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Bonded particle simulation of ice block breakage in ice-to-ice contact compression

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ABSTRACT

In this study we simulate failure of ice blocks in ice-to-ice contact compression using a bonded particle method (BPM) tool HiDEM (Helsinki Discrete Element Model) [1]. Objectives of these simulations are to study the numerical techniques that can be used to simulate compressive failure of quasi-brittle materials and to investigate the mechanics of failure process of ice under compression. Modeling of the compressive failure of quasi-brittle materials is one of the major challenges within computational solid mechanics, which motivates our effort. Prasanna *et al.* [3] experimentally studied ice block breakage under compressive ice-to-ice contact (Figure 1). In the experiments, three 300 mm × 300 mm × 110 mm (length × width × thickness) ice blocks were set to form two ice-to-ice contacts and compressed until the failure of the three-block system. The ice blocks failed predominantly due to a strength of material type shear-band formation (Figure 1a). Here, we setup a material model in HiDEM to to numerically reproduce the laboratory experiments.

In brief, HiDEM models ice as a lattice of dense packed spherical particles connected by Euler-Bernoulli beam elements. Micro-cracks are formed when the beams break, which eventually leads to formation of larger cracks. A beam can break via an intermediate cohesive crack forming at one of the ends of the beam. The cohesive crack dissipates the elastic energy stored in the beams and gradually brings down the internal forces to zero, which replicates material softening during quasi-brittle failure. Contact interaction between spheres is modeled using a Hertzian contact model, where the contact force is proportional to the overlap between spheres. Energy dissipation from the particles is modeled using a viscous damping model. The beam lattice topologies in BPM models have significant bias on the failure paths. Therefore, an anisotropic micro-structure model (AMSM) replicating the grain structure of natural ice was used in

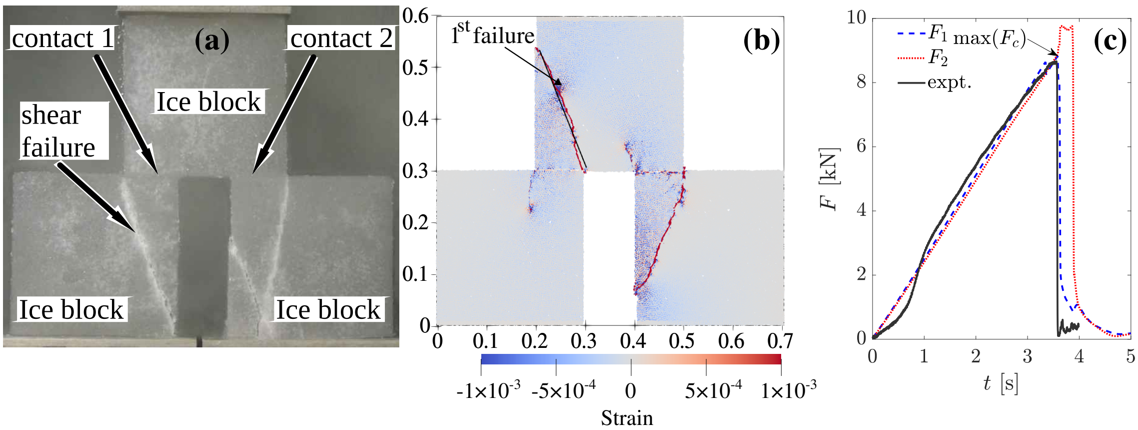

Figure 1: Shear failure of ice blocks in (a) experiment and (b) HiDEM simulation. (c) Force-time curves from simulation compared with experiment.

this work. Naturally grown ice has a vertically aligned columnar grained micro-structure, with the grains aligned parallel to the direction of ice growth. Thus, the AMSM has randomly placed particles in horizontal plane with hexagonal closed packing in the vertical plane [2].

Figure 1b presents the typical shear failure pattern obtained from simulations which agrees well with the experimental observations. Figure 1c presents the representative force-time ($F - t$) curves obtained from simulations compared with experimental records. Here F_1 and F_2 refer to force transmitted by contacts 1 and 2, respectively. Simulated $F - t$ curves follow a similar trend to the experimental curve and the maximum force transmitted by the first contact to fail (max(F_c)) is same in the simulations and the experiments, which gives confidence in our modeling results. In order to understand the underlying mechanics of block failure, we tested the applicability of Mohr-Coulomb failure criterion to predict the failure planes. Stress distribution of ice blocks right before the failure was obtained from HiDEM simulations by computing the Cauchy-stress tensor for the spherical particles. Then we examined the Mohr-Coulomb failure criterion for arbitrary planes using the stress distribution within the ice blocks. The black straight line in Figure 1b shows the failure plane predicted by using Mohr-Coulomb theory. The orientation of the plane agrees well with the failure plane obtained from HiDEM. Thus, it can be concluded that the local shear failure in ice-to-ice contact compression can be modeled simply, yet reliably, by using Mohr-Coulomb failure criterion.

Keywords: Discrete element method, Sea ice, Ice failure.

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