Work on structural integrity for semi submersibles exposed to bergy bits – integrated analysis of ice structure impacts

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Abstract. Bergy bits and growlers (i.e., glacial ice features with a waterline diameter < 15 m) travelling with waves are identified as risk to the integrity of offshore structure and ships operating in the high North. It is generally more difficult to detect and monitor these small ice features and apply concurrent ice management operations. Therefore, it is important to study the corresponding damage assessment of a potential impact with such glacial ice features. Traditionally, while carrying out a structural damage assessment, the ice feature is often treated as a rigid body, whereas structural deformation and fractures are simulated with, e.g., NonLinear Finite Element Method (NLFEM). However, this method is too conservative and neglects that the ice feature crushes and dissipates part of the impact energy (often obtained with the so-called external mechanics). On the other hand, it is possible to treat both the ice and the structure deformable, and a fully coupled simulation can be carried out with NLFEM. This method can capture the physical essence that the impact energy dissipation is shared by both ice crushing and structural deformation, thus leading to a less conservative structural damage assessment. However, this method is often too computationally expensive and can only take care of the so-called ‘internal mechanics’ part. In this paper, we propose an integrated approach. This approach is mainly based on the innovative Simulator for Arctic Marine Structures (SAMS) to calculate the impact energy following the principle of ‘external mechanics’. Afterwards, the simulated results are integrated with NLFEM simulations to re-construct the shared impact energy dissipation between both the ice feature and structure. A case study regarding a glacial ice feature (diameter = 15 m) impacting a semi-submersible is carried out in this paper. This integrated simulation approach (i.e., SAMS + NLFEM) is proved to be significantly more effective than the fully coupled analysis; more versatile and less conservative than the limiting scenario analysis when dealing with the impact between ice features and man-made structures.

1. Introduction
The objective of this paper is to present background for the work initiated by the Petroleum Safety Authority (PSA) as a part of the NORD-initiative to assess challenges and possible improve the safety level of operation of oil and gas installation in the high north. Two of the main activities have been to: Achieve a better understanding of the extent of and uncertainty about icebergs and growlers in the Barents Sea, including methods for mapping and forecasting snow and ice. And to assess the risk level
of loss of structural integrity for semi submersibles exposed to bergy bits, and identification of possible gaps in knowledge.

In this paper the consequences of ice to the structural integrity is presented. Ice actions should be taken into the design considerations for structures to be deployed/installed in ice-prone areas. The calculation of ice action depends on a wide spectrum of parameters [1], among which, the design ice condition is of paramount importance. The Petroleum Safety Authority Norway (Petroleumstilsynet) recently initiated a series of projects to study the structural safety in the Northern areas (of Norway). One of the most recent projects was carried out by ArcISo AS and the study site was chosen at the northernmost Block A in the 23rd licensing round (located at N74°, E35.67°). For the ice condition in this selected study site, it is bergy bits and growlers (i.e., glacial ice features with a waterline diameter less than 15 m) that are of major concern. This is because these relatively small glacial ice features are more difficult to detect and monitor by concurrent ice surveillance system; and more difficult to perform existing ice management operations due to their limited sizes. Given this selected ice features’ potential threat, their impacts with offshore structures and consequent damage assessment should be carried out. This paper describes an effective yet relatively accurate approach to perform such damage assessment with respect the impact between an ice feature and an offshore structure. This method is based on integrated analyses using the Simulator for Arctic Marine Structures (SAMS) and NonLinear Finite Element Method (NLFEM); and will be described in the following sections.

2. Background

From a regulators perspective the attention to bolted connections is associated with the risk it imposes. The PSA definition of risk is defined in guideline to Framework regulation, Section 11: “Risk means the consequences of the activities, with associated uncertainty”.

Two of the main activities have been to: Achieve a better understanding of the extent of and uncertainty about icebergs and growlers in the Barents Sea, including methods for mapping and forecasting snow and ice. This has been reported in the project “Challenges linked to ice and snow – Icebergs in the Barents Sea” (24). And second to assess the risk level of loss of structural integrity for semi submersibles exposed to bergy bits. This has been reported in the projects “Aspects of structural safety in the Barents Sea” (25) and Loads, design and operation of floaters in the Arctic (26-27). The conclusion of this effort is that the risk of ice hazards to structural integrity has to be further studied.

3. Method

For the considered ice feature – structure impact study, ice crushing plays an important role. There are many ways to characterize the ice crushing properties, e.g., the design Pressure-Area (P-A) curves and process P-A curves. The design P-A curves are often viewed in the context of local or global ice loads and in the context of probabilistic or deterministic approaches to design. The process P-A curves (termed by Frederking [2]) describe the process of a structure penetrating into an ice feature or of an ice feature hitting a structure. It is a continuous plot of pressure versus nominal contact area variation during an ice-structure interaction process.

The choice on how we characterize the ice crushing process is again influenced by the chosen design limiting state. Generally, we have the Ultimate Limit State (ULS), in which, the designed structure is supposed to undergo only elastic or small plastic deformations for the given impact. For the internal mechanics (i.e., local damage assessment), when the structure is not allowed to deform, localized high pressures can develop anywhere in the contact area and they govern the local design for the ULS state. This contact pressure can be characterized by the design P-A relationships.

On the other hand, for the Accidental Limit State (ALS), the structure is permitted to undergo substantial plastic deformations given an ice impact. In this case, it is the crushing process, not the peaks of the crushing force that are of interest. Because the structure in direct contact are most likely to ‘give in’, the contact force peaks due to localized high pressures, as in the ULS scenario, are not applicable herein. Instead, it is the overall process (without the formation of localized high pressure zones) that governs the contact force. For this paper, it is the ALS condition that is focused. Therefore, the impact
studies carried out in this project are following the ALS design principles when it comes to characterizing how the ice crushes and its associated contact force.

According to NORSOK code [3] for ALS designs, several design formats can be found for ice actions. For example, the ductile design, in which the ice feature can be assumed as a rigid body and the collision energy is mainly absorbed by the structure. For its simplicity and convenience, this approach is adopted in a previously related study project [4].

4. SAMS simulation

For the first limiting scenario (i.e., impacting between a crushable ice feature and rigid structure), SAMS is adopted to offer a unique and effective solution. SAMS can construct contact force – penetration depth curves for each impact cases with varying impact direction and location. In addition, for each impact case, SAMS also yields the solutions to external mechanics to determine the demand for energy dissipation. It is how much of the kinetic impact energy must be dissipated by deformation of the structure and/or the ice feature and how much that will remain as kinetic energy, possibly transferred to other rigid body motions and surrounding fluid field. The demand for energy dissipation only specifies the total amount of deformation energy, not how this is distributed/shared between the structure and the ice feature. Further quantification of energy sharing is determined by the proposed integrated analysis when incorporating both limiting scenario analyses.

4.1. A Brief Introduction to SAMS

SAMS is a time-domain simulation product of Arctic Integrated Solutions (ArcISo AS) and it is largely based on the non-smooth Discrete Element Method (DEM) whose contact algorithm is tailor-developed for ice materials. Until recently, time domain models of sufficient quality to perform numerical simulations of ice and marine structures interactions have not existed. Today, this has changed, partly through the efforts at the Norwegian University of Science and Technology (NTNU) hosting SAMCoT (Centre for Research-based Innovation - Sustainable Arctic Marine and Coastal Technology), laying the foundation of a versatile and accurate numerical simulator for fixed and floating structures in various ice conditions. As continuum-mechanics-based methods are not valid for representing realistic ice conditions in major parts of the Arctic, SAMCoT has placed a considerable emphasis on developing DEMs that enable modelling the interactions between individual ice blocks (e.g., floe ice, level ice, ridges and icebergs) and the structure of interest [5].

The DEM can broadly be divided into two main categories: smooth discrete element modelling (SDEM) and non-smooth discrete element modelling (NDEM). The difference between the two can be seen as the difference between explicit and implicit time integration, allowing much larger simulation time steps, while maintaining stable simulations, when using NDEM. SAMS falls under the NDEM category, but it applies a novel implicit time stepping scheme and an improved contact model, enabling general visco-elastic contacts. SAMS distinguishes two types of contacts: the rigid contacts and the compliant contacts. The earlier does not adopt any upper-limit to the contact force resulting in computationally inexpensive contact model that can properly estimate the average contact force, but not the exact contact behavior. This limitation makes rigid contacts inadequate if ice fracturing is to be encountered and thus they should only be used to model contacts between small ice fragments and the structure. Compliant contacts, on the other hand, are able to predict the exact contact behavior. They consider the contact crushing force as well as the force-penetration gradient, leading to highly accurate contact force predictions [6]. For this study, i.e., one ice feature impacting an offshore structure, it is the compliant contact model that is utilized to simulate the contact between the ice feature and the structure; and the crushing process of the ice feature at the contact zone is characterized by such compliant model.

Aside from the novel contact model SAMS built upon [6], it is also worth mentioning other modules SAMS contains, such as the ice fracture module characterizing the fracture of (mainly) floe ice [7-10] and the hydrodynamic module [11, 12] calculating multiple floating objects’ motion in waves, wind and currents.
4.2. Derivation of CSE for Ice Crushing Simulations

As introduced previously, the simulations of an ice feature impacting a structure by SAMS yield results including the contact energy dissipation as a function of time, as well as the occurring contact forces. The contact energy dissipation can be used in combination with the contact forces to derive a force-penetration curve from the SAMS results for the ice feature. Both the contact energy dissipation as well as the contact force depend on the crushing specific energy (CSE) of the ice feature, which is a necessary input parameter of SAMS. The CSE is the amount of energy needed to crush a unit volume of ice (unit: kJ/m³). It is obtained by analyzing full-scale data from in-situ indentation experiments. Through personal communication, we were granted access to the Pond Inlet test data (Geotech Arctic Services, 1985), and we re-analyzed the data set. Force-time histories for the spherically-ended indenters with radius R = 900 mm, 1280 mm and 2300 mm are gathered (ten sets in total). Negative force values are excluded from the analysis. The data sets have been converted from force-time histories to force-displacement history. The indenter displacement, u, during each test was controlled according to the following (1), where t is time and \( \omega \) is \( \frac{100 \text{ mm/s}}{0.1 \text{ R mm}} \) [13].

\[
u = 0.1R \sin(\omega t)
\]  

(1)

To avoid scale effects caused by small strained volumes in relation to the grain size, data points from outmost 5.0 cm of ice have been excluded from the analysis. Penetration depth at the conclusion of the test is 0.1R. For each data point, the crushing specific energy is calculated as in (2),

\[
\psi(u_j) = \frac{\int_0^{u_j} F(u) \, du}{\frac{1}{3} \pi u_j^2 (3R - u_j) \rho}
\]  

(2)

where \( \psi \) is the crushing specific energy (J/kg), \( F \) is the measured force (N), \( u \) is displacement of the indenter (m), \( R \) is the indenter radius (m) and \( \rho \) is the ice density (\( \rho = 900 \text{ kg/m}^3 \)). For NN scalar data points, the average is defined as in (3)

\[
\psi_\mu = \frac{1}{NN} \sum_{k=1}^{NN} \psi_k
\]  

(3)

The resulting average value \( \psi_\mu = 2.96 \text{ kJ/kg} \), range is from 1.30 kJ/kg to 6.09 kJ/kg.

![Figure 1. Pond Inlet data and CSE model curve.](image-url)
Based on the above results, CSE in SAMS is chosen as 3.0 MJ/m³ (Figure 1). Note that with this approximation method, the high-frequency variation in the contact force, caused by local failure events such as spalling, recrystallization and cracking will not be visible in the SAMS results.

5. NLFEM simulations

After solving the external mechanics part in the previous section, for the other limiting scenario, i.e., a rigid ice feature impacting a deformable structure, numerical simulations were carried out by using explicit NLFEM software LS-DYNA 971. This is also the process to solve for the internal mechanics and conduct local damage assessment.

5.1. Selection of Finite Elements

Since only the local damage is concerned, only part of the structure needs to be modelled into detail. In our case, only the column of the chosen offshore structure (in Figure 6 and to be described below) is modelled with shell elements. More specifically, the four-node Belytschko-Lin-Tsay shell element with reduced integration was used with 5 integration points through the thickness. Hourglass stiffness is added using the stiffness based form (option 4 in LS-DYNA). This is very efficient and gives low dissipation of spurious hourglass energy of less than 2-3%.

5.2. Material and Fracture Modelling

Material and fracture modelling are crucial to determine the structural strength in the ice impact analysis. Material fracture will degrade the structural strength to and beyond the point of collapse. Another effect is leakage and flooding of compartments, leading to stability problems. It is very challenging to accurately simulate fracture initiation and propagation with large scale shell elements. The complexity lies in that fracture is a localized phenomenon in the length scale of plate thickness, and is difficult to capture with large shell elements, the sizes of which are several times larger than the plate thickness. In addition, fracture depends highly on the stress state, material deformation history and is sensitive to the mesh size adopted. It is essential to correctly calibrate the material properties in order to capture accurately strain localizations and the subsequent fracture. The probabilistic nature of material properties makes the fracture modelling even more complicated [14]. Due to the significance of material and fracture modelling and its physical complexity, a proper model is necessary for achieving realistic results.

For material modelling, the power law hardening with a yield plateau is used to model the material. The hardening is described by the yield criterion in (4).

\[
f = \sigma_{eq} - \sigma_f(\varepsilon_{eq}) = 0
\]  

(4)

where \(\sigma_{eq}\) is the von-Mises equivalent stress. The current flow stress \(\sigma_f\) is a function of the equivalent plastic strain \(\varepsilon_{eq}\) via the Hollomon-type power law hardening rule in (5).

\[
\sigma_f(\varepsilon_{eq}) = \sigma_0 \quad \text{if} \quad \varepsilon_{eq} \leq \varepsilon_{\text{plateau}} \\
\sigma_f(\varepsilon_{eq}) = K(\varepsilon_{eq} + \varepsilon_{0,\text{eff}})^n \quad \text{if} \quad \varepsilon_{eq} > \varepsilon_{\text{plateau}}
\]  

(5)

in which, \(K\) and \(n\) are the hardening parameters and \(\sigma_0\) is the initial yield stress. To account for the existence of a strain plateau, the hardening is delayed until the plastic strain reaches the plateau strain \(\varepsilon_{\text{plateau}}\). Thus, \(\varepsilon_{0,\text{eff}}\) is defined by the relation in (6),

\[
\varepsilon_{0,\text{eff}} = \varepsilon_0 - \varepsilon_{\text{plateau}} = \left(\frac{\sigma_0}{K}\right)^{\frac{1}{n}} - \varepsilon_{\text{plateau}}
\]  

(6)

\[
\]
where $\varepsilon_0$ is the strain at initial yield. The BWH (Bressan-Williams-Hill) instability criterion is used to model fracture in the ice impact simulation. The BWH instability criterion was proposed by Alsos, Hopperstad, Törnqvist and Amdahl [15], which combines Hill’s local necking model [16] and the Bressan-Williams shear stress criterion [17]. The BWH criterion considers that fracture occurs at the onset of local necking instability neglecting the post-necking regime, and this is conservative. The BWH criterion has been validated of good accuracy by comparison with various impact experiments [18, 19].

Fracture is simulated by eroding the failed elements when the fracture criterion is fulfilled. A through-thickness integration point is failed by setting the stresses to zero once a 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, and the material properties are shown in Table 1. The outer shell material is with a yield stress of 420 MPa, while the stiffeners are modelled with a 355 MPa yield stress steel.

| Steel Grade | Plate | HP |
|-------------|-------|----|
| Young’s Modulus [MPa] | 2.07×10^5 | 2.07×10^5 |
| Yield Strength [MPa] | 420 | 355 |
| Poisson Ratio [-] | 0.3 | 0.3 |
| Power law K [MPa] | 860 | 780 |
| Power law n | 0.16 | 0.22 |
| $\varepsilon_{plateau}$ | 0.0 | 0.0 |

6. Integrated analysis

In order to calculate the distribution of energy dissipation between the ice and the structure we will adopt the same principles as those used for ship impact according to NORSOK N-004 Appendix A [20]. The principle is sketched in Figure 2. The ship may represent the ice feature in the present context. The force-deformation curve for the installation is established assuming the ship to be rigid. Likewise, the force-deformation curve for the ship is established assuming the installation to be rigid. The resulting damage is determined when the energy dissipation (equal to the area under force deformation curves) reaches the demand for energy dissipation, as determined by the external mechanics analysis in Section 4.

Figure 2. Estimation of force and damage (deformation) for ship impact against an installation according to NORSOK N-004.
It is noted that this approach does not take the coupling of interaction effects into account; deformation of the ship bow increases the contact area and may hence increase the resistance of the installation. Simplified methods to account for this interaction are proposed in a proposed revision of DNV-GL RP-C204, (which is virtually identical to NORSOK N-004).

Similarly, interaction effects exist for ice-structure impacts, but these are associated with significant uncertainties at present. Hence, coupled ice-structure interaction will be neglected in the current investigation.

In summary, the following procedure will be used to determine the damage and energy dissipation:

- Analysis principles for ship-installation impacts in NORSOK N-004/DNV-GL RP C204 will be adopted.
- Extreme local pressures over limited areas will not be considered; it is the resistance to the total force that is essential in the ALS.
- Coupled analysis of the interaction between structural deformation and ice crushing is at present stage not viable and will be disregarded.
- Only the two limiting scenarios described in Section 3 will be analyzed and integrated in this paper for assessment of structural damage. The analysis procedure illustrated in Figure 3 and are summarized below:
  - Contact force – penetration depth relationships for the ice will be established using SAMS, i.e., by analyzing ice impacts against a rigid structure.
  - Force-deformation relationship for the structure will be established using NLFEM analysis in LS-DYNA, i.e., by analyzing rigid ice impacts against the structure.
  - 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 determined by the external mechanics analysis in Section 2.
- The above procedure will be sufficiently accurate as long as the impact period is small compared to the relevant eigenperiods, i.e., the impact force and inertia forces predominate the response.

![Figure 3. Determination of resulting damage in ice and structure. Pond Inlet data and CSE model curve.](image)

7. Ice impacts case studies

In this section, we will demonstrate the above introduced integrated approach by a case study. In this case study, we pre-define an ice feature and an offshore structure. By virtue of SAMS’ efficient simulations, we are able to run a large number (∼1800) impact simulations with varying impact direction and location. Among all these simulations, solutions to the external mechanics are achieved. This allows us to create an energy map showing sensitive locations around the structure, where collision energy is critical (see Section 4). In addition, contact force – penetration depth curves for each impact case are also generated by SAMS. Detailed damage assessment (i.e., internal mechanics) are thereby carried out using NLFEM at selected critical locations.

7.1. Ice Feature and Structure Modelling

In this case study, we choose a spheroidal ice feature in Figure 4 for both the external and internal mechanics analyses. It is cautioned here that a different geometry can have a significant influence on the local damage assessment. This is because the local sharpness of an ice feature at the contact location is decisive regarding if the collision energy is absorbed mainly by the ice feature or by local deformation of the structure. For continuation of the study (i.e., a previous study has chosen the
spheroidal geometry for local damage assessment [4]) and without deviating from the purpose of demonstrating this method, we chose the same ice feature geometry (in Figure 4) in this case study.

Figure 4. Geometry and size of the spheroidal ice feature.

For the external mechanics analysis (i.e., a crushable ice feature + a rigid structure), we need to explicitly model the global geometry of the structure. In this regard, we choose the global geometry of the Exwave semi-submersible as described in a previous literature [21] (see Figure 5). Its global geometry is digitalized into .obj format and imported in SAMS. In addition, available mass and hydrodynamic properties are also fed into SAMS as inputs for external mechanics analysis so as to construct the energy map and associated contact force – penetration depth curves.

Figure 5. Global geometry of the structure (in model scale).

For the internal mechanics analysis (i.e., a rigid ice feature + a deformable structure), we need not to model the entire structure. Only the part of the structure that is involved in the impact needs to be modelled into detail. In this regard, we choose the ‘Midgard’ semi-submersible’s column structure for the local damage analysis (see Figure 6). The column leg (C10, S10) of the Midgard structure was modelled by Tavakoli and Amdahl [22] for the assessment of structure strength against supply vessel impacts. Detailed FEM modelling of the column is performed in LS-DYNA with shell elements (see Section 5 for details). 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).

Figure 6. The column (in red dashed square) of the Midgard semi-submersible chosen for local damage assessment.
Figure 7 illustrates the finite element model of the structure. The column outer shell is in the range of 16-18 mm. The vertical stiffeners used in the column are HP320x12, HP300x11 and HP240x10. These stiffeners were modelled as L-bars with dimensions 320x50x40x12 (mm), 300x50x50x11 (mm) and 240x40x30x10 (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 7. The finite element model of the column structure of the Midgard semi-submersible.

7.2. Impact Simulations by SAMS and NLFEM
With the available modelling of the ice feature and both global and local geometry of the structure, SAMS and LS-DYNA are employed to analyze the two limiting impact scenarios separately.

For the external mechanics analysis with SAMS, ice crushing against a rigid structure is simulated extensively with varying impact locations and directions. In total, around 1800 simulations were conducted. In all simulations, as the structure is symmetric, we only simulate scenarios when the ice feature is approaching the structure from the North-West direction (i.e., only a quarter of the structure is directly exposed to the ice feature’s impacts). Detailed simulation matrix is presented in an accompanying report [23]. Figure 8 illustrates only two critical impacting scenarios. We see from Figure 8 that both the ice feature and the entire structure is modelled. The left snapshot of Figure 8 also shows that although the ice feature is travelling from the North-West direction, it is possible that the ice feature manages to travel through the semi-submersible and only impacts the downstream column at the South-East direction. For each of the 1800 impact scenarios, SAMS yields the collision energy and its associated contact force – penetration depth curves.

Figure 8. The SAMS simulation snapshots of the two selected impact scenarios of a crushable ice feature impacting a rigid structure (external mechanic analysis).
For the internal mechanics analysis with NLFEM, the simulation is more focused on the deformable structure under the impact of a rigid ice feature. This is achieved with LSDYNA simulations. Aside from detailed structure modelling presented in Section 7.1, the rigid ice feature is given a prescribed motion velocity of 3 m/s (attained through motion analysis in the accompany report [23]), 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.

Depending on the angle of impact and location of impact, different simulations can be defined in LS-DYNA. Figure 9 illustrates three possible impact simulations between a rigid ice feature and a deformable local structure column. In practice, as SAMS simulation is much more efficient than the NLFEM analysis, we first carried out a large amount (~1800) of external mechanics analysis by SAMS and then identify critical locations (~7) for further NLFEM analysis.

With both limiting scenarios analyzed, for each impact case, we can create the contact force – penetration depth/deformation curve. This further allows us to quantify collision energy dissipations following the shared-energy principle.

![Figure 9. LS-DYNA simulation snapshots of the three selected impact scenarios of a rigid ice feature impacting a deformable column structure (internal mechanic analysis).](image)

8. Results and discussion

This section presents the results of the case studies. The results include the external mechanics analysis by SAMS and internal mechanics analysis by LS-DYNA following the NLFEM.

8.1. Simulation Results by SAMS

The external mechanics (i.e., mainly solving for the collision energy) is obtained by SAMS simulations. The large amount of simulations under various impact scenarios (i.e., impact direction and location) enable us to construct an energy map showing sensitive location of impact. Figure 10a) first illustrate the ice feature’s trajectory both before (in red) and after (in green) impacting with structure. Note here that impact scenarios with only a quarter of the structure are illustrated in the figure given various initial location and direction of the advancing ice feature in waves. The impact velocity and probability depends on the coupled motion of the ice feature and the structure in chosen wave conditions. This part of the study is conducted in the accompany project [23].
Combining the SAMS simulation results (mainly the collision energy) with the probability of impact and impact velocity, we are able to construct an energy map in Figure 10b) showing sensitive locations that is most exposed to high collision energy. Out of the 1800 simulations, it is found that critical impacts mainly occur on the structure columns. Impacts on the pontoons have a very low probability – only 0.6% of impacts will occur on the pontoons under the considered wave and current conditions. We see from Figure 10b) that most of the impact take place at around the Still Water Level (SWL at $Z = 0$ m in the figure). Moreover, higher collision energy (to maximum at around 7.32 MJ) are expected as the impact location gets higher (at around +5 m above the SWL) on the structure column. However, high energy impacts have a low probability. 90% of the simulated open water impacts result in an impact energy lower than 4.3 MJ.

With the energy map presented in Figure 10b), we can select several critical locations for further NLFEM analysis. We take a combined reasoning in selecting a critical location on the structure, i.e., a location is qualified as critical only if relatively large collision energy is encountered at a relatively less re-enforced structural locations.

With this combined reasoning, we chose 7 critical locations around the column structure shown in Figure 11.

8.2. Simulation Results by NLFEM

Based on the SAMS simulation results presented in Section 8.1, seven critical locations (together with its associated impact scenarios) were chosen for further local damage assessment by the NLFEM using LS-DYNA. In this section, for exemplifying purpose, we only present the simulation results of impact scenarios (a), (b) and (c) in Figure 11. The entire simulation results can be found in the accompanying report [23]. In addition, it should also be emphasized that the results presented here is only one of the limiting scenarios (i.e., a rigid ice feature impacting a deformable structure). It is incomplete by itself.
Only after integrating the results from both Sections 8.1 and 8.2 can we establish the complete picture with respect to how the collision energy is shared between the ice feature and the structure.

A rigid ice feature impacts on the structure’s column corner are presented here. This includes impacts on (a) stiffened deck, (b) the transverse frame and (c) the column corner in between (a) and (b) (refer to Figure 11). Take impact scenario (a) as an example, and the sectional cut of column deformation at different time instants are given in Figure 12. Note that the impact velocity is 3 m/s. As the crushing distance increases, buckling of the stiffened deck and HP stiffeners are clearly observed until final fracture. Deformation and fracture of the column corner structure at an indentation of 1.5 m is plotted in Figure 13.

![Figure 12. Snapshots of the impact scenario (a) on the stiffened deck (side view).](image)

![Figure 13. Deformation and fracture of the column corner in scenario (a) at an indentation of 1.5m.](image)

![Figure 14. Internal mechanics analysis results: Rigid ice crushing resistance and energy versus crushing distance for scenarios a) – c).](image)
The rigid ice crushing resistance and energy with increasing crushing length is plotted in Figure 14, and the outer shell fracture initiation is marked with short bold lines. Results show that the initial bending capacity of the column corner on the stiffened deck and the transverse frame is about 5 MN. As crushing continues, the indentation resistance increases. Initial outer shell rupture occurs at a crushing length of 0.6 m-0.9 m.

8.3. SAMS and NLFEM Integrated Analysis

We have analyzed two limiting impacting scenarios (i.e., #1 a crushable ice feature impacting a rigid structure and #2 a rigid ice feature impacting a deformable structure) at seven critical locations hitherto. For each impacting scenario, we constructed two limiting curves characterizing the contact force – penetration depth/deformation during the impact. Next, we need to integrated these results and quantify how the collision energy is dissipated between the ice feature and the structure. This is achieved by the plot in Figure 15.

Figure 15 plots on the right-hand side, the structural impact resistance on seven different locations from NLFEM simulations assuming rigid ice, while on the left-hand side of Figure 15, the ice crushing resistance calculated from SAMS assuming rigid structures is plotted. The ice load of \( F_{ice} = 3.2A^0.9 \) calculated using the process P-A model (as described in Section 4) is also plotted. It is assumed that under 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 are the corresponding energy that is dissipated in ice and the structure, respectively.

From Figure 15, the column bulkhead and cruciform represent hard points of the structure, and are capable of crushing ice significantly. Below a certain force level (around 6 MN for bulkhead and 12 MN for the cruciform), all the deformation goes to the ice. The column stiffened panels have similar force level with that of the ice, and therefore both the ice and the stiffened panels deform and absorb around 50% of the total energy. The resist force of the column corner is much lower than the column side, but it is interesting to observe that the ice crushing force on the corner defined by SAMS is also lower than the ice crushing force from the column side. This makes the strength of ice and structure on the column corner very close, and both objects will deform to absorb the energy.

Figure 16 summarizes the energy absorption with increasing crushing distances. In Section 5, we have calculated a maximum energy dissipation of 7.32 MJ. For simplicity, we take 7.5 MJ here as an example to explain Figure 16. If all the energy 7.5 MJ goes to the structure, this will result in a crushing distance of 0.4-0.7 m. In reality, the total energy should be shared by both ice crushing and structural deformations, and the resulting deformation of the structures will be less. Considering shared energy in ice and the structure, the permanent deformation of the structures with a total energy dissipation of 7.5 MJ is summarized in Table 2.

It is found that given a total energy of 7.5 MJ, both the ice and the column structure should deform and dissipate part of the energy. The structural deformation can vary from 0.25 to 0.55 m depending on the impact locations. These numbers are much smaller than their corresponding values in Figure 16 (between 0.4 to 0.7 m), signifying the shared energy approach analysis as carried out in this paper is less conservative when it comes to structural damage assessment. More specifically, as initial outer shell rupture generally occurs at 0.6 to 0.9 m, the structure is considered safe from compartment flooding for the given impact energy (7.5 MJ). It is noted that the markers on Figure 15 represent initial fracture of the outer shell when one element is eroded. There is still considerable capacity from one element erosion to large outer shell opening.
9. Conclusions

Following a same principle to analyze ship impacts as in NORSOK N-004 Appendix A, we propose an efficient method to carry out ice-structure impact analysis. This method allows us to quantify collision energy’s dissipation in both the ice feature and the structure, thus leading to a less conservative structural damage assessment comparing to the ductile design criteria, in which, the ice feature is normally considered as rigid.

In this proposed method, we integrate the simulation results of two limiting scenarios. These are: 1) external mechanics, in which impact analyses between a crushable ice feature and a rigid structure using the Simulator for Arctic Marine Structures (SAMS); and 2) internal mechanics, in which, impact analyses between a rigid ice feature and a deformable structure using NonLinear Finite Element Method (NLFEM). Important modelling inputs for both SAMS (i.e., the Crushing Specific Energy) and NLFEM (i.e., element types, material modelling and fracture criteria) are described into detail. To demonstrate this integrated method, a case study (i.e., a spheroidal ice feature impacting the Exwave semi-submersible) is carried out.

By virtue of SAMS’ efficient simulation to solve for the external mechanics, a large amount of impact scenarios (~1800) were simulated. This leads to the creation of an energy map illustrating the distribution of collision energy around the structure. Major conclusion in the results to SAMS simulations are:

Table 2. Ice crushing depth and structural deformation with a total energy of 7.5 MJ.

| Location | Ice crushing [m] | Structure deformation [m] | Energy in Ice [MJ] | Energy in Structure [MJ] |
|----------|------------------|---------------------------|-------------------|--------------------------|
| (a)      | 0.41             | 0.51                      | 2.5               | 5.0                      |
| (b)      | 0.42             | 0.55                      | 2.7               | 4.8                      |
| (c)      | 0.48             | 0.50                      | 3.55              | 3.95                     |
| (d)      | 0.37             | 0.29                      | 4.1               | 3.4                      |
| (e)      | 0.33             | 0.27                      | 3.2               | 4.3                      |
| (f)      | 0.33             | 0.38                      | 3.2               | 4.3                      |
| (g)      | 0.36             | 0.36                      | 3.75              | 3.75                     |
1. Out of the 1800 simulations, it is found that critical impacts mainly occur on the structure columns. Impacts on the pontoons have a very low probability, i.e., only 0.6% of impacts will occur on the pontoons under the considered wave and current conditions.

2. The maximum impact energy resulting from the simulations is 7.32 MJ. However, high energy impacts have a low probability. 90% of the simulated open water impacts result in an impact energy lower than 4.3 MJ.

Damage assessments were carried out at seven selected critical locations on the structure’s column. The integrated SAMS and LS-DYNA analysis results yield rather rich information to quantify impact energy’s dissipation in a shared manner. As an example, for a conservatively chosen total impact energy of 7.5 MJ, it is found that:

a. Both the ice and the column structure should deform and dissipate part of the impact energy.
b. The indentation depth into the structure can vary from 0.25 m to 0.55 m depending on the impact locations. As the outer shell rupture generally is predicted to occur at 0.6 m-0.9 m, the structure is considered safe from compartment flooding risks with the given impact energy.
c. For any other impact energy levels, one can refer to Figure 15 to obtain information about the shared energy dissipation, structural deformation and ice crushing depth respectively.

Through the above case study, the simulation efficiency of SAMS is demonstrated. Given the time constraint of the project, SAMS is capable of simulating a large amount of impacting scenarios (i.e., around 1800 cases), whereas NLFEM analysis can only be conducted in selected scenarios (i.e., 7 cases). Moreover, integrating the simulation results from both SAMS and NLFEM, we are able to quantify the collision energy’s dissipation between both the ice feature and the structure. As comparisons between Figure 15 and 16 shows, the shared energy approach yields much less conservative damage assessment comparing to if we assume the structure absorb all the collision energy. PSA will promote continued work on “Snow and ice” and “Structural integrity” for the design and operations of floaters for oil and gas activity in areas open for exploration in the north.

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References
[1] Løset S, Shkhinek K, Gudmestad O T and Høyland K 2006 Actions from Ice on Arctic Offshore and Coastal Structures, Krasnodor, St Petersburg, Russia, 2006.
[2] Frederking R 1998 The pressure area relation in the definition of ice forces, The Eighth Int. Offshore and Polar Eng. Conf., Int. Society of Offshore and Polar Engineers, 24 - 29 May, Montreal, Canada.
[3] NORSOK, NORSOK Standard N004. Design of steel structures, Appendix A, design against accidental actions. Det Norske Veritas 2004, 2004.
[4] Ekeberg O-C, Shipilova O, Birkenes-Berg J and Johansen A 2018, Glacial Ice Impact, DNV GL Report No. 2017-0425, Rev. 2.
[5] Lubbad R, Løset S, Lu W, Tsarau A, Van den Berg M 2015 An overview of the Oden Arctic Technology Research Cruise 2015 (OATRC2015) and numerical simulations performed with SAMS driven by data collected during the cruise, Cold Regions Science and Technology.
[6] van den Berg M, Lubbad R and Løset S 2018 An implicit time-stepping scheme and an improved contact model for ice-structure interaction simulations, Cold Reg. Sci. Technol. 155 193-213.
[7] Lu W, Lubbad R and Løset S 2015 In-plane fracture of an ice floe: A theoretical study on the splitting failure mode, Cold Reg. Sci. Technol. 110(0) 77-101.
[8] Lu W, Lubbad R and Løset S 2015 Out-of-plane failure of an ice floe: Radial-crack-initiation-
controlled fracture, *Cold Reg. Sci. Technol.* 119 183-203.

[9] Lu W, Lubbad R, Løset S and Kashafutdinov M 2016 Fracture of an ice floe: Local out-of-plane flexural failures versus global in-plane splitting failure, *Cold Reg. Sci. Technol.* 123 1-13.

[10] Lubbad R and Løset S 2011 A numerical model for real-time simulation of ship-ice interaction, *Cold Reg. Sci. Technol.* 65(2) 111-27.

[11] Tsarau A, Løset S and Grindstad T 2014, Propeller wash by an icebreaker, 22nd IAHR International Symposium on Ice Singapore, 2014.

[12] Tsarau A 2015 Numerical Modelling of the Hydrodynamic Effects of Marine Operations in Broken Ice, Civil and Environmental Engineering, Norwegian University of Science and Technology, Trondheim, 2015, p. 159.

[13] GEOTECH, Medium Scale Iceberg Impact Simulation Test Program, 1985.

[14] Yu Z and Amdahl J 2018 A review of structural responses and design of offshore tubular structures subjected to ship impacts, *Ocean Eng.* 154 177-203.

[15] Alsos H S, Hopperstad O S, Törnqvist R and Amdahl J 2008 Analytical and numerical analysis of sheet metal instability using a stress based criterion, *Int. J. Solids Struct.* 45(7) 2042-55.

[16] Hill R 1952 On discontinuous plastic states, with special reference to localized necking in thin sheets, *J. Mech. Phys. Solid* 1(1) 19-30.

[17] Bressan J and Williams J 1983 The use of a shear instability criterion to predict local necking in sheet metal deformation, *Int. J. Mech. Sci.* 25(3) 155-68.

[18] Storheim M, Amdahl J and Martens I 2015 On the accuracy of fracture estimation in collision analysis of ship and offshore structures, *Mar. Struct.* 44 254-87.

[19] J.N. Marinatos, M.S. Samuelides 2013, *Material characterization and implementation of the RTCL, BWH and SHEAR failure criteria to finite element codes for the simulation of impacts on ship structures*, 6th Int. Conf. on Collision and Grounding of Ships and Offshore Structures, ICCGS 2013, Trondheim, 2013, p 57-67.

[20] NORSOK, Actions and action effects, N-003, Oslo: Norwegian Technology Standards Institution (2017).

[21] Fonseca N and Stansberg C T 2017 *Wave Drift Forces and Low Frequency Damping on the Exwave Semi-Submersible*, Proc. of the ASME 2017 36th Int. Conf. on Ocean, Offshore and Arctic Engineering, Trondheim, Norway.

[22] Tavakoli M T and Amdahl J 2010, Analysis of collision between Midgard platform and 8000 tonnes displacement ship (2010).

[23] Lu W, Yu Z, Van den Berg M, Lubbad R, Amdahl J, Løset S and Kim E 2018 *Assessment of Structural Damage due to Glacial Ice Impact*, in: P.P.S.A. Norway) (Ed.) PTIL-Konstruksjonssikkerhet i Nordområdene, Petroleumstilsynet, Stavanger, 2018, p. 96.

[24] www.psa.no/Challenges linked to ice and snow – Icebergs in the Barents Sea (ST3)

[25] www.psa.no/Aspects of structural safety in the Barents Sea (ST5)

[26] www.psa.no/Loads, design and operation of floaters in the Arctic (ST20-2018)

[27] Ommani B, Berthelsen P A, Lie H, Aksnes V and Løland G 2019, OMAE2019- 95798.