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Ice Crushing and Cyclic Loading in Compression

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Abstract

At very slow loading rates, ice will creep; as the rate is increased, microstructural changes occur and the rate of creep is enhanced as a result. These microstructural changes are referred to as "damage". As the rate of loading is increased further, the damage becomes localized into a layer adjacent to the indentor. This layer is associated with "high-pressure zones" (*hpz*'s). A bulb of pressure develops over these zones with values up to 100 MPa at the centre. Processes within the layer vary with distance from the centre; microfracturing and recrystallization occur near the outside with recrystallization and pressure melting (it is supposed) along grain boundaries in the central part. Cyclic loading can result since the cycle of pressure softening and subsequent hardening upon release of the pressure results in a repetitive cycle. An analysis has been performed using the ABAQUS computer program that encapsulates the principal features of the process. Some results of this analysis are given. It is also shown that the mechanics can be scaled geometrically without any basic change. This explains why the *hpz*'s are found over widely differing scales. Laboratory and field data involving cyclic loading, including Molikpaq and medium scale data, are reviewed and discussed in the context of feedback mechanisms and ice-induced vibration. Finally, data and results from impact tests on other materials, as well as dynamic recrystallization at high speeds are reviewed and discussed in the context of ice compressive failure.

Introduction

The word "crushing" as applied to compressive failure in ice obscures a rather complex process. The failure of ice in compression is a rate dependent process. At very slow loading rates, ice will creep; as the rate is increased, microstructural changes occur and the rate of creep is enhanced as a result. These microstructural changes are referred to as "damage". As the rate of loading is increased further, the damage becomes localized into a layer adjacent to the indentor. This layer is associated with "high-pressure zones" (*hpz*'s). Pressures within the center of these zones can reach values of up to 100 MPa. This means that most of the load transmitted to a structure during an interaction occurs through these areas of localized high pressure. The *hpz's* vary in both intensity and location with time. Their spatial distribution is highly dependent upon the geometry of the contact zone (Figure 3). During an interaction, localized spalls occur close to the edges of the contact zone leaving a fracture plane that is in limited contact with the structure. In the case of a narrow ice sheet, this causes the *hpz*'s to become concentrated in the center of the ice sheet and produces a 'line load'. Across a large interaction area, these zones are distributed throughout the contact zone, which now covers a much larger area. In this case, the distribution of the *hpz*'s can be considered to be random as opposed to the 'line loads' found in ice sheets. The formation and evolution of *hpz's* can be directly linked to crushing failure during an interaction.

Cyclic loading can occur as the result of extended periods of crushing failure. These vibrations are important in design. As an example, ice-induced vibrations were experienced by the Molikpaq during a crushing event on April 12, 1986. In this case, the cyclic loading experienced by the structure was found to have been significant enough to cause partial liquefaction of the core of the structure (Hardy et al., 1998). Load cycling behavior is not limited to full-scale interactions. Vibrations and crushing have been observed both in small-scale laboratory experiments as well as in medium-scale field trials as shown in Figures 2 and 3. Figure 2 shows photographs of crushing events that were observed at three scales of interaction. Figure 3 shows load cycling behavior that was observed at three scales of interaction.

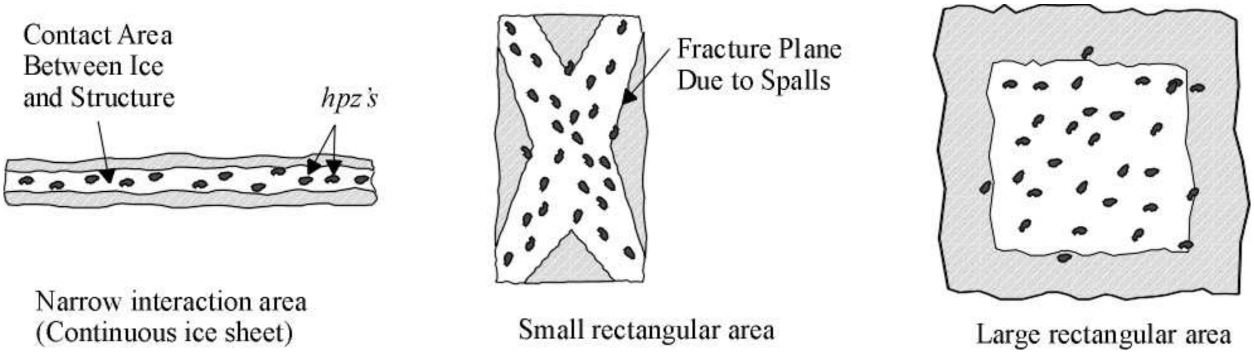

Figure 1. Schematic representation of distributions of *hpz's* for different contact zone geometries.

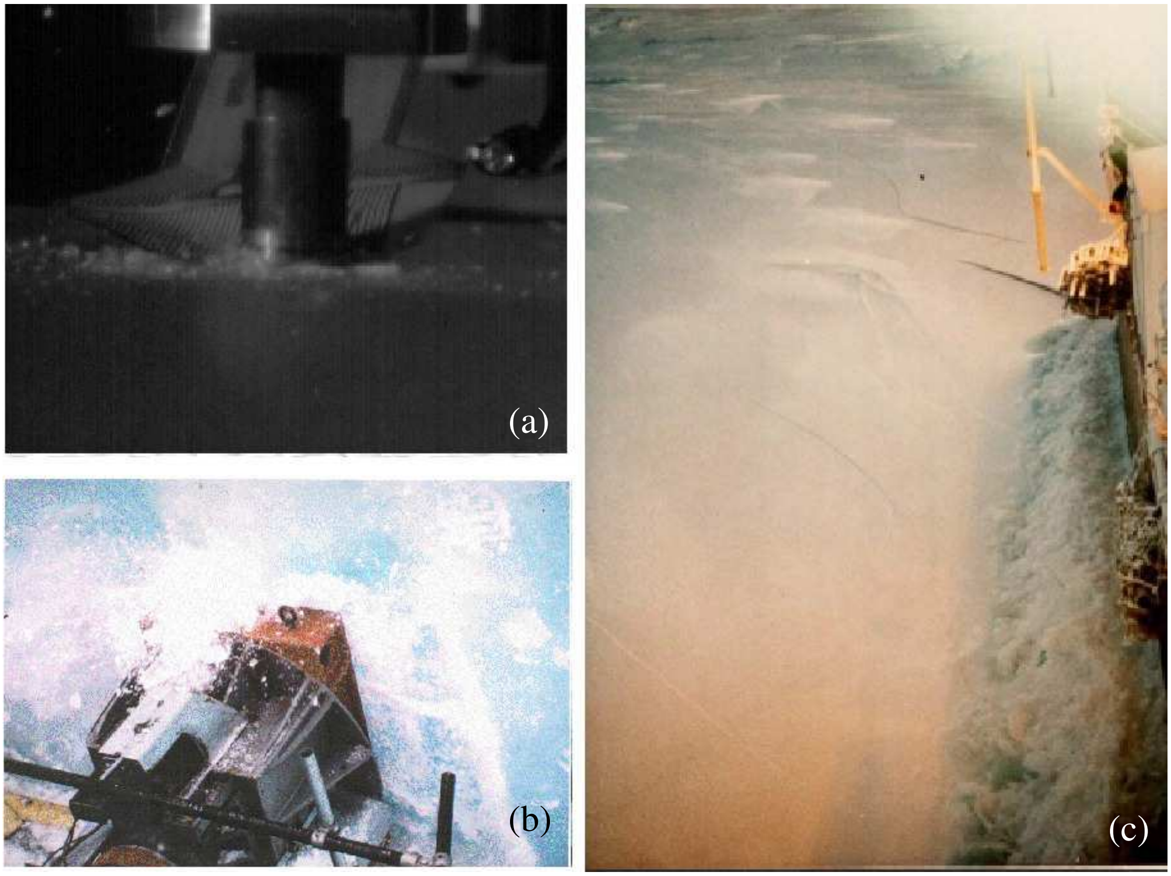

Figure 2. Photographic example of dynamic loading events observed during crushing events at three scales. (a) Small-scale laboratory tests (Embedded crystal paper, in preparation). (b) Extrusion of crushed ice during a medium-scale test at Hobson's Choice (Jordaan, 2001) (c) Mound of crushed ice that developed during the April 12, 1986 event at the Molipaq.

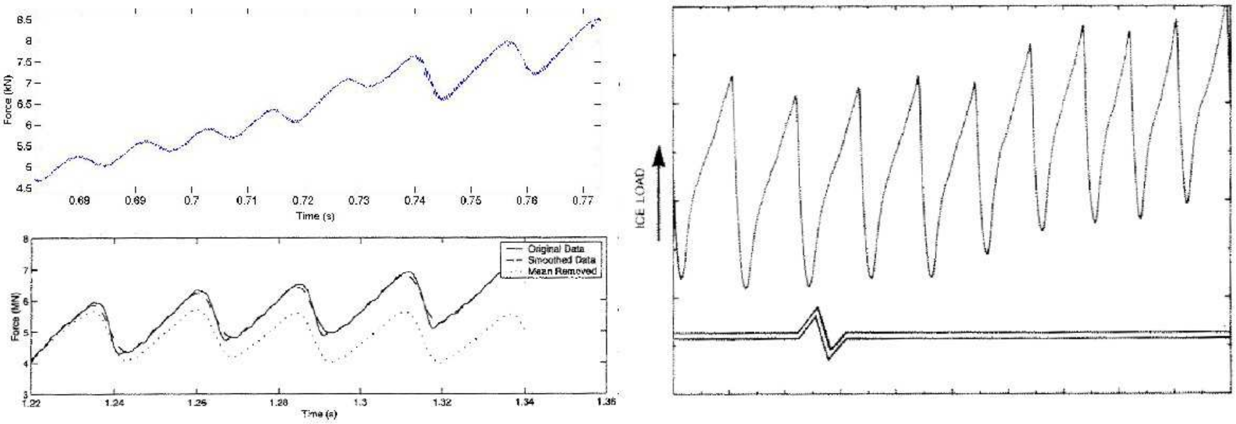

Figure 3. Sample load traces observed during crushing events at three scales. (a) Small-scale laboratory tests (Embedded crystal paper, in preparation), (b) Medium-scale test at Hobson's Choice (Jordaan, 2001), (c) Full-scale crushing event at the Molipaq (Jefferies and Wright, 1988).

High-pressure Zone (*hpz*) Formation and Influence

The formation of high-pressure zones (*hpz'*s) is associated with two processes (Jordaan et al., 1999, Barrette et al. 2002). The first is a concentration of stress in the area of the *hpz*, which results from spalling and fracture processes (Mackey et al., 2007). Since the focus of this paper is on the crushing process, spalling and fracture will not be explored in any detail herein. The second process is the formation of the damaged layer. This layer has been found to exist in both small and medium scale tests and have shown remarkable physical similarity at both scales (Jordaan et al., 2005). The damaged layer that forms under the indenter in tests represents what would be found many times over in a large scale interaction, which would consist of many *hpz's* spread over the entire area of interaction. An initial analysis of the case of more than one hpz interacting with a structure was conducted by Jordaan and Singh (1994). The evolution of a full-scale interaction is strongly dependent on the formation of *hpz's* as they help reduce the total load felt by the structure in a number of ways. The most significant contribution comes through the softening processes that occur within the damaged layer. Within the layer, processes vary with distance from the centre; microfracturing and recrystallization occur near the outside with recrystallization and pressure melting along grain boundaries in the central part (the latter mechanism is hypothesized). The crushing process involves the extrusion of the softened ice from the periphery of the *hpz*, which promotes very regular ice-induced vibrations. Stress concentrations also exist around flaws in the surrounding area. Therefore, during a full-scale interaction, the total load will be significantly reduced by a combination of the localized extrusion of ice from the many *hpz's* and fracture promoted by the presence of flaws. Since the *hpz's* vary in time and space, their presence would promote non-simultaneous failure across a large interaction area. In this paper, we will focus on the contribution of the crushing process to load reduction.

Link Between Ice-Induced Vibrations and *hpz* Formation

Tests have shown that the main mechanism of the ice-induced vibrations can be directly linked to failure processes occurring in the ice. When ice fails by crushing, a repetitive cycle of pressure softening and subsequent hardening upon release of the pressure occurs within the damaged layer as shown in Figure 4. This figure illustrates the behavior of ice in the immediate vicinity of a single *hpz* (Jordaan, 2001). When the ice first encounters the structure, microcracking begins to occur near the outside of the *hpz*, accompanied by extensive recrystallization (A). This leads to a 'white zone' containing cracks and air pockets and eventually causes fragmentation of the ice near the edge of the zone. In the center of the *hpz*, pressure-softening processes occur due to the high confinement and pressure. This causes the formation of a zone of fine-grained, recrystallized ice (B). Extrusion of the crushed and pressure softened ice occurs resulting in a lowering of the pressure in the *hpz* (C). The layer then hardens due to the release of pressure (D). A cycle of pressure softening and hardening develops that produces the load cycling behavior associated with the crushing process. The periods of load cycling are occasional broken up by localized spalls, which reduce the contact area in the vicinity of the *hpz* (E). In the case of a small or medium scale test, these spalls may cause the load cycling to be halted until the pressure builds sufficiently for the cycle of pressure softening and hardening to be renewed. In the case of a full-scale test, these spalls have less significance in the overall crushing process since these interactions involve many *hpz's*.

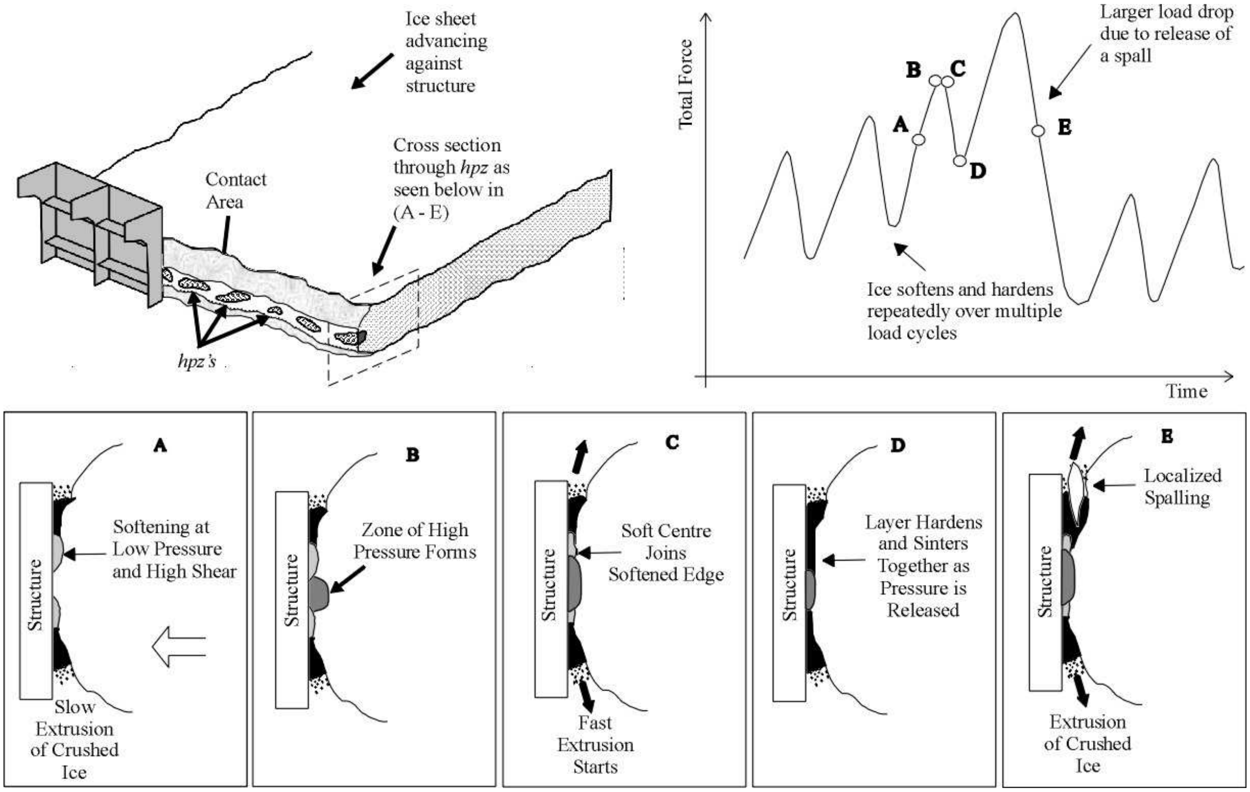

Figure 4. Schematic representation of the link between load cycling and layer dynamics (after Jordaan, 2001).

Laboratory Experiments

A great deal of evidence has been found for the formation of a damaged layer of ice and its relation to the crushing process. In small-scale laboratory tests performed by Barrette et al. (2002) a 2 cm spherical indenter was used to study the failure behavior of the ice in the vicinity of a single, stationary *hpz*. The authors found that the crushing process and load cycling were directly linked and were influenced by both temperature and rate. At relatively warm temperatures, in the range of -2^{o}C, and at a low velocity of 0.2 mm/s, ice fails by a ductile failure mechanism. No extrusion of crushed ice or spalls was seen to occur and a 'smooth' increase in total force was observed. Similar behavior has been modeled previously by Jordaan and Xiao (1992), in which the authors were able to successfully reproduce the smooth increase in total force. In the tests by Barrette et al. (2002), load cycling behavior periodically begins to appear in low temperature tests performed at $-10\,^{o}$C and -20^{o}C with speeds greater than 2 mm/s and continues for speeds increasing to 10 mm/s. This load cycling was accompanied by the extrusion of crushed ice and the formation of damaged layers at the indentation site.

This behavior was studied in greater detail in a recent test series by Wells et al. (2008). In this test series, a 20 mm indenter was again used. The tests were recorded using a high speed video camera with frame rates of 1000 and 1600 fps. A thin, pressure sensitive film (the I-Scan system by Tekscan) dynamically recorded the pressure distribution at the ice-indenter interface. During the tests, crushing events were visually apparent and were classified by the continuous extrusion of material from under the indenter. The crushing events were accompanied by load cycling, which was apparent on the synchronized load traces. An example of a crushing event is given in the sequence of frames in Figure 5. Each successive drop in load shown in Figure 5 (e) is accompanied by the ejection of material from the indentation area. This extrusion appears on the pressure distribution as regular reductions in contact area from the periphery of the loaded area. The peaks in pressure in this case are mainly concentrated in the central regions of the indenter and remain relatively constant throughout the entire crushing event. This behavior reflects what has been found to occur in the vicinity of *hpz's* during the JOIA program, medium-scale tests. In the case of these tests, when first-year ice sheets were indented with a flat indenter, multiple *hpz's* were distributed across the area of interaction in a 'line-load'. In the vicinity of individual *hpz's* layer dynamics were observed similar to the results shown in Figure 5 (Taylor et al., 2008).

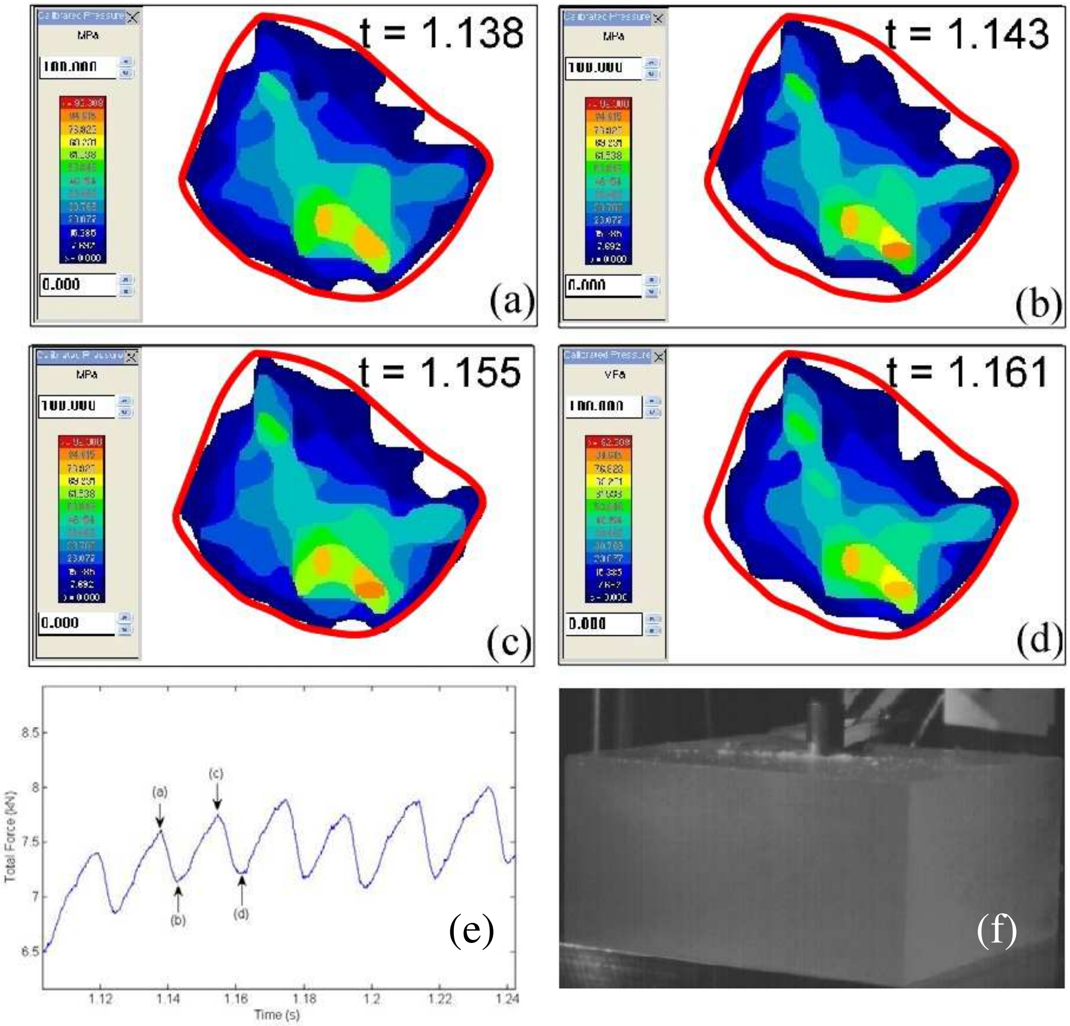

Figure 5. Crushing event during a small-scale laboratory test. (a-d) Pressure distribution recorded during the crushing event. The red circle drawn on the figures represents equal areas. (e) Load cycling observed in the synchronized load trace during the event (f) Frame taken from a high-speed video recording of the event. (Embedded crystal paper, in preparation)

The mechanics involved in this process can be scaled geometrically without any basic change (Jordaan, 2001). This explains why the *hpz*'s are found over widely differing scales. The physical composition of the damaged layer also shows remarkable similarity at both the small and medium scales. It can be assumed that this similarity exists at the full-scale as well. Therefore, it is no surprise that a dependence on loading rate for ice-induced vibrations was observed during the Hobson's choice medium-scale field trials (Jordaan, 2001), similar to what is observed in small-scale tests. Neither extrusion of crushed ice or load cycling behavior was observed in slow rate tests. As the rate is increased, crushing behavior becomes apparent along with damage layer formation. Load cycling begins at rates above 3 mm/s and is accompanied by the production of large quantities of crushed ice (Masterson et al., 1999). The rate dependence of ice-induced vibrations and link to the crushing process has also been observed at the full-scale. In the case of ice-interactions with the Molikpaq, velocities in the range of 2.5 – 10 cm/s promoted high total loads while being accompanied by vibrations in the range of 0.5 – 4 Hz (Sanderson, 1988). Within the range of velocities that cause vibrations, crushing failure was always observed. As an example, in the April 12, 1986 event alluded to earlier, a velocity of approximately 5 cm/s was recorded. While the event was occurring, ice was completely pulverized and extruded upwards, creating piles of crushed ice as high as 8 - 10 m. The crushing was accompanied by ice-induced vibrations with a frequency of 0.8 – 1.4 Hz (Sanderson, 1988).

Dynamic Recrystallization at High Speeds in Compression

A critical feature of the formation of the damaged layer of ice is recrystallization. The high pressures and confinements in the center of hpz's have been found to lead to a zone of recrystallized ice in the center of the damaged layers. There has been ample evidence of grain refinement and recrystallization observed during small and medium scale testing. A few examples will be given herein. Recrystallization has been observed during indentation tests both at the small (Wells et al., 2008; Barrette et al., 2002; Frederking and Gold, 1975; Barnes and Tabor, 1966) and medium (Kennedy, 1990; Jordaan, 2001) scales. For example, Figure 7 shows three examples of damaged layers containing recrystallized zones that were observed during tests by Wells et al. (2008).

Recrystallization in ice has also been observed in other types of testing. Triaxial tests have been used to reproduce the confining pressures felt by ice in the center of *hpz's*. For example, Melanson et al. (1999) found that at low strain rates, very little micro-cracking occurs and the resulting grain size reduction was the result of dynamic recrystallization. Kuon and Jonas (1973) performed a series of tests that were performed by extruding the specimens of ice backwards through a die and hollow ram. It was found that at constant extrusion temperature, the grain size decreased with increasing strain rate. At constant strain rate on the other hand, the grain size increased with temperature. Also, the presence of subgrains was observed within some of the recrystallized grains. The authors speculated that this implies that the subgrains were formed during the deformation and thus, were caused by dynamic recrystallization.

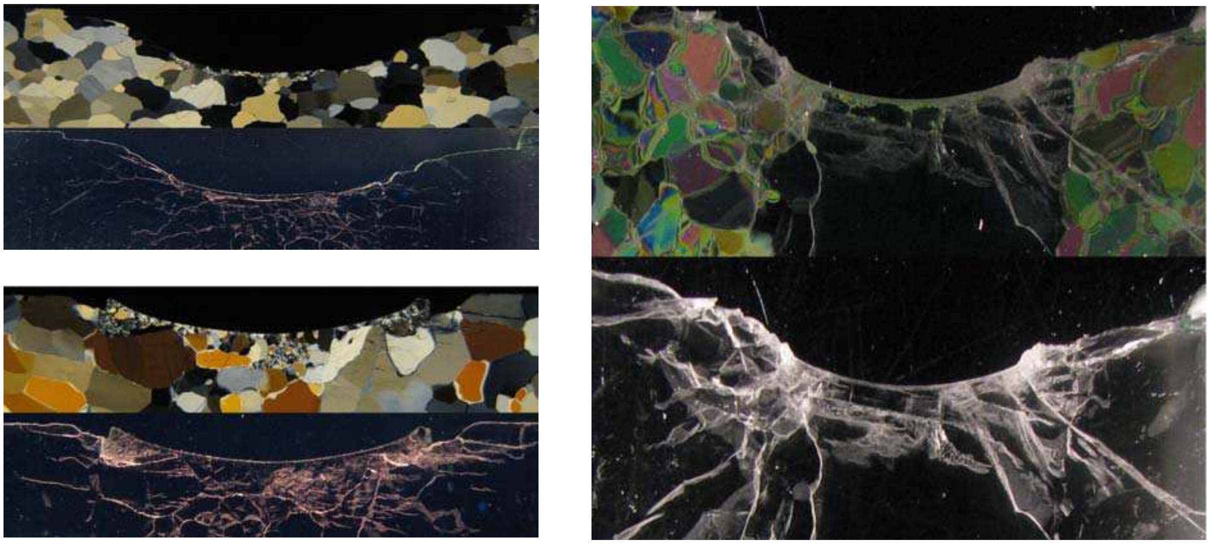

Figure 7. Three examples of thin-sections taken during small-scale tests by Wells et al. (2008). The upper photograph in each picture shows the thin-section viewed using cross-polarized lighting conditions. The lower photograph shows the same thin-section viewed using side-lighting conditions. Each set of photographs show fine-grained recrystallized ice in the damaged layer. The recrystallization is apparent since when viewed under cross-polarized conditions, the grains in these areas are much smaller than the parent grains, yet the side-lighting conditions show that these zones are free from cracks. (Mackey et al., 2007). (a) Indentation speed of v = 3.0 mm/s (b) Indentation speed of v = 10.0 mm/s (c) Indentation speed of v = 5.0 mm/s.

Recrystallization of single-crystals of ice has been studied using thin monocrystalline ice specimens and a transparent glass surface (Offenbacher et al., 1973). The contact zone between the ice and the upper glass plate was observed and it was noted that at loads above ~ 1.5 kg or at lower loads that were held for longer periods of time, cracks were often produced in a direction perpendicular to the c-axis. Recrystallization was found to begin along these cracks and then spread into the ice. The inadvertent presence of a grain boundary caused a similar recrystallization behavior to occur. After a sufficient period of time, the small crystals began to grow at the expense of neighboring crystals. A similar behavior was found to occur during a relatively quick indentation test performed by Wells et al. (2008). Figure 7 (e-f) shows a thin-section taken from an indentation test performed at 10 mm/s. The figure shows the formation of recrystallized grains along cracks that formed within a large single-crystal of ice within the indented sample.

Formation of damaged layers has also been observed to occur during quick impact tests by Kheisin and Cherepanov (1973). During these tests, a cast steel ball was dropped onto fresh water lake ice. After impact, the top 2 cm of ice showed a distinguishable, opaque white layer of total fracturing and compression. The upper portion of the layer (1 – 1.5 cm) was semi-transparent. The authors hypothesized that this was a result of melting and refreezing at the surface. The ice in the layer contained fine-grains which were much smaller than the parent ice and had a random crystal orientation. Additionally, it was observed that after all impacts a layer of finely crushed ice was present. It was hypothesized that particles of submicroscopic size were dispersed throughout the damaged ice. These small particles acted to “lubricate” the system such that the extruding crushed ice can be considered as a viscous fluid (Kheisin and Cherepanov, 1973).

Finally, there also exists a great deal of precedent for the formation of recrystallized grains in fast impact tests in warm metals (Li et al, 2005; Murr et al., 1998; Duan et al., 2003; and Murr et al, 2002). In all these tests, permanent craters are formed by quickly impacting various warm metals with projectiles. Under certain circumstances, the walls of these impact craters are found to contain recrystallized grains, implying that the process of dynamic recrystallization can occur on a relatively fast time scale as opposed to only occurring during slow creep as had been supposed earlier.

Shear Softening Model as Influenced by Pressure

An analysis has been performed using the ABAQUS computer program that encapsulates the principal features of the process. The analysis was developed based on damage mechanics (Jordaan et al., 1999, 2001). Comprehensive experimental studies (Meglis et al., 1999; Barrette and Jordaan, 2002) of ice under states of stress that are typical of those within *hpz'*s showed that ice softens considerably as a result of previous stress history. The key to the layer development lies in the increase in the softening that occurs at high pressure and shear. Based on previous work Xiao (1997) proposed the model

$$\mathrm{S} = \int_0^t \left\{ f_1(p)\left(\frac{s}{s_0}\right)^{q1} + f_2(p)\exp\left(\frac{s}{s_0}\right) \right\} \mathrm{dt} \qquad \textbf{[1]}$$

where $S =$ damage, $p =$ pressure, $s =$ von Mises shear stress and $f_1(p)$ and $f_2(p)$ are increasing and decreasing functions of pressure, respectively. From this, the damage rate dS/dt is given by the term in the parenthesis $\{g\}$ in equation (1). Implementation of particular functions corresponding to this equation are shown in Figure 6. As explained in Barrette and Jordaan (2002), the softening at high pressures and shear is virtually limitless, so that sharp drops in load result, as is observed.

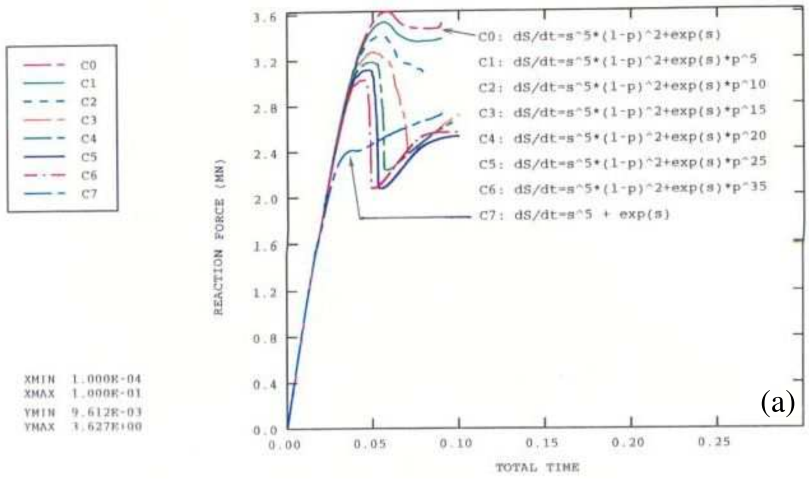

Figure 6. (a) Force-time curves for analysis with the damage model proposed in equation (1)

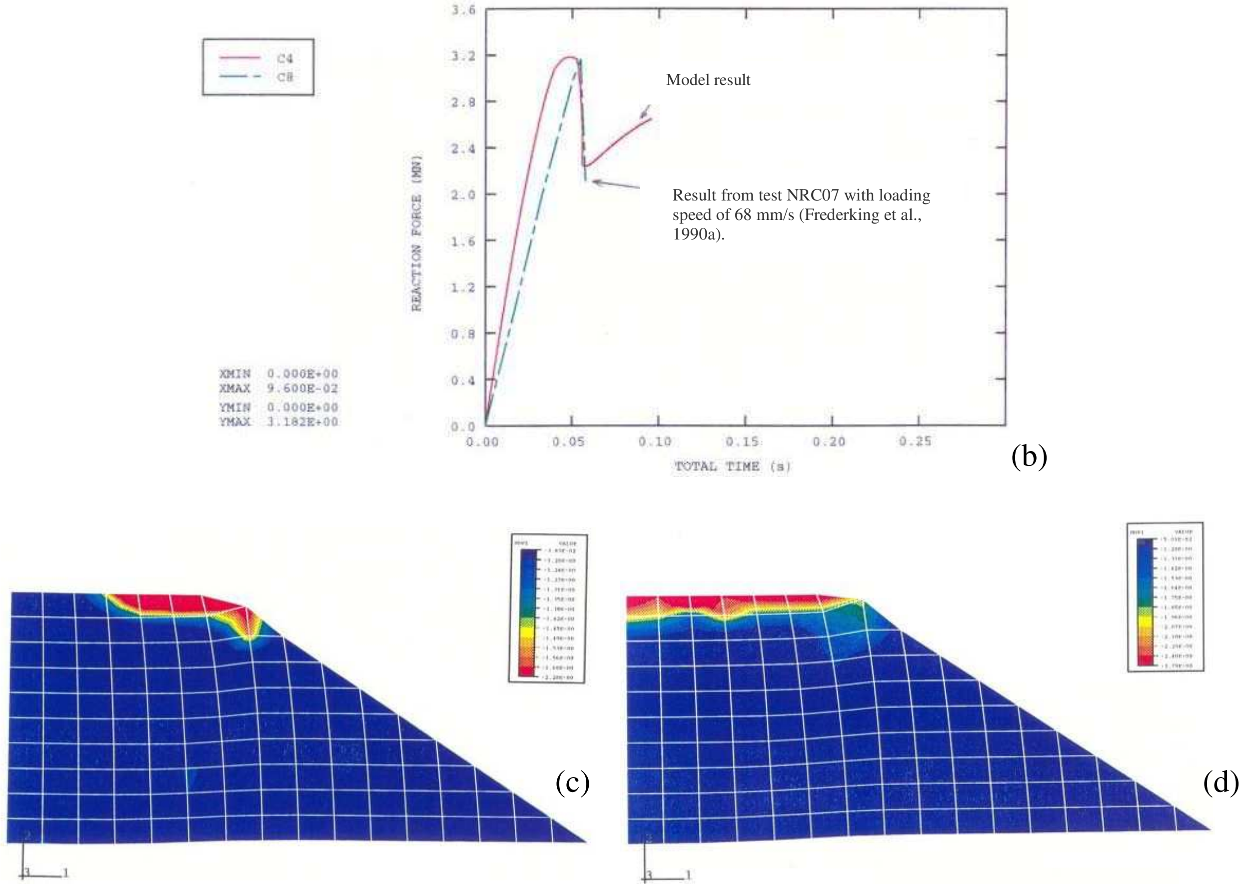

Figure 6 (continued). (b) Force-time curve comparison of model and test results. (c) Damage distribution for $dS/dt = s^5(1-p)^2 + \exp(s)p^{10}$; and for (d) $dS/dt = s^5(1-p)^2 + \exp(s)p^{15}$. (Xiao, 1997)

Conclusions

The cyclic process of ice failure in compression can lead to dynamic loading. The formation of *hpz's* during an interaction plays a direct role in this process through the creation of a damaged layer of softened ice at the ice-structure interface. Dynamic recrystallization plays an important part in the softening process at high pressures and shear. Vibrations arise from the repetitive cycle of pressure softening and hardening that occurs in the vicinity of the *hpz's* during crushing failure. This behavior is seen at all scales of interaction and has been illustrated by small-scale laboratory tests and modeled by damage mechanics.

Acknowledgements

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