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# SIMULATOR FOR ARCTIC MARINE STRUCTURES (SAMS)

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## ABSTRACT

As offshore activities in the Arctic constitute a relatively new field with only a handful of relevant operations to draw experience from, and since full-scale trials are extremely expensive, there is an expressed need for much more extensive, detailed and cost-efficient analysis of concepts based on numerical simulations. However, until recently simulation tools of sufficient quality to perform such numerical analysis have not existed. The only verification available has been through a limited set of experiments in ice model basins. 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 highly accurate high-fidelity numerical simulator for offshore structures in various ice conditions such as level ice, broken ice and ice ridges.

Arctic Integrated Solutions AS (ArcISo) is a spin-off company from NTNU established in 2016 with the vision of increasing the technology readiness level of SAMCoT's numerical models to become a professional software package for the analysis of sea ice actions and action effects on Arctic offshore and coastal structures. This software package is called *Simulator for Arctic Marine Structures* (SAMS) and it was first released in 2017. This paper introduces the software implementation and the theoretical basis of SAMS, and it discusses the use of full-scale data to validate the simulator.

## INTRODUCTION

The design of offshore and coastal structures in the Arctic is often governed by sea-ice actions. The latter depends broadly on the ice conditions, the structure geometry and the interaction speed. In more detail, sea-ice action is a function of the ice feature, the ice properties, the limiting mechanism, the interaction geometry, and the ice failure modes (Løset et al., 2006).

To estimate sea-ice actions, most design standards and recommended practices suggest to start by defining the design scenario. This implies that the designer should select the one ice feature and the one limiting mechanism that yield the highest ice action. Apart from icebergs (and bergy bits), the limit stress is usually thought of as the one mechanism the gives the highest ice action. The ice failure is typically chosen based on the structure geometry, e.g. crushing and bending failure modes against vertical and sloping-sided structures, respectively. Eventually, the design standards provide a set of empirical and semi-analytical formulae to estimate the ice actions that correspond to the design scenario, e.g., level-ice actions on sloping structures and ice ridge actions on vertical structures.

The above is obviously inadequate when dealing with floe ice. This is because the interaction processes between floe ice and structures are highly nonlinear and the outcome depends strongly on the initial conditions (e.g. ice concentration and floe size distribution), boundary conditions (e.g. confinement), driving forces such as wind and current, structure response, etc. The different limiting mechanisms will coexist and it is very challenging to identify the limiting mechanism that will cause the highest action on the structure. The term floe ice here is quite generic, and can be used to describe level ice or any fragmented ice field whether it is naturally broken, e.g., by gravity waves, or artificially broken by ice management (IM) operations.

Because of the nonlinearities, time-domain modelling becomes inevitable to calculate floe-ice actions and action effects on Arctic marine structures. Until recently, time-domain models of sufficient quality to perform numerical simulations of floe ice and marine structures interactions have not existed. Today, this has changed, partly through the efforts at 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 highly accurate high-fidelity numerical simulator for offshore and coastal structures in various ice conditions such as level ice, broken ice and ice ridges.

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## SAMS DESCRIPTION

The distinct nature of ice floes in a broken ice field has often promoted the use of discrete element modelling methods (DEM). The latter 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 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 behaviour. This limitation makes rigid contacts inadequate if ice fracture 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 behaviour. They consider the contact crushing force as well as the force-penetration gradient, leading to highly accurate contact force predictions, see Van den Berg et al. (2018).

Moreover, the current version of SAMS adopts an analytical framework that supplements the NDEM method with analytical closed-form solutions to simulate the fracture of sea ice. This methodology was first presented by Lubbad and Løset (2011) to model the bending failure of ice. Later, the method was expanded with a number of closed-form solutions that cover other failure modes such as splitting and radial cracking of ice. These solutions are published in a series of papers (Lu et al., 2015a; Lu et al., 2015b; Lu et al., 2016).

In addition to the improved NDEM formulation and the comprehensive set of analytical solutions to ice fracture, SAMS applies innovative numerical solutions to calculate different hydrodynamic force components on the structure and every ice floe in the calculation domain. This includes e.g. drag forces from wind, current and propeller flow. These solutions are calibrated and validated against full-scale and lab-scale data, see (Tsarau et al., 2014; Tsarau and Løset, 2015). Fig. 1 illustrates the aforesaid building blocks of SAMS, namely: 1) the NDEM or multi-body dynamics module, 2) the fracture module, and 3) the hydrodynamic module.

## SAMS VALIDATION

The different modules described above were developed over many years by a number of researchers at NTNU. Despite the common vision of creating a numerical simulator for calculating ice actions and action effects on Arctic structures, the development of each module was carried out almost independently from the other modules. At that stage, many attempts were also made to validate each module against available full-scale and lab-scale data (Lu et al., 2015a; Lu et al., 2015b; Lu et al., 2016c, Tsarau and Løset, 2015; Tsarau et al., 2014).

In 2016, ArcISo was established to refactor and integrate the different modules to build SAMS as a versatile and highly accurate high-fidelity numerical simulator of offshore and coastal structures in floe-ice conditions. To achieve this, a firm quality control system was implemented to ensure clean, readable, maintainable code that is tested and verified. In addition, great attention is given to the validation and documentation of SAMS.

In regard to the validation of SAMS, the Oden Arctic Technology Research Cruise 2015 (OATRC2015) provides ample cases and data sets to validate each module separately and collectively. OATRC2015 was performed by NTNU, in cooperation with the Swedish Polar Research Secretariat, and support and participation by ExxonMobil. The expedition was conducted in the Arctic Ocean in September 2015 with the icebreakers Oden and Frej. A general description of OATRC2015 is provided by Lubbad et al. (2016).

For example, Tsarau et al. (2018) utilised the OATRC2015 data to validate the developed propeller wash model within the hydrodynamic module, and Lu et al. (2018a; 2018b) developed and validated analytical formulae to account for the kinking behaviour of long splitting cracks, and these analytical formulae became a further enrichment to the existing fracture module. The following text, on the other hand, focus on the overall validation of SAMS using OATRC2015 full-scale data.

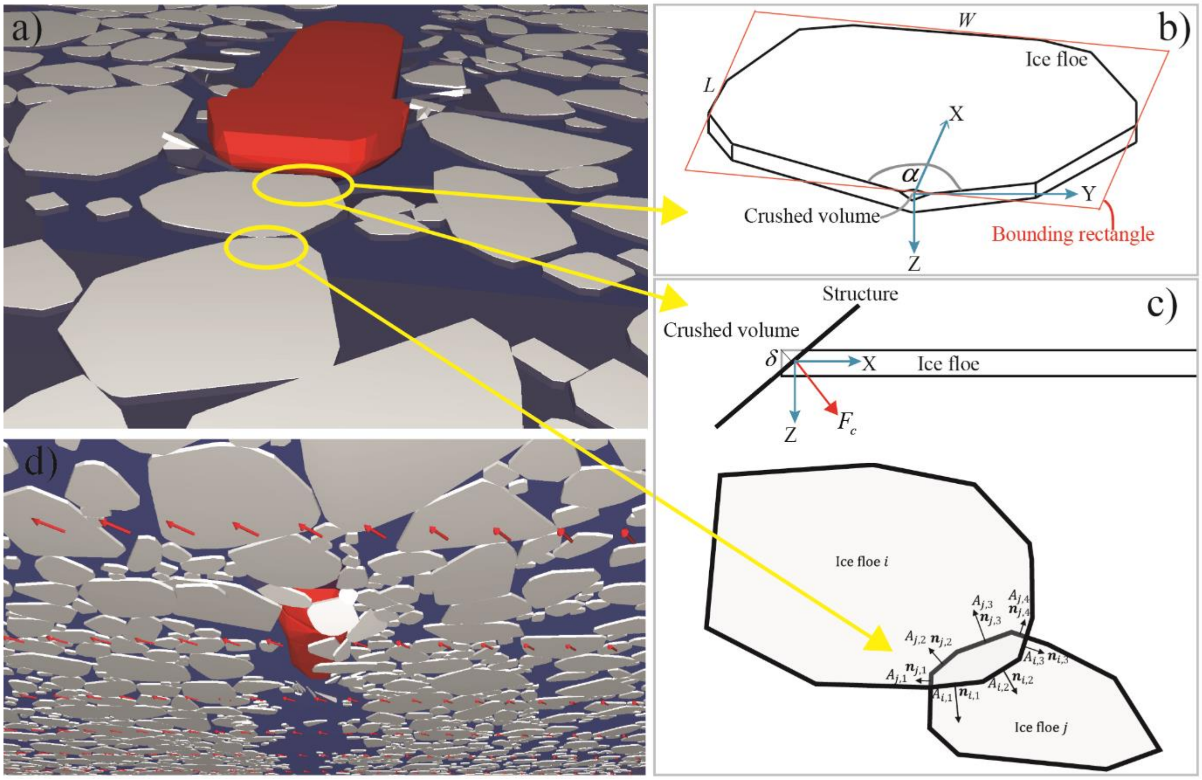

Fig. 1. Illustration of different modules within SAMS: a) the simulation environment; b) the fracture module; c) the NDEM or multi-body dynamic module illustrating the non-rigid contact due to ice crushing at the contact interface; d) illustration of the fluid domain, e.g., current flow, with velocity vectors.

**Validation Case Study**

We present a case during Oden's transit in the Marginal Ice Zone (MIZ) of the Arctic Ocean on September 30th, 2015. On that date, a helicopter flight was conducted to document the ice conditions using high-resolution photography. The AS-335NP helicopter was used for photographing, and it was equipped with a camera system consisting of a 6-axes gyro stabilised camera support (i.e., ShotOver F1) and a Red Dragon camera with a Fujinon 25 – 300 mm lens. The resolution of the images was 1114 by 627 pixels, and the ratio between the physical size and the length of a pixel is 1.1794 m/pixel. All the images were enriched with real-time information, such as latitude, longitude, and the camera's filming parameters (i.e., pan, tilt and roll angles). Fig. 2a shows one of these images.

Ideally, it is possible to utilise all the collected images along the route to build a large mosaic image characterising the detailed ice conditions Oden had transited through. Such information can be utilised to initialise the ice conditions in SAMS, and we can explicitly simulate the transiting process of Oden within the given ice field. Note that position of digitised ice floes relative to Oden must be updated continuously to account for ice drift. The simulation output would be a time history of the resistance encountered by Oden. These simulated results can, in turn, be compared with the ice resistance calculated based on the on-board inertial measurement units (IMUs) measurements (Kjerstad and Skjetne, 2016; Kjerstad et al., 2018). This gives us an opportunity to utilise the OATRC2015's data to validate the capabilities of SAMS to model Oden's transit in the MIZ.

In this paper, we do not attempt the full validation exercise described above. Instead, we assume that the information in the image in Fig 2a, which covers a spatial scale of 700 m by 1300 m, is representative for the ice conditions along the entire track of Oden in the MIZ. We digitise this image using image processing techniques of Zhang and Skjetne (2015). The digitalised ice field, after excluding brash ice and resolving the overlap between the digitised floes, is shown in Fig. 2b. Further, we analyse Oden full-scale data, e.g. navigation, IMUs, and propulsion data to obtain time series of full-scale ice forces, propulsion forces (thrust), hydrodynamic and aerodynamic resistance, etc. Subsequently, SAMS uses the generated ice field and the estimated full-scale thrust as input to simulate the transit of Oden in the MIZ. The hydrodynamic and aerodynamic resistance in SAMS are calculated according to the same formulae we use for the analysis of the full-scale data. The model of Oden in SAMS preserves her exact three-dimensional (3D) geometry and allows her to move in six degrees of freedom (6 DoF). Finally, we validate SAMS by comparing the simulated and full-scale time series of ice forces in the surge direction.

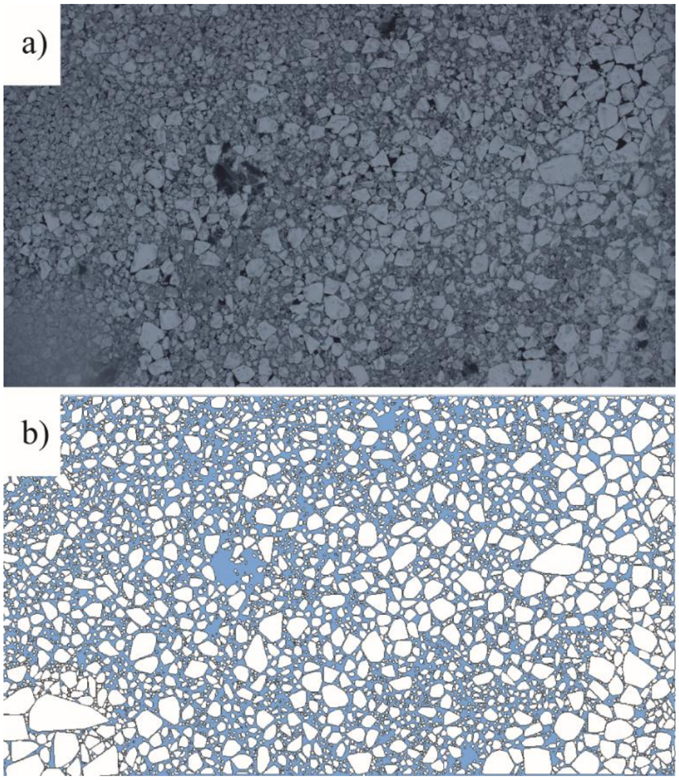

Fig. 2. a) Initial helicopter camera image; and b) Digitalised ice field for simulation input.

**SAMS inputs**

To simulate the transition of Oden in the MIZ with SAMS, we need to define the ice conditions and to prepare a model for Oden. In addition, we need to specify the external forces that cause the motion of Oden.

Here, we use the ice field, shown in Fig.2b, as input to the simulation. The geometrical model for Oden in SAMS is stored in the Wavefront OBJ format (.obj file), which can be generated by using 3D graphics software, and may comprise multiple triangle meshes. Each of the meshes is assumed to represent a convex hull. For the simulations presented in this paper, Oden's geometry was accurately digitalised using readily available software packages, such as Blender and FreeCAD. The input model of Oden contained 35 convex bodies, which in total contained 2240 vertices, 6510 edges and 4338 faces. The large number of mesh elements allow a very detailed approximation of Oden's hull, as seen in Fig. 3.

In addition to ice forces, Oden is subjected to different external forces such as propulsion forces (thrust), hydrodynamic resistance and wind drag forces. The measured full-scale thrust is used an input to the simulation. The hydrodynamic and aerodynamic forces are calculated by SAMS according to the same formulae we use for the analysis of the full-scale data.

The input mechanical parameters of sea-ice are summarised in Table 1. Most of the values are chosen with reference to Timco and Weeks (2010), with a preference for engineering applications. For the fracture toughness of sea ice, the chosen value is based on the work of Dempsey et al. (1999).

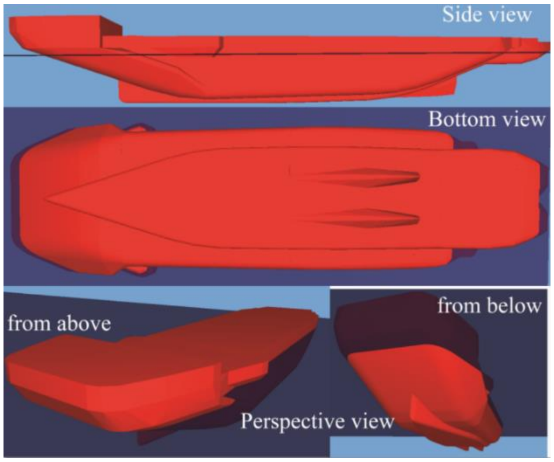

Fig. 3. Geometric representation of Oden.

Table 1. Inputs for the simulations.

| | |
|---|---|
| $\Delta t = 0.01\text{s}$ | Simulation time step; |
| $\rho_i = 900\,\text{kg/m}^3$ | Ice density; |
| $\rho_w = 1025\,\text{kg/m}^3$ | Water density; |
| $C_f = 0.005\ [-]$ | Skin friction coefficient; |
| $C_d = 0.5\ [-]$ | Form drag coefficient; |
| $h = 1\text{m}$ | Ice thickness; |
| $E = 5\,\text{GPa}$ | Young's modulus; |
| $v = 0.3\ [-]$ | Poisson ratio; |
| $K_{IC} = 150\,\text{kPa}\sqrt{\text{m}}$ | Fracture toughness; |
| $\sigma_c = 2\,\text{MPa}$ | Compressive strength of ice; |
| $\sigma_f = 500\,\text{kPa}$ | Flexural strength of ice; |
| $\mu_{ii} = \mu_{is} = 0.15\ [-]$ | Ice-ice, and ice-structure friction coefficient. |

**Simulation results**

A visual illustration of the simulated transit is presented in Fig. 4. The simulated time series of ice load on Oden in the surge direction $F_X$ together with its averaged value, $\mu_{F_{X-Sim.}} = 974$ kN, are shown in Fig. 5. These simulated results shall be compared with ice load estimated from the field measurements. The simulated ice loads are the sum of the compliant and rigid contact forces between ice and Oden. The simulation results in Fig. 5 are filtered with a moving average that has time windows of 0.5 s and 20 s for the compliment and rigid contact forces, respectively. The use of a larger time window to filter the rigid contact forces is justified because of the nature of this contact model, i.e. estimate only the average contact force.

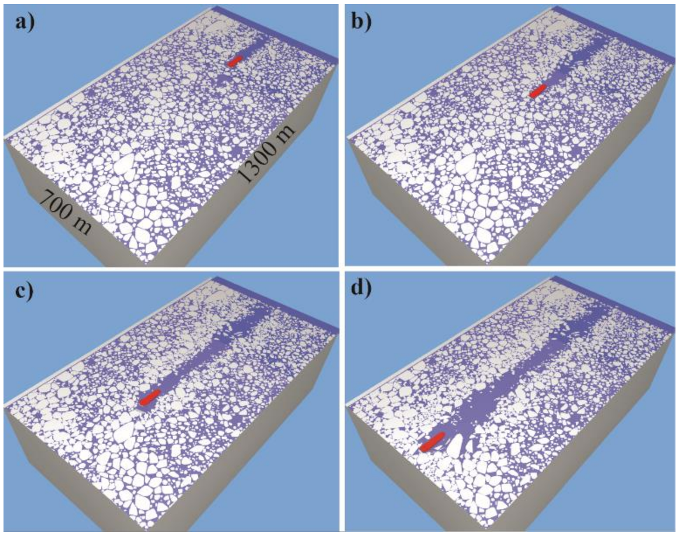

Fig. 4. A visual illustration of the simulated transit of Oden.

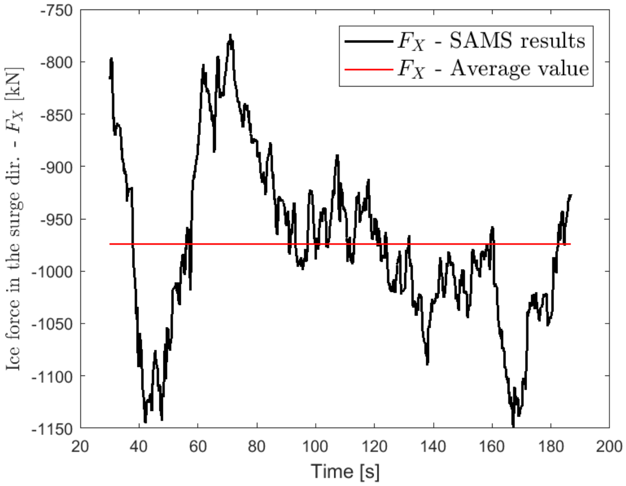

Fig. 5. Simulated ice load history in the surge direction (in black) and its averaged value (in red).

### Comparison with full-scale data

To verify the simulation results, it is necessary for us to obtain the ice load history encountered by Oden during the transit. However, direct measurement of global ice load acting on an icebreaker is rather challenging, if it is at all possible.

Instead, we shall utilise several indirect measurements to back-calculate the global ice load history. These measurements include: 1) four Inertia Measurement Units (IMUs) to obtain the ship's acceleration history; 2) the ship's propulsion data; and 3) other ship data (including the ship's position and heading, wind direction and speed, and geometry of the ship). The identification model, follows the formulations by Fossen (2011), reads

$$M\dot{v} = \tau_a + \tau_h + \tau_w + \tau_i \qquad (1)$$

in which,

| | |
|---|---|
| $M$ | is Oden's mass matrix [surge, heave, yaw]; and it is estimated here as: $M = 10^6 \operatorname{diag}[13\,\mathrm{kg}, 13\,\mathrm{kg}, 9286.4\,\mathrm{kg}\cdot\mathrm{m}^2]$ |
| $\dot{v}$ | is Oden's accelerations in the surge, heave and yaw directions measured by the IMUs and filtered with a moving average of 0.1 s time window. |
| $\tau_a$,<br>$\tau_h$,<br>$\tau_w$, and<br>$\tau_i$ | are ship propulsion, hydrodynamic resistance wind resistance and global ice load, respectively. They are calculated with a frequency of 2 Hz (or 0.5 s time interval). Their detailed formulation and calculations are presented in the companion paper (Kjerstad et al., 2018). |

In this paper, the results of the ice load identifications/calculations are presented in Fig6. The average full-scale ice resistance in the surge direction is $\mu_{F_{X-Full.}} = 1038$ kN.

## DISCUSSIONS

For the presented case study, SAMS yielded statistically satisfactory results for the ice forces on Oden in the surge direction, i.e. around 6% error compared to the full-scale value. Recall, that the average values of the full-scale data and the simulation results are calculated over time windows of 900 s and 200 s, respectively. This suggests that a better convergence may be achieved if the simulations were ran for a longer period.

The numerical ice field, which was used as input to SAMS, is generated from a single image. In addition, the drift of ice due to wind and current was not considered in the simulations. Moreover, many input parameters in Table 1 are not in situ measurements, i.e. they are estimated based on recommended values in the open literature. All this indicates that a deviation between the simulation results and the full-scale data is to be expected. However, the results of the current study show that this difference is considerably smaller than initially anticipated.

Aside from the global ice resistance's simulation, it is also important to stress the detailed physical processes that SAMS has captured during the simulation. Figs. 7a and b illustrate SAMS' multi-body dynamics' capability to capture the 6 DoFs motion of an ice floe. In the consecutive image of Fig. 7c, the ice floe's splitting fracture is demonstrated. Fig. 8 shows a good example of the coupling between the local bending and global splitting failure modes in an off-centre collision case.

In addition to the multi-body interactions and the ice floe's failure mode demonstrations, a different scenario with a constant 0.5 m/s current flowing with 45° to Oden's surge direction is simulated with SAMS and is illustrated in Fig. 9. With the presence of current drag, ice floes within the ice field are packing to the upper right corner of the simulation domain. This visually demonstrated the effectiveness of the hydrodynamic module within SAMS.

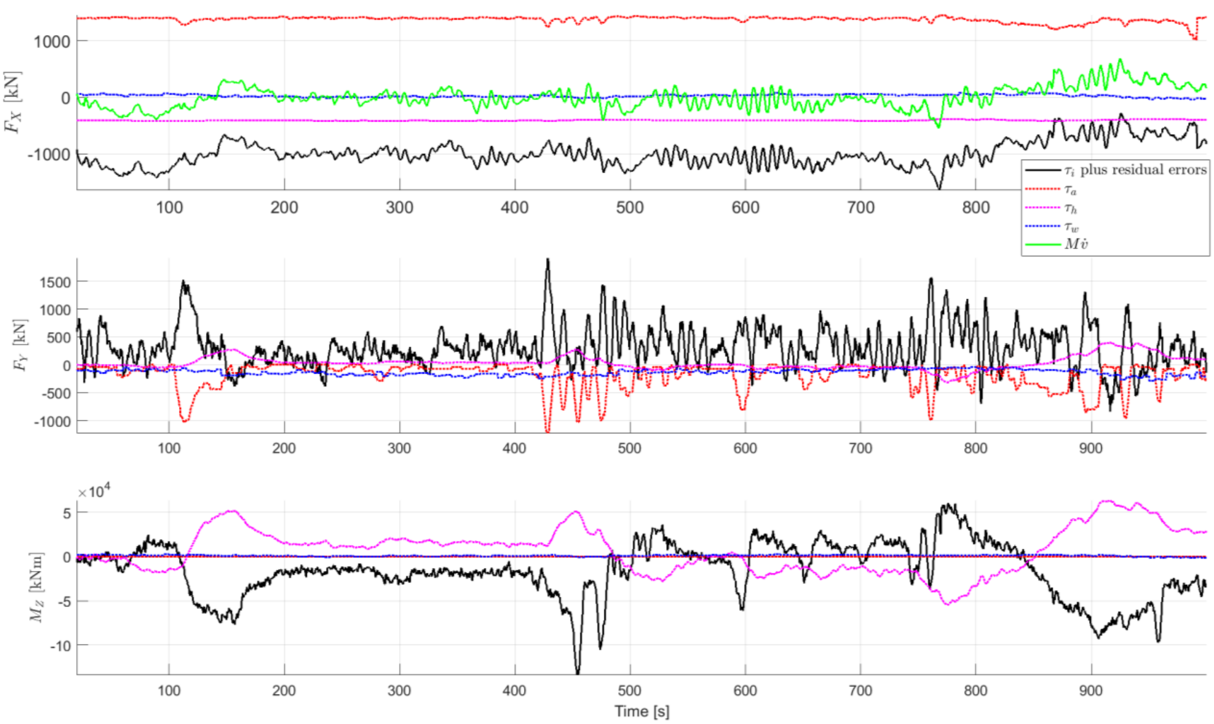

Fig6. Different load components' history (in surge, sway and yaw directions) during Oden's transit within the selected time window.

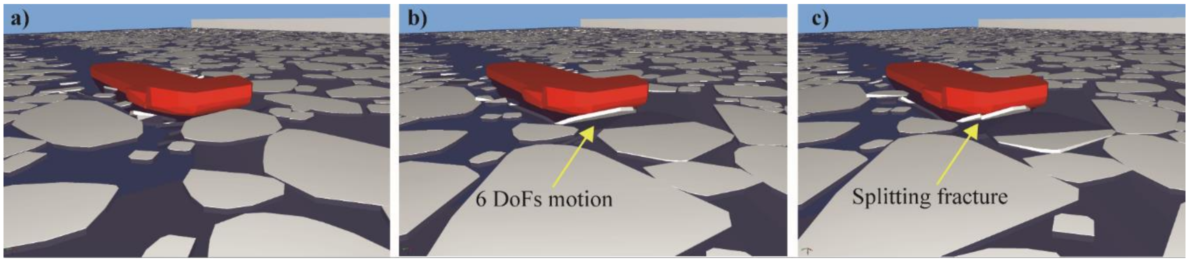

Fig. 7. Detailed physical processes simulated within SAMS.

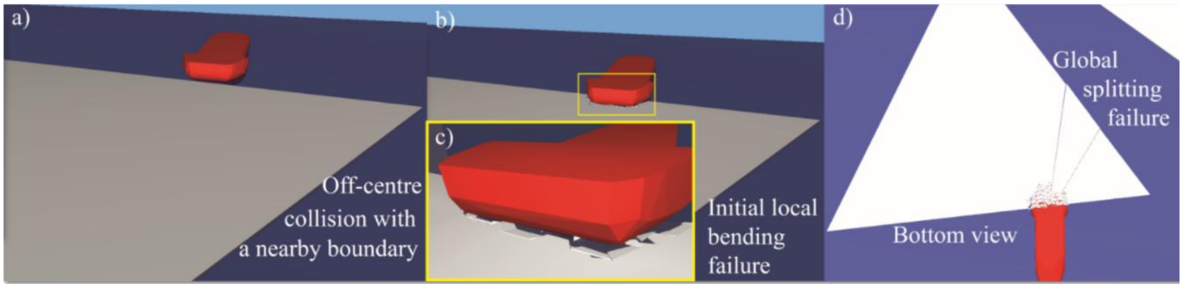

Fig. 8. Coupled local bending and global splitting failure modes in an off-centre collision case.

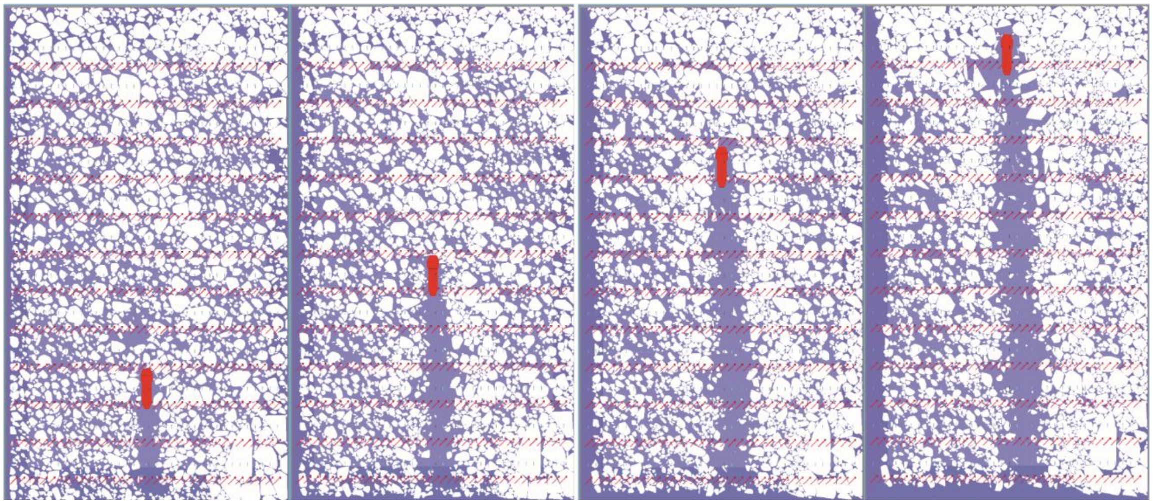

Fig. 9. Illustration of the hydrodynamic module introducing the influence of current force (0.5 m/s and with 45° with reference to the surge direction) in the entire ice field.

## CONCLUSIONS

Simulator for Arctic Marine Structures (SAMS) is a high-fidelity numerical simulator for structures in various ice conditions such as level ice, broken ice and ice ridges. SAMS is a product of Arctic Integrated Solutions AS (ArcISo) - a spin-off company from the Norwegian University of Science and Technology (NTNU). This paper gives a brief presentation of the history and theoretical basis of SAMS. The paper discusses the validation of SAMS and presents a case study from OATRC2015 full-scale data.

We used Oden's transit data (from 06:50:00 to 07:05:00 on September 30th, 2015) for the case study. In particular, one representative image taken by the helicopter along Oden's transit route was chosen to digitalise the ice field to extract information, such as ice floe size, geometry and locations. Given such real field ice information, we reconstructed this ice field (1.3 km by 0.7 km) within SAMS, and simulated Oden's transit within it.

- Statistically, SAMS yields rather satisfactory ice resistance values, i.e., about 6% error compared to the value calculated based on measurements;
- Through the validation process, different modulus within SAMS are collectively verified. Individually, the functionalities of different modulus are visually demonstrated. This includes: the multi-body dynamics accounting for each individual ice floe's motion and their interactions with themselves and the structure; the multi-failure modes of each ice floe according to previous theoretical development; and the hydrodynamic module's capability to consider the effect from the ambient fluid (both air and water).

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