Simulation of ice action loads on off shore structures

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Abstract:

During the last years, there has been an increasing amount of work published regarding simulation of ice action on structures using finite element models of the ice. The effect of ice fracture is in these models approximated using cohesive elements. In this article we give an overview of the cohesive element method for ice modelling including recent improvements made by the authors. A description is given of the implementation of the cohesive element method for modelling floating ice sheets in LS-DYNA including effects such as buoyancy. To demonstrate the performance and robustness of the implementation, numerical results are presented from a full scale simulation of an ice sheet impacting an offshore structure.

Keywords:

CEM, cohesive elements, erosion, buoyancy, ice modelling, failure, continuous crushing

1 Introduction

Today, structures which are designed for resistance against drifting sea ice sheets are dimensioned using design codes. A recently issued design code is ISO/DIS 19906 [1]. Bjerkås et al. [2] show in a case study how the ice loads defined by this design code are significantly lower compared to earlier design codes.

Apart from design codes, structures designed for ice loads are dimensioned using scaled test models. Such physical testing is both time consuming and expensive. Naturally, there has therefore been an interest in developing simulation methods, e.g. finite element based, that could save both time and cost, and in addition hopefully also increase the reliability of the used design loads. Research efforts have been made in this direction in the latter years, see e.g. Gürtner [3], Gürtner et al. [5] and Konuk et al. [6]-[8]. Physical measurements are a necessity to validate ice action simulation methods; apart from scale test data there are high quality full scale test data available through the projects LOLEIF, see Jochmann and Schwarz [4], and STRICE (www.strice.org).

In nature three main types of ice fracture modes can be identified. One important parameter that determines the ice fracture mode has been identified as the drift speed. The ice fracture mode studied in this article is the so called Continuous Crushing (CC) mode. In this fracture mode the ice breaks and is crushed into very small fragments, i.e. "snow flakes", during interaction with the structure.

The proposed analysis methodology developed by Gürtner et al is referred to as the Cohesive Element Method, (CEM). In order to capture the failure in the ice sheet, cohesive elements are used to represent the cracks. The elements are thus capable of separating as a result of stress and strain and thereby representing the ice fragmentation. However, when the ice fragment sizes becomes significantly lower than any computationally affordable element size, such as in the CC mode, further development is needed. In this article, the proposed solution is to use a homogenisation approach in combination with the CEM. The energy consumed by the cohesive elements represent both energy from that particular crack and also, to some extent, the energy consumed by several other cracks within one element. Plasticity is used to represent fractures within an element allowing a capture of further fragmentation of the ice sheet below the element scale.

All simulations are performed with LS-DYNA, see Hallquist [9].

1.1 Outline

The article focuses on the numerical methodology which is reflected in the disposition of the article. First a small description of the problem at hand is given in Section 2. In sections 3 and 4 the simulation methodology is described and motivated. In Section 5 the results are presented and, finally, the conclusions are given in Section 6.

2 Problem description and simulation approach

The physical problem to be studied is loading onto offshore structures by drifting ice sheets, in this article represented by the lighthouse Norströmsgrund situated in the Gulf of Bothnia. There are measurements made at Norstömsgrund Lighthouse which will be used later on for comparison with simulation results, see Figure 1.

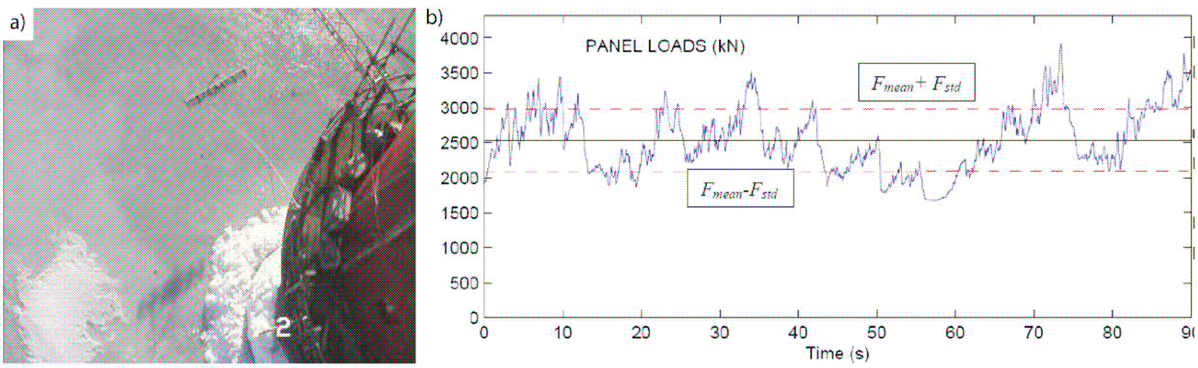

Figure 1: Physical measurements and ice failure at Norströmsgrund lighthouse.

There are three different categories of ice fracture processes, see Figure 2, where the process of continuous crushing (CC) is the one of interest here. In this fracture mode, cracks on different scales form in the ice sheet and the ice sheet disintegrates in the ice-structure contact zone. The fragmented ice is then transported around the structure, both beneath and above the ice sheet.

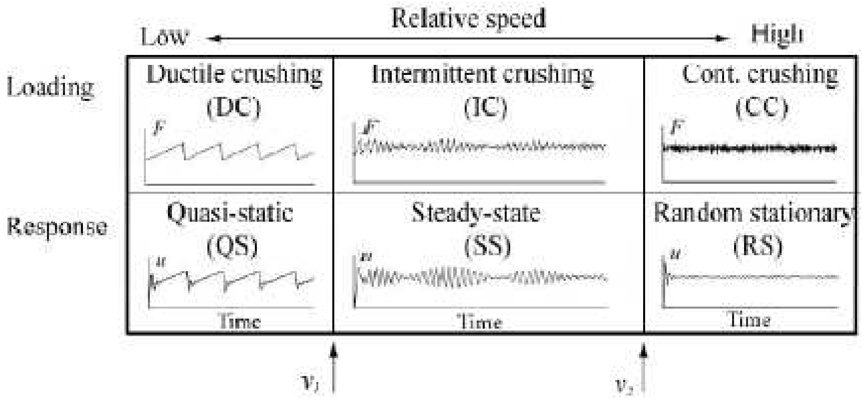

Figure 2: The observed relation between ice drift velocity and fracture mode in ice sheet, from Bjerkås et al. [2].

The intention is to use the cohesive element method to capture the separation of ice pieces, see Section 3.2. In order to capture further fragmentation and crushing of the ice a homogenization of the material is performed, see Section 3, although this means that the possible orientations of cracks on a macro level is limited.

The transportation of fragments is also addressed and therefore a proper influence from the buoyancy and drag of ice in water is needed. An implementation of special buoyancy and drag models were made in order to avoid time consuming CFD modelling techniques for the water, see Section 4.

The Norströmsgrund lighthouse finite element model has been developed in LS-DYNA according to the physical lighthouse including the instrumentation used for the ice force measurements. Both rigid and deformable models of the Norströmsgrund lighthouse were developed.

3 Description of the ice modelling technique

3.1 Introduction

The ice is modelled using the Cohesive Element Method with Homogenization (CEMH). Before deriving the homogenization approach developed by the authors, an introduction is given to ice models based on the Cohesive Element Method (CEM).

The CEM is not new. Similar methods such as the cohesive zone method have a long history in the field of fracture mechanics for modelling crack propagation in solids, such as metals and concrete. The extended application to modelling ice fracture during complex ice-structure interaction is a recent development that was pioneered by Gürtner [3]. Usage of a cohesive zone model for the pure study of ice fracture was first described by Mulmule and Dempsey [10].

3.2 Cohesive Element Method – CEM

In the following a basic or simplistic version of the CEM is described. The point is to provide the reader with the basic idea behind the method proposed by Gürtner [3] as the Computational Cohesive Element Method.

Assume the ice is an elastic or elasto plastic continuum that can fracture. As cracks are formed the ice can slide along the crack-planes, developing a frictional ice mass. Here a fixed pattern of potential cracks is assumed. The finite element implementation can be outlined as follows. The block of ice is built up using standard solid finite elements, e.g. hexahedral elements. Each individual element is attached to its neighbours using so called cohesive elements, which are the potential crack planes. A cohesive element is a zero thickness element that when subject to tension or shear responds by deforming according to a given traction-separation curve. When the force or deformation reaches a limit value the cohesive element is removed and thus a crack is formed and a fracture energy G is dissipated or released. A crack can grow by the deformation and failure of neighbouring cohesive elements. Contact conditions are added to the crack faces so that friction can occur if sliding occurs in a closed crack. It follows that for a sufficiently large deformation the block of ice is reduced to rubble of ice elements interacting only by contact and friction. Figure 3 shows an illustration of a block of ice built up by hexahedral elements connected with cohesive elements.

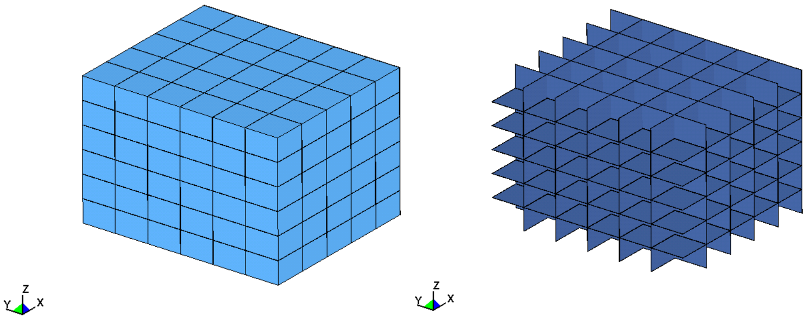

Figure 3: A block of ice built up by elastic hexahedral elements is shown to the left. To the right the cohesive elements that hold together the hexahedral elements in the block are shown.

3.3 Cohesive Elements with Homogenization – CEMH

In the following the CEM with Homogenization, CEMH is derived. The fairly simplistic homogenization approach described here can be seen as an attempt aimed at testing the usefulness of such an approach for ice modelling.

Crushing of a sheet of ice against a stationary object, see Figure 1, involves crushing of the ice in the interaction zone close to the object. Multiple cracks are formed followed by crack branching on multiple scales until ultimately a “snow-like” material is produced as is shown in Figure 1. Current computationally feasible mesh sizes are too coarse to capture the small scale fractures and cracks directly using the CEM. Therefore an approach is chosen here in which the effect of “sub-element” size or microscopic phenomena are modelled by a special material model on the macroscopic level, involving observable macroscopic state variables. Such an approach is typically referred to as homogenization.

The key is to derive a macroscopic material model that can represent the macroscopic effect of sub-element size cracks. The material model should be as uncomplicated as possible and preferably computationally cheap. This means that cracks cannot be explicitly modelled; rather the model must express the average effect of cracks forming in the material. The first step is to make the following ad hoc assumptions about a representative volume of ice that is crushed and thus develops internal cracks:

1. Until the first crack arises the ice is elastic.
2. The volume is preserved during the deformation. This is reasonable if the ice is subject to constraints from surrounding ice.
3. The cracks occur on planes with maximum shear stress. This corresponds to mode II and III cracks. This assumption also agrees well with assumption 2.
4. The process is irreversible, i.e. cracks cannot disappear or mend.
5. The macroscopic effect of cracks is that the ice softens, i.e. deforms more easily.
6. When the ice element is totally crushed it behaves as a viscous fluid.

The amount of cracks in the ice is assumed to be proportional to the amount of deformation. The effective shear strain is here used as a deformation measure since a shear deformation is volume preserving, i.e. the effective shear strain is a deformation measure compatible with assumption 2.

An isotropic elasto plastic material model with a Tresca yield condition fits assumption 1 through 6 and is therefore used here. This type of material model is also computationally cheap. To implement assumptions 5 and 6 a hardening curve like in Figure 4 is used.

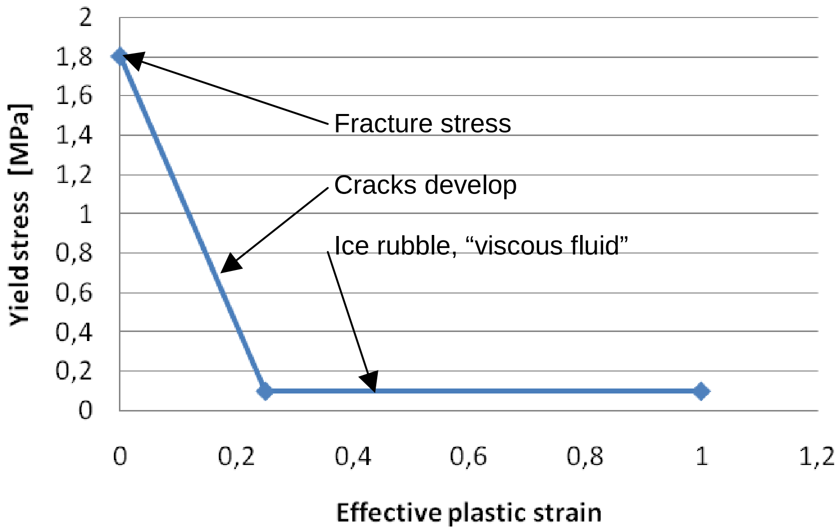

Figure 4: Schematic hardening curve for ice elements with a homogenized crack model.

3.3.1 Summary of CEMH

In summary we have shown that, under suitable assumptions, it is plausible that one can actually model the macroscopic effect of the sub-element size cracks in the CEM mesh using a homogenization method based on standard elasto plastic material theory with a non-standard hardening curve, see Figure 4. We will refer to the CEM with the described homogenization as CEMH. The proposed CEMH is rather crude and needs to be improved upon both regarding rigor and by using a more advanced macroscopic material model.

The Tresca yield condition can be difficult to handle numerically, thus in the simulations the von Mises yield condition is used instead.

3.4 A theoretical analysis of the CEMH

The following thought-experiment is used to analyse the CEMH. Consider a continuous crushing similar to the one in Figure 1, but where a stationary ice sheet is crushed by a cylinder moving at a low constant velocity. Assume a CEMH mesh of cubical elements like in Figure 3. Using the principal of virtual work the following relations can then be set up between the external work supplied to the system and the work from the formation of new surfaces in the ice, plastic deformation, and consumed work by frictional forces between ice and cylinder:

$$\partial E^{ext} \approx \partial E^{CE} + \partial E^{pl} + \partial E^{fr} \tag{1}$$

$$\partial E^{ext} \approx F \cdot \partial x \tag{2}$$

$$\partial E^{CE} \approx G \frac{D}{h} \cdot t \cdot \partial x + G \cdot D \cdot \frac{t}{h} \cdot \partial x + G \cdot t \cdot D \cdot \frac{\partial x}{t} \tag{3}$$

$$\partial E^{pl} \approx \frac{1}{2} \varepsilon^{p} \cdot \sigma_{Y} \cdot D \cdot t \cdot \delta x \tag{4}$$

$$\partial E^{fr} \approx 2 \cdot (p \cdot \mu \cdot t \cdot D) \cdot \partial x \approx // \, p \approx \frac{2F}{Dt} // \approx 2 \cdot \mu \cdot F \cdot \partial x \tag{5}$$

Nomenclature: Superscripts *ext* refers to the cylinder, *CE* refer to cohesive element, *pl* refer to plasticity, and *fr* refers to the frictional work between cylinder and ice. *D* is the diameter of the indenter, *t* is the ice thickness, *G* is the energy release rate for the macroscopic cracks forming in the ice that are explicitly modelled using cohesive elements, *F* is the constant force needed to move the cylinder through the ice, *μ* is the coefficient of friction between ice and structure, *p* is the pressure applied to the cylinder by the ice, ε^p is the plastic strain in the CEMH sub-element fracture model for completely fractured ice, σ_Y is ice the yield stress in Figure 4, *h* is the characteristic element size in the ice sheet, and ∂x is the virtual displacement of the cylinder towards the ice. It is here assumed that inertial forces are negligible.

Make the ad hoc assumption that with the given element size the work is the same for all processes on the RHS in Eq. 1, which of course is just a rough guess. This assumption together with Eq. 1 through 5 yields:

$$\frac{F}{3} = 3 \cdot G \frac{Dt}{h} = \frac{\varepsilon^p \cdot \sigma_Y}{2} \cdot D \cdot t = 2 \cdot \mu \cdot F \ , \tag{6}$$

which implies

$$G = \frac{\varepsilon^p \cdot \sigma_Y}{6} \cdot h \tag{7}$$

By applying parameters, see tables 1 and 2: ε^p=0.25, σ_Y=2 MPa, and the element size in the simulation h≈0.1 m a value of G ≈ 8333 J/m^2 is derived. This value of G is on the order of one hundred times larger than typical values reported in the literature for the fracture energy of ice. The conclusion is that it may well be motivated to increase the fracture energy release energy considerably compared to the nominal value due to the finite element size.

4 Ice and water interaction

4.1 Bouyancy

In order to treat the ice sheet as a floating objective, buoyancy forces need to be accounted for. In Gürtner [3] buoyancy forces were calculated by explicitly simulating the water media by a coupled Arbitrary Lagrangian Eulerian (ALE) approach. This method is accurate but not computationally efficient enough for the model sizes investigated here. Therefore, a parametric buoyancy model was developed and implemented as a user loading in LS-DYNA as follows.

The buoyant pressure *p* of a surface in a liquid equals

$$p = \rho g \max(0, -z) \tag{8}$$

where ρ is the density of the liquid, i.e. water, and g is the gravitational constant. The surface is here represented by a finite element segment

$$S = \left\{ \quad \mathbf{x}_I N_I(\xi,\eta) = (x_I, y_I, z_I)^T N_I(\xi,\eta) \quad : \quad -1 \le \xi,\eta \le 1 \quad \right\} \tag{9}$$

where N_I are the standard iso-parametric shape functions and $\mathbf{x}_I = (x_I, y_I, z_I)^T$ are the nodal coordinates of the segment. The pressure can thus be rewritten as

$$p = \rho g \max(0, -z_I N_I) \tag{10}$$

and it acts in the negative direction of the segment outward normal $\mathbf{n}$. The principle of virtual work states that

$$-\int_S p \mathbf{n}^T \delta\mathbf{x} dS = \mathbf{f}_I^T \delta\mathbf{x}_I \ . \tag{11}$$

The left hand side can be expanded to

$$-\int_S p \mathbf{n}^T \delta\mathbf{x} dS = \rho g z_J \int_{S_{z\le 0}} N_J N_I dS \mathbf{n}^T \delta\mathbf{x}_I \ , \tag{12}$$

where $S_{z\le 0} = S \cap \left\{ \quad \mathbf{x} \quad : \quad z \le 0 \quad \right\}$. The resulting finite element nodal forces equal

$$\mathbf{f}_I = \rho g z_J \int_{S_{z\leq 0}} N_J N_I dS\mathbf{n} \,. \tag{13}$$

In the implementation any warped segments are made planar by projecting the nodes onto a mid-plane before undergoing the calculations described above.

4.2 Drag

Broken off ice blocks may be thrust into the water during the ice crushing. To have a more realistic behaviour of the motion of these ice blocks a simple drag model for fully developed turbulent flow is implemented. The drag force on an object moving through a liquid at high Reynolds numbers[1] is approximately according to e.g. Batchelor [4]:

$$F_D = \frac{1}{2}\rho v^2 A C_D \,, \tag{14}$$

where v is the velocity and A the cross section area. The drag coefficient C_D is about 1.05 for a cube moving head on through still water.

5 Full scale ice event study - Norströmsgrund ice force measurements

5.1 Software tools

All simulations were performed using the MPI-parallel version of LS-DYNA 971, Hallquist [9]. The simulations were run on a cluster, Intel Xeon CPUs, with a fast interconnect (Infiniband).

To include the effect from the buoyancy, i.e. that the ice floats on the water, and drag on the ice a special drag and buoyancy subroutine was implemented in LS-DYNA as an UDF (User Defined Module).

5.2 Set up

The simulation of ice drift onto the lighthouse is modelled with a prescribed velocity, 0.15 m/s of the lighthouse into the ice sheet. Only the part of the ice sheet that is close to the lighthouse contains zero volume cohesive elements in order to reduce the simulation time. The material parameters for the under-integrated solids and the cohesive elements are given in Table 1 and Table 2, respectively. For purely numerical reasons the yield curve increases for strains above 0.5, see Figure 5, to avoid excessively distorted elements.

The ice has an average thickness of 0.69 m and geometrical perturbations were used to avoid a perfect, regular mesh. The size of the finite elements in the ice is about 0.13x0.2x0.2 m. The ice sheet has fixed boundary conditions along the edges except on the side where the lighthouse makes contact with the ice.

*CONTACT_ERODING_SINGLE_SURFACE is used for the contacts between ice fragments and *CONTACT_ERODING_SURFACE_TO_SURFACE is used between the ice and the lighthouse to optimize the number of available contact surfaces during the simulation. Several different *CONTACT_FORCE_TRANSDUCER_PENALTY are used to extract the forces on different areas onto the lighthouse for more detailed analysis.

Table 1:Material parameters used for water and ice

Ice density	910 kg/m^3
Ice elastic modulus	5 GPa
Ice Poisson's ratio	0.3
Ice element yield curve	See Figure 5a, ε^p=0.25 and σ_Y =2 MPa..
Water density	1000 kg/m^3
Coefficient of friction ice to ice	10 % static, 5 % dynamic
Coefficient of friction ice to steel	20 % static, 10 % dynamic

[1] Reynolds number, Re, above about 1000.

Table 2:Material parameters used for the cohesive elements

Parameter	Vertical cohesive elements	Horizontal cohesive elements
Shear strength	1 MPa	1.1 MPa
Tensile strength	1 MPa	1.1 MPa
G_{IC}	5200 J/m^2	5200 J/m^2
G_{IIC}	5200 J/m^2	5200 J/m^2

Note: Artificially high values are used for G_{IC} and G_{IIC} as motivated in Section 3.3. Experimental values of G_{IC} and G_{IIC} are on the order of 50 J/m^2

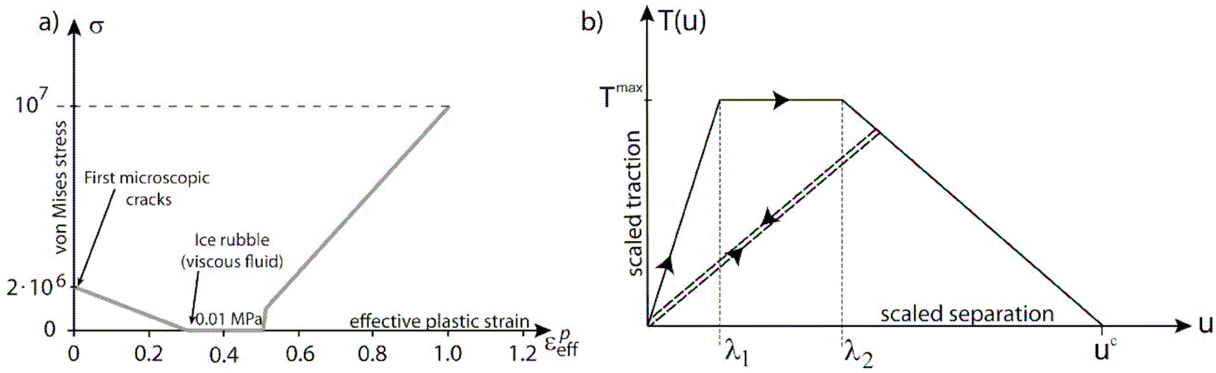

Figure 5:a) Schematic of yield curve of the softening material, with von Mises stress plotted against effective plastic strain; and b) Non-reversible traction separation law for the ice cohesive elements.

5.3 Results

Presented here are some of the simulation results obtained with a rigid lighthouse. However, the following topics were investigated in the project

1. The mesh density influence.
2. The mesh size influence.
3. The model geometry (if ice should be around the lighthouse or if a square sheet can be used).
4. Rigid versus deformable lighthouse.
5. Boundary conditions used in the model to position the ice.

The responses of greatest interest here is of course the deformation of the ice sheet, the force level obtained on the lighthouse, the transportation of material from the crush zone and the piling of ice in front of the lighthouse.

5.3.1 Ice deformation and rupture

The typical deformation and rupture of the ice sheet is shown in Figure 6.

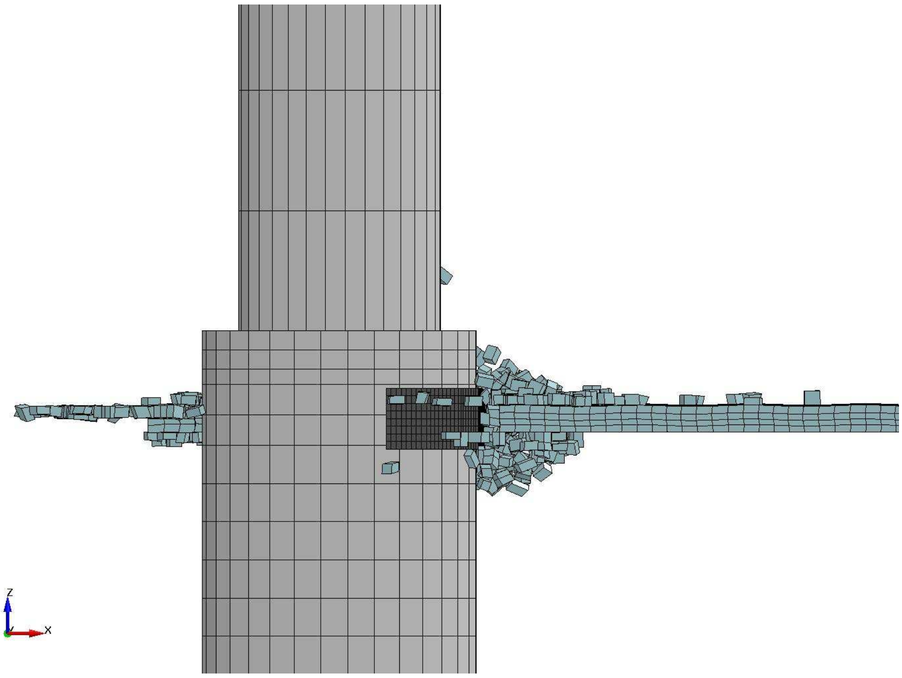

Figure 6: Typical situation in front of lighthouse in the simulation. Ice piles up in front of lighthouse beneath the ice sheet. Somewhat more material is moved downwards but not as much as compared to real life test.

The typical energy levels of the processes involved in this simulation are shown in Figure 7.

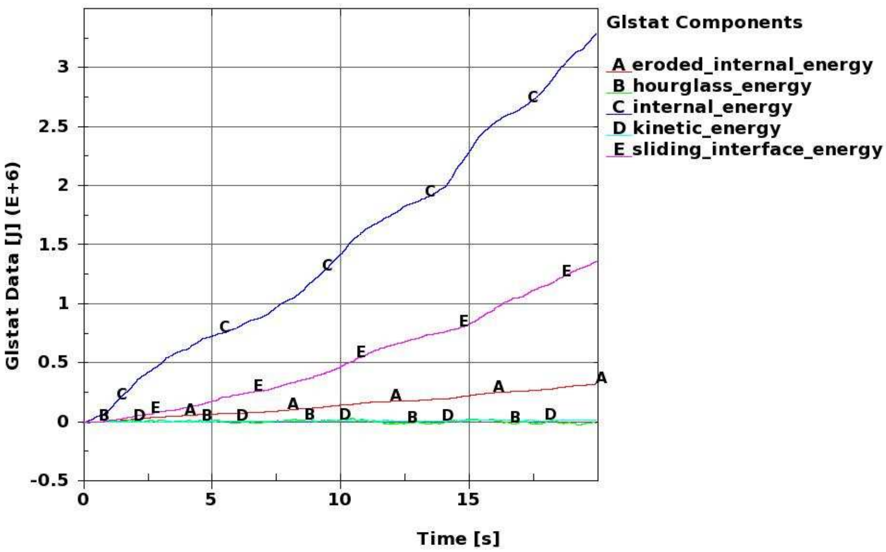

Figure 7: The relation between different processes consuming energy in a typical simulation.

The influenced zone in the ice sheet is typical 1-3 elements away from the contact between the lighthouse and ice sheet. Although, the cohesive elements are affected to some extent even further away.

5.3.2 Force level on the lighthouse

The force levels measured on the lighthouse from three different simulations are shown in Figure 8. It should be noted that the initial peak in the force level is also shown in real-life when the ice starts to drift and the ice surrounds the lighthouse with a nearly perfectly contact zone. It can be observed that the overall force-time appearance is quite similar a few seconds into the simulation regardless of the starting condition.

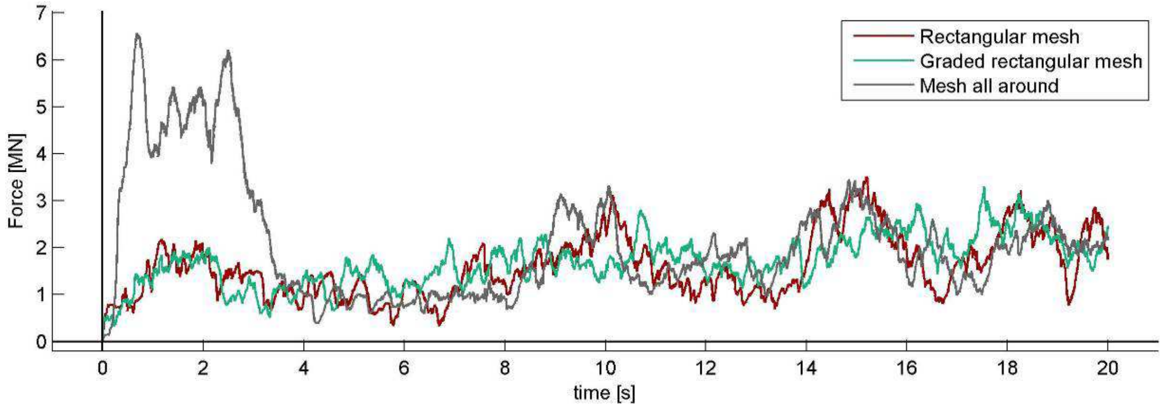

Figure 8: Force levels obtained with different meshes and also one where the ice encloses the lighthouse.

The results should be studied on an average point of view. The oscillations found in the simulation results do not correspond to abrupt fundamental physical transitions. Also, the contact behaviour between the lighthouse and ice is more discrete than in nature. This may be due to the finite element size.

The measured load on the lighthouse is shown in Figure 9. Comparing Figure 9 with Figure 8, the force level is smaller in the simulations. Hence, further material homogenization parameter fitting may be needed to achieve better results.

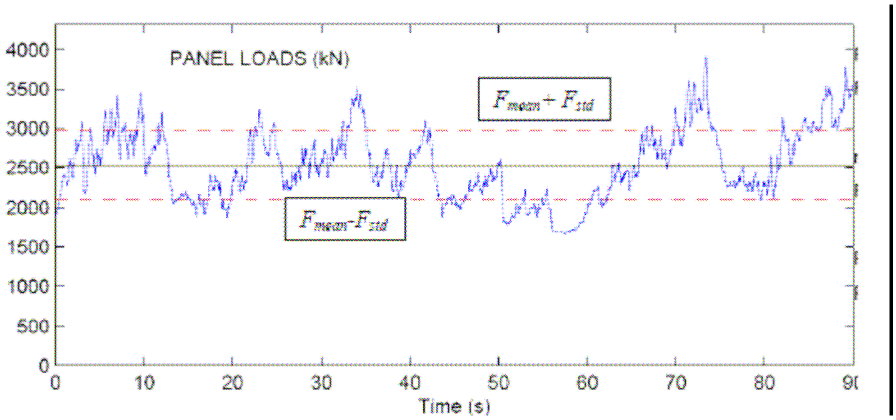

Figure 9: Measured total force applied on the lighthouse during an CC event.

6 Conclusions

The main achievement of the study is that it demonstrates the feasibility of full scale simulations of the continuous crushing fracture mode of ice sheets against offshore structures. This achievement was made possible by combining:

1) The cohesive element method for ice fracture modelling.
2) A newly developed homogenization approach to capture the effect of small fractures in a computationally efficient manner.
3) Implementation of computationally efficient methods to capture buoyancy and drag.
4) The parallel mpp/LS-DYNA-solver running on a high performance compute cluster.

It is further shown that the simulation results are qualitatively and also partly quantitatively in agreement with field observations including measured ice forces.

While the described CEMH method certainly is only one step towards accurate ice simulation we judge it to a promising approach. There are also several possible improvements within the CEMH framework that could further improve the realism.

Finally, thanks to the parallel efficiency of LS-DYNA, the solution times are most reasonable.

7 Acknowledgement

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8 Literature

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