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Cohesive zone micromechanical model for compressive and tensile failure of polycrystalline ice

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ABSTRACT

In this work, a cohesive zone model is applied to model fracture behavior of polycrystalline cylindrical samples under uniaxial loading conditions. The model is based on the implicit finite element method that is combined with Park-Paulino-Roesler formulation for cohesive potential. We implement an adaptive time stepping scheme that takes into account the rate of damage and failure of cohesive zones. Material properties and model parameters have been calibrated using available experimental data for laboratory-made freshwater ice samples. Simulations are performed for samples with different grain sizes, and the resulting stress-strain and damage accumulation curves are recorded. Investigation of the dependency between the grain size and fracture strength shows a strengthening effect that is consistent with experimental results. Fracture patterns observed in simulated failure events are also consistent with observations from experiments.

1. Introduction

Numerical modeling of ice failure is an ongoing research topic where one goal is to predict the failure behavior of naturally occurring ice under various loading conditions while accounting for statistical variability. Design codes presently used for ice-strengthened structures rely largely on methods derived from empirical relations obtained from the analysis of full-scale data (e.g. [1]). New physics-based models of ice failure that link interaction loads with the mechanics of ice failure processes would complement current design load methodology. Computer simulations that capture physical processes that occur during experiments offer the potential to allow study of scenarios not readily accessible to experimentation and to support the interpretation of full-scale ice load data. At the same time, ice is a very challenging material to simulate using numerical modeling due to the complex interplay between continuum and discrete failure processes that occur during ice compressive failure [2,3]. In this work we investigate the stress-strain relationships of ice samples up to the point of failure for uniaxial specimens under compression and tension, as a means to investigate the modeling of accumulating microcracking damage and corresponding macroscopic fractures that ultimately cause specimen failure in unconfined specimens.

Among the various types of naturally occurring ice, glacial ice typically has a granular microstructure and is formed from fresh water (snow) with few impurities. To study the mechanical properties of freshwater ice in the laboratory, test specimens are typically made from equiaxed polycrystalline freshwater ice [4]. It is important to note that during full-scale interactions, while the state of stress is typically triaxial when ice is failing in compression against a structure [5], modeling the uniaxial compressive behavior of ice is an essential first step in the development of a numerical framework that can be expanded upon to account for more complex states of stress. For this reason, in the present work emphasis is placed on modeling failure behavior of ice under uniaxial conditions.

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Nomenclature

E	Young's modulus
$\mathbf{D}$	Rayleigh damping matrix
$\mathbf{M}$	mass matrix
$\mathbf{R}$	rotation matrix of the element
d	penetration distance in collision model
d_i	grain size
$\mathbf{f}_{cz}$	vector of forces from the cohesive zones
$\mathbf{f}_{el}$	vector of elastic forces
$\mathbf{f}_{ext}$	vector of external forces
k	stiffness constant in collision potential
m,n	non-dimensional exponents in PPR model
v_i	grain volume
$\mathbf{u}_n$	nodal displacement vector at time step n
α,β	shape parameters for traction-separation curves
Γ_n,Γ_t	energy constants in PPR model
Δ_n,Δ_t	normal and tangential separations
Δt	initial time step
$\dot{\varepsilon}$	strain rate
λ_n,λ_t	initial slope indicators in PPR model
ν	Poisson's ratio
ρ	density of the material
σ_0	materials constant for the starting stress for dislocation movement
σ_{max},τ_{max}	normal and tangential cohesive strengths
σ_y	yield stress
ϕ_n,ϕ_t	normal and tangential fracture energies
Ψ	potential
$\langle\cdot\rangle$	Macaulay bracket $\langle x\rangle = \begin{cases} 0 & x < 0, \\ x & x \geqslant 0. \end{cases}$

Triaxial ice failure behavior will be considered in future work.

For validation purposes, measurements of uniaxial ice compressive strength are readily available and new experiments can be carried out using a standard materials testing apparatus placed in a sub-zero environmental chamber. From such experiments on polycrystalline ice samples, it is evident that repeat measurements will vary due to natural variability of the material, such as different sizes and arrangements of grains [6]. However, average trends in the strength behavior do indicate that grain size, temperature, and strain rate have significant influence on the measured compressive strength, making it possible to estimate the average uniaxial failure stress from material properties and loading conditions [5,7].

Usually, models apply established techniques with various modifications to focus on certain aspects of ice behavior. For example, polycrystalline samples can be viewed as solids comprised of grains with accumulated microscopic damage. Such a concept is based on experimental observations of ice damage [8,9]. The finite element technique (FE) is well-suited for modeling deformable solids, where the number of interacting fragments is limited. With regard to ice, this technique is suitable for processes that lead to moderate fragmentation, where individual pieces remain solid, but are not pulverized into fine crushed particles. In cases where geometries of individual grains are not important, or where extreme crushing or distortion has taken place in sub domains of the larger region of interest, particle-based or meshless methods can be more computationally efficient. The current work focuses on fractures that originate between individual grains since grain boundaries are known to produce local stress concentrations in polycrystalline ice (e.g. [10]) and hence their precise shapes are kept as tetrahedral meshes and the finite element method is used.

A micromechanical model explicitly tracks microscopic damage associated with microcracking and local deformation for given macroscopic load states. It is a direct mathematical description of the underlying physical processes based on continuum mechanics. In the context of ice fracture, the applicability of this model is limited to certain types of behavior and a given range of parameters associated with brittle fracture. Future expansion of the model is planned to incorporate failure phenomena associated with other states of stress and more complex loading conditions.

In this paper, individual grains are treated as linear elastic solids within a FE framework, with an intrinsic zone (CZ) model used to represent the fracture mechanism. More complex microscopic damage is modeled through degradation and eventual breakdown of cohesive zones. Strictly speaking, ice is a viscoelastic material [7,11], but for small deformations and sufficiently high strain rates undamaged polycrystalline ice can be treated as a linear solid. A collision response scheme is applied to prevent the separated fragments from interpenetrating after the fracture occurs. Ice behavior is limited primarily to brittle fracture at temperatures below $-10\,^{\circ}$C and strain rates between 10^{-3} and $10^{-1}\,\mathrm{s}^{-1}$, where viscous flow may be assumed to be negligible for unconfined specimens [5]. Simulation results are compared with uniaxial tests on small-scale laboratory samples.

1.1. Related work

Micromechanical models apply to heterogeneous materials, such as composites and polycrystals by resolving the individual constituents of the material. Premachandran and Horii [12] proposed a finite element micromechanics-based model that is applicable only for a limited range of deformation rates, where creeping and microcracking are the only dominant mechanisms of deformation. Their model predicts crack density and stress-strain curves for a two-dimensional indentation of an ice sheet.

In more recent studies by Taylor and Jordaan [13] and Moore et al. [14], which builds on previous work of Jordaan and coworkers [15–18] the accumulated damage is a parameter that is recorded per element in a finite element model, which affects the viscoelastic properties of the material. Calculations are performed in ABAQUS with an explicit integration scheme. In this model, individual fractures are not explicitly modeled, but rather the effects of discrete microcracking events on the "smoothed" continuum response is governed by modeled damage parameters. This approach focuses on constitutive behavior covering a wide range of confinement conditions that may be present during an ice-structure interaction, but these aspects are beyond the scope of the present work. Ejection of the material, which is often observed experimentally, is handled via removal of damaged elements from the simulation once the damage reaches a certain threshold.