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Effect of Confining Stress on Brittle Indentation Failure of Columnar Ice

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ABSTRACT

The effect on the brittle indentation failure of confining stress applied transverse to the direction of edge-indentation of plates of S2 columnar fresh-water ice at -10°C was investigated. Indentation was performed at rates comparable to strain rates of $\dot{\varepsilon} = 10^{-3}\ s^{-1}$ and $\dot{\varepsilon} = 10^{-1}\ s^{-1}$. The confining stress had an effect similar to that observed by Smith and Schulson (1992) for uniform biaxial stresses; namely, confining stress suppresses the process of shear-faulting in the loading plane, and eventually activates a cross-columnar failure mode out of the loading plane that limits the indentation resistance of the ice. The indentation strength increases linearly with increasing confining stress in the regime of low confinement, but is unaffected by further confinement once the out-of-plane failure mode is activated. Direct observations of damage show that failure initiates within grains about 2 indenter half-widths into the ice.

INTRODUCTION

The action of a rigid structure on the edge of a moving ice-plate can be separated into two domains: transient indentation associated with initial failure; and the continuous penetration that follows this initial stage (Timco, 1986). Experimental ice basin studies covering both domains reveal that the highest loads on the indenter are commonly associated with the transient indentation domain (Sodhi, 1990; Michel and Blanchet, 1983; Sodhi and Nakazawa, 1988), indicating that under conditions of contact across the entire width of the indenter the initial impact sets the design load for structures operating in ice-infested waters. The penetration domain normally results in lower global loads, but often causes dynamic excitation of structures which can result in significant vibrations (Sodhi, 1988; Kärnä and Turunen, 1989).

When the ice-plate thickness is comparable to the width of the indenter, indentation failure is highly localized in front of the indenter, and the highest indenter loads are observed (Timco, 1986; Michel and Blanchet, 1983). This domain can be studied using laboratory-size samples indented in a loading frame (Frederking and Gold, 1975; Michel and Toussaint, 1977). The penetration domain is better studied using scale models in ice-test basins (Timco, 1986; Michel and Blanchet, 1983; Sodhi and Nakazawa, 1988) where the larger size of the apparatus permits the time-dependent variations in the penetration pressure to be examined. The penetration behavior is related to transient indentation because similar microstructural failure processes are likely to be effective in both domains, although in the latter domain the indenter acts upon rather heavily damaged material.

The studies mentioned above cover a broad spectrum of indentation rates, spanning both the ductile (low rate) and the brittle (high rate) regimes of behavior. The latter regime is less well studied, however, and it is for this reason that brittle failure is the focus here. The emphasis is on the transient indentation failure and on the effect of confinement on the failure pressure of plates of S2 columnar ice loaded perpendicular to the long axis of the columns.

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KEY WORDS: Columnar ice, brittle indentation failure, stress.

To our knowledge, this study is the first systematic investigation of the role of confinement on the indentation failure of this material.

EXPERIMENTAL PROCEDURE

The experiments were performed at -10°C in the cold rooms of the Ice Research Laboratory at Thayer School of Engineering. The indentation tests were conducted with the multiaxial testing system (MATS) located in the laboratory. The MATS is a servo-hydraulic, true triaxial testing system, capable of loading test specimens independently along the three major cartesian axes through three sets of opposing actuators.

Selection of Indenter

The indentation failure modes which are active in ice vary with aspect ratio, 2b/h, where 2b is the indenter width and h is plate thickness (Timco, 1986: Michel and Blanchet, 1983). For the higher aspect ratios (2b/h $\gtrsim$ 5) failure is influenced primarily by processes such as buckling which are not directly related to the micromechanical properties of the ice, although crushing can still occur at high indenter speeds (Sodhi, 1983). For aspect ratios $\lesssim$ 5 the ice is stable enough against buckling to allow observation and analysis of the microstructural damage, although some variation in failure mode is still observed (Timco, 1986; Michel and Blanchet, 1983). An aspect ratio of unity was therefore selected.

The MATS places certain limits on the size of the samples. The dimensions of the plates were thus chosen to be $203 \times 152 \times 38\ mm^3$. Specimens of this geometry and size will fail before they buckle. An indenter that is 38 mm wide spans at least 7 grains (grain size 2.5-6 mm, see below) and thus avoids the "size effect" that has been suggested by Michel and Toussaint (1977), who observed that indentation failure pressure is constant when the indenter width is more than 7 grain diameters, but increases when the indenter width is less than 7 grain diameters.

The indenter was manufactured from an extruded aluminum bar about 39 mm on edge. The faces were milled and then carefully polished with 440 grit metallurgical paper. Another indenter, geometrically identical and of the same material, was also prepared, but the surface was sandblasted to permit an assessment of the importance of surface roughness. To reduce the magnitude of the stress concentrations at the indenter edges (Johnson, 1985; Gdoutos and Theocaris, 1975; Miniatt et al., 1990), they were