On The Flow and Fracture of Sea Ice: The Transition from an Anisotropic Continuum to a Granular Medium

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LONG-TERM GOALS

The long-term goals of this research are (i) to better understand the mechanisms underlying the inelastic deformation of sea ice, with the aim of improving sea ice models, and (ii) to understand the deformation of sea ice within the larger context of the flow and fracture of brittle materials in general.

OBJECTIVES

The principal scientific objectives of this work are (i) to understand the transition from continuum-like brittle compressive failure which characterizes intact ice to granular-like sliding along sliplines/shear faults which characterizes the deformation of interacting ice floes, and (ii) to formulate the sliding criterion in terms of a physically-based failure mechanism.

APPROACH

We are taking a combined experimental and analytical approach. Experiments are being performed by a graduate research assistant, Erik Russell, under the PI's guidance. Analysis is being performed by the research assistant and the PI. The working hypothesis that sliding commences when Coulomb's criterion is satisfied; viz. when

$$\tau = \tau_0 + \mu \, \sigma_n$$

where τ and σ are the shear stress and normal stress acting along and across the sliding (i.e., fault) plane, respectively, τ_0 is a measure of cohesion along the fault plane, and μ is a friction coefficient. The experiments are being performed on specimens $150 \times 150 \times 25$ mm (along the columns) of S2 ice which is grown in the laboratory and then biaxially compressed across the columnar-shaped grains under proportional loading using a true multiaxial press. Two variables being explored, loading path (i.e., ratio of normal to shear stress) and sliding speed. The material simulates the kind of ice from which first-year sea ice covers are made, and the loading simulates wind-induced biaxial stress states. Shear faults are introduced into test specimens by deforming virgin material to terminal failure under moderate confining stresses. Subsequently, deformation continues by sliding across the fault. Measurements are being made of the sliding stresses.

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WORK COMPLETED

Two complete sets of data have been obtained at one temperature, -10°C, and the results have been analyzed.

RESULTS

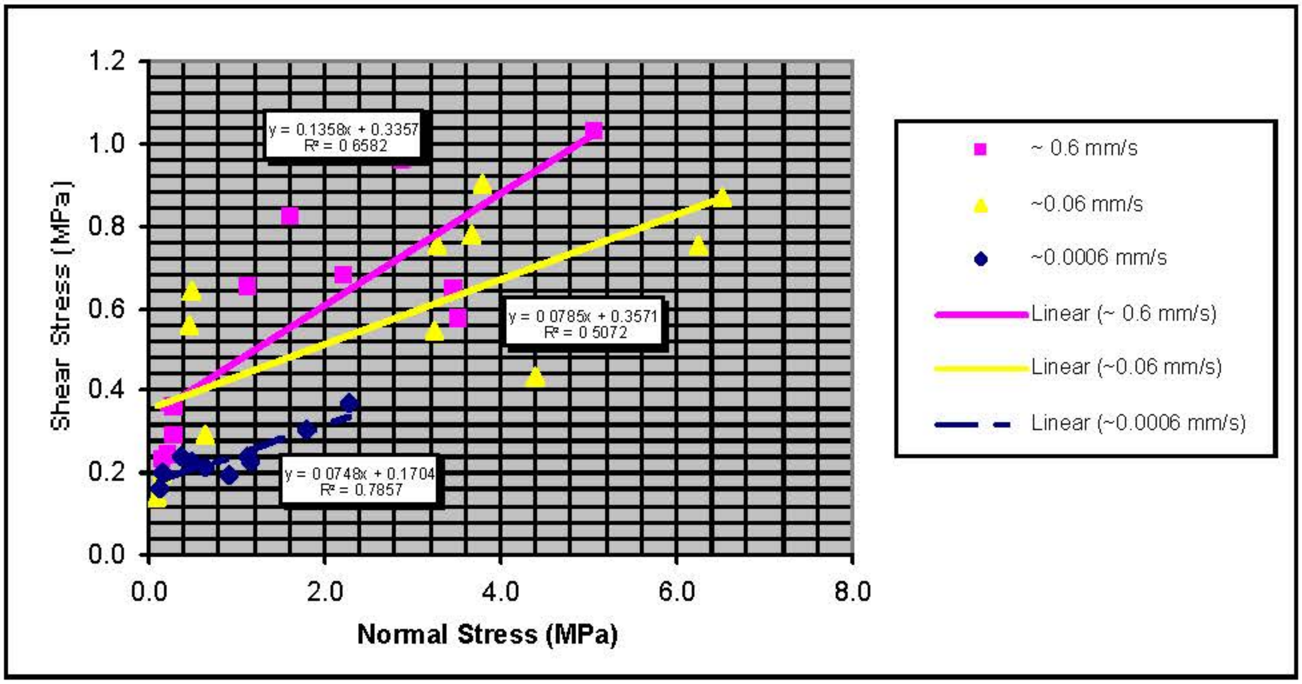

Figure 1. *Graph of shear stress vs normal stress across sliding shear faults in S2 ice at –10 °C*

Figure 1 shows the shear stress versus the normal stress applied across natural faults, for three sliding velocities, 0.6 mm/s, 0.06 mm/s and 0.0006 mm/s. Although scattered, the data reveal several points:

(i) To a first approximation, the shear stress is directly proportional to the normal stress, in accord with Coulomb's criterion.

(ii) The sliding friction coefficient, μ, at the two lower sliding speeds is ~0.07-0.08. The coefficient increases to ~0.14 at the highest speed. Correspondingly, the ice exhibited ductile-like behavior at the two slower speeds and brittle-like behavior at the highest speed. In this scenario, ductile means no crumbling or loss of material from the fault during sliding. Brittle means significant material loss.

(iii) The cohesion, τ_0, across the fault increases with sliding speed within the "ductile regime", from ~0.2 MPa at the slowest speed to~0.35 MPa at the higher speed. Within the "brittle regime", the cohesion is ~0.35 MPa. Curiously, this kind of transition from rate-sensitive to rate-insensitive flow also characterizes the bulk compressive behavior of ice and the transition there from ductile to brittle behavior.

IMPACT/APPLICATIONS

These are the first results of this kind ever generated from ice. We will now begin to consider whether they make any sense in relation to sliding of sea ice floes against each.

TRANSITIONS

The results of the study are currently being written up for dissemination to the "PIPS 3.0" modeling community and to others.

RELATED PROJECTS

Currently in progress (31-03-00 to 30-03-02) is a study entitled, "Arctic Sea Ice Stress Array" (by Overland, Richter-Menge and Schulson, Grant no. N00014-00-1-0402). The present project will input laboratory observations to the field observations, in hopes of better understanding the latter.

PUBLICATIONS

Schulson, E.M. and Renshaw, C.E., "Universal Behavior in Compressive Failure of Brittle Materials", *Natur*e, vol.412, 897-900, 2001

Schulson, E.M. "Brittle Failure of Ice", *Eng. Fracture Mech.* (in press)

Schulson, E.M., "Fracture of Ice", *Eng. Fracture Mech.* (in press)

Schulson, E.M., "Fracture of Ice on Scales Large and Small", Proc. IUTAM Symposium on Scaling Laws in Sea Ice Mechanics, Fairbanks, AK, June 2000 (in press)

Schulson, E.M., "On Compressive Shear Faulting in Ice: Coulombic vs Plastic Faults", submitted to *Philosophical Magazine A*

Schulson, E.M., "On the Origin of a Wedge-Crack within the Icy Crust of Europa", submitted to *J. Geophysical Research.*