Proceedings of The Fourteenth (2004) International Offshore and Polar Engineering Conference
Toulon, France, May 23–28, 2004

ISBN 1-880653-62-1 (Set); ISSN 1098-6189 (Set)

The Flexural Strength of Partially Refrozen Cracks in Sea Ice

Patricia J. Langhorne
Department of Physics, University of Otago,
P.O. Box 56, Dunedin, New Zealand
Timothy G. Haskell
Industrial Research Ltd,
P.O. Box 31-310, Lower Hutt, New Zealand

ABSTRACT

Flooded cracks in first year sea ice refreeze rapidly, their physical and mechanical properties being governed by heat flow to the ice-air interface and laterally to the surrounding ice sheet. Here we investigate the crack strength by first finding the flexural strength of the pristine ice sheet using an *in situ* cantilever beam test. An artificial crack was then formed at the hinge of the beam and allowed to refreeze. The flexural strength of the ice containing the partially refrozen crack was then tested, and examined as a function of refreezing time and of crack width. The results are interpreted in relation to the brine fraction within the partially refrozen crack.

KEY WORDS: Refrozen cracks; land-fast; sea-ice; cantilever beam; flexural strength

INTRODUCTION

Linear cracks are a feature of first year sea ice in regions where the ice sheet is under stress from wind, ocean currents, temperature change or the motion of terrestrial ice. Bending cracks may appear in an ice cover where the water level changes, perhaps due to tidal activity near a shore or structure. Some such cracks remain dry after formation, but many fill with water and refreeze, provided the surrounding temperatures are low enough. By refreezing, the structural integrity of the sea ice sheet is regained. However it is not known whether the refrozen crack provides a line of weakness or strength within the sea ice sheet, and in what way this depends on the width of the crack or the time available for the freezing process to take place.

In spite of their widespread existence in sea ice, refrozen cracks have received relatively little attention, often being relegated to minor discussion within a paper on another topic. For example, Weeks and Ackley (1982) describe the arch-shaped ice-water interface resulting from two-dimensional heat flow and propose that the preferential direction for the c-axes in a linear crack will be parallel to the long-side of the crack.

Recently our group has conducted a study to examine and model the physical properties of refrozen cracks in sea ice (Divett, unpublished; Petrich et al, 2002; 2003). Recognising that during much of the polar year brine-filled cracks refreeze rapidly, Petrich et al (2003) have shown that the shape of the freezing front is governed by heat flow to the ice-air interface and laterally to the surrounding ice sheet. This pattern of refreezing generates salinity, temperature, brine inclusion and crystal orientation profiles that differ markedly from those seen in a uniform sea ice sheet. The physical properties of such a refrozen crack have been examined experimentally in the laboratory (Divett, unpublished) and in first year sea ice (Petrich et al, 2003), and their development has been modelled by finite volume analysis (Petrich et al, 2002).

Cracks in freshwater ice have been more closely scrutinised. In his thesis, which is a study of thermal cracks in lake ice, Metge (unpublished) deals with the rate of refreezing at the centre of these parallel-sided cracks. Other geometries have also been studied. From laboratory experiments, Christensen (1986) provides a formula for the strength of partially refrozen, flooded, bending cracks in floating freshwater ice sheet at any time after initial cracking. An opening angle and the temperature-time product parameterised the wedge-shaped cracks of this study. The ratio of force required to fracture the ice sheet containing the refrozen crack, to that to fracture the pristine ice sheet was derived in terms of these parameters. Natural ice from icebergs has also been examined. Tests, conducted to determine the effect of healed cracks in iceberg ice on the flexural strength of the material (Barrette and Jordaan, 2002), have been inconclusive, although these cracks are not believed to have been flooded then refrozen.

In the present paper we are concerned with the refreezing of fluid-filled, parallel-sided, linear cracks through the entire sea ice thickness. These cracks are generated artificially in the host sea ice sheet, fill rapidly with seawater and have connection with ocean beneath (see Fig. 1). It is assumed that the dimension perpendicular to the width, x, of the crack is infinite and that the air temperature is well below freezing, ensuring rapid refreezing of the crack. The aspect ratios of the cracks in this study are h/x = 7 to 70 (see Fig 1). The aim of this project is to determine the flexural strength of a sea ice sheet containing a crack of width, x, which has been allowed to refreeze for time, t. The measurements will be considered in terms of the apparent flexural strength of the refrozen material of the crack in relation to its brine content.

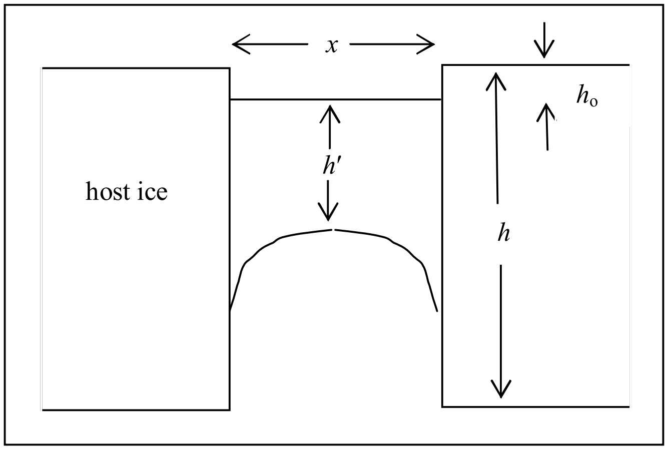

Fig. 1: Schematic diagram of partially refrozen crack

EXPERIMENT

The Host Ice

The experiments described in this paper were carried out in the austral spring of 1998 and 1999 on the first year landfast sea ice of McMurdo Sound, Antarctica. There was little evidence of surface rafting in the areas chosen for the experiments. In 1998 a probe, frozen into the sea ice sheet, provided temperature profiles (see Fig. 2(a)), while in 1999 the only temperature measurements available in the host sheet were those measured in cores taken in the sea ice. The salinity profiles of Fig. 2(b) show that the ice displayed the expected C-shaped profile (Weeks and Ackley, 1982), and that these ice properties were similar over the consecutive years observed, although the ice thickness was approximately h = 1.81 m at the site of the 1998 experiments, compared with h = 1.92 m in 1999. These salinity and temperature profiles have been plotted as a function of depth below the upper ice surface. From the salinity and temperature measurements (Frankenstein and Garner, 1967), we display in Fig 3 representative values of brine fraction for the host ice. Note that these data are plotted as a function of distance below the water level to make them easier to compare with data from refrozen

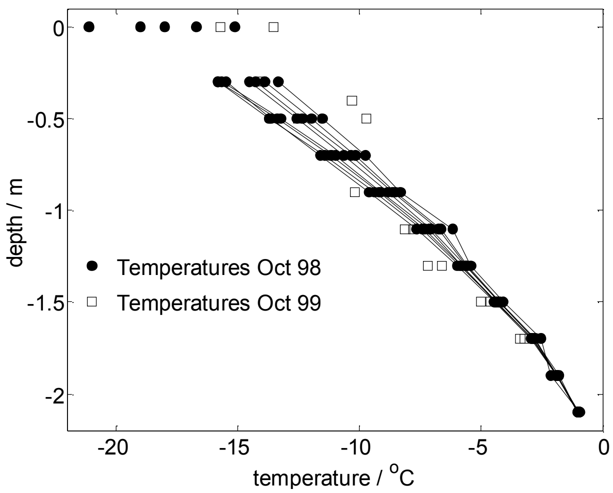

Fig. 2(a): Temperature as a function of depth in the sea ice sheet for 1998 and 1999

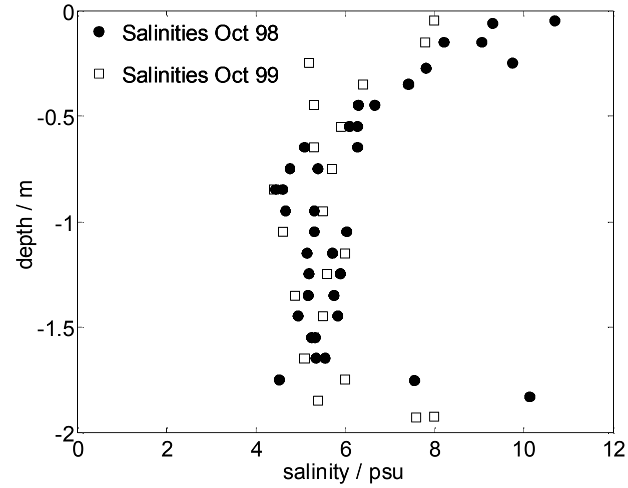

Fig. 2(b): Salinity as a function of depth in the sea ice sheet for 1998 and 1999.

cracks. The freeboards measured in the experiments were in the range h_o = 0.12 to 0.18 m.

The refrozen crack

The artificial cracks in the sea ice sheet were produced in one of two ways. In the first method, a fracture through the ice sheet was formed at the hinge of an *in situ* cantilever beam during a flexural strength test of the host ice sheet. Immediately after the test, the free-floating beam was moved to form a crack of the desired width at the hinge. This was then allowed to refreeze for the desired time. This type of artificial crack formation was used in both 1998 and 1999. In the second method, which was used during the field work of 1999, slots were cut through the sea ice sheet using a ditch digger with an extended arm. One such slot was instrumented with temperature sensors, while others were excavated at various times after refreezing to measure the salinity distribution and structural characteristics in the refreezing cracks. Data

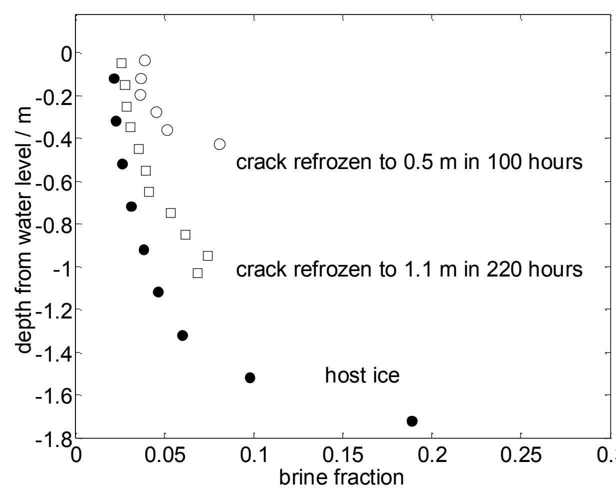

Fig. 3: Brine fraction in the ice as a function of depth below the water level. Filled circles are representative values for the sea ice sheets of 1998 and 1999. Open symbols are representative of a partially refrozen crack of width 120 mm.

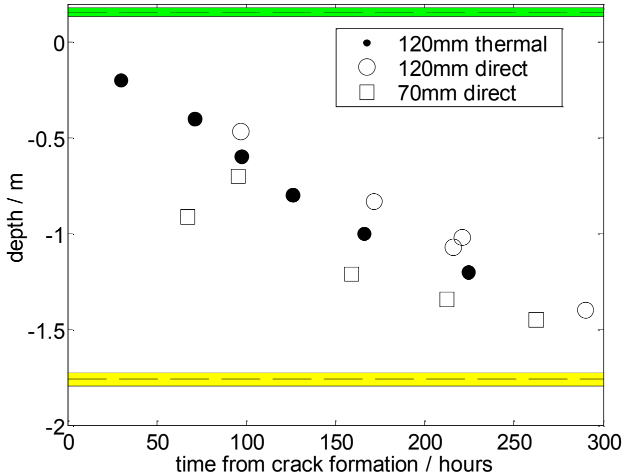

Fig 4(a): Progress of refreezing in cracks of 70 mm and 120 mm widths. Range of freeboard and ice thickness measurements are shown by the bands above and below the data respectively. All depths are referenced to the water level.

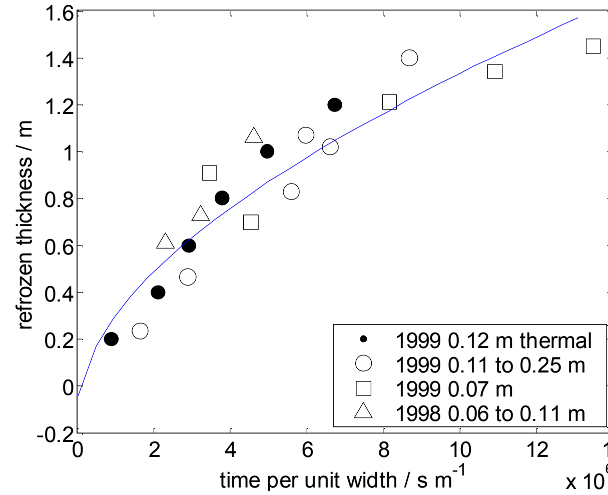

Fig. 4(b): Refrozen crack thickness for a range of crack widths from 60 to 250 mm, fitted by equation (1).

from vertical temperature measurements at a crack centre are combined with salinity profiles at two times after the commencement of refreezing to produce the brine fraction profiles in the crack shown in Fig 3. It can be seen that the warmer temperature and higher salinity at the centre of the crack causes the liquid content of the sea ice at a given depth to be higher than that in the host ice at the same vertical level.

The refrozen thickness, h', of ice in the crack has been derived from temperature measurements at the centre of a slot of width x = 120 mm. These are plotted as a function of time in Fig. 4(a). Direct measurements of crack thickness for slots and cracks of x = 70 and 120 mm are also shown on Fig 4(a). It is clear from Fig. 4(a) that wider cracks freeze less rapidly than narrower ones. Hence we plot refrozen thickness, h', as a function of time per unit width, t/x, in Fig 4(b) and find that the data for a range of crack widths (0.06 to 0.25 m) are approximated by a polynomial curve in $\left(t/x\right)^{1/2}$ of the form

$$h' = A\left(\frac{t}{x}\right) + B\left(\frac{t}{x}\right)^{1/2} + C \qquad (1)$$

where A, B and C are constants, fitted by our data such that $A = 1.68 \times 10^{-8}\ \mathrm{m^2 s^{-1}}$, $B = 1.09 \times 10^{-4}\ (\mathrm{ms})^{-1/2}$ and $C = -0.13$ m. The relationship between refrozen thickness, h', and $(t/x)^{1/2}$ is the classic Stefan term. The linear relationship between h' and t/x, the dominant term at small times, has previously been included in the modelling of the formation of thin ice in leads (Wettlaufer et al, 2000). We use this empirical relationship to estimate the crack thickness in cases where this has not been measured.

The flexural strength

The flexural strength of the sea ice sheet was measured by loading the free end of an *in situ* cantilever beam to fracture. Experimental details of the mechanical testing are provided in Haskell et al (1996) and Langhorne and Haskell (1996). The beams were nominally 10 m in length. Load and displacement were measured at the free end of the beam, and strain was measured at the hinge. In earlier measurements of the *in situ* fatigue properties of sea ice using similar techniques to those described here (Langhorne and Haskell, 1998), the position of the neutral plane was derived from the measured brine volume profiles in the sea ice sheet and the stress at the upper ice surface was estimated assuming the sea ice sheet was horizontally isotropic. Further, corrections for the influence of buoyancy, for the deflection and rotation of the plate supporting the cantilever beam and for the deflection due to shear (Frederking and Timco, 1983) were applied to the measurement of the deflection at the free end of the beam (Langhorne and Haskell, 1996). These corrections, along with a vertical variation of the sea ice modulus, adjust the stress by up to 10% in some circumstances, but more generally the adjustment is of the order of 5%. In the present experiments the difficulty in monitoring the temperature and salinity profiles through each of the cracks has forced us to assume that the material of the refrozen crack is homogeneous. Consequently, for the purposes of this paper, we make a similar assumption for the host ice.

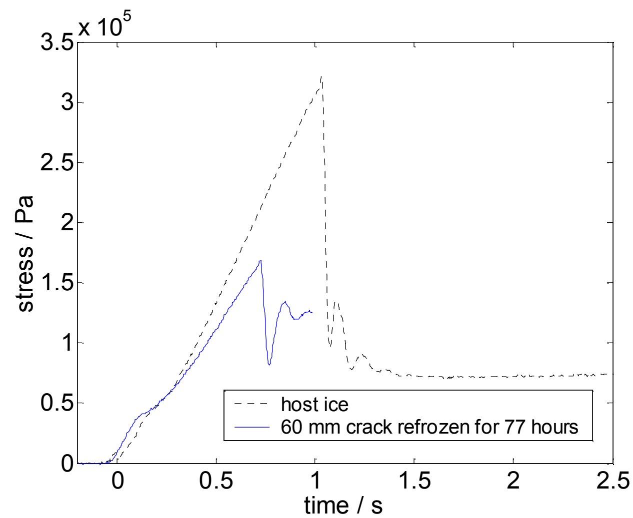

Fig. 5: Samples of stress-time data for the host ice and for the ice containing a 60 mm crack that has been allowed to refreeze for 77 hours.

The flexural strength of the host ice sheet, σ, was calculated using the elastic flexure formula for a cantilever beam of rectangular section,

$$\sigma = \frac{6Pl}{bh^2} \qquad (2)$$

where P is the load applied to fracture the beam, l is the length between fracture plane at the hinge of the beam and the load, b is the width of the beam and h is the ice thickness. Values of σ are given in Table 1.

An artificial crack was then formed at the hinge of the beam and this was allowed to refreeze. The "flexural strength" of the sea ice sheet, σ', with the refrozen crack at its hinge is then tested, and calculated according to

$$\sigma' = \frac{6P'l'}{bh^2} \qquad (3)$$

where P' is the load applied to fracture the beam containing the refrozen crack and l' is the length between fracture plane at the hinge of the beam and the load. The thickness of the ice sheet was used in this calculation as it was intended that this quantity should be representative of the ice sheet. An example of the stress-time profile for the pristine ice sheet, and that containing a partially refrozen crack is shown in Fig. 5. In both cases, the loading time to failure is of the order of 1 second in accordance with the recommendation of Schwarz et al (1981) when testing *in situ* beams of ice. Values of σ' are also given in Table 1.

Table 1. Flexural strength data

x mm	σ kPa	σ' kPa	t hour	h m	h' m	year & comment
30	355	210	78	1.81	0.81	98 0^{o+}
60	322	169	77	1.83	1.06	98 0^{o+}
80	328	60	72	1.82	0.73	98 0^{o+}
110	348	0	71	1.80	0.61	98 0^{o+}
26	403	215	95	1.82	-	98 90^{o+}
55	326	133	94	1.80	-	98 45^{o+}
-	379	-	-	1.79	-	98 135^{o+}
-	474	-	-	1.81	-	98 90^{o+}
50	-	98	216*	1.80	1.47	98 natural
70	307	77	68	1.92	0.91	99 random$^{\$}$
75	320	159	95	1.92	0.7	99 random$^{\$}$
70	360	228	159	1.93	0.21	99 random$^{\$}$
70	370	245	213	1.89	1.34	99 random$^{\$}$
70	362	230	263	1.91	.145	99 random$^{\$}$

*estimated from time of arrival at field site;
$^{+}$ angle between long axis of beam and dominant c-axis direction at depth in the host ice sheet;
$^{\$}$ the c-axes of the ice sheet in 1999 were not strongly aligned.

In most cases crack thicknesses, h', were estimated at the end of the experiment by cutting, from the ice sheet, a 1 m by 1 m block containing the partially refrozen crack. This was lifted up onto the ice surface for examination. One natural crack was found at the field site. Unfortunately we can only guess the time at which this crack formed. Figure 6(a) shows the flexural strength as a function of crack refreezing time, and Fig 6(b) as a function of crack width.

Note that the flexural strength of the host ice in Fig 6(b) is dependent on the relative orientation of the long axis of the beam and the dominant c-axis found at depth in the sea ice sheet. This alignment of c-axes is believed to be due to the tidal current which is predominant in the north-south direction in this area. Those beams with the long axis perpendicular to the c-axes were found to have a higher flexural strength. We would not expect this current-dependent variation in strength to exist in the refrozen material of the cracks. No such c-axis alignment and orientation-dependent flexural strength were noted at the site occupied in 1999.

In order to interpret the results of Fig. 6 we assume that a beam of thickness h containing a refrozen crack of thickness h' at the hinge behaves in the same way as a beam of thickness h' formed from the refrozen material. We postulate that the flexural strength of the refrozen material is equal to that of the host ice. In this case

$$\sigma = \frac{6Pl}{bh^2} = \frac{6P'l'}{bh'^2}\,. \qquad (4)$$

The strength ratio, σ'/σ, is given by

$$\frac{\sigma'}{\sigma} = \left(\frac{P'l'}{Pl}\right) = \left(\frac{h'}{h}\right)^2, \qquad (5)$$

where the left hand equality follows from equations (2) and (3), and the right hand one from equation (4). Our data have been plotted in this way in Fig. 7, where the line is the relationship of equation (5). It can be seen that the data suggest that the material of the partially refrozen crack has a higher flexural strength than that of the surrounding ice.

DISCUSSION

It can be seen from Fig. 3 that the brine fraction in a refrozen crack is higher than the brine fraction at same depth in the host ice sheet. Timco and O'Brien (1994) have presented a correlation between the flexural strength of sea ice and its average brine fraction. In their case, the average brine volume was calculated from an average temperature and an average salinity, both of which were assumed constant through the sea ice sheet. Using temperature and salinity averages from the profiles of Fig. 2 in Timco and O'Brien's correlation, we find a predicted flexural strength for the host ice sheet of 550 ± 30 kPa, well above the measured values shown in Fig. 6 which lie in the range 310 to 480 kPa. From our knowledge of the brine fraction in the crack, the prediction for the flexural strength of the refrozen material after 100 hours of freezing is 480 ± 20 kPa, rising to 510 ± 20 kPa at 220 hours (see brine fractions of Fig. 3). However, we add a note of caution. If the brine volume profile of Fig. 3 is converted to a flexural strength profile which is then averaged through the ice sheet then the predicted flexural strengths of host and partially refrozen crack are all within 515 ± 15 kPa. In other words, the result obtained depends upon how the averaging of the physical properties is performed. We conclude that the errors in the estimation of sea ice strength are too large for us to detect a difference in flexural strength between the host ice and the material of the partially refrozen crack based on brine fraction differences alone.

Let us consider the conclusions we may draw from Fig. 7. If the measured strength of the sea ice sheet containing a partially refrozen crack was governed only by the change in thickness of the ice sheet at

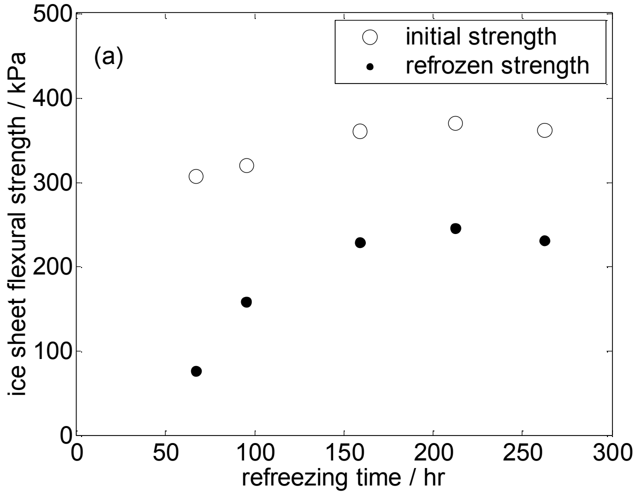

Fig. 6(a): Ice sheet flexural strength versus refreezing time. Initial ice sheet strengths are shown at corresponding times to the refrozen data. The crack width is 70 ± 3 mm for these data.

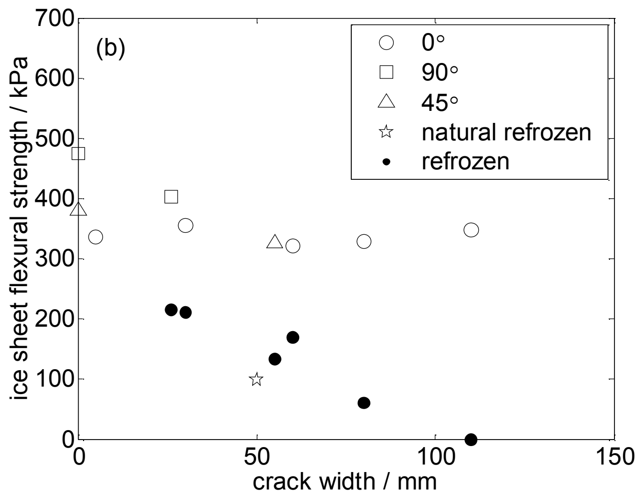

Fig. 6(b): Ice sheet flexural strength versus crack width. Initial ice sheet strengths are shown at corresponding widths to the refrozen data. Note the orientation dependence of the initial flexural strength due to the alignment of the crystal c-axes. Excepting the natural crack, the refreezing time is 80 ± 10 hours for these data.

the crack, then the data of Fig. 7 would be clustered about the straight line shown in the figure. That most data lie in the upper left portion of this figure suggests that the material of the partially refrozen crack has a greater flexural strength than that of the host ice. In the preceding paragraph we argued that a significant difference in flexural strength would not be expected from differences in brine fraction alone. However, within the crack there is a very significant change in the structural properties of the sea ice, in particular in crystal size and orientation and in the configuration of brine channels (Petrich et al, 2003). We suggest that it is these changes that account for the change in material properties.

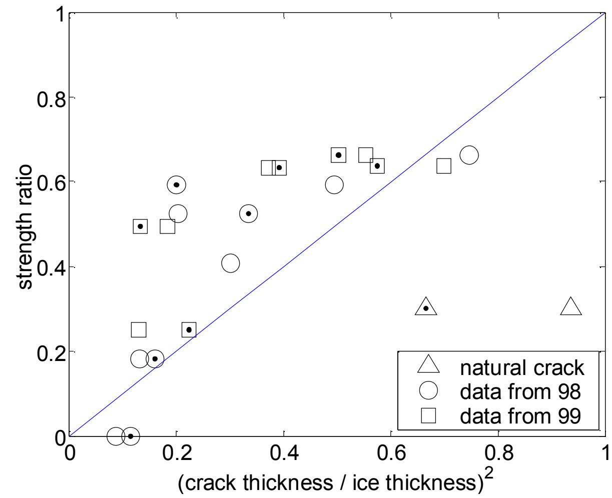

Fig. 7: Plot of strength ratio, σ'/σ, against the square of the ratio of crack thickness to ice thickness, $(h'/h)^2$. The solid line represents the equality of equation (5). Measured values of h', when available, are denoted by a symbol with a dot at the centre. For all data h' is also calculated using equation (1) and these data are represented by open symbols.

The notable exception to the behaviour described above is that of the natural crack. We suggest that the processes that had formed the crack prior to our arrival at the field site were still taking place. This is contrasted by the artificial cracks which were allowed to refreeze in a stress-free environment. Thus our results represent the maximum flexural strength likely to be found for an ice sheet containing a refrozen crack.

CONCLUSIONS

In situ cantilever beam experiments on first year sea ice have shown that, for crack widths in the range 26 to 110 mm and refreezing times from 68 to 263 hours (3 to 11 days), a sea ice sheet containing a refrozen crack has a flexural strength that is less than 70% of the strength of the pristine ice sheet. The flexural strength of an ice sheet containing a partially refrozen crack increases with refreezing time and decreases with crack width. We present an empirical correlation that relates the ice thickness in the crack to refreezing time and crack width, and this is used to make deductions regarding the flexural strength of the refrozen material.

Taking account of the thickness of the refrozen crack, it appears that the material of the partially refrozen crack has a greater flexural strength than that of the host ice. This difference cannot be explained by the difference between the brine fraction in the crack and that in the host ice sheet. We surmise that the difference is due to the abrupt change in crystal structure and orientation at the crack location.

A natural crack that existed at the site at the time of our arrival was found to have a flexural strength that was much less than the artificial cracks. We suggest that the processes that had formed the crack prior to our arrival at the field site were still taking place. This is contrasted by the artificial cracks which were allowed to refreeze in a stress-free environment. Consequently, our results place an upper bound on the flexural strength of the ice sheet containing a refrozen crack.

ACKNOWLEDGEMENTS

This project was funded and supported by Foundation for Research, Science and Technology, Industrial Research Ltd and the University of Otago. Logistics were provided by Antarctica New Zealand. The authors are grateful for the assistance of Simon Gibson, Dave Cochrane, Nick Wilson and Eberhard Deuss in conducting the field experiments.

REFERENCES

Barrette, P.D. and Jordaan, I.J. (2002) Healed cracks in iceberg ice. *J. Glaciol*., Vol 48, No 163, pp 587-591

Christensen, F.T. (1986) Refreezing of cracks formed by bending of floating ice sheets. *Cold Reg. Sci. and Technol*., Vol 12, pp 29-37.

Divett, T.A. (unpublished) Refreezing cracks in sea ice. Honours thesis, University of Otago, Dunedin, New Zealand, 2000.

Frankenstein, G. and Garner, R. (1967) Equations for determining the brine volume of sea ice from -0.5^{o} to -22.9^{o}C. *J. Glaciol*., Vol 6, No 48, pp 943-944.

Frederking, R.M.W. and Timco, G.W. (1983) On measuring flexural properties of ice using cantilever beams. *Ann. Glaciol*., Vol. 4, pp 58-65.

Haskell, T.G., Robinson, W.H. and Langhorne, P.J. (1996) Preliminary results from fatigue tests on in situ sea ice beams. *Cold Reg. Sci. and Technol*., Vol 24, pp 167-176.

Langhorne, P.J. and Haskell, T.G. (1996) Acoustic emission during fatigue experiments on first year sea ice. *Cold Reg. Sci. and Technol*., Vol 24, pp 237-250.

Langhorne, P.J. and Haskell, T.G. (1998) Sea ice fatigue. In *Ice in Surface Waters*, Proceedings of *International Association for Hydraulic Research 14th International Symposium on Ice*, Potsdam, New York, July 27-31, pp 855-862.

Metge, M. (unpublished) Thermal cracks in lake ice. PhD thesis, Queen's University, Kingston, Ontario, Canada, 1976.

Petrich, C., Langhorne, P.J. and Haskell, T.G. (2002) Modelling of refrozen cracks in sea ice. In *Ice in the Environment: Proceedings of the 16th IAHR International Symposium on Ice*, V.A. Squire and P.J. Langhorne (eds), University of Otago, Dunedin, Vol 2, pp 235-242.

Petrich, C., Haskell, T.G. and Langhorne, P.J. (2003) Structure of refrozen cracks in first-year sea ice. *Can. J. Phys./Rev. Can. Phys.* Vol 81(1-2), pp 293-299.

Timco, G.W. and O'Brien, S. (1994) Flexural strength equation of sea ice. *Cold Reg. Sci. and Technol*., Vol 22, pp 285-298.

Schwarz, J., Frederking, R., Gavrillo, V., Petrov, I.G., Hirayama, K.-I., Mellor, M., Tryde, P. and Vaudrey, K.D. (1981) Standardized testing methods for measuring mechanical properties of ice. *Cold Reg. Sci. and Technol*., Vol 4, pp 245-253.

Weeks, W.F. and Ackley, S.F. (1982) The growth, structure and properties of sea ice. CRREL Monograph 82-1.

Wettlaufer, J.S., Worster, M.G. and Huppert, H.E. (2000) Solidification of leads: Theory, experiment and field observations. *J. Geophys. Res*. Vol 105, pp 1123-1134