POAC'17
Busan, KOREA

Proceedings of the 24th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 11-16, 2017, Busan, Korea

Some Limitations of Using Saline Ice in Lab Tests to Study Structure Interaction with Sea Ice at Full Scale

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ABSTRACT

Studies show that crushing of small-scale freshwater ice samples against smooth platens exhibits high-amplitude sawtooth load patterns (HASLP), due to spalling. For comparable ice temperatures and crushing rates it is known that sea ice sheets encroaching on structures (e.g. Molikpaq) can produce HASLP. Hence, small-scale freshwater ice tests are useful for studying the large-scale phenomenon. The present small-scale crushing tests on lab-grown saline ice, however, produced no HASLP at any crushing rate for temperatures higher than –16 °C. Therefore small-scale saline ice tests may not be suitable to study large-scale HASLP. Some differences in behaviour of the two ice types is attributable to brine channels/pockets within the saline ice matrix that tend to make the ice more compliant at the small scale, where there is less confinement, than at field scale. Similarly, when Blade-Runners platens, that had regular arrays of small prominences, were used for the saline ice tests no ice spallation at individual blades was observed, whereas for previous freshwater ice tests small spalling events at the blades were prevalent and were the reason why the technology reduces HASLP. At the lab scale, where the individual blade dimensions and spacing were comparable to that of the size and spacing of brine channels/pockets in the saline ice, the compliance of the ice in the vicinity of blades may limit non-uniform local stresses to values lower than that needed to nucleate the small fractures/spalls at the blades. This suggests that full-scale experiments are required to properly test the technology for sea ice.

KEY WORDS: High-amplitude sawtooth load patterns; Spalling; Saline ice crushing tests; Scale effects; Blade Runners technology.

INTRODUCTION

Many studies have been successfully performed in the lab to gain insight into the behaviour of ice when it interacts with structures at full scale, including those focused on ice crushing characteristics and ice induced vibration (IIV) (e.g. Määttänen et al., 2011; Gagnon, 2008; Sodhi, 1991; Evans et al., 1984). In the latter case the most widely known and studied events are those associated with the Gulf Canada Resources Ltd. Molikpaq caisson facility that occurred in 1986 during operations at the Amauligak I-65 site in the Canadian Beaufort Sea. IIV is caused by cyclic loading that is due to repetitive spalling from hard-zone regions, relatively intact ice, at the ice contact zone (Gagnon, 2012). While much has been learned about the full-scale phenomena from small-scale laboratory experiments using freshwater ice samples, we have seen in the present saline ice crushing experiments that considerable caution should be exercised before assuming that results from small-scale saline-ice lab tests will also manifest at full scale for sea ice at similar temperatures and crushing-rates. This paper discusses scale and geometry related reasons for the differences in ice behavior and further points out why a new technology for reducing ice-induced vibration, known as Blade Runners, should be tested under full-scale sea ice conditions rather than in small-scale lab tests using saline ice.

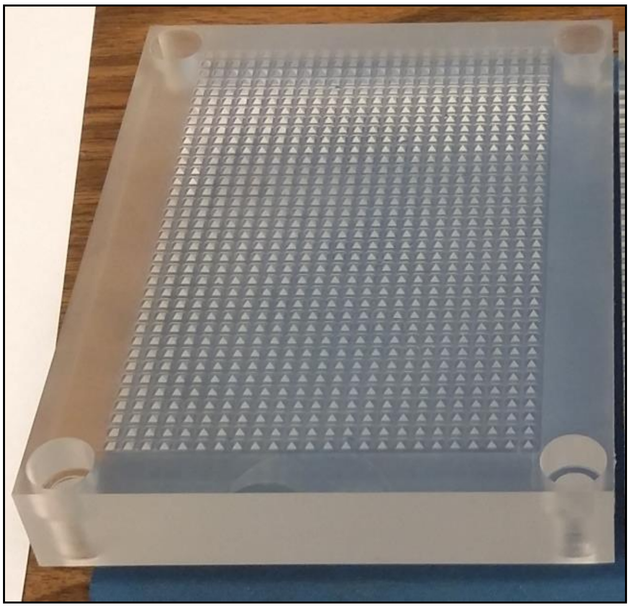

Figure 1. Photograph of the acrylic platen with the array of small regular square pyramids on its surface (platen dimensions: 166 mm x 129 mm x 25 mm). The pyramids were 1 mm in height and 2 mm wide at the base. The space between each adjacent pyramid was 2 mm. The arithmetic average of the high-roughness profile for the surface of the platen was 0.075 mm. From Gagnon (2016).

EXPERIMENTAL SETUP

To test the Blade Runners concept two styles of crushing platens were fabricated, with square columns and square pyramids blade shapes. Figure 1. is a photograph of the crushing platen with square pyramids. The pyramids and columns were 1 mm in height and 2 mm wide at the base. The space between adjacent blades was 2 mm. In previous tests using freshwater ice samples (Gagnon, 2016) these two platens were the best performers in terms of reducing large-amplitude cyclic loading due to spallation. All platens, except one made of aluminum, were made of acrylic. The ice crushing tests were performed in NRC-OCRE’s Cold Room facility. The initial plan was to crush samples of ice against platens with blade arrays and compare those results with those from crushing experiments using a flat platen with no blade array.

2 shows the essentials of the test setup where the ice, confined in a rigid holder, is pressed in the vertical direction at a fixed rate against a transparent acrylic crushing platen (2.5 cm thickness) in a testing frame. The crushing platen is backed by a secondary polished acrylic support plate (5 cm in thickness). The ice holder is attached to the top face of a 2.5 cm thick metal plate. For the acrylic platens high-speed images of the ice-platen contact region were

recorded by viewing through both the support plate and the crushing platen by means of a mirror situated between the supporting posts for the plate and platen.

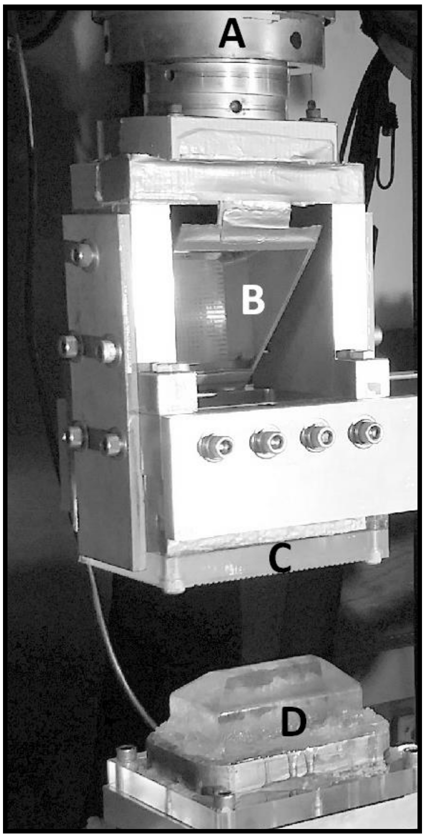

Figure 2. Essentials of the ice-crushing test setup, from an earlier program. (A) Vertically-oriented test-frame load cell for measuring the normal load; (B) Mirror; (C) Acrylic crushing-platen; (D) Ice specimen in ice holder.

Ice samples were prepared from the saline ice grown in the lab. During tests the columnar grains (roughly 3 mm in diameter) were orthogonal to the vertical crushing direction and the long axis of the ice sample. Each ice sample was approximately 7 cm in height, and 12 cm by 6.5 cm at its base. The top of the samples was given a rounded-wedge shape. Each sample's base was freeze-bonded to an ice holder consisting of an acrylic plate with a rectangular band of steel (2 cm in height) attached to it that encompassed the base of the ice specimen. The ~ 1 cm gap between the ice sample and the confining steel band was filled with snow and then saturated with water near 0 ^{o}C so that, when frozen, it provided confinement at the base of the ice sample to prevent it from shattering during testing. Tests were carried out at –10 ^{o}C, –16 ^{o}C and –21 ^{o}C. The load data from the vertical crushing actuator were acquired at 6144 samples per second. The vertical crushing rates used for these tests were 5, 10, 20 and 40 mm/s. Ice samples were crushed to a depth of ~ 35 mm.

ICE GROWTH AND CHARACTERISTICS

Figure 3. Thin section of the ice showing the initial vertical columnar structure that became disrupted and somewhat jumbled (about half-way down the image). The markings on the

Figure 4. Same thin section as in Figure 3., with side lighting and without using polaroid filters, showing brine and air filled channels and pockets in the ice. The section is 1.0 mm thick. The markings on the scale at the left are mm
scale at the right are mm. The section is 0.5 mm thick.

The purpose of the test program was to test the efficacy of the Blade Runners technology for reducing ice induced vibration of structures in small-scale experiments using lab-grown saline ice. The ice was grown in a cold room in a basin that was initially filled with fresh water and cooled to ~ 2 ^{o}C. Then commercial ‘sea salt’ was added to obtain a concentration of ~16 ppt. The basin and contents were further cooled by setting the air temperature to – 16 ^{o}C. Just prior to the initiation of freezing, the surface of the liquid in the basin was seeded with granular freshwater ice with a grain diameter of approximately 3 mm. Columnar-grained ice started to grow within minutes of seeding. After a certain period of freezing (approximately 24 hours), when the ice was about 6.0 cm thick, the basin was inadvertently disturbed/shaken somewhat during ice thickness measurements. Consequently, the uniform columnar ice structure changed to a more jumbled structure because vertically-oriented flakes at the bottom of the growing ice were dislodged and changed their orientation thereby altering the fabric and texture of the ice that grew following the disturbance (Figure 3.). This attribute of the ice proved to be beneficial, as will be seen below. The salinity of the ice was approximately 5.2 ppt, that is typical for first year sea ice (e.g. Dempsey et al., 1999). Figure 4. shows brine and air filled channels/pockets in the same ice section shown in Figure 3.

RESULTS AND DISCUSSION

As mentioned, the original intention of the test program was to investigate the efficacy of the Blade Runners technology using saline ice. At the start it was decided to test some saline ice samples by crushing them against a flat platen at –10 ^{o}C and rate of 10 mm/s (typical conditions for previous testing of the technology (Gagnon, 2016) to establish a baseline of high-amplitude cyclic sawtooth load patterns (HASLP) that could be used for later comparisons with records using the Blade Runners platens. But these initial tests did not exhibit the expected HASLP (see Figure 5.), in spite of the fact that sea ice sheets crushing against structures (e.g. Molikpaq, Figure 6.) at similar temperatures and rates do exhibit HASLP. However, when tests were conducted at –16 ^{o}C HASLP did occur (Figure 5.). Fortunately the high-speed imaging system captured visual data (500 – 1500 images/s) that helped explain the difference in results at the two temperatures. This will be discussed below. Having established conditions where HASLP would occur for crushing against a flat platen, the next tests were conducted at –16 ^{o}C using the Blade Runners platens, where one platen had square-column blades and the other had square pyramids (described above). In these experiments the HASLP was not affected, indeed the load patterns looked the same as that obtained with a flat platen, i.e. as though the blades were not present (Figure 7.). Subsequently, in attempts to get the desired effect from the blades, i.e. nucleation of small-scale spalls at the blades (the key mechanism of the technology), the temperature was lowered to –21 ^{o}C and more experiments were performed for a variety of crushing rates (5, 10, 20 and 40 mm/s). HASLP persisted for all these tests. Even when platens (one acrylic and one aluminium) with blades that had twice the height of the original blades were used the results still showed HASLP, that is, the blades were not performing as anticipated. We note that with respect to the Blade Runners technology the ice behaviour did not appear to depend on whether the hard-zone region, that wandered upwards and downwards in the view during the course of an experiment, encompassed the columnar structure of the ice or the jumbled structure mentioned above (Figure 3.). A similar observation was made during earlier tests using columnar and granular freshwater ice samples (Gagnon, 2016).

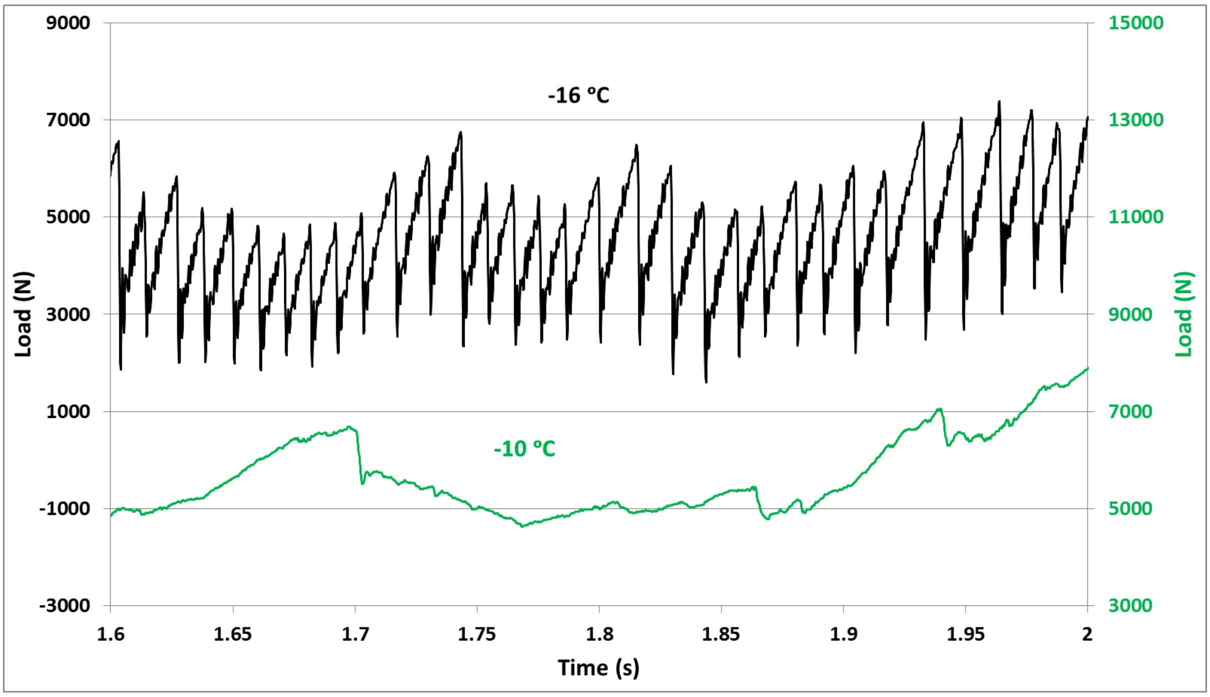

Figure 5. Comparison of load data from two tests using saline ice samples that were crushed against a flat platen where one test was conducted at –10 °C and the other at – 16 °C.

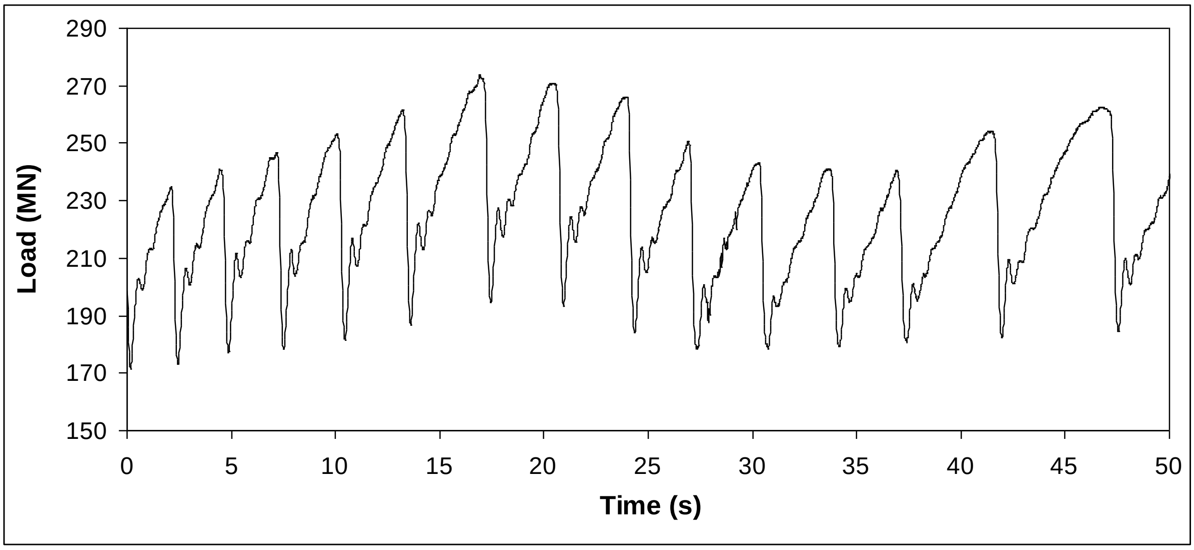

Figure 6. Full-scale load record illustrating a high amplitude sawtooth load pattern (HASLP) that occurred when a sea ice sheet encroached on the Molikpaq structure in 1986. The cyclic pattern is due to ice spalling events that regularly occur in the ice/structure contact zone, as described by Gagnon (2012).

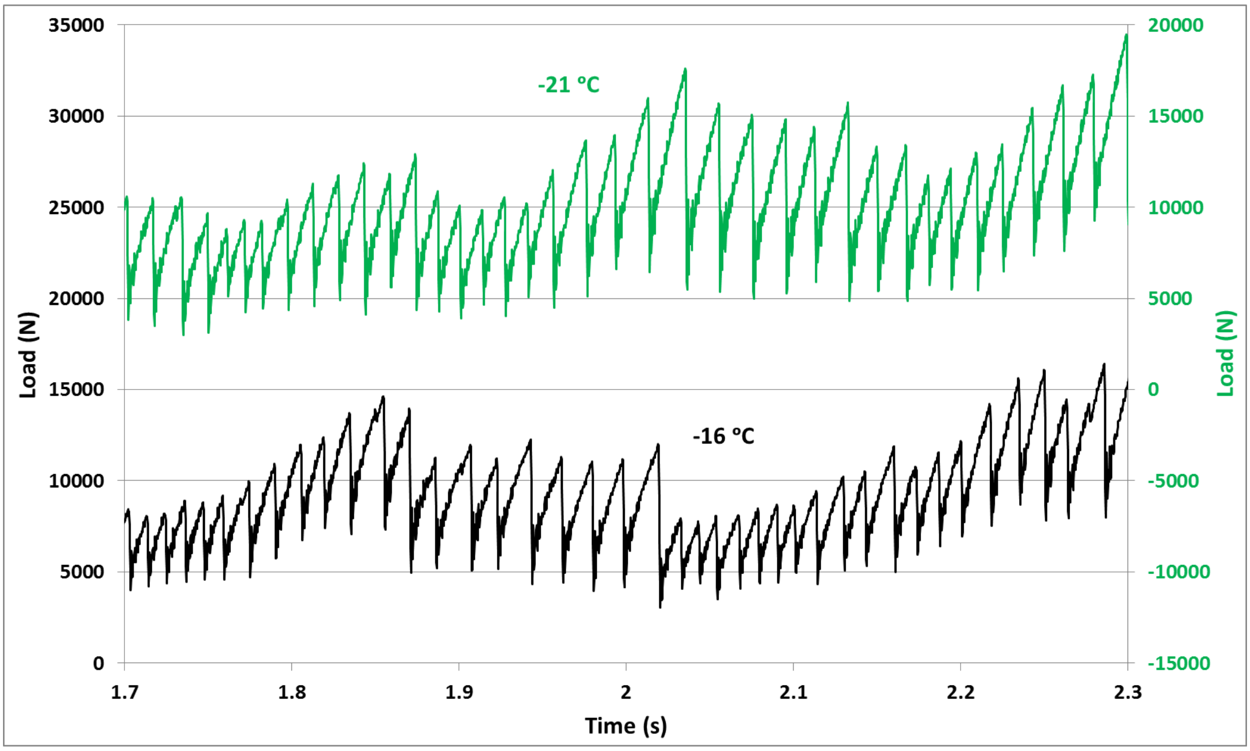

Figure 7. Comparison of load data from two tests using saline ice samples that were crushed against a Blade-Runners platen with an array of square-columns blades where one test was conducted at –16 °C and the other at – 21 °C.

EXPLANATION OF THE SALINE ICE CRUSHING BEHAVIOR AT SMALL-SCALE

We now present an explanation (in point form) of the initially perplexing observations, above, that not only relates to the Blade Runners technology but that also has implications regarding the use of saline ice in small-scale dynamic crushing tests in general. The explanation is based on the size and spacing of the brine and air filled channels/pockets in the ice, the similar size and spacing of the blades on the crushing platens and the shape and dimensions of the ice hard zone (relatively intact ice) that is characteristically present during crushing. Since we make reference to earlier crushing experiments using freshwater ice in the lab to test the Blade Runners technology that were successful in reducing IIV, we include an example (Figure 8.) for comparison with the present results.

Point 1. For saline ice crushing against a flat surface at -10 °C the interfacial pressure in the hard-zone area is lower than the value for freshwater ice (~55 MPa; Gagnon, 2016), but it is high enough to nucleate small

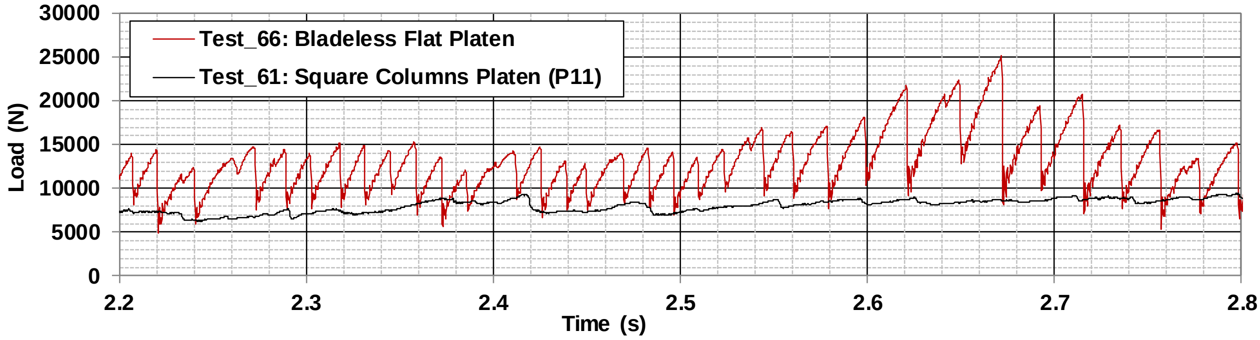

Figure 8. Partial load records from one of the best performing Blade Runners crushing platens (P11 – with square columns blades) and from a 'bladeless' flat acrylic platen. A typical high-amplitude sawtooth load pattern (HASLP) is evident for the test using the flat platen whereas the Blade Runners platen shows a dramatic reduction in HASLP. From Gagnon (2016).

uncoordinated spalls on the scale of the size and spacing of the brine channels/pockets that act as flaws in the ice (see Figure 8.). The lower interfacial pressure in the hard-zone region is due to the brine pockets and channels in the ice that reduce actual ice contact on the surfaces (i.e. lowering the average pressure) and that also make the ice more compliant due to grain-boundary sliding and reduced solid ice density. Small-scale spallation is facilitated by the fact that the hard-zone lateral span (its vertical extent in Figure 9.) is on the scale of the brine channels/pockets size and spacing that, as mentioned above, act as flaws.

The differences in hard-zone interface pressure between freshwater ice and saline ice were confirmed from observations of damage to the blades on acrylic platens. Several square-column blades (with 1 mm height) were partly or completely broken off at their base during the course of a few crushing tests for the freshwater ice case whereas no blades of that height were damaged when crushing saline ice. The cleavages were obviously from side forces on the blades that cause fracture at the base of the blade that expands outwards and away (plumose style) from the higher pressure side of the blade (i.e. generally upwards or downwards when viewing the high-speed images (Figure 9.), that is, perpendicular to the long axis of the linear hard zone, except at its ends. For saline ice the differential pressure on the opposing faces of a blade may be roughly ½ to ¼ that for freshwater ice from considering the moment exerted by a uniformly-distributed load on a cantilever beam, since we know that extensive blade damage did occur for square–column blades that were 2 mm in height while no damage occurred for blades that were 1 mm in height.

Point 2. Lowering the temperature to – 16 ^{o}C strengthens the ice enough to inhibit small-scale crack nucleation so that small spalls, and associated stress relief, do not occur. Consequently stress builds up in the bulk ice until a large spall occurs that is many times the size and spacing of the brine channels/pockets (Figure 10.), that is, HASLP occurs.

Point 3. Since the saline ice is more compliant and the hard-zone interface pressure is lower, as stated in point 1 above, in penetrating the hard-zone ice during crushing the blades do not create enough local differential pressure at the sides and/or tops of the blades to nucleate small spalls on the scale of the blades. Only large spalls that are many times the size of the blades are produced due to the large build ups of stress in the ice (i.e. HASLP), as though the blades were not present.

Point 4. It is anticipated that for full-scale testing of the Blade Runners technology in sea ice, or in large-scale tests in the lab using big saline ice samples, that the difference in scale will eliminate the peculiar behaviors observed during the small-scale tests on saline ice. That is, in the case of large lab-grown saline ice samples (or typical sea ice in the field), the size of the hard zones will be much greater than the size and spacing of brine channels/pockets so that the ice will exhibit HASLP throughout the typical range of ice temperatures (- 4 to -12 ^{o}C) when crushed against a flat surface. Furthermore, when the Blade Runners technology is used the blades, blade spacing and hard-zone size will be much greater than brine channels/pockets size and spacing. Hence, behavior related to similarity of scale of the blades and brine channels/pockets in the small-scale saline ice tests should be eliminated. In that case the blades will nucleate many relatively small uncoordinated spalls (on the scale of the blades) rather than repetitive large-scale spallations that cause HASLP. Under these realistic scaling conditions the ice presents itself as a uniform material.

Point 5. The interfacial pressure in the hard-zone regions may be higher for large-scale tests than small-scale tests for the same reasons outlined in Point 4, that is, the hard-zone size is much greater in size than the brine channel/pocket sizes and spacing so that confinement in the hard zone is greater. As mentioned above, the ice essentially presents itself as a uniform material at the large scale.

CONCLUSIONS

At –10 ^{o}C saline ice crushing against a flat platen leads to similar behavior that Blade Runners platens create when freshwater ice crushes against them. That is, the hard-zone ice region experiences many small uncoordinated spall events. In the latter case of the freshwater ice it is the blades that nucleate the tinny uncoordinated spalls whereas in the former case of the saline ice crushing against a flat platen it is the small closely-spaced flaws (brine channels/pockets) that serve as weak spots in the ice for small-spall cracks to nucleate.

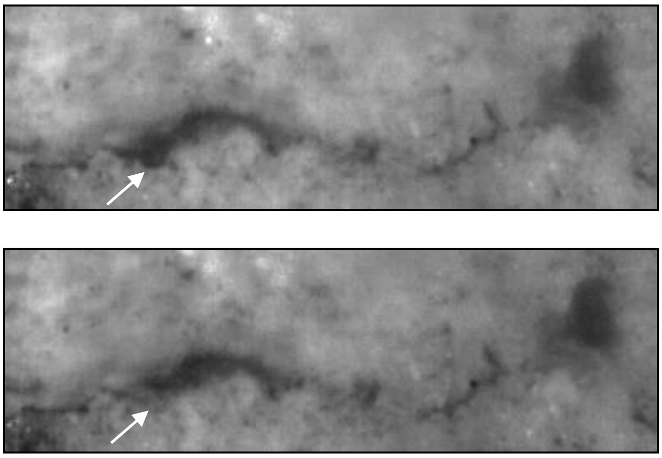

Figure 9. Two images from the high-speed imaging record, as viewed through the flat acrylic crushing platen, of a test where saline ice was crushed against the platen at a temperature and rate of -10 ^{o}C and 10 mm/s. A hard zone, the dark snake-like shape of varying thickness that spans the images, is visible. The white material above and below the hard zone is crushed ice, i.e. shattered spall debris. The top image was taken just prior to a small-scale spalling event (indicated by the arrow) and the bottom image was captured just afterwards. The width of the images is ~ 5.8 cm.

Considerable caution has to be exercised when using small-scale saline ice samples in lab tests to study the crushing behavior of full-scale sea ice. For example, high amplitude sawtooth load patterns, that typically occur when actual sea ice sheets crush against structures, will not occur unless the temperature for the small-scale lab tests is sufficiently low. Alternatively, it may be advisable in such studies to use freshwater ice samples instead since the ice's characteristic crushing behaviors, as observed in previous studies, reflect the behavior of full-scale sea ice for similar temperatures and crushing rates.

The difficulties that arise when using small-scale saline ice samples for crushing tests are due to the similarity of scale of the hard-zone region and the flaws (brine channels/pockets) in the ice. That is, at certain temperatures spalling behavior is highly influenced by the flaws since the vertical width of the elongated horizontal hard zone is roughly on the scale of the size and spacing of the inclusions. In the same vein, if the efficacy of a technology such as Blade Runners is being investigated in small-scale crushing experiments using saline ice the size and spacing of the blades will be unrealistically similar to that of the flaws in the ice (Figure 11.) so that results, whether favorable and unfavorable, may not be valid. To avoid this situation large-scale experiments, either in the lab or the field, are required to observe the actual behavior of sea ice and to properly test the Blade Runners technology.

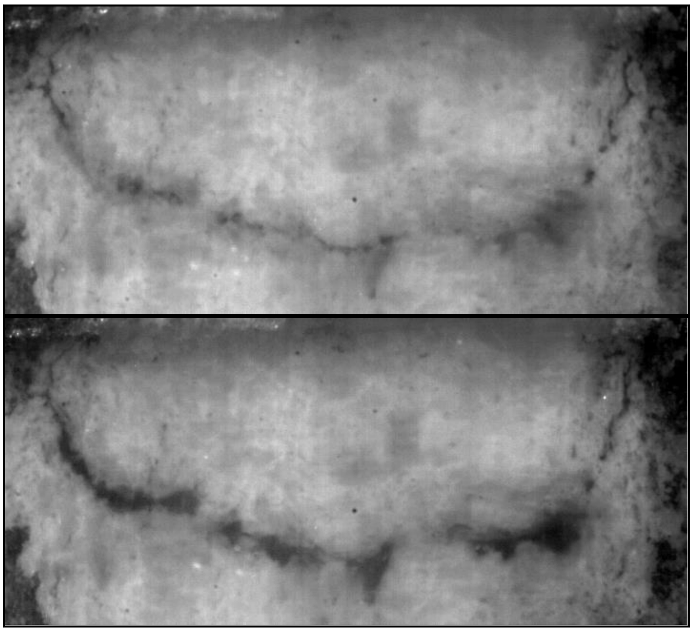

Figure 10. Two images from the high-speed imaging record, as viewed through the flat acrylic crushing platen, of a test where saline ice was crushed against the platen at a temperature and rate of -16 ^{o}C and 10 mm/s. A hard zone, the dark catenary-like shape of varying thickness that spans the images, is visible. The white material above and below the hard zone is crushed ice, i.e. shattered spall debris. The top image was taken just prior to a large-scale spalling event that spanned the full length of the hard zone and substantially reduced its thickness. The bottom image was captured just after the event. The width of the images is ~ 10.5 cm.

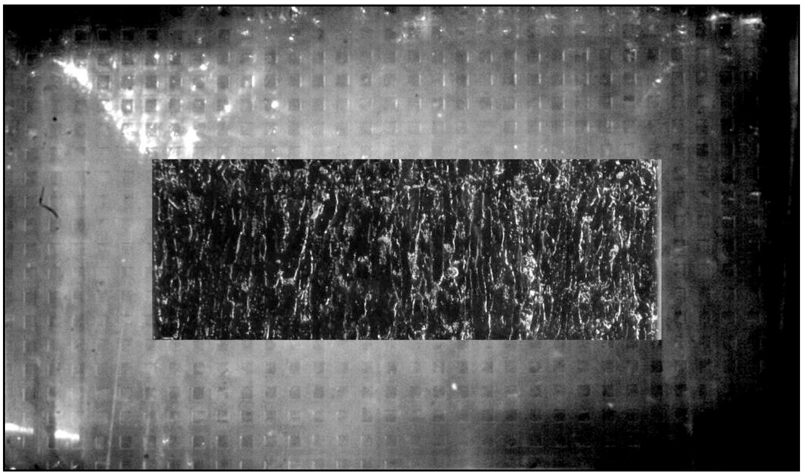

Figure 11. View through the acrylic crushing platen that had the square-columns blade array (square tops of the columns are visible in the image) just prior to a test. The wedge-shaped ice sample (light-colored object) is visible. A second image, the dark centrally-located rectangle, has been inset (at the same scale) on the central portion of the ice sample image. The inset is a photo of the brine and air filled channels/pockets in the ice obtained from a thin section. The size and spacing of the brine/air inclusions are on the scale of that of the square columns. The width of the image is ~13.2 cm.

ACKNOWLEDGEMENTS

I would like to thank Austin Bugden for technical assistance during the test program and analysis of results, and I am grateful to NRC for its support of this work.

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