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2-DIMENSIONAL EDGE CRUSHING TESTS ON THICK SECTIONS OF ICE CONFINED AT THE SECTION FACES

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Abstract

A crushing apparatus incorporating the novel characteristics of the apparatus used by Gagnon and Bugden (2007), and fabricated at 3 times the scale, has been used to conduct crushing experiments on polycrystalline ice, large single crystals of ice and iceberg ice at –10^{o}C. The results confirmed that the behaviours of the different ice types were essentially invariant for the change of scale and that the apparatus functioned as intended at the larger scale, that is, it provided visual data of a 2-D slice of ice during crushing as though it was part of a larger piece of ice. Rectangular thick sections (3 cm thickness) of ice were confined between two thick borosilicate glass plates and crushed from one edge face at a rate in the range 1.5 – 2.5 cm/s using a transparent acrylic platen (3 cm thickness) inserted between the plates. Three identical pressure sensors, of the same type used before, were placed side-by-side to measure pressure across the full breadth of the platen/ice contact area between the glass plates as the samples were being crushed. The pressure data corroborated with the smaller-scale pressure data from the earlier tests and the apparatus served as a test bed to demonstrate that the pressure-sensing technology could function effectively in the side-by-side configuration. This technology will be used to obtain high spatial resolution pressure data during an upcoming full-scale study of ship / bergy bit impacts within the next few years.

Gagnon, R.E. and Bugden, A., 2007. Ice Crushing Tests Using a Modified Novel Apparatus. Proceedings of POAC-07, 235-244.

1. Introduction

Various techniques have been utilized to gain insight into ice crushing processes. Such knowledge is essential for reliable assessment of ice/structure interactions forces and pressures that are needed for design and operational purposes. Following on from the successful tests using the first apparatus incorporating this method (Gagnon and Bugden, 2007) we present results from a larger apparatus (3 times the scale). The purpose was to both demonstrate the effectiveness of the method and to study the behaviour of ice, at the larger scale. The experiments with this larger apparatus also provided the opportunity to test multiple pressure sensors, in a side-by-side configuration, that were successfully used singly in the smaller apparatus. These types of experiments provide rich visual observations of ice crushing processes coupled with in situ pressure measurements.

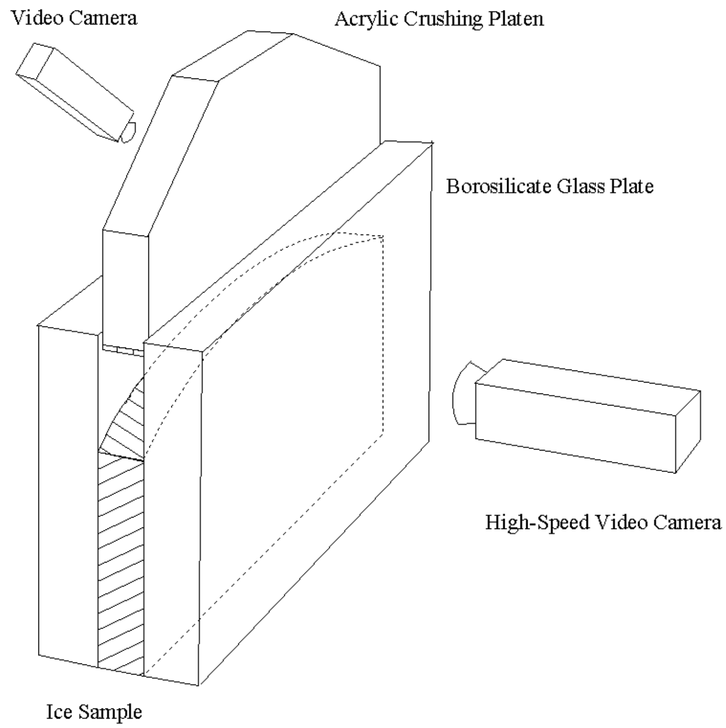

Figure 1. Conceptual schematic of the ice crushing test method and present configuration.

2. Apparatus and Setup

Figure 1 shows the concept for these experiments and has been described in detail for the smaller scale apparatus (Gagnon, 2004; Gagnon and Daley, 2005; Gagnon and Bugden, 2007). The ice is confined between rigid flat transparent plates and crushed at one of its edges by an acrylic platen inserted between the plates. Visual data are acquired by side-viewing using a high-speed video camera (1000 images/s) and from above through the transparent platen itself using a regular video camera and in one instance using a moderately high-speed video camera (240 images/s). Figure 2 shows the present 3 x scale apparatus mounted in the test frame.

Figure 2. Crushing apparatus and sample mounted in the test frame with the high-speed camera in the foreground.

Thick steel plates, with a rectangular port for viewing, hold transparent thick borosilicate glass plates in place that serve to confine the ice laterally during tests. Figure 3 shows the acrylic crushing platen with the three pressure sensing strips attached and how they function. The calibration for the pressure sensing strips has been given in Gagnon and Bugden (2007).

Tests were conducted at –10°C with the crushing platen moving at nominal speeds in the range 15-25 mm/s.

3. Test Using a Single-Crystal Sample

Figure 4 shows an image from one of the crushing experiments using a single-crystal sample of ice, where the c-axis is in the plane of the image and vertically oriented. The crushing rate was nominally 17 mm/s. Various aspects of the test are indicated to assist the reader in following the description below. Figure 5 shows a series of six images from the high-speed video record of the test on the single-crystal sample. Figure 6 shows the corresponding load record where the points at which the images were acquired are indicated.

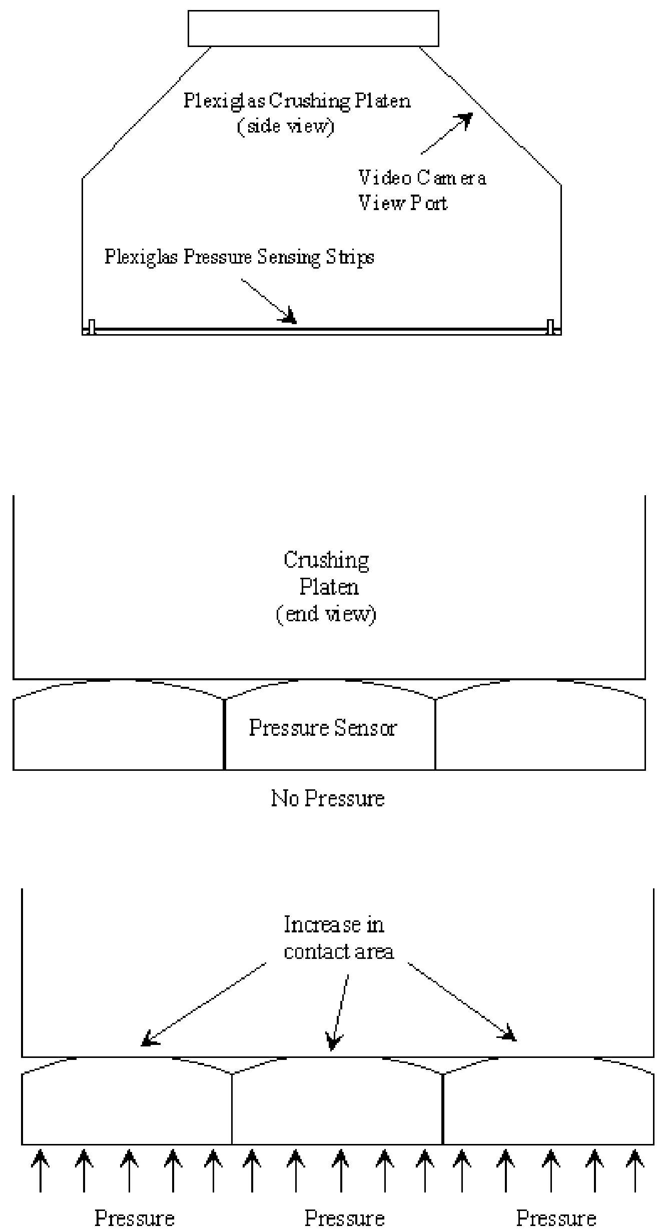

Figure 3. Schematics of the crushing platen (top) and pressure sensor working principle (middle and bottom).

The first image in Figure 5 shows some cracking behavior as load is accumulating, however the cracks have not extended far enough to create spalls that would result in a reduction in contact area and load. High pressure (50-70 MPa) exists throughout the contact zone. The second image was taken after the first spalling event and the spall debris is seen at the left side of the contact zone. The corresponding drop in load is evident in the load record (Figure 6). The third image was taken after the second spall event, to the right of the central contact zone. The ice in the central peak, while somewhat fractured, is still relatively intact and experiences high pressure at the platen interface, while the shattered spall debris on either side of the peak can only support low pressure (< 6 MPa) since it is not confined. The fourth image shows the ice just prior to a very large spalling event that shatters most of the

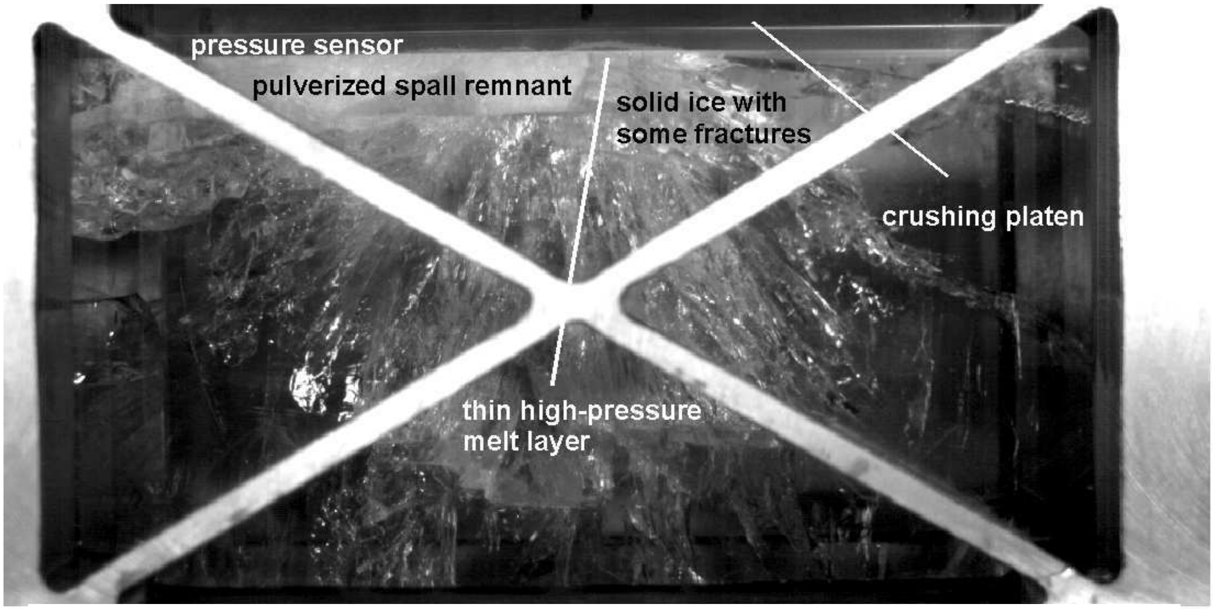

Figure 4. Image from the high-speed video record of a test on a single-crystal ice sample indicating various aspects of the apparatus and ice behavior. The ice slab is in the plane of the image as shown in Figure 1.

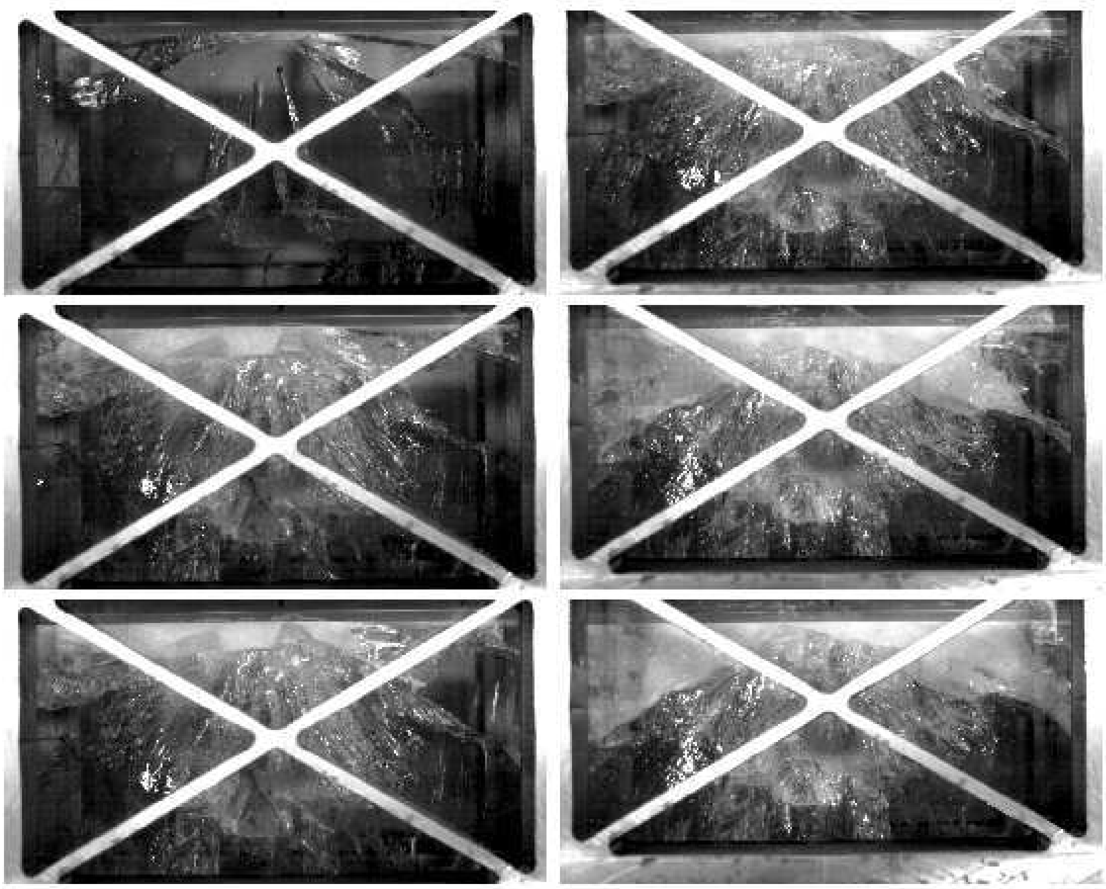

Figure 5. Sequence of high-speed digital images (from top left to bottom right) of a test on a single-crystal ice specimen. Figure 6 shows the corresponding points in time on the load record for the images.

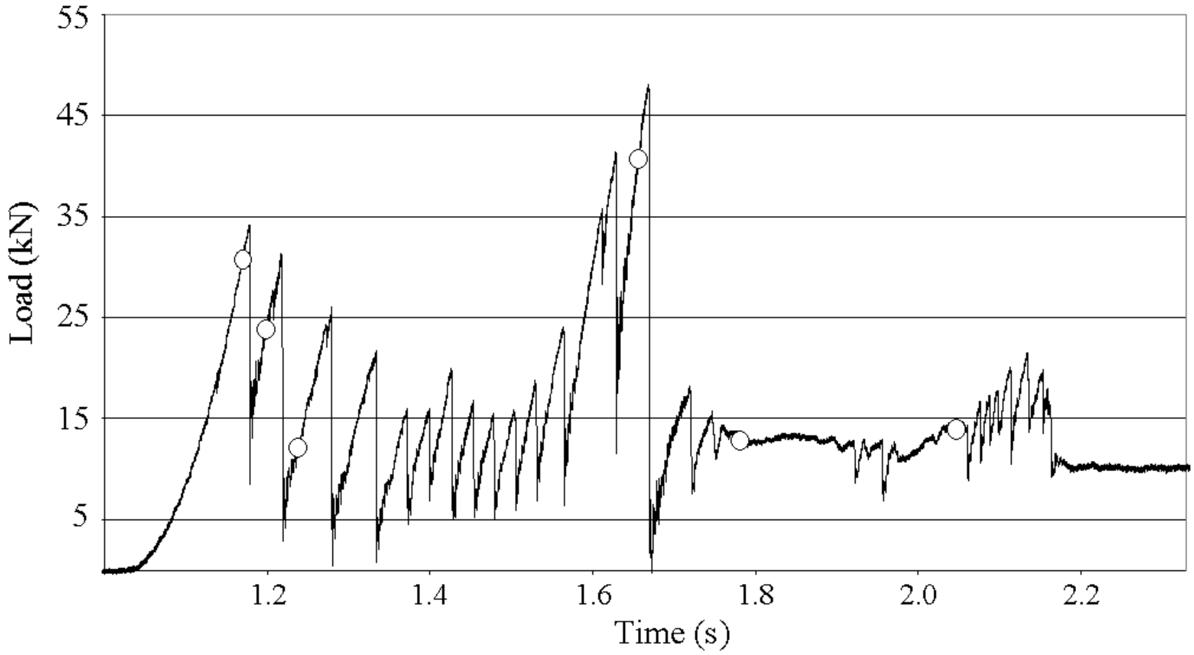

Figure 6. Load record for the test shown in Figure 5 with markers (open circles) corresponding to the six images.

so this mushy contact leads to a period of extrusion where no sawteeth are evident in the load record (i.e. the smooth region just following the time when image 5 was taken (Figure 6)). The final image was taken just prior to the onset of a series of spall induced load drops that start when fresh intact ice pushes up through the mushy material and makes contact with the platen.

Figure 7 shows two images from the downward-looking view through the transparent crushing platen. For most tests a regular video camera was used however for this test a moderately high-speed camera (240 images/s) was used (Sony HDR-FX7). The images show the output from the three pressure sensing strips overlaying the view of the ice behaviour. The two images show the sensor and ice behaviour just prior to (left image) and immediately after (right image) the second spall event in Figure 6 where roughly half of the intact ice spalls away from the upper region of ice/platen contact. The time span between the images is 1/120 s. We note in one region that solid intact ice fully spans the width of the space between the borosilicate plates, as is the intention of the apparatus design. We also note in the left image that the pressure sensors each show near full width contact, indicating pressures in the 50 - 70 MPa range, and that the pressure sharply diminishes to much lower values above and below the intact ice region where ice is pulverized. The widths of the pressure sensor contact indicators in the right image for the intact ice are less than the corresponding widths in the left image only because a spall event and load drop has just occurred. This is due to inertial effects of the ice/apparatus system during the rapid load drop. As load accumulates during the ascending portion of the subsequent load sawtooth (3rd sawtooth, Figure 7) the pressure sensor contact widths eventually increase to similar values as shown in the left image.

Experiments were also performed using lab-grown polycrystalline ice and iceberg ice. Similar behaviours were observed to that of single crystal samples but with generally lower load values and fewer spalling events. These characteristics were also observed in the tests using the smaller scale apparatus and have been discussed before (Gagnon and Bugden, 2007).

Figure 8 shows an image from the high-speed video record of a test using polycrystalline ice. The crushing rate was nominally 25 mm/s. The characteristic shape of the contact zone is evident, that is, a relatively intact central region (in spite of many intergranular cracks), with pulverized ice at the sides. An image from the downward looking regular video camera is inset to the approximate location and scale. It shows high pressure in the central intact ice region and low pressure at the sides as expected. The ability of the polycrystalline ice to maintain its strength and intactness even with many small internal cracks at grain boundaries is remarkable and was previously noted in the experiments with the smaller apparatus (Gagnon and Bugden, 2007).

Figure 7. Images from the downward-viewing camera just before (left) and just after (right) the second spall event in Figure 6. Each image is 3 cm wide.

Figure 9 shows a similar image to that in Figure 8 but in this case iceberg ice was used. The crushing rate was nominally 25 mm/s. The features of the contact zone and pressure distribution are similar to that of Figure 8 and are basically the same as that observed for iceberg ice tested in the smaller apparatus (Gagnon and Bugden, 2007). A noteworthy comparative feature of Figures 8 and 9 is that the pressure sensors indicate that more load is borne by the pulverized ice to the sides of the intact ice in the center of the contact region in Figure 9 than in Figure 8. This is probably associated with the fact that the peaked shape of the intact ice has shallower angles in the case of the iceberg ice, i.e. the pulverized ice is somewhat more confined. The capacity of the pulverized material to support substantial pressure and load, depending on its degree of confinement, was observed and discussed by Gagnon and Bugden (2007).

Another aspect that was characteristic of all experiments was the production and flow of melt from the high-pressure contact zones. The melt could be seen wetting the surrounding pulverized ice and was also evident running up the sides of the crushing platen in the thin space between the platen and the glass plates where it refroze to the glass as a very thin layer of ice (Figure 10). In certain instances, near the end of some tests, liquid could also be seen squeezing up between the

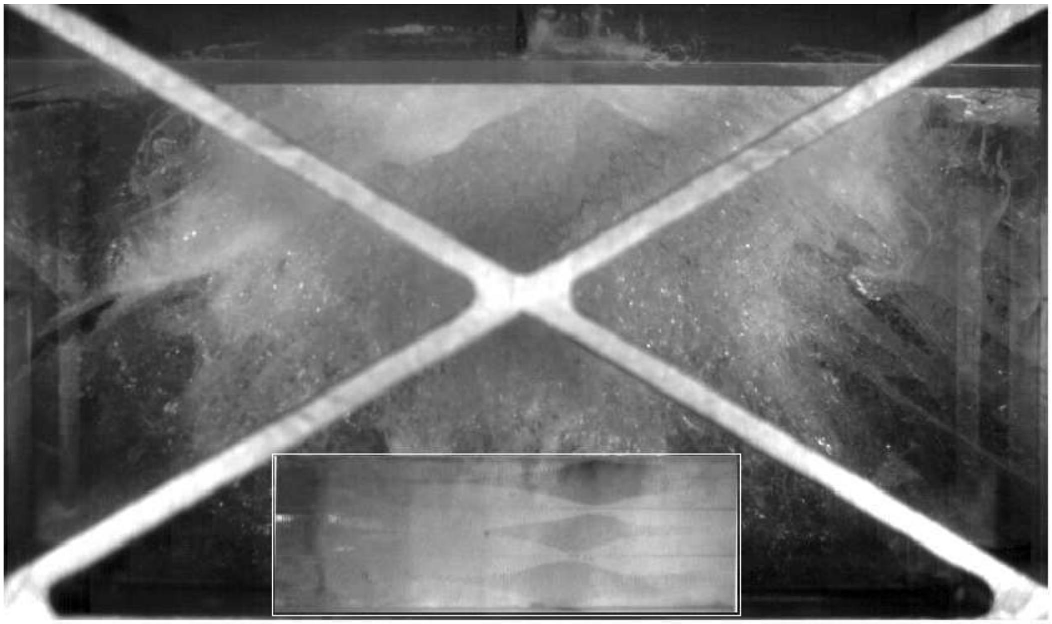

Figure 8. An image from the high-speed video record of a test using lab-grown polycrystalline ice. A corresponding image of the platen/ice contact and pressure sensors from the top-viewing camera is inset to the approximate scale and location.

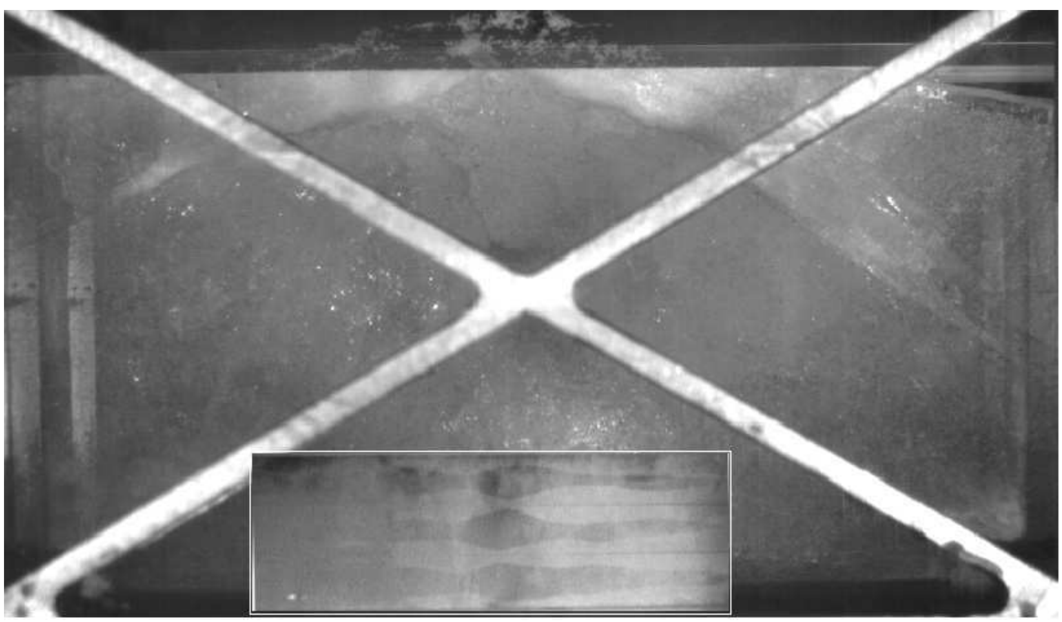

Figure 9. An image from the high-speed video record of a test using iceberg ice. A corresponding image of the platen/ice contact and pressure sensors from the top-viewing camera is inset to the approximate scale and location.

pressure sensor strips and into the thin space between the strip's gently curved surfaces and the flat head of the crushing platen. The production and flow of the melt has been explained and discussed extensively in previous studies (Gagnon, 1994a; Gagnon, 1994b; Gagnon, 1999).

All of the behaviours observed in these tests have been seen and discussed before in the context of the smaller apparatus. If anything was different in the behaviour of ice in the large apparatus it was possibly that there were longer episodes of repetitive spalling events (sawteeth) than with the smaller setup. This was most evident in the tests with single crystals. This implies that for the case of the single crystal samples, at least, that the larger scale somehow reduced the number of times that the whole contact region of intact ice was shattered and pulverized leading to mushy sections in the load records rather than sawteeth.

Not surprisingly, loads using the larger apparatus were roughly 3 to 5 times that for tests using the smaller apparatus.

Figure 10. A thin layer of refrozen melt left on the inside of one of the borosilcate glass plates following a crushing test. The thin ice layer is visible just above the X shape in the photo and extends towards the upper right. The changing horizontal location of the ice layer on the glass from top to bottom is a rough 'strip-chart' record of the horizontal position of the high-pressure intact ice zone at the platen/ice interface as the test progressed.

4. Conclusions

2-D edge crushing experiments using a larger scale apparatus than the original one have shown essentially the same ice behaviours as the former smaller scale apparatus for tests with various types of ice. The pressure sensor technology functioned properly when configured in a side-by side orientation. Consequently the technology will be used on the front surface of a large impact panel intended for head-on ship/bergy bit collisions in a future field study.

5. Acknowledgements

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