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# A study of the effect of contact surface geometry and crushing rate on the behavior of the ice

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ABSTRACT

The crushing behavior of ice can be classified into three regimes as ductile, ductile-to-brittle and brittle behavior, and the most significant factor in characterizing between brittle and ductile modes is strain rate. The magnitude of ice load is highly influenced by the ice behavior, but the behavior and resulting ice loads are dependent on the shape of the indenter. The ice behavior transitions in accordance with structural shape were assessed in this study using cylindrical ice specimens crushed against flat and wedge-shaped indenters at three different angles. In addition, the effect of crushing rate is also examined for the different indenter shapes. The indenter shape influenced the failure process of the ice, and this led to changes of the ice behavior as well as the magnitude of ice loads. However, the rate dependent failure regimes, ductile, transition and brittle remained effectively the same.

## 1. Introduction

Based on extensive existing literature, the crushing failure/deformation behavior of ice can be classified into three regimes: ductile, ductile-to-brittle (intermediate) and brittle behavior. This is based significantly on ice crushing tests on cylindrical samples and more recently on work using conical sample (Dillenburg, 2012). Other work has shown that ice crushing loads are also dependent on the shape of the indenter (Kim, 2014; Kim and Daley, 2013, 2014). The current work was recently completed to determine if structural shape has a significant effect on the effective ice load. In these cases it was shown that indenters that tend to confine the ice during crushing lead to differences in failure pattern and generally higher loads. The work detailed in this paper extends the work on indenter shape to determine if the same ductile through brittle behavior is exhibited for differing indenter shapes and to determine if indenter shape alters the rate dependent regime transitions.

The factors affecting the behavior of ice have been evaluated by many researchers (Sanderson, 1988; Cole, 1987; Jordaan, 2001; Jones, 1982; Gagnon, 1999; Renshaw and Schulson, 2001; Schulson, 1990, 1997, 1999, 2001, 2002; Sodhi, 1998, 2001, 2006) and the most important factor in differentiating between brittle and ductile behavior is strain rate. If the strain rate is less than $10^{-7}$ 1/s, the ice presents a ductile behavior and the trend of load increment is almost linear as displacement increases. If the strain rates are between $10^{-7}$ 1/s and $10^{-3}$ 1/s, the behavior of the ice is in the ‘intermediate’ region, where ductile and brittle behaviors coexist. If the strain rate is larger than $10^{-3}$ 1/s, the behavior of the ice is brittle and instantaneous load decreases are frequently observed, in a pattern of load often called a sawtooth pattern.

As mentioned earlier, the most significant factor in characterizing the failure regime of ice is the strain rate. Dillenburg (2012) crushed a cylindrical-shaped ice specimen with a flat and rigid indenter and analyzed its behavior. Kim (2014) and Kim and Daley (2013, 2014) also conducted a compressive ice crushing test using a cylindrical-shaped ice specimen in a concave-shaped indenter, specifically a wedge-shaped rigid indenter, using a diverse crushing rate. In this study, changes in the behavior of the ice according to the structural shape (contact surface shape) and crushing rate are assessed through the evaluation of the comparison results obtained in the two studies.

## 2. The behavior of the ice

A sufficient understanding of the behavior of ice experiencing a uniaxial compressive load has been made by Schulson (1990, 1997, 1999, 2002) and other researchers. The most significant factor in categorizing the three typical types of the behavior of ice: ductile, ductile-to-brittle (intermediate) and brittle behavior, is the strain rate, among other less influential factors such as temperature, grain size, etc. Fig. 1 shows stress-strain curves for each individual definition of the behavior of the ice. In the case of ductile behavior, the stress-axial strain curve indicates that the stress gradually increases linearly due to

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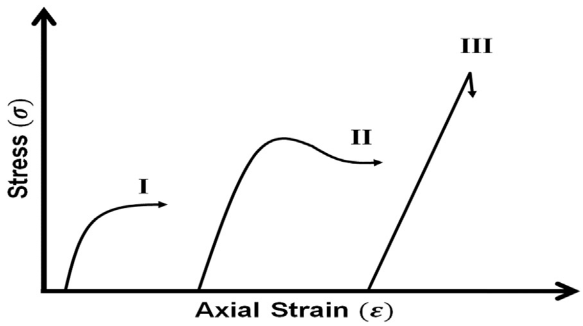


**Fig. 1.** Schematic stress-strain curves in compression for low (I), intermediate (II), and high (III) strain rates (reproduced, Schulson, 1999).

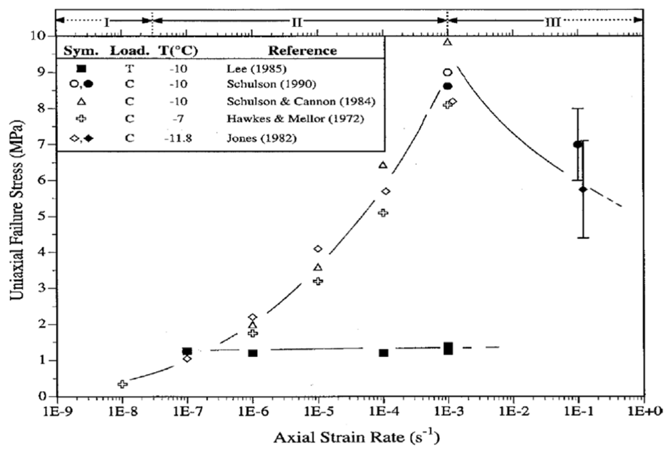


**Fig. 2.** Tensile and compressive strengths of equiaxed and randomly oriented freshwater ice of about 1 mm grain size vs. strain rate (Schulson, 1999).

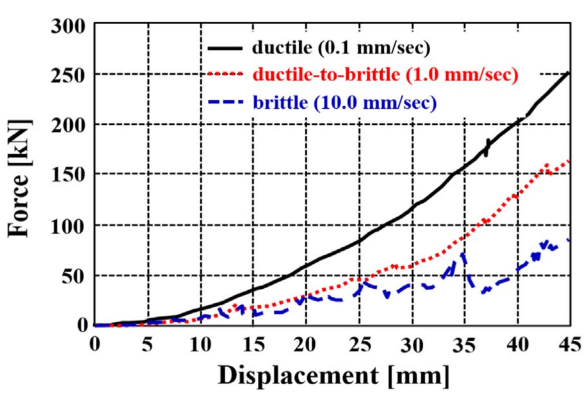


**Fig. 3.** Example force-displacement curve for three different ice crushing rates representing ductile (black), ductile-to-brittle (red) and brittle behavior (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

axial strain increase and converge as a plateau shape afterward. If the ice shows ductile behavior, there is almost no cracking of the material itself; however, strain hardening and thermal softening are the main characteristics of the ice behavior. On the other hand, a sharp load increment in a very short period of time as linear as well as a sudden load drop by the spalling event are observed if the ice exhibits brittle behavior. These features are caused by the occurrence of nucleation and fine cracks in the material during an interaction. The ductile-to-brittle (intermediate) region can be defined where a mixture of the features of the ductile and brittle behavior coexist.

Ice is in the ductile region if the strain rate is $\dot{\varepsilon}=10^{-7}1/s$ or below, and the ice represents brittle behavior if the strain rate is $\dot{\varepsilon}=10^{-3}1/s$ or above. In addition, the behavior of the ice will be able to be represented as intermediate when the strain rate value is between the two ranges (Cole, 1987; Schulson, 1990, 1997, 1999). More detailed information about the behavior of the ice according to the strain rate can be found in the literature referred to in this study (Fig. 2).

Dillenburg (2012) performed multiple compressive tests on a specimen of cone-shaped ice on a laboratory scale for a range of crushing rates (0.01–100 mm/sec) to evaluate the crushing rate dependency. The individual behaviors of the ice specimens depend on each crushing rate and these were analyzed and characterized followed by the force-displacement curves. As shown in Fig. 3, the ice load tends to increase almost linearly as the displacement increases when the crushing rate is 0.1 mm/sec (black solid line). This is a ductile deformation. If the crushing rate is increased to 10 mm/sec (blue solid line) the brittle behavior can be clearly seen in Fig. 3. The ice is less resistant to the applied displacement when the crushing rate is relatively high and multiple sawtooth patterns are repeated as frequent spalling events dominate the ice failure behavior. This is the major indication of brittle behavior of the ice. In the case of a 1.0 mm/sec crushing rate (red solid line), the ice load proportionally increases in a specific period (ductile behavior) but the instantaneous load reduction (brittle behavior) is also observed at the same time. This is the case where the characteristics of two combined behaviors, ductile and brittle, occur in combination.

In this study, the behavior of the ice under certain conditions was distinguished by the observation of the force-displacement curve based on the previous test results.

## 3. Test setups

### 3.1. Ice specimen preparation

Ice can be defined as the "solid state of water" in the aspect of phase in the material view. Diverse crystalline structures can exist in ice; however, only 'Ih' type ice, which the oxygen atoms of water arranged in the hexagonal structure, can exist in nature and all other types of ice can only be created by artificial treatment (Sanderson, 1988).

To conduct a series of test using a laboratory-grown ice specimen, it is essential to control certain ice properties (i.e. grain size, ice strength, etc.) to insure reasonably repeatable tests. The ice specimen preparation procedure applied in this study was developed by Bruneau et al. (2011, 2013), and this confirmed that the characteristics of ice specimens are sufficiently uniform. The direction of ice growth can be controlled by the method of insulating the mold in which the ice specimen is grown (Dillenburg, 2012; Kim, 2014). In addition, the water was distilled, de-ionized and deaerated (cooled to zero degree prior to use) as an extra effort to minimize air bubble inclusion in the ice specimen during preparation. A polycrystalline fresh water ice specimen can thus be obtained from this preparation procedure. The ice specimens being produced from the same material and method is advantageous because 1) the quality of the ice specimen can be managed more consistently and 2) the repeatability of the test can be better secured with similar quality samples.

### 3.2. Test data measurement

As part of this research, tests were performed in a cold room facility at a temperature of −10 °C. Force and displacement of crushing depth (penetration depth) at each test are automatically logged through a MTS Linear Variable Displacement Transducer (LVDT) and load cell and data was saved in text file format (Fig. 4). Video records were also taken for some test cases.

### 3.3. Test conditions

Dillenburg (2012) carried out the two compressive ice crushing tests using a cylindrical ice specimen at a rate of 1 mm/sec on a flat-rigid indenter. Tests were carried out at −5 °C and −10 °C temperature