22nd IAHR International Symposium on Ice
Singapore, August 11 to 15, 2014

First Lab Tests of the Blade Runners Concept for Reducing Ice Induced Vibration of Structures

R. Gagnon
Ocean, Coastal and River Engineering
National Research Council of Canada
St. John's, NL, Canada
robert.gagnon@nrc-cnrc.gc.ca

To test the Blade Runners concept for reducing ice induced vibration and loads on structures a simple configuration consisting of a single stationary blade on a rigid flat metal crushing plate was chosen for ice crushing tests in NRC-OCRE's Large Cold Room facility. Five wedge-shaped columnar-grained freshwater ice samples were crushed against a thick plate with a low-profile blade on it and the results were compared with those from another five crushing experiments using a plate without a blade. The two crushing plates were made of aluminum and had identical characteristics other than that one of them had a blade on it. The blade had an isosceles right triangular section profile with a height of 1 mm and base of 2 mm. The blade spanned the length of the plate and was centered relative to the wedge-shaped ice samples and parallel with their long axes. Tests were conducted at -10^{o}C and the nominal crushing plate displacement rate was 10 mm/s. High-speed imaging was used to observe the ice contact zone, by viewing through the ice samples, as it evolved and moved around somewhat during the tests. Load records from the tests using the bladeless crushing plate exhibited a high-amplitude sawtooth load pattern, resulting from fairly regular ice spalling events, that is typical of ice crushing in the brittle regime. This type of spalling behaviour, and associated sawtooth load pattern, is responsible for ice induced vibration of structures when ice sheets encroach on them. The average loads were roughly the same during either set of tests. However, for those tests where the plate with the blade on it was used it was observed that when the blade was in the hard zone region of the ice contact area the load pattern was dramatically affected. In those cases the blade effectively smoothed the sawtooth loading pattern by greatly increasing the spalling rate and reducing the spall size. Consequently the amplitudes of the load sawteeth were significantly reduced.

Proceedings of the 22nd IAHR International Symposium on Ice

ISBN: 978-981-09-0750-1
doi:10.3850/978-981-09-0750-1_1270

1. Introduction

Ice crushing induced vibration has been the subject of interest in many investigations ever since problems were first encountered for some offshore structures when ice sheets moved against them. 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. Various analytical and numerical approaches have been applied to explain ice crushing induced vibration. However, none have had the capability to explain the phenomenon as complexly manifested during Molikpaq episodes. Recently new understandings of ice crushing, with emphasis on spalling behavior, have been applied to the problem and when large-scale aspects of the ice are sufficiently taken into account this can explain ice-induced vibrations, including lock-in behavior (Gagnon, 2012).

The Molikpaq is a caisson-type structure that was designed for placement on an underwater sand berm that permits operations over a range of water depths. On May 12, 1986, a 7 km x 15 km ice floe comprised primarily of thick first-year ice with several multiyear ice inclusions began interacting with and loading the structure on its northeast and north faces. Extensive crushing was observed for a significant portion of the 27 minutes that the floe was moving. Cyclic oscillations in load occurred for much of the interaction and the load on the north face reached about 250 MN. More details are given in Gagnon (2012) and Jefferies (2010).

2. Concept Description

From the new understandings of the mechanisms that constitute spalling phenomena it should be possible to incorporate static (or active components) into the design of a structure's faces that could disrupt or control the ice spalling process. Studies such as the Hobson's Choice Ice Island tests and small-scale laboratory ice crushing tests have shown that the fractures that create spalls nucleate roughly from the central region of the ice-structure contact zone (Gagnon, 1998, 1999, 2008). In the case of the edge of an ice sheet interacting with a large structure we could envisage, in an idealised case, a linear series of static (or hydraulically-driven) horizontally-oriented relatively thin metallic 'blades'. These blades would punch/run slightly into the hard zone area of the ice contact region (Figures 1 and 2) to initiate/nucleate spall-creating fractures that would mitigate excessive cyclic loading and reduce loads. Note that every spalling event that occurs during ice crushing results in an abrupt reduction of load because a piece of ice breaks away from the intact ice and shatters. A realistic scenario would involve arrays of blades having suitable dimensions and spacing, that span the full horizontal extents of the structure faces.

3. Results from the Lab Tests

To test the Blade Runners concept a simple stationary configuration of a single blade on a flat metal plate was chosen for ice crushing tests in NRC-OCRE's Cold Room facility. The idea was to crush five samples of ice against a plate with a blade on it and compare those results with those from another five crushing experiments using a flat plate without a blade. The two plates were made of aluminum and had identical characteristics other than that one of the plates had a blade on it. Figure 3 is a photo of the ends of the two plates. The profile of the small triangular-shaped blade is visible on the top of the upper plate. Details of the plate with the blade on it are shown in Figure 4.

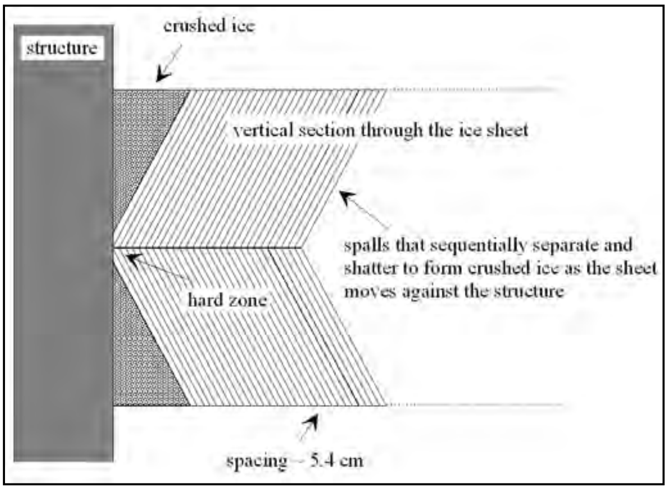

Figure 1. Schematic illustrating the sequence of spalls that will occur as an ice sheet moves to the left and crushes against the Molikpaq-type structure. Regions of relatively soft crushed ice, located above and below a central region of relatively intact hard ice, are also indicated. From Gagnon (2012).

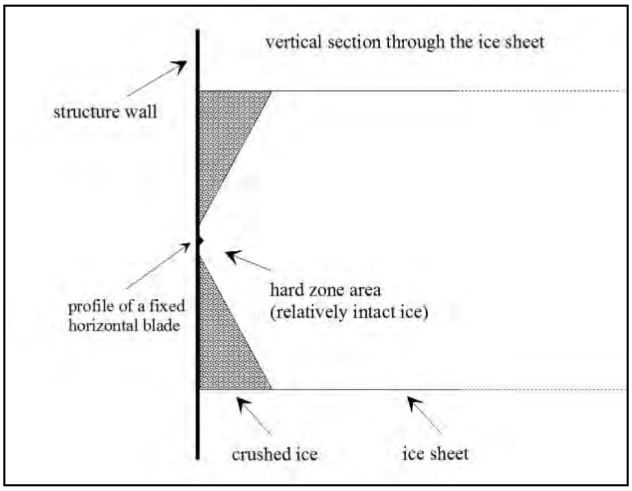

Figure 2. A schematic illustration of a single horizontal blade attached to a wall of a structure at an elevation so that it is inside the hard zone of an ice sheet interacting with the wall.

Figure 3. End views of the two aluminum plates used in the ice crushing experiments. The small triangular profile of the blade is visible on the top of the upper plate. The lower plate was bladeless.

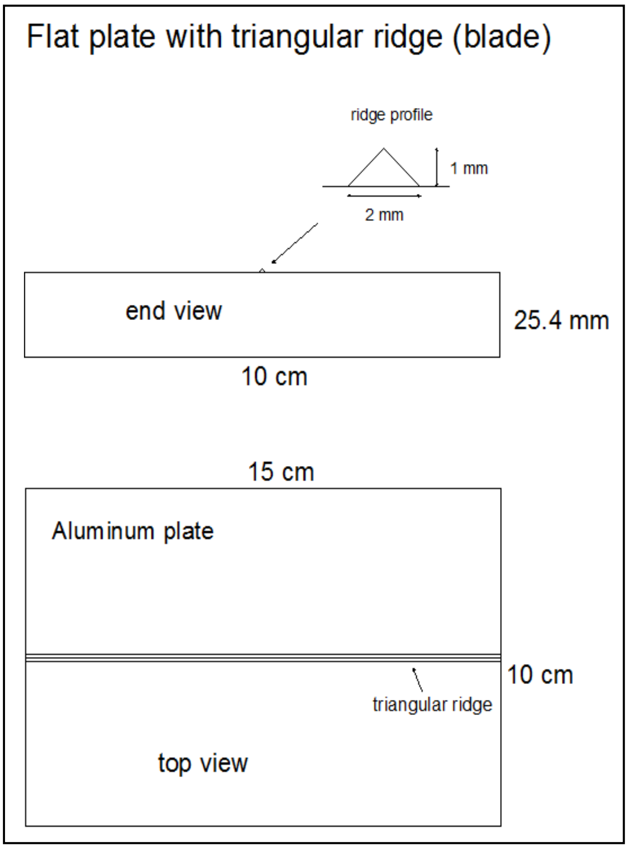

Figure 4. Schematic of the crushing plate that had a small triangular-shaped blade on its top surface.

A columnar-grained freshwater ice sheet, from which ice specimens were cut, was grown in a basin in a NRC-OCRE cold room. Columnar freshwater ice was chosen for the tests because it is fairly easy to grow and shape, and furthermore the ice in sea ice sheets is also columnar-grained. The grain structure of the ice is shown in Figures 5 and 6. The test setup is

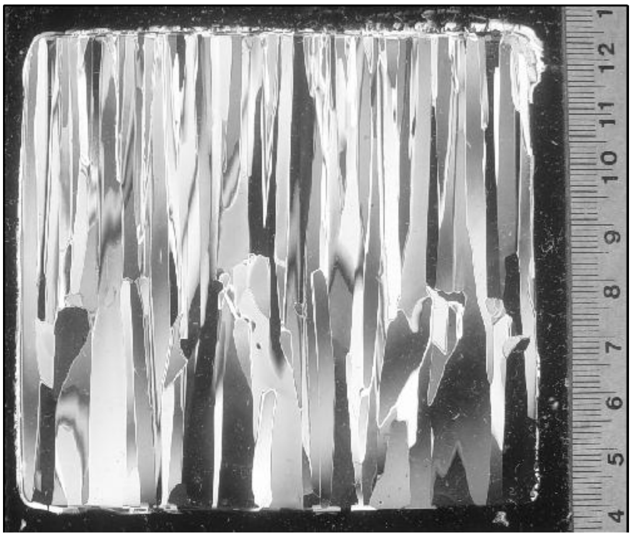

Figure 5. Thin section of the ice viewed through cross-polarized filters showing the columnar grain structure. The unit on the scale at the right is cm.

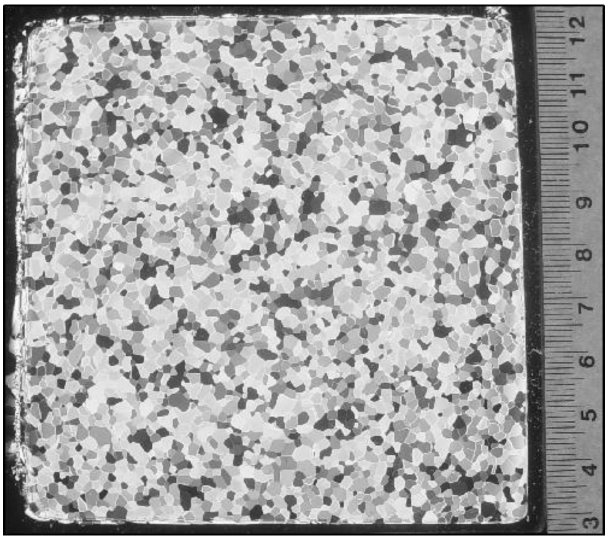

Figure 6. Thin section of the ice viewed through cross-polarized filters showing an end-on view of the columnar grain structure near the top of the ice sheet. The unit on the scale at the right is cm.

shown in Figure 7. The ice samples were confined at their bases by freezing them into the ice holders. The bottoms of the holders were made of acrylic to permit viewing of the ice crushing behaviour at the contact zone through the reasonably transparent bulk of the ice samples. Figures 7 and 8 show ice samples mounted in holders just prior to when the crushing plate was pushed against the ice at a constant rate. Note that Figure 8 shows the plate with the blade on it, visible directly below the ice specimen. Figure 7 shows the plate that did not have a blade on it. Tests were conducted at -10^{o}C and the nominal crushing plate displacement rate was 10 mm/s. The ice was crushed to a depth of approximately 3.4 cm for all tests. The ice samples were initially brick-shaped, as viewed from above, when cut from the ice sheet. Each sample was mounted on edge and lengthwise in its holder. The edge of the brick-shape that projected out of the ice holders was given a rounded wedge shape. In Figure 8 the columnar ice grains that make up the sample are oriented horizontally and their long axes are perpendicular to the direction of view.

A key aspect of this technology is that for a blade to be effective it must be positioned in the hard zone region of ice contact. High speed imaging observations of the ice contact zone, as viewed through the ice samples themselves, showed that for three of the tests where the plate with the blade was used, the hard zone region of the ice contact zone was not at

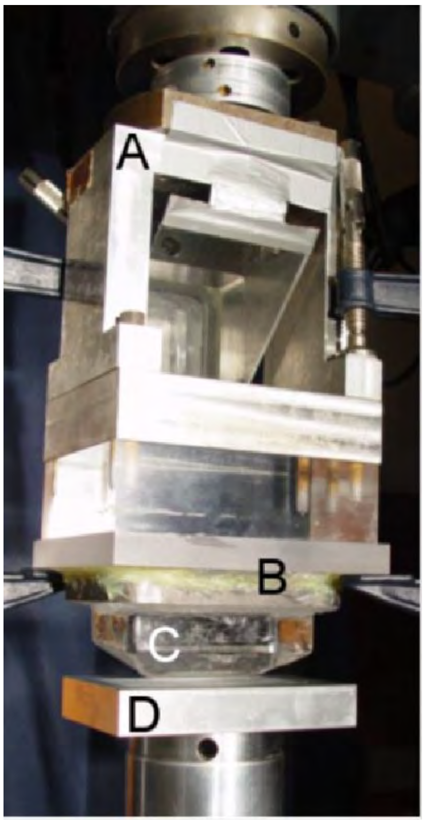

Figure 7. Test setup. (A) Strong housing for the viewing mirror. (B) Acrylic and steel Ice holder. (C) Ice sample. (D) Aluminum crushing plate.

the location of the blade, that is, the hard zone was for most of the test duration somewhere to either side of the blade and was therefore not influenced by the blade. This was caused by the high degree of unrealistic confinement of the ice attributable to the ice holder that would not be the case if, for example, the edge of an ice sheet was crushed against the plate. In that case the hard zone would have stayed quite localized in the mid region of the sheet thickness, as has been shown in real ice edge crushing experiments (e.g. Frederking, 2004; Määttänen et al., 2011; Sodhi et al., 2001; Takeuchi et al., 1997). Fortunately, for two of the present tests the video records showed that the hard zone of the ice contact was in the blade region and consequently the load record was affected. The nature of the effect is best described by viewing the load record from a typical test (Test #1) without the blade and a load record from one of the tests with the blade where it was well-positioned relative to the hard zone of the ice contact (Test #4).

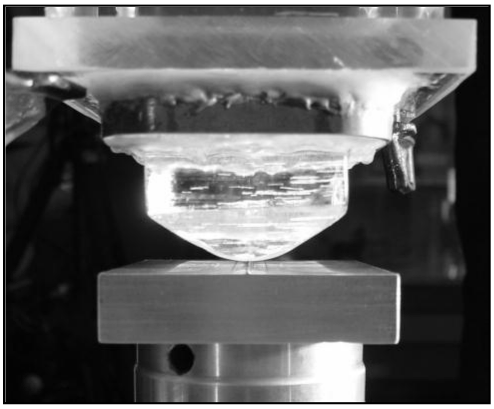

Figure 8. End view of an ice sample mounted in an ice holder positioned above a crushing plate that has a blade just prior to a crushing test. The small triangular-shaped blade is visible directly below the ice specimen.

Figures 9 and 10 show the complete load time series for the cases where the blade was present and when it was not. The two records are distinctly different in that there are a large number of sawtooth oscillations in the record corresponding to the ‘no blade’ case, whereas the ‘blade’

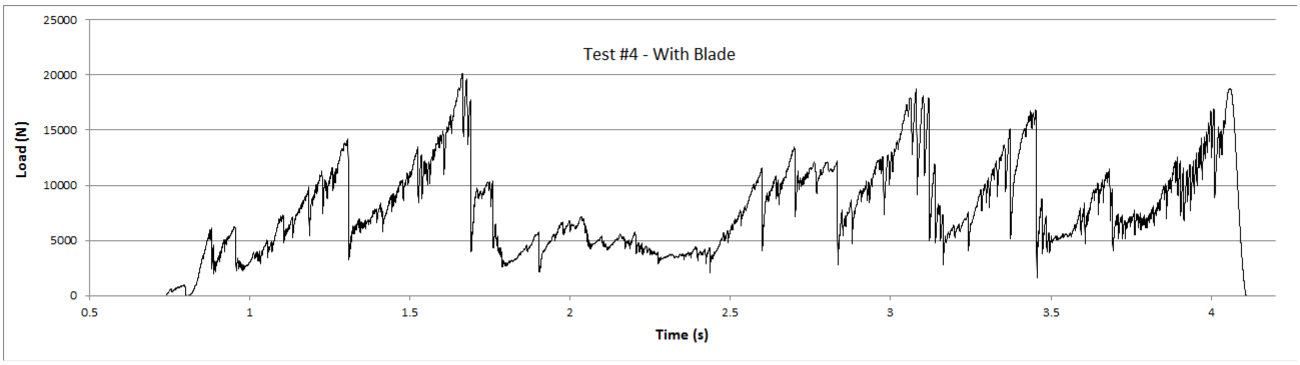

Figure 9. Load time series for Test #4 where the crushing plate had a blade on it.

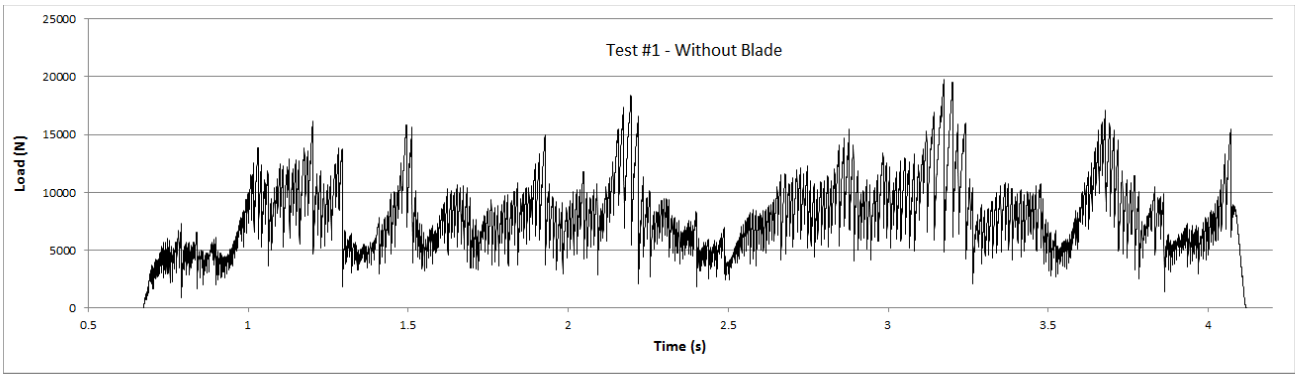

Figure 10. Load time series for Test #1 where the crushing plate did not have a blade on it.

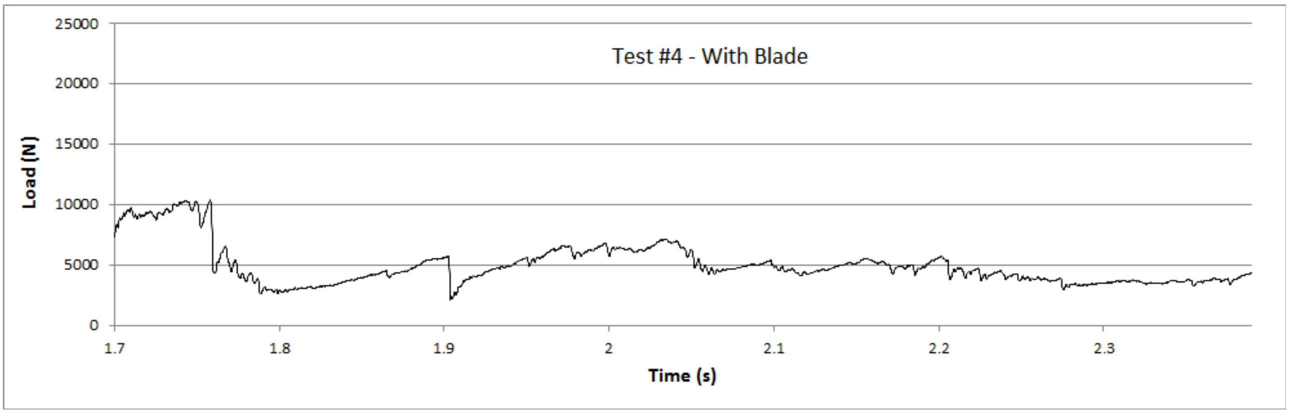

Figure 11. Expanded view of a segment of data from the load time series for Test #4.

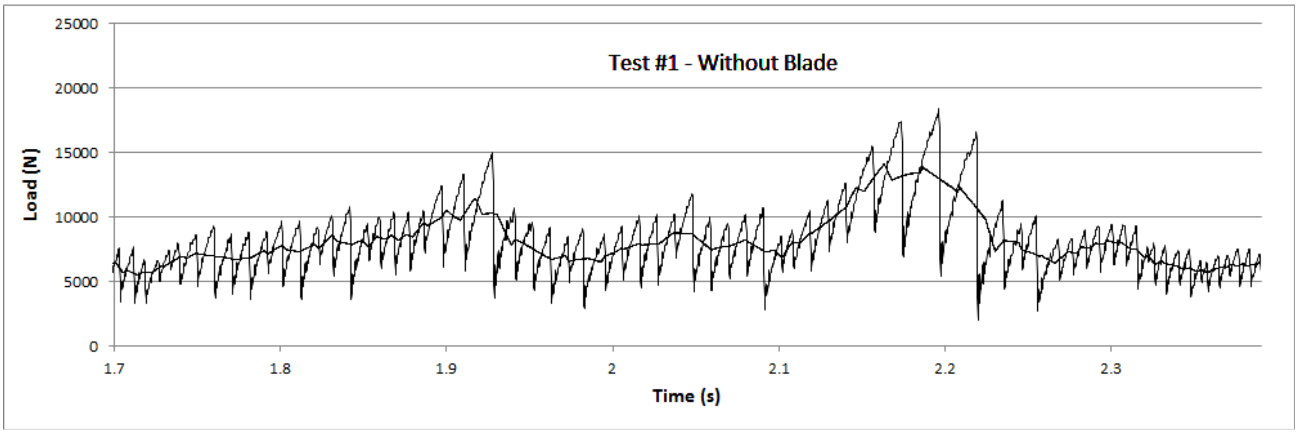

Figure 12. Expanded view of a segment of data from the load time series for Test #1. The second trace overlying the actual load data is a running average of the real data that roughly illustrates the anticipated effect on the load trace that a blade would have had.

case shows relatively few sawtooth oscillations. Figures 11 and 12 show expanded views of segments from the two load records so that the presence and absence of the sawtooth episodes is more clearly visible. The frequency domain plots of the records are also instructive (Figure 13).

The physical behaviour of the ice during the crushing is responsible for the load record characteristics in both cases. The key thing to note is that an ice spalling event is responsible for the sharp drop in load associated with any particular load sawtooth. A spalling event generally refers to what happens when a portion of relatively intact ice, a hard zone, rapidly separates from the ice contact region and shatters, leading to a sudden drop in load. The shattered spalls have properties of crushed ice that is capable of supporting low pressure, whereas the remaining hard-zone ice will be relatively intact and is capable of supporting high pressure. In the case where no blade is present the spacing of the load sawteeth is such that there is significant build-up of elastic stress in the ice/apparatus system between spalling events, hence the load sawteeth have high amplitudes. In the case where the blade is present there are still spalling events occurring, and associated load sawteeth, however the frequency of the sawtooth pattern is much higher than in the previous case and there is consequently much less elastic stress build-up in the ice/apparatus between the events. Hence the amplitudes of the sawteeth are very small and barely

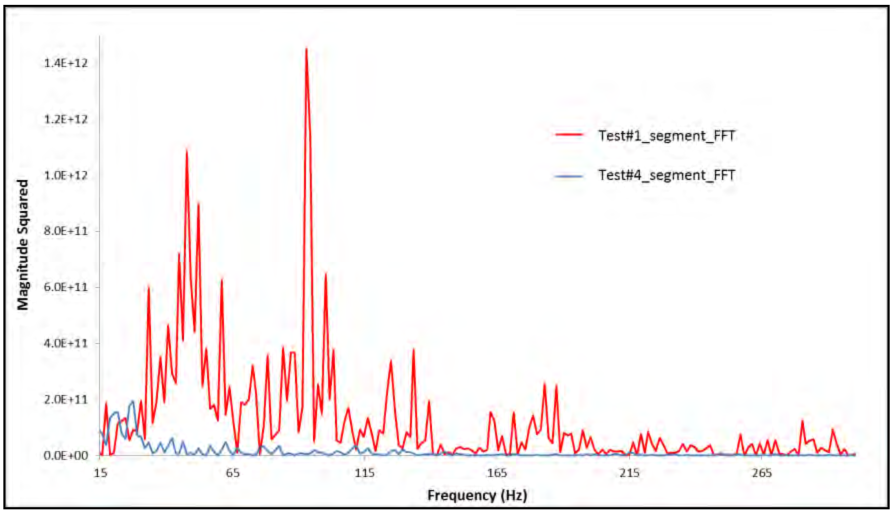

Figure 13. Magnitude-squared frequency domain plots, obtained from Fourier transforms of the time domain load traces in Figures 11 and 12, showing power amplitudes at respective frequencies. Note that the high amplitude peaks associated with the 'no blade' case (Test#1) are substantially reduced in the case with the blade (Test#4).

discernible compared to the 'no-blade' case. The effect of the blade is to initiate many more spalling events than would have occurred with a bladeless crushing plate. From previous experiments (mentioned above) it was observed that spalling events initiate from the central region of the hard zones during ice crushing. In the present tests the blade accelerates the initiation of spalling events dramatically.

Statistics from the present tests indicated that the average loads over the durations of the tests were roughly the same regardless of the presence or absence of the blade. The effect of the blade is to greatly increase the frequency of spalling events and in so doing reduce the size of the spalls and the associated amplitudes of the load sawteeth. The second trace overlying the actual load data in Figure 12 is a running average of the actual data to roughly illustrate the anticipated effect on the load trace that a blade would have had in that particular test.

4. Conclusions

In these first tests of the blade runners technology it was observed that the blade effectively mitigated large-amplitude sawtooth loading by increasing the spalling rate and consequently reducing the sawtooth load amplitude. Note that the main characteristics of ice crushing behaviour apply to a wide range of scale size (Gagnon, 1999). Hence the type of blade effect observed here would be very beneficial in the case of a large offshore structure against which an ice sheet is moving and crushing, such as occurred with the Molikpaq structure in the Beaufort Sea in 1986. Very large oscillations of the structure occurred as the result of the sawtooth load pattern that developed as the ice sheet advanced (Gagnon, 2012). We would expect that had there been a stationary blade, appropriately scaled, horizontally-oriented, spanning the width of the structure and positioned in the middle of the ice sheet thickness that the large and dangerous spalling-induced oscillations of the structure would not have occurred. Figure 14 shows actual sawtooth load data from the May 12, 1986 Molikpaq event. The second data trace on the chart is simply a linear fit to the load data that roughly approximates the anticipated load trace that would have resulted if a stationary blade had been installed on the north face of the Molikpaq structure.

5. Acknowledgements

I would like to thank Darrell Sparkes for technical assistance during the test program and I am grateful to NRC for its support of this work.

6. References

Frederking, R., 2004. Ice Pressure Variations during Indentation. Proc. IAHR Symposium on Ice, St. Petersburg, Russia, pp. 307–314.

Gagnon, R.E., 1998. Analysis of Visual Data from Medium Scale Indentation Experiments at Hobson's Choice Ice Island. Cold Regions Science and Technology, Vol. 28, 45-58.

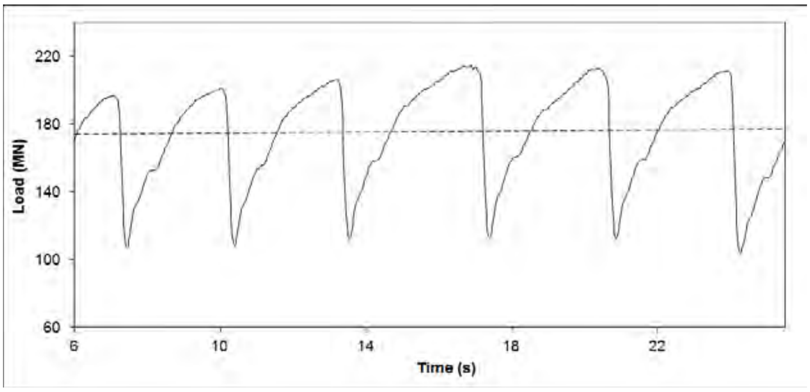

Figure 14. Actual sawtooth load data from the May 12, 1986 Molikpaq event. The dashed-line trace on the chart is a linear fit to the load data that roughly approximates the anticipated load trace that would have resulted had a stationary horizontally-oriented blade been installed on the north face of the Molikpaq structure.

Gagnon, R.E., 1999. Consistent observations of ice crushing in laboratory tests and field experiments covering three orders of magnitude in scale. Proc. POAC-99, Helsinki, Finland, 2, pp. 858–869.

Gagnon, R.E., 2008. High-speed imaging of mechanisms responsible for sawtooth cyclic loading during ice crushing. Proceedings of IAHR 2008, Vancouver, Canada, volume 2, pp. 983–991.

Gagnon, R., 2012. An Explanation for the Molikpaq May 12, 1986 Event. Cold Regions Science and Technology 82 (2012) 75-93.

Jefferies, M., 2010. Molikpaq dynamic ice–structure interaction at Amauligak 1985–6: measurements and data. Ice Induced Vibrations JIP workshop 29th -30th of November, Oslo, Norway. Copies can be obtained from M. Jefferies at geomek@hotmail.com.

Määttänen, M., Marjavaara, P., Saarinen, S., 2011. Ice crushing pressure distribution against a compliant stiffened panel. Proc. 21st Int. Conf. On Port and Ocean Engineering under Arctic Conditions, Montreal, Canada, POAC 2011, paper #038.

Sodhi, D.S., Takeuchi, T., Nakazawa, N., Kawamura, S.A.M., 2001. Measurements of ice force and interfacial pressure during medium-scale indentation tests in Japan. Proc. 16th International Conference on Port and Ocean Engineering under Arctic Conditions, Ottawa, Ontario, Canada, pp. 617–626.

Takeuchi, T., Masaki, T., Akagawa, S., Kawamura, M., Nakazawa, N., Terashima, T., Honda, H., Saeki, H., Hirayama, K., 1997. Medium-scale field indentation tests (MSFIT)—ice failure characteristics in ice/structure interactions. Proc. of the 7th Int. Offshore and Polar Engineering Conference, Honolulu, USA, vol. II, pp. 376–382.