9}$	2.96 kJ/kg	Iceberg ice at Pond Inlet
2	$F=2.01A^{0.3}$ $F=2.9A$ ($A\leq0.6$ m^2)	One impact per 10000 years	Ice of glacier origin
3	$F=3.39A^{0.3}$ $F=4.8A$ ($A\leq0.6$ m^2)	Three impacts per 10000 years	Ice of glacier origin

NUMERICAL RESULTS

Local ice shape and impact location

Figures 3 and 4 plot on the right-hand side, the structural impact resistance from LS-DYNA simulations assuming rigid ice, while on the left-hand side is the ice crushing resistance is calculated analytically assuming a rigid structure and using the ice load Model #1 from Table 3. Figure 5 shows the levels of the equivalent plastic strains at different impact locations. We have assumed that for the same force level, both the ice and the structure should deform and absorb energy in accordance with the resistance curves, and the area below the curves represents the energy that is dissipated in ice and the structure, respectively.

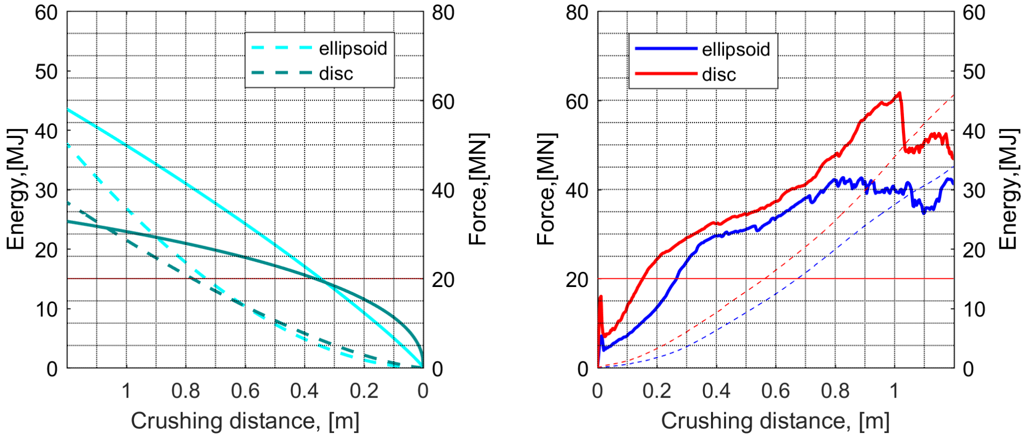


Figure 3. Ice-structure impact resistance at the location (a) – the bulkhead. Left: Contact force (full line) and energy dissipation (dotted). Right: Structural resistance.

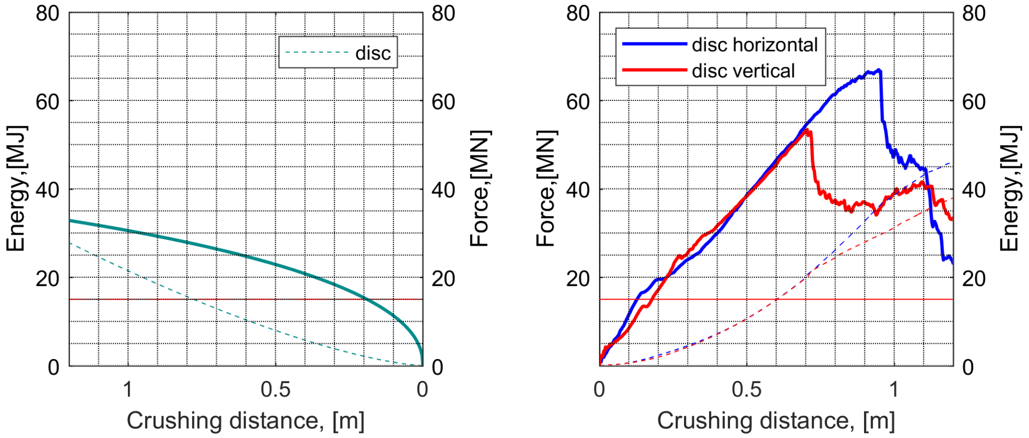


Figure 4. Ice-structure impact resistance at the location (b) – stiffened panels at the column front. Left: Contact force (full line) and energy dissipation (dotted). Right: Structural resistance.

Ice impacts on the bulkhead are studied first, including impacts from a disc-shaped and ellipsoidal ice feature. The crushing resistance and energy of the structure with increasing crushing distances are plotted on the right hand side in Figure 3. The column bulkhead represent a hard point of the column structure. The initial collapse capacity of the bulkhead depends on the local ice geometry and is about 7 MN and 16 MN for ellipsoidal and disc shaped ice, respectively. Below this load level little structural damage is expected, all the deformation goes into the ice. Outer shell fracture for the ellipsoidal ice feature occurs at a crushing distance of about 0.84 m, and for the disc-shaped ice, it takes place after 1.0 m. For the ellipsoidal ice, the fracture propagates along the root of the bulkhead and the transverse frame. For the disc-shaped ice, the fracture propagates along the adjacent transverse frames rather than along the bulkhead. In both cases, the crack involves initially two adjacent compartments and propagates further to four compartments.

The results from simulations of rigid ice impacts on the stiffened panels in the column (location (b)) are plotted in Figure 4. It shows that the structural resistance increases as the crushing continues, and the initial outer shell rupture occurs at a crushing distance of 0.8 m and 0.7 m for horizontal and vertical orientation of the disc-shaped ice respectively.

Let us consider a critical energy dissipation of 15 MJ (e.g., as used in Husky Oil Operations Limited, 2001). If all this energy goes into the structure, it will result in a crushing distance of 0.6-0.7 m, depending on the ice shape and the impact location. In reality, the total energy will be shared by both ice crushing and structural deformation, and thus, the resulting deformations of the structure will be less. When shared energy assessment is performed, the permanent deformation of the structures with a total energy dissipation of 15 MJ is summarized in Table 4.

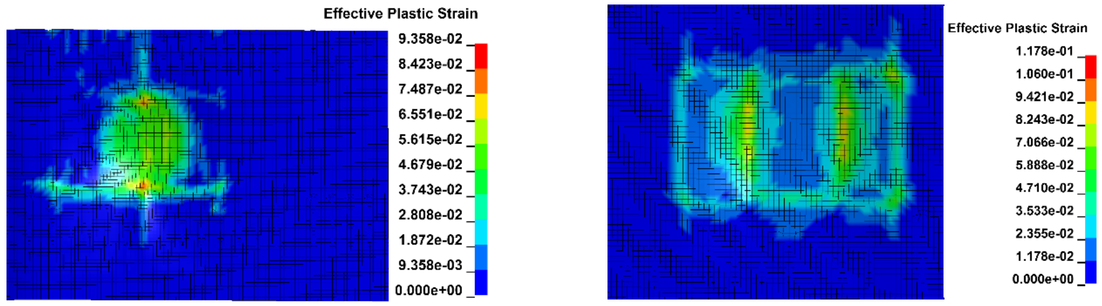
Table 4: Ice and structural deformation with a total energy of 15 MJ

Scenario	Location (a) ellipsoidal ice		Location (a) disc-shaped ice		Location (b) horizontal disc-shape		Location (b) vertical disc-shape	
Ice model	#1	#3	#1	#3	#1	#3	#1	#3
Ice deformation (m)	0.5	1.8	0.64	2.1	0.59	2.1	0.62	2.08
Structural displacement (m)	0.4	0.145	0.216	0.04	0.32	0.07	0.29	0.09
Energy in ice (MJ)	8.6	14.0	11.4	14.5	10.0	14.7	11.0	14.5
Energy in the structure (MJ)	6.4	1.0	3.6	0.5	5.0	0.3	4.0	0.5
ALS (outer shell rupture)	No	No	No	No	No	No	No	No
SLS (Jordaan et al.)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

It is found that given a total energy of 15 MJ, both the ice and the column structure will deform and dissipate parts of the energy. Generally, the ice dissipates more energy than the structure, and notably for the disc-shaped ice. The structural displacement can vary from 0.04 m to 0.4 m depending on the impact locations and local ice geometry. As initial outer shell rupture generally occurs at 0.7 m - 1.0 m, the structure is considered safe from compartment flooding for the given impact energy. It is noted that initial fracture of the outer shell is considered when one finite element is eroded. Hence, there is still considerable capacity from one element erosion to large outer shell opening.

Ice load model and acceptance criteria

Considering that the total energy will be shared by the ice crushing and the structural deformation, we have tested three different ice load models: one model is based on the assumption of constant energy absorption capacity of ice during crushing, and the other two models are obtained using probabilistic approach in ISO 19906 considering one and three ice impacts in 10000 years (Table 3).



Effective plastic strain distribution at the location (a)   Effective plastic strain distribution at the location (b)

Figure 5. Contours of the effective plastic strain within the outer shell structure (all the 15 MJ have been absorbed by the structure).

Figure 6 shows the force and impact energies in ice for the different ice load models listed in Table (3). The results of the calculations for Models #1 and #3 are given in Table 4. It is found that the area exponent in the ice load model plays an important role in defining the energy absorbed by ice and thus the level of permanent structural deformation. For all cases, the structure is considered safe from compartment flooding for the given impact energy of 15 MJ. However, the maximum displacements of the outer shell is larger than the specified plate thickness. The latter violates the serviceability condition specified by Jordaan et al.

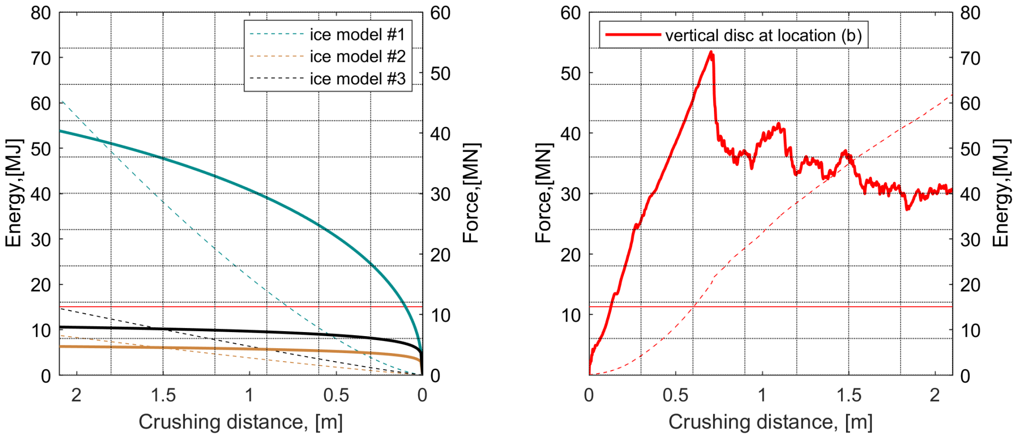


Figure 6. Ice-structure impact resistance for different ice load models for disc-shaped local ice geometry at location (b). Left: Contact force (full line) and energy dissipation (dotted). Right: Structural resistance.

DISCUSSION

In this study, we have focused on the uncertainties related to the local ice geometry, the ice load models and to the acceptance criteria. We have studied how variances in the input parameters affect the assessment of structural damage when the shared energy approach is used. Specifically two different local ice geometries (ellipsoidal and disc-shaped ice) have been considered. Three different ice load modes generated from deterministic and probabilistic approaches have been studied as well as serviceability and survivability criteria for the structure. It has been assumed that the impact energy is dissipated by both the ice feature and in the structure. The results of NLFEM analysis and analytical calculations have been combined to obtain the permanent deformation of the structure, depending on the impact location, ice load model and local ice geometry. The results of the integrated analysis show that the considered variations of ice load model and local ice geometry significantly influence the energy absorbed in the structure and ice. Within the considered variations in local ice geometry and ice load models, the latter have bigger impact on the results. The probabilistic approach based on rare ice events (one-three impacts in 10000 years) results in smaller energy absorption capacity of ice compared to that derived from the Pond Inlet tests. There is a concern whether the assumption of the Poisson process is valid for such rare ice events. Acceptance criteria are important in evaluating the onset of the serviceability limit state and/or accidental limit state (survivability of the structure).

SUMMARY AND CONCLUDING REMARKS

It was not the intention of this study to find limitations of each ice load model, or with each acceptance criteria, or with a regulation pertaining to ALS. The objective of this study was to investigate how the variations in input data to the shared energy approach might affect the conclusions. The results of this investigation show the following:

- For the cases considered, ice load models may be more important than the local ice geometry in defining the level of permanent deformation.
- For all cases, the structure is considered safe from compartment flooding for the given impact energy of 15 MJ, however, the structural deformations will exceed

the plate thickness of 17 mm.

- Following the rule-based models may be insufficient for the damage assessment under the ALS due to ice. It requires a case-tailored view on the energy absorption capacity of ice and the ALS criteria.

Further work should focus on studying effects of moving ice loads, repeated impacts and sharpness of local ice protrusions. In addition, the question on how to use the probabilistic model for rare events should be addressed.

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