Proceedings of the 26th International Conference on
Port and Ocean Engineering under Arctic Conditions
June 14-18, 2021, Moscow, Russia

Ice Behavior under Cyclic Flexural Loading

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ABSTRACT

Recent studies revealed that the flexural strength of S2 columnar-grained laboratory-grown freshwater and saline ice, loaded cyclically across the columns, increases linearly with stress amplitude, in a manner similar for both materials. The studies were conducted over the range of stress amplitudes from 0.1 to 2.6 MPa, frequencies of ~ 0.1 Hz and temperature of -10 ºC. The flexure experiments were conducted under reversed 4-point bending. Cyclic strengthening is attributed to the development of an internal back stress that opposes the applied stress and originates possibly from dislocation pileups or grain boundary sliding.

KEY WORDS: Flexural strength; Rheology; Fatigue; Cyclic loading; Ice mechanics

INTRODUCTION

The Arctic and Antarctic floating ice covers and ice shelves are subjected to cyclic loading from ocean swells that can penetrate deeply into an ice pack and potentially result in the breakup of the ice cover (Squire, 2007). A number of instances have been witnessed and described where, under the action of surface waves, a floating cover exhibited sudden breakup into pieces much smaller than the peak wavelength (Shackleton, 1982; Liu and others, 1988; Prinsenberg and Peterson, 2011; Asplin and others, 2012; Collins and others, 2015; Kohout and others, 2016; Hwang and others, 2017). The question arises: what process accounts for sudden failure of the cover? One hypothesis is that the ice may behave similarly to other materials which, when subjected to cyclic loading, fail at stresses below their nominal flexural strength. This type of behavior is called fatigue. As a result, mechanical behavior of ice with a history of repetitive deformations may be different from ice with no thermal-mechanical history. Of the relatively little research that has been performed on the cyclic loading of ice, most of it was done on freshwater ice (Bond and Langhorne, 1997; Cole, 1990; Gupta et al., 1998; Hammond et al., 2018; Haskell et al., 1996; Iliescu et al., 2017; Iliescu and Schulson, 2002; Murdza et al., 2020c, 2021; Nixon and Smith, 1987; Weber and Nixon, 1997); very little work has been done on sea/saline ice. Therefore, we decided to explore and compare the behavior of both freshwater and saline ice under cyclic loading. For this purpose, we conducted cycling experiments in the laboratory. We prepared ice beams, flexed them in a 4-point bending manner and measured the flexural strength. Details of this study are provided below.

EXPERIMENTAL PROCEDURE

We produced the ice in the laboratory through unidirectional solidification of water in an 800 L circular polycarbonate tank in the manner described previously (Golding et al., 2010, 2014; Smith and Schulson, 1993). To grow freshwater columnar-grained S2 ice, tap-water was used. Saltwater columnar S2 ice was produced as follows: the commercial product “Instant Ocean” was added to tap water to reach a salinity of 17.5 ppt by mass. The salinity of the well-mixed solution was measured using a calibrated YSI Pro30 conductance meter. The solution was then chilled to a temperature T= 4±0.5°C. To maintain a uniform column diameter, the top of the solution was seeded with ice crystals. Growth was allowed to continue for ~7 days using a top-loaded cold plate maintained at T = -20°C. This procedure produced pucks ~1 m in diameter and ~ 0.3 m thick.

Thin-section analysis revealed that c-axes of the individual grains of ice in both materials were oriented more or less perpendicular to the long axis of the columnar-shaped grains but randomly oriented within the plane normal to the long axis. The length of the columns exceeded 50 mm; the average column diameter of freshwater and saline ice, respectively, was 5.5±1.3 and 3.8±0.9 mm. Density of freshwater ice was 914.1±1.6 $kg \cdot m^{-3}$ and density of saline ice was 878±11 $kg \cdot m^{-3}$. Melt-water salinity of saline ice was 3.0±0.9 ppt which is similar to the salinity of natural sea ice. Saline ice contained both sub-mm sized brine pockets and supra-mm sized drainage channels. Figure 1 shows the microstructure of both freshwater and saline ice. The microstructure of saline ice is similar to natural first-year sea ice (for comparison, see Figure 3.7 of Schulson and Duval (2009)).

Once grown, the ice was cut into blocks of dimensions ~ 10 x 30 x 20 cm^3, which were stored in a cooler at -10 °C. Specimens for flexing were manufactured by milling from the ice blocks thin beams of dimensions h ~16 mm in thickness (parallel to the long axis of the grains), b ~ 85 mm in width, and l ~300 mm in length. The test specimens were allowed to equilibrate to the test temperature of -10 ± 0.5 °C for at least 24 hours before testing.

A detailed description of the specimens' preparation and loading can be found elsewhere (Iliescu et al., 2017; Lishman et al., 2020; Murdza et al., 2018, 2019, 2020c, 2020a, 2020d). To summarize: The ice beams were flexed up and down under 4-point loading under constant displacement rate using a servo-hydraulic MTS loading system to which we attached a custom-built 4-point loading frame. A calibrated load cell and a linear variable differential transformer (LVDT) gauge were used for measurements of load and displacement of the upper surface of the ice beam during cycling.

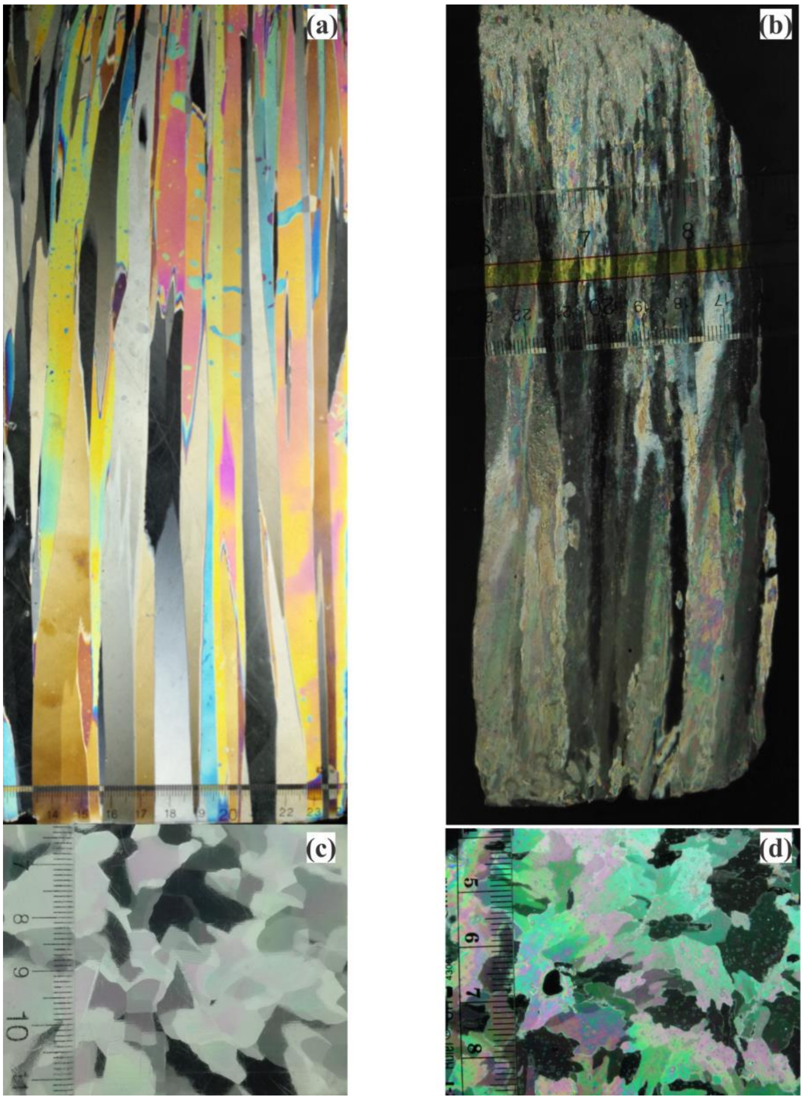

Figure 1. Photographs of a vertically-oriented (a) and a horizontally-oriented (c) thin-sections (~1mm) of columnar-grained freshwater ice as viewed between crossed-polarized filters; photographs of a vertically-oriented (b) and a horizontally-oriented (d) thin-sections of saline ice.

The experiments were performed in a cold room at a temperature of -10°C at an outer-fiber center-point displacement rate of 0.1 mm s^{-1} (or outer-fiber strain rate of about 1.4 x 10-4 s^{-1}). This displacement rate resulted in an outer-fiber stress rate of about 1 MPa s^{-1}. The major outer-fiber stress σ_f was calculated from the relationship:

$$\sigma_f = \frac{3PL}{4bh^2}\ , \qquad (1)$$

where P is the applied load and L is the distance between the outer pair of loading cylinders and is set by the geometry of the apparatus to be L = 254 mm.

We used two different loading procedures in the present study. Type I loading was a completely reversed stress cycle with constant stress amplitude and mean stress of zero. Type II was similar to Type I but incorporated incremental steps of increasing stress amplitude. This second type of loading essentially consisted of several Type I steps of increasing stress amplitudes. In the present study we used Type I loading to cycle freshwater ice below stress amplitudes of ~1.6 MPa; we used Type I to cycle the saline ice at stresses up to 0.7 MPa. To cycle at stress amplitudes above these values, we first pre-conditioned the specimens through Type II step-loading procedure at progressively higher levels of stress amplitude for ~300 cycles at each step. After pre-conditioning, the specimens were cyclically loaded according to Type I loading at least 300 times and generally for ~2000 times. Separate experiments revealed that the effect of cycling (described below) saturated after ~300 cycles.

RESULTS AND OBSERVATIONS

Flexural strength of non-cycled ice

To establish the strength of the non-cycled ice, we conducted a series of experiments where flexural strength was measured at -10 ºC at a nominal outer-fiber center-point displacement rate of 0.1 mm s^{-1}. The average and standard deviation of the measured flexural strength of freshwater and saline ice are 1.67±0.22 and 0.96±0.13 MPa, respectively. These values compare favorably with the values of 1.73±0.25 and 0.85±0.20 MPa reported by Timco and O'Brien (1994) for freshwater ice at temperatures below -4.5 °C and for saline ice of similar salinity.

Flexural strength versus stress amplitude

The experiments performed to investigate the effect of cyclic loading on strength of ice revealed that the flexural strength of both freshwater and saline ice increases with stress amplitude, Figure 2. As already noted, the ice was cycled more than 300 times, often around 2000 times, before being bent to failure. For comparison, we also provide measurements obtained from laboratory tests on S2 lake ice, where ice beams were cycled non-reversely under 3-point loading at -12 °C (Murdza et al., 2020b, 2021). The relationship between the flexural strength, σ_{fc} and cycled stress amplitude, σ_a, appears to be linear for both freshwater and saline ice and can be described by the equation:

$$\sigma_{fc} = \sigma_{f0} + k\sigma_a \ , \qquad (2)$$

where σ_{f0} is the flexural strength of non-cycled ice and k is a constant of value 0.7**.** Based on Figure 2, freshwater ice is stronger than saline ice; however, it appears that upon cycling, the strength of both freshwater and saline ice increases at about the same rate.

Points on Figure 2 with a cycled stress amplitude above 1.6 MPa in case of freshwater ice and 0.7 MPa in case of saline ice were pre-conditioned through step-cycling Type II at progressively higher stress amplitude levels (see Iliescu and others (2017) for details).

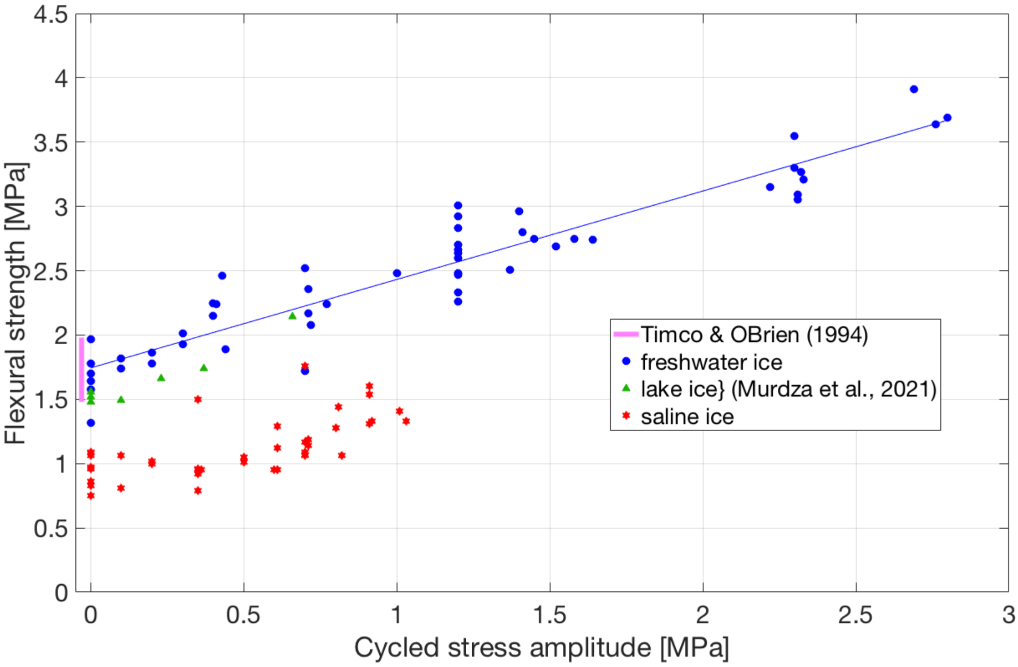

Figure 2. Flexural strength of laboratory-grown freshwater ice and saline ice at -10^o C and lake ice at -12^o C as a function of cycled stress amplitude, at a mid-point displacement rate of 0.1 mm s^{-1}. During all depicted tests the ice did not fail during cycling but was broken by applying one unidirectional displacement until failure occurred.

Deformation features

It is important to note an absence of remnant microcracks, at least of the size detectable by the unaided eye and optical microscope, in the two parts of freshwater and saline ice beams that were broken after cycling. The implication of this point is noted below.

A second point to note is the absence of recrystallization in cycled and broken freshwater and saline ice. We compared the microstructure of samples before and after cycling and did not find any difference at the level of resolution (~0.1 mm). This suggests that insufficient plastic strain had been imparted to activate this solid-state transformation.

We observed, however, evidence of grain boundary sliding (termed decohesion zones or decohesions). The evidence appeared in the form of whitish features of grain size length upon cycling of freshwater ice. Decohesions were not detected in saline ice specimens upon cycling which is most likely due to the opacity of the material.

Acoustic emissions were not detected in freshwater ice specimens during cycling over the frequency response of 3 kHz–3 MHz and minimum AE amplitude detection threshold of 45 dB during cycling (unlike Cole and Dempsey (2006, 2004); Langhorne and Haskell (1996); Lishman et al. (2020)). We did, however, detect acoustic emissions in saline ice samples during cycling while measuring AE in the same way as in freshwater ice experiments.

DISCUSSION

What is the origin of ice failure in our experiments? Owing to the higher value of compressive strength of ice compared with the tensile strength, failure in ice at bending occurs on a surface that undergoes tensile deformation. Hence, in our work ice strength is always governed by tensile strength. This is consistent if we compare our results on freshwater ice with the results obtained by Carter (1971), who provided measurements on tensile strength of laboratory grown cylindrical freshwater ice samples. Our flexural strength values, if divided by 1.7 (Ashby and Jones, 2013), are very similar to the Carter's data. Moreover, obtained values of flexural strength of saline ice in the present study, if divided by 1.7, are similar to the values obtained by Richter-Menge and Jones (1993) for the tensile strength of columnar-grained first-year sea ice of 4.1±0.3 ppt salinity loaded uniaxially across the columns at a temperature of -10 °C and strain rates of 10-5 and 10-3 s-1.

Given that the grain size (i.e., column diameter) of the specimens used in the present study is relatively large (~ a few millimeters) and given the absence of remnant microcracks in broken parts of ice specimens after cycling and failure, we conclude that crack nucleation governs the failure strength and nucleation of the first crack is followed by immediate propagation and creation of the fracture surface. According to Schulson and Duval (2009), either pile-ups of dislocations against other boundaries or grain boundary sliding may be responsible for the nucleation of cracks in ice under crack nucleation regime. Both processes lead to concentrations of stress high enough to overcome the surface energy obstacle to crack nucleation.

The behavior of both freshwater and saline ice under cyclic loading is essentially the same, as suggested by Figure 2, i.e. flexural strength increases at about the same rate. Hence, it is reasonable to assume that the strengthening mechanism for the freshwater and saline ice is similar. However, we should note that there is a possibility of a different strengthening mechanism for saline ice. The prolific flaw structure in saline ice allows for damage accumulation due to a great number of microcracks in regions of microstructural weakness. For example, the brine drainage channels in the test specimens constitute regions of high porosity and thus provide favorable sites for the concentration of such damage. Due to the inherent weakness of the saline ice microstructure, the microstructural stress relief may occur through localized damage via microcracking which may be associated with the acoustic emissions detected in saline ice during cycling. However, the origin of the acoustic emissions during cycling of saline ice could also be explained by a water-hammer effect in which brine entrapped within pockets impacts the wall, first in one direction and then another (discussed in more details in Murdza et al. (2020a)). We refrain, therefore, from further speculation on this point as more research is needed.

SUMMARY

From systematic experiments on the flexural strength of sub-meter sized beams of S2 columnar-grained freshwater and saline ice stressed principally across the columns through reversed cyclic loading at a temperature of -10 °C and outer-fiber strain rate of about 1.4 x 10-4 s^{-1}, it is concluded that:

(i) The flexural strength of ice subsequent to cycling appears to scale linearly with the amplitude of the outer-fiber stress for both freshwater and saline ice.

(ii) Crack growth is not a significant contribution to the fatigue life of both freshwater and saline ice.

(iii) Cycling induced grain-boundary sliding occurs in freshwater ice.

(iv) Cyclic strengthening is attributed to the development of an internal stress that opposes the applied stress and thus raises the level of the applied stress that is required to nucleate a crack.

(v) The increase in flexural strength of freshwater ice and saline ice attributable to pre-failure load cycling is roughly equivalent.

ACKNOWLEDGEMENTS

We acknowledge helpful discussions/communications with Prof. Harold Frost, Dr. Robert Gagnon, and Dr. Daniel Iliescu. This work was supported by the US Department of the Interior-Bureau of Safety and Environmental Enforcement (BSEE), contract no. E16PC00005 and by National Science Foundation (FAIN 1947-107).

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