Simulation of Loads from Drifting Ice Sheets on Offshore Structures

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Abstract

In later years, there has been an increasing amount of work published regarding simulation of ice action on structures using finite element models of the ice.

Here we will present results from a method development project aimed at evaluating the feasibility of full scale simulation of ice action from drifting ice sheets on offshore structures. The used methodology is presented including new developments, the implementation in LS-DYNA®, and results from a benchmark study where simulation results are compared with full scale measurements of ice forces.

The methodology is based on using the cohesive element method for modeling the ice fracture in conjunction with an ad hoc homogenization method developed by the authors. The homogenization method is used to capture sub element size cracks in a cost efficient manner.

Introduction and background

Currently structures that 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.

Structures designed for ice loads are also dimensioned using scaled test models. Such physical testing is both time consuming and expensive. There has therefore been an interest in developing alternative methods, such as simulation methods, that can save time and cost. 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].

Continuous crushing of ice sheets against off shore structures

There are several types of ice fracture. The ice fracture mode studied in this article is the so called continuous crushing mode. In this fracture mode the ice breaks and is then crushed into very small fragments, <1cm, during the interaction with the structure. The crushed ice accumulates both below and above the ice sheet, see e.g. Figure 6.

Figure 1a below shows the lighthouse Norströmsgrund situated in the Gulf of Bothnia in a situation where an ice sheet is slowly moving against the light house resulting in a continuous crushing event. The ejected crushed ice is clearly seen on top of the ice sheet in Figure 1a. Figure 1b shows results from measurements of the force from the ice on the light house.

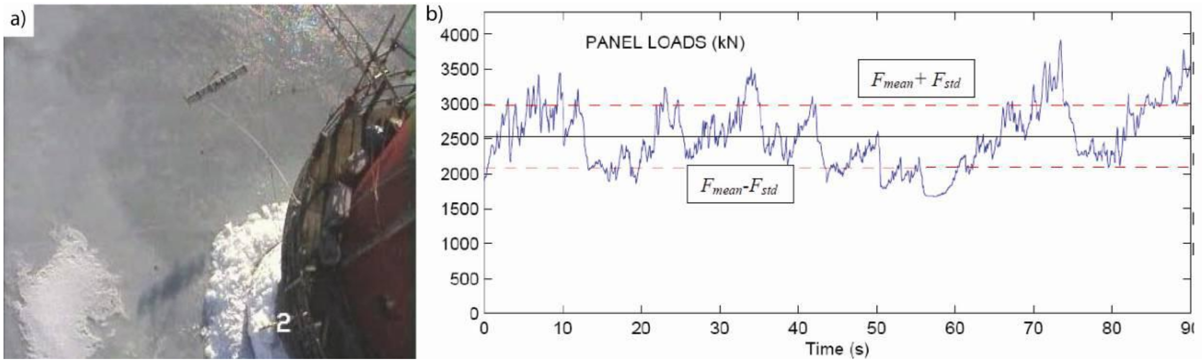

Figure 1: Physical measurements and ice failure at Norströmsgrund lighthouse.

Ice model - Cohesive element method with homogenization (CEMH)

The ice is modeled using the Cohesive Element Method with Homogenization (CEMH). The cohesive element method has a long history, but its application to modeling of ice fracture for complex ice-structure interaction is a recent development that was pioneered by Gürtner [3]. The usage of a cohesive zone model for the pure study of ice fracture was first described by Mulmule and Dempsey [10].

The CEMH as realized in the present article can summarily be described as follows for the special case of a block of ice built up by hexahedral finite element, as shown in Figure 2a below.

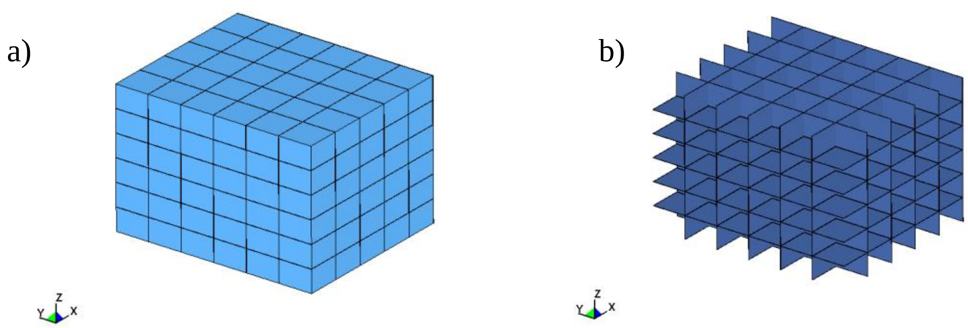

Figure 2: A block of ice built up by elastic hexahedral elements is shown to the left. To the right the cohesive elements that hold together the hexahedral elements in the block are shown.

To capture the cracks that are of a size comparable to the element size or larger, zero-thickness cohesive element are used to connect all the individual finite elements in the block. This grid of cohesive elements is shown in Figure 2b above. When the cohesive element have deformed sufficiently they will fail and be deleted thus forming a crack in the ice. The energy required to the fail the cohesive elements is the fracture energy G. Given a hexahedral mesh, cracks can only propagate in vertical and horizontal directions.

In the continuous crushing mode of ice crushing that is of interest here, the ice is crushed to subcentimetre size particles. The crushing process produces very many cracks and a corresponding large absorption of fracture energy that determines the behaviour of the ice. Given that the objective is to simulate large ice sheets with a volume of >> 100 m^3, is currently not computationally feasible to have a fine enough mesh that would allow the simulation the of crushing of ice to subcentimetre ice particles using the above cohesive element approach. To remedy this issue the homogenization approach was introduced by the authors.

The homogenization approach to be described has the goal to capture the macroscopic effect of the ice crushing without the need to model all small cracks. The idea is that for cracks with a size below the element size only their average effect on the macroscopic level is expressed. This is described in the following.

The first step is to make the following ad hoc assumptions about a representative volume element 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 or, approximately, von Mises yield surface 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 3 is used.

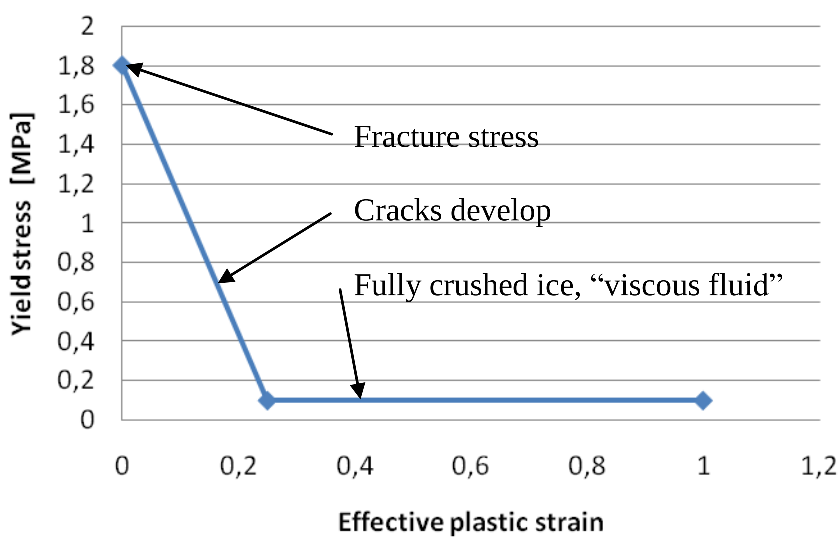

Figure 3: Schematic hardening curve for ice elements with a homogenized crack model.

Ice and water interaction

Including the effect of the interaction between ice and water is important to get a realistic behavior of the flow of ice around the structure. Using an explicit representation of the water, using e.g. CFD, would be the approach closest in adherence to the realistic simulation approach of LS-DYNA. An explicit representation of the water will have the drawback to be quite computationally demanding. Thus in the present study as phenomenological model is used instead where only buoyancy and drag forces are included. The buoyancy model is very important as it allows the ice sheet and crushed ice to float and move realistically around the structure.

The buoyancy module was implemented as a user defined loading in LS-DYNA that applies the buoyant pressure *p* to all wetted surfaces:

$$p = \rho g \max(0, -z)$$

where ρ is the density of the liquid, i.e. water, and g is the gravitational constant.

The drag force on the ice from the water was also implemented as a user defined loading under the assumption that there is a fully turbulent flow. The drag force on an object moving through a liquid at high Reynolds numbers is approximately, according to e.g. Batchelor [4]:

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

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. The main effect of adding the drag force was that ice-cubes that are broken off from the ice sheet and hurdled under the ice moved in a more realistic manner.

Software

Most of the models in the application examples were built using LS-PrePost® with the aid of a custom built software tool that created all the cohesive elements between the individual ice elements. All simulations were run using mpp/LS-DYNA 971 on a high performance compute cluster, Intel Xeon CPUs, with an Infiniband interconnect.

Full scale ice event study - Norströmsgrund ice force measurements

Full scale test data from ice-structure interaction are available from the projects LOLEIF, see Jochmann and Schwarz [4], and STRICE (www.strice.org). Both these projects measured ice-forces on the Norströmsgrund light house in the Gulf of Bothnia. To evaluate the performance and accuracy of the CEMH-method a simulation of a continuous crushing event from these studies was made.

Full scale ice event study – model set up

The set up of the light house simulation with the ice sheet is shown in Figure 4 below.

Table 1:Material parameters used for water and ice

Parameter	Value
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

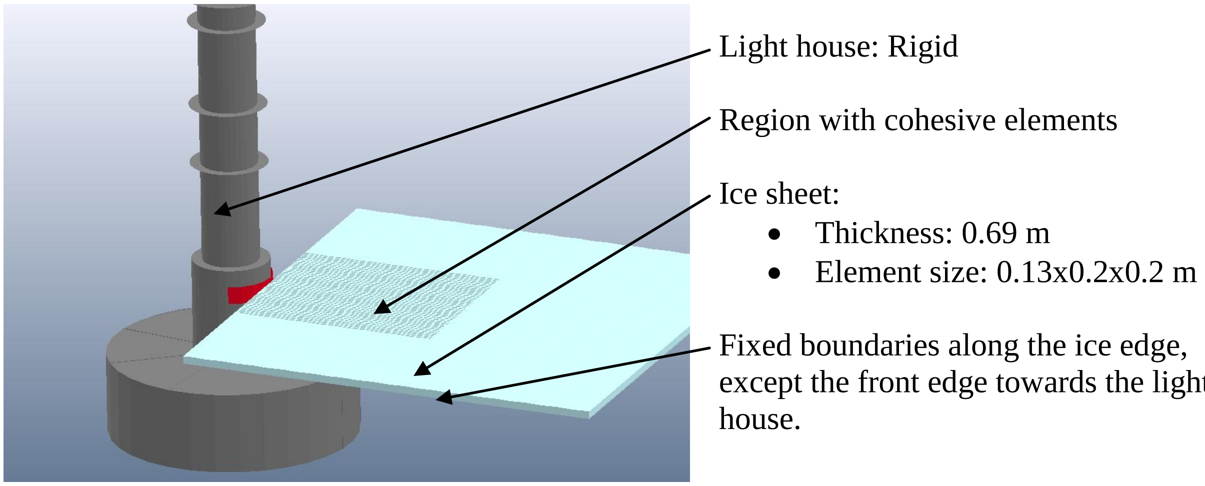

Figure 4. Model with light house and ice sheet. The force measurement panels are shown in red.

Cohesive elements area only used in the region where fracture actually will occur in order to reduce the computational effort, see Figure 4 above. 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 5a, to avoid excessively distorted elements. The traction law for the cohesive elements is shown in Figure 5b.

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

Please note that the values of G_{IC} and G_{IIC} have been raised by a factor of about 100, compared to what is typically observed in measurements of sea ice fracture energy. This was done to prevent premature fracture of the ice.

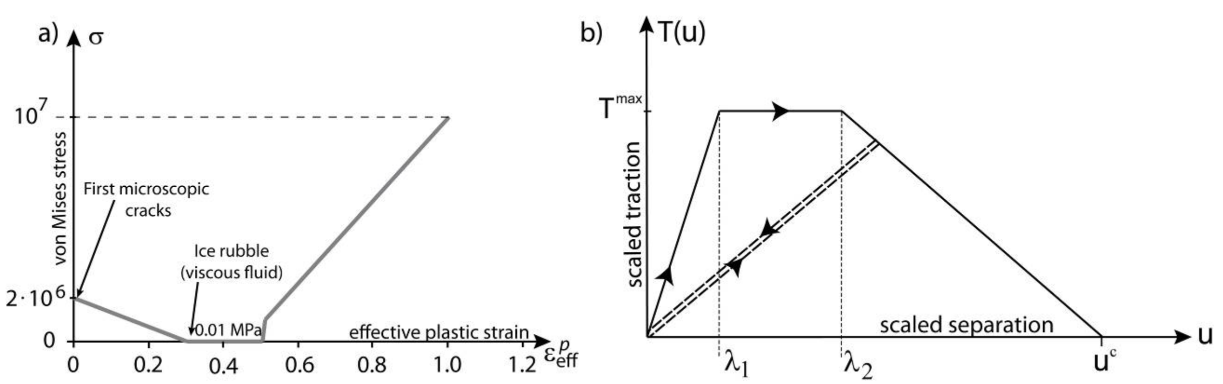

Figure 1: a) Schematic of the yield curve of the ice material, with von Mises stress plotted against effective plastic strain; and b) Non-reversible traction separation law for the ice cohesive elements.

The following contacts were used: *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. Several different *CONTACT_FORCE_TRANS-DUCER_PENALTY are defined to extract the forces on different areas onto the lighthouse for more detailed analyses of the force distribution.

Full scale ice event study – results

In the following a small excerpt of the results from the study is given. The responses of greatest interest in the study were the deformation of the ice sheet, the force level obtained on the light-house, the transportation of material from the crush zone, and the piling of ice in front of the lighthouse.

The wall clock time for simulation of 1 physical second on an 8 core cluster was about 5 to 15 minutes depending of element size and other factors.

The typical deformation and piling up of crushed ice is shown in the figure below.

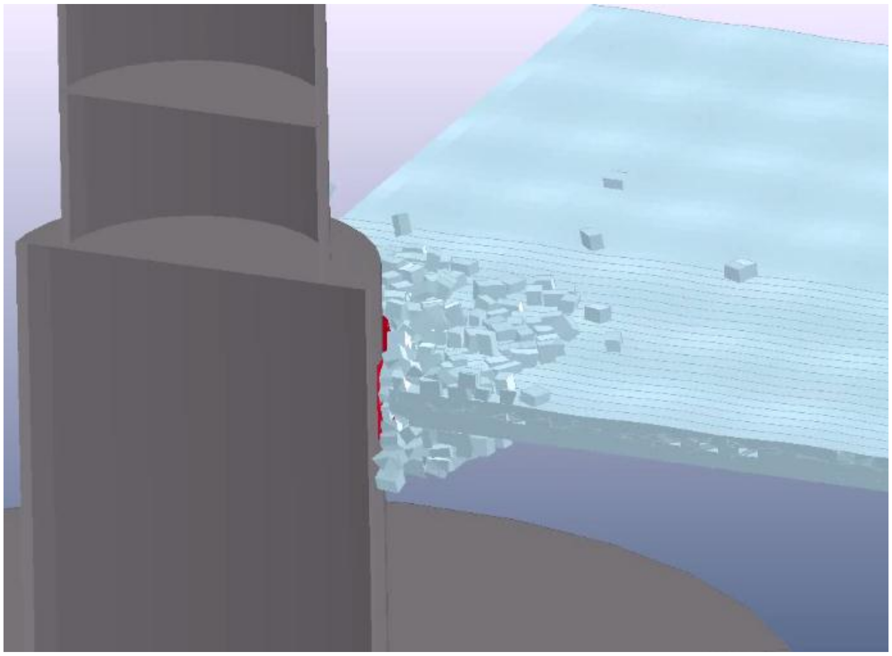

Figure 6: Typical situation in front of lighthouse in the simulation. Crushed ice piles up in front of lighthouse above and beneath the ice sheet. This is similar to what was observed in the field.

Several simulations were made with different mesh sizes and ice sheet sizes. The force levels measured on the lighthouse from three different simulations are shown in the Figure 7 below. Note that the initial peak in the force level was also observed in the field in the situation where the ice initially surrounded the lighthouse with a nearly perfectly contact zone before the ice started to drift. It can be observed that the overall force-time appearance is quite similar a few seconds into the simulation regardless of the starting condition.

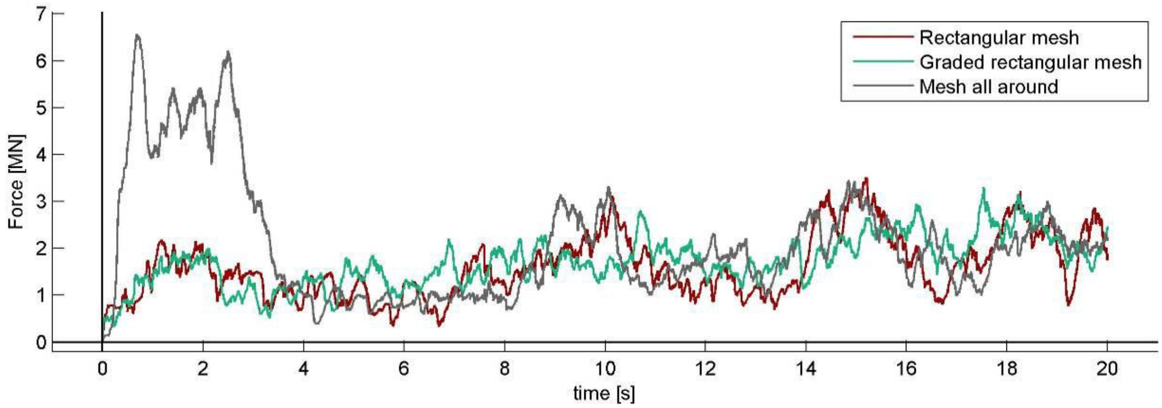

Figure 7: Force levels obtained with different meshes and also one where the ice encloses the lighthouse (mesh all around).

The results from simulation and field measurements should be compared with respect to the average force value. The oscillations found in the simulation results do not correspond to abrupt fundamental physical transitions. Also, the contact behavior between the lighthouse and ice is more fluctuating in the simulation than what was observed in the field. This may be due to a too coarse finite element mesh.

The measured load on the lighthouse is shown in Figure 8. Comparing Figure 7 with Figure 8, it can be seen that the average force level is smaller in the simulations. Hence, there is room for improvement regarding the mesh, material modeling, or choice of material parameters et c.

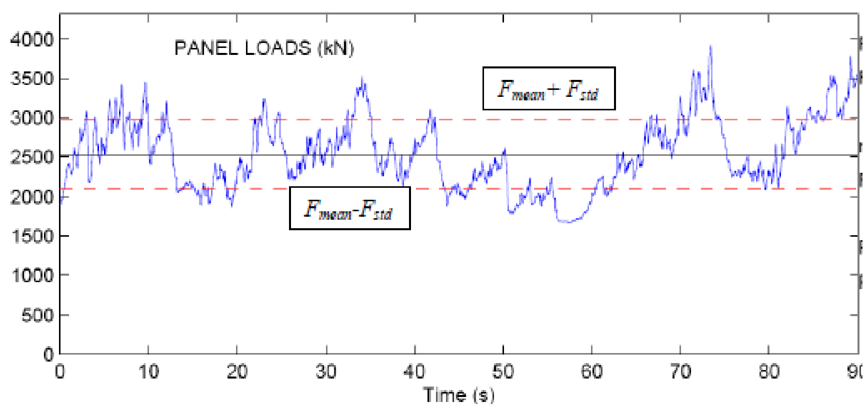

Figure 8: Measured total force applied on the lighthouse during a continuous crushing event.

Conclusion

It is true that the ice model used in the study is slightly coarse and that there is room for improvement of the physical modelling of the ice material. Still, the main goal of the project was reached, which was to show that it is numerically and practically possible to carry out very detailed full scale ice-interaction simulations with plausible results compared to field measurements. This means that, given continued research and that the current performance increase in computers continue, that there can be little doubt that full scale simulation of ice-interaction has the potential to become a useful engineering tool in the not too far future.

Acknowledgement

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References

[1] ISO/FDIS 19906: Petroleum natural gas industries – Arctic offshore structures, ISO TC 67/SC 7 N. International Organization for Standardisation (Draft).

[2] Bjerkås M, Albrektsen A and Gürtner A: "Static and Dynamic Ice Actions in the Light of new Design Codes", Proc. of 29th Int. Conf. on Offshore mechanics and Arctic Engineering, Shanghai, China OMAE2010-20036.

[3] Gürtner A: "Experimental and Numerical Investigations of Ice-Structure Interaction", Doctoral thesis, Norwegian University of Science and Technology, No. 2009:26.

[4] Jochmann P and Schwarz J: "Ice Force Measurement at Lighthouse Norströmsgrund – Winter 1999", Validation of Low Level Ice Forces on Coastal Structures: LOLEIF, Report No.:5, Hamburg, 2000.

[5] Gürtner A, Bjerkås M, Kühnlein W, Jochmann P and Konuk I: "Numerical simulation of ice action to a lighthouse", Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering, 2009.

[6] Konuk I, Gürtner A and Yu S: "A cohesive element framework for dynamic ice-structure interaction problems – Part I: Review and Formulation", Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering, 2009a.

[7] Konuk I, Gürtner A and Yu S: "A cohesive element framework for dynamic ice-structure interaction problems – Part II: Implementation", Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering, 2009b.

[8] Konuk I: "Study of dynamic ice and cylindrical structure interaction by the cohesive element method", The 20th Intl. Conference on Port and Ocean Engineering under Arctic Conditions, June 9-12, 2009 – Luleå, Sweden.

[9] Hallquist J: "LS-DYNA Keyword User's Manual, version 971". Livermore Software Technology Corporation, Livermore, 2007.

[10] Mulmule S V and Dempsey J P, "A Viscoelastic Fictitious Crack Model for the Fracture of Sea Ice" Mechanics of Time-Dependent Materials 1:331-356. Klüwer Academic Publishers, Netherlands, 1998.

[11] Batchelor, G: "An introduction to fluid dynamics", Cambridge University Press, Cambridge, 2000.