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Simulation of ice crushing experiments with cohesive surface methodology

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ABSTRACT

Ice crushing experiments were simulated using cohesive surface methodology. In the simulations possible fracture planes were inserted at all interelement boundaries so that fracture may initiate at arbitrary locations made possible by the discretization. The simulations modelled the experiments of Määttänen et al. (2011). Effects of mesh density, mesh layout and different material softening behaviours were studied. Sequential ice failure process where each failure event affects the next was realistically simulated and simulation results agree with experimental observations. High pressure zone type contact was obtained in the simulations and the simulated crushing forces are in agreement with the experimental results. Mesh density and layout and material softening behaviour affected the simulated failure process progression indicating high sensitivity to analysis initial conditions. The results presented here are one of the few successful simulations of continuous local crushing.

1. Introduction

Failure initiation, propagation and fragmentation of intact ice in ice-structure interaction is a complex process that can include multiple failure modes from crushing to bending. In indentation failure ice can fragment into several big blocks or pulverise locally into fine powder. While small-scale laboratory experiments provide information on ice behaviour and failure modes and strength, *in situ* experiments are needed to verify fracture process. Also the information of ice thickness, salinity, temperature and strength is often not known. However *in situ* experiments are expensive and results are not as easily adapted to other cases. The experimental data is often supported by numerical simulations. By calibrating and validating the simulation models for the experiments the same methods can then be applied in other scenarios with same fracture behaviour.

Still the most widely applied computational framework is finite element analyses. However modelling of ice failure requires advanced simulation tools and material models in order to obtain realistic failure behaviour. Initiation and propagation of multiple cracks that usually occur in case of ice failure leads to material fragmentation or flaking. The subsequent interaction of the rubble must be included in the simulations as it can affect the fracture process. In the finite element framework one popular tool for modelling brittle failure is cohesive methods. The increase of computational capacity has made it possible to model cohesive fracture paths throughout the mesh that allows the fracture to occur at unspecified locations.

In this work the laboratory ice crushing experiments reported by Määttänen et al. (2011) are studied using the cohesive surface methodology. In the experiments medium scale ice blocks were pushed against vertical structure to study the effect of structural flexibility on the crushing pressure distribution. The experiments were modelled numerically to study the applicability of the cohesive surface methodology in ice failure and fragmentation. In addition it was studied whether line-like contact is obtained also in the simulations. The effect of cohesive laws to failure modes and crushing loads was studied as well.

Local pressure data from ice-structure interaction tests have been collected in various fields and laboratory tests. Naturally local pressure data is linked with global ice load. Applying probabilistic approach local pressure data can be used to estimate global ice loads (Bjerkås, 2004; Fransson and Lundqvist, 2006). In this paper local pressure data during ice-structure interaction has been studied using only a relatively thin slice of ice in the width direction.

2. Ice indentation failure

Ice-structure interaction from a mechanical point of view is a complex process where ice can experience multiple failure modes such as creep, ductile fracture and brittle fracture, depending on type of structure, ice properties, ice velocity and other loading conditions. As ice fails it breaks into smaller pieces that either stay in the failure region or clear away. Ice can fragment in a global manner into several big blocks by bending of buckling failure or pulverise locally into fine powder by microcracking or flaking, for example. The local failure process of ice under compression is described here to outline the type of results that should be expected from the crushing simulations of this

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work. The failure is often referred as crushing as the process most notably produces small-grained crushed ice but at least four distinctive failure mechanisms can be identified. They are microcracking, macrocracking with flake explosion, macrocracking with flake progressive failure and rapid cascade of macrocracks. The following chapter summarises the ice crushing mechanisms presented by Daley et al. (1998).

In the microcracking failure mechanism, microcracks initiate and grow in the crushing region until a critical load is reached and microcracks propagate rapidly to form pulverised ice. This mechanism is also called pulverisation. In the macrocracking mechanism with flake explosion flakes that are separated from solid ice first form by macrocracking. The separated flake then rapidly explodes to pulverised ice with a microcracking failure mechanism. In the macrocracking mechanism with flake progressive failure the separated flakes do not explode but fail progressively into smaller particles if they remain in the crushing region after flake separation due to self-contact or contact with structure or solid ice. This continuous failure process where large fragment breaks into smaller fragments is also called comminution. When ice fails with rapid cascade of macrocracks, macrocracks are formed continuously but do not cause flaking that would relieve the stresses in ice. Instead the macrocracking continues in a rapid fashion until ice in the contact region has broken into small particles that flow out. According to Schulson (1990, 1997, 2002) macroscopic splitting along planes parallel to the direction of highest compressive stress occurs when ice is in unconfined state. When confinement is increased macroscopic shear faults at acute angles are also observed.

Daley et al. (1998) conclude that temperature, ice velocity, confinement and contact geometry are important parameters that govern which of the failure mechanisms occur in ice compression. At higher temperatures ice behaves more ductile and microcracking and creep occur. At slow velocities microcracking and creep are dominant mechanisms and at high crushing velocities ice fails by macrocracking and flaking. If the contact surface between ice and structure is flat the process is confined and microcracking will occur first and flaking afterwards when the contact has become irregular. All described failure modes are present with some more dominating than others and mode changes can occur throughout the process. Daley et al. (1998) emphasise that ice failure is a continuous event where each failure event changes the geometry and boundary conditions and affects next failure event. Fig. 1 shows an indentation scenario with all described failure modes occurring.

Laboratory ice crushing experiments have also clarified the type of the ice-structure contact and force time series. The contact between ice and structure is found to be concentrated on either specific areas (hot spots) (Jordaan et al., 2008), or a narrow band, *i.e.* line-like contact (Joensuu and Riska, 1989; Sodhi et al., 1998). The location of the like-like contact or hot spots usually moves as the crushing progresses. The typical force time series observed in the crushing experiments has a saw-tooth nature that arises from the repeating fracture cycles (Jordaan et al., 2008). Magnitude of the force peaks is governed by the force required to break the ice sheet. These characteristics were also present in the results of Määttänen et al. (2011).

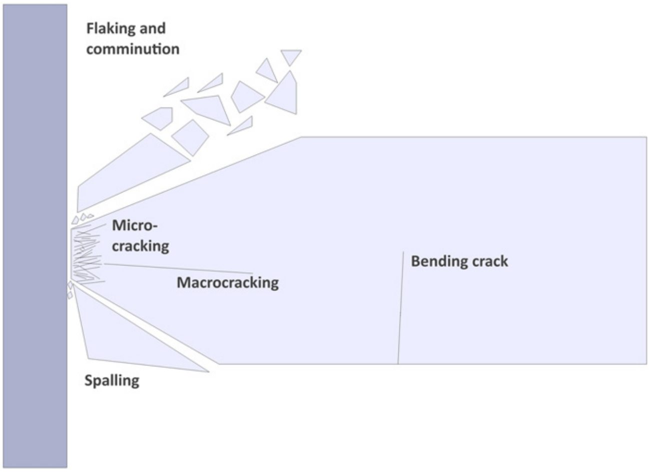

Fig. 1. Ice crushing failure modes.

While experiments provide valuable information on ice behaviour on their own, findings are often utilised in developing numerical models that can be applied to a wider range of applications than just the experimental test setup. A brief discussion on the numerical modelling of failure of ice in indentation is presented next.

3. Modelling of ice crushing and fragmentation

Natural ice is a complex material that exhibits both ductile and brittle behaviours depending on the temperature and the strain rate. Under uniaxial compression natural polycrystalline ice undergoes ductile-to-brittle transition above critical strain rate level (Batto and Schulson, 1993). In brittle regime compressive strength is increased with decreasing grain size. The ductile deformation mechanism is governed by the grain boundary sliding and micro-cracking (Sinha, 1978, 1984). In the brittle regime the wing crack mechanism (*e.g.* Ashby and Hallam, 1986; Schulson, 2001) and interaction and coalescence of wing cracks govern deformation and failure (Batto and Schulson, 1993).

Numbers of constitutive models for ice under ductile and brittle range have been proposed (Ashby and Sammis, 1990; Derradji-Aouat, 2003; Karr and Das, 1983; Kolari, 2007; Nadreau and Michel, 1986; Santaoja, 1988; Schreyer et al., 2006; Xiao and Jordaan, 1996; Zhan et al., 1996). Typical continuum models are not suitable for continuous ice-structure interaction simulation without modifications. The fundamental requirements in the simulation of the ice-structure interaction process are: 1) the modelling material failure initiation, propagation and the orientation of the failure; 2) the modelling of the fragmentation such that new free surfaces are created in the model; 3) modelling the interaction of fragments, structure and the intact ice. The constitutive models are able to fulfil the first requirement. The two other model requirements demand additional techniques. The simplest approach relies on removing the failed elements from the analysis that creates explicit free surfaces and discrete fragments but also violates the conservation of mass and creates empty voids in the model. Removal of solid material can be avoided if crack paths are known beforehand and mesh is designed to coincide with the cracking. This does not however suit cases with severe cracking and fragmentation as crack paths are not known *a-priori*.

If crack trajectory is not known in advance, various numerical techniques have been utilised in literature. One example is the cohesive surface methodology (*e.g.* Camacho and Ortiz, 1996; Tijssens et al., 2000; Xu and Needleman, 1994) where each element in the numerical model is surrounded with cohesive elements that are able to transmit tractions across the interface and fail when sufficient loading is applied. It was found that unstructured meshes provide more realistic results than structured meshes that tend to guide crack propagation along straight paths. Similar observations were made using damage models by Jirásek and Grassl (2008). More recent methods that are able to predict fractures without element removal utilise mathematical techniques to represent the effect of discontinuity within the mesh such as the extended finite element method (XFEM) (Moës and Belytschko, 2002). In these methods the fracture is typically represented as internal degrees of freedom. This makes it more difficult to capture the full failure process due to limitations and difficulties in treatment of multiple interacting and propagating cracks and interaction of broken-off particles.

Although modelling and simulation of ice-structure interaction have been studied for three decades the models have been mainly