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A TENSILE FRACTURE MODEL FOR ICE

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ABSTRACT

The fracture of ice under tensile loading is characterized in terms of the stress versus separation behavior in the process zone. This process zone characterization can be used in numerical simulations based on discrete crack models. The stress-separation model is then integrated with a rate-sensitive tensile stress-strain-strength model to account for strain-softening at the continuum scale. The resulting constitutive theory can be applied, in conjunction with an objective energy criterion proposed here, to simulate localized fracture processes based on the blunt crack band theory. Quantitative estimates of the fracture process zone size are obtained to assess the validity of toughness measurements based on linear elastic fracture mechanics (LEFM).

INTRODUCTION

In most real world applications involving ice either as a load bearing medium or as a load transmitting medium, the strength of ice is limited by fracture. Investigations on the fracture behavior of ice have been relatively few in comparison to the work on its continuum behavior. They include the works of Gold (1), Goetze (2), Goodman (3-5), Hamza and Muggeridge (6,7), Urabe et al. (8-10), Timco and Frederking (11,12), and Schulson and Nixon (13,14). Mellor (15) has reviewed much of this research. The general emphasis of past work has been to characterize the mode I fracture behavior of both pure and sea ice in terms of the linear elastic fracture toughness parameter, K_{Ic}, through a sequence of tests conducted under varying rates of loading and varying temperature. Since for rates of loading greater than about 10 KPa $m^{1/2}$ and temperatures below about -10°C the fracture toughness parameter K_{Ic} tends to become insensitive to rate and temperature, it is believed that LEFM applies under such conditions. Theoretical support for the loading rate criterion has been proposed by Urabe et al. (9) based on Riedel and Rice's (16) analytical study of tensile cracks in creeping solids which assumes that elastic strains dominate almost everywhere in the specimen except in a small "creep zone", which grows around the crack tip. The analysis models ice as an elastic, power law material and considers the fracture "process zone" to be of negligible size within the creep zone.

This paper is motivated by the following three concerns:

1. Numerical models for simulating fracture processes during ice-structure interaction may be developed on the basis of two distinct theories. The first theory leads to discrete crack models (17-20) which assume that all cracking activity is localized on a plane. The second theory leads to smeared or blunt crack models (21-24) which assume that cracking activity is distributed over a characteristic width representing a material property. Constitutive models describing fracture of ice under tensile loading suitable for use with either of the two numerical approaches are lacking at the present time.

2. In many practical applications, fracture in ice is accompanied by significant nonlinear viscoelastic deformations. For example, in the Arctic nearshore zone viscoelastic deformations accumulate during the winter months prior to "breakout" which occurs in early spring as a result of crack nucleation and propagation. The associated states of stress and strain in the ice tend to be multiaxial, the strains typically being tension-compression in the region where cracks nucleate (25,26). This precludes the use of LEFM-based fracture toughness parameters.