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# The Effect of Cyclic Loading on the Flexural Strength of Columnar Freshwater Ice

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## ABSTRACT

New experiments reveal that the flexural strength of freshwater, columnar-grained S2 ice loaded normal to the columns may be increased by as much as a factor of two or more upon reversed cyclic loading. The experiments were performed over ranges of temperature (-3°C to -25°C), frequency (~ 0.03 – 2 Hz) and stress amplitude (0.1 – 2.6 MPa).

KEY WORDS: Ice mechanics; Ice engineering; Ice physics; Fatigue; Cyclic loading.

## 1.Introduction

A number of instances have been reported where a floating sea ice cover exhibited sudden breakup into many pieces much smaller than the peak wavelength (for example, Collins and others, 2015; Asplin and others, 2012). In these instances, the ice was first-year and multi-year, respectively. In both cases a rapid swell buildup occurred, thus, the fractured ice had almost no effect on damping wave energy, which is opposite to the case with a parent solid ice cover. In addition, the destruction of the ice cover led to the increase of the total ice floe perimeter which allowed incoming radiation into the floes to increase and, therefore, intensify melting.

Based on the scenario stated above, the following question arises: what leads to sudden failure of the ice cover? Collins and others (2015) assumed that the ice not only attenuates incoming waves, but also deforms under the wave action. Waves penetrate deeply into the ice field and bend the ice cover in both directions, upwards and downwards, until fracture occurs. Although this phenomenon requires thorough exploration, one hypothesis is that the ice may behave similarly to other materials which, when subjected to cyclic loading, fail at stresses below their flexural strength. This type of behavior under repeated loading is called fatigue. As a result, mechanical properties of ice may be lower than those reported in Carter (1971); Richter-Menge and Jones (1993); Timco and Weeks (2010); Murdza and others (2016).

Our aim is to characterize ice fatigue life with ultimate goal of a better prediction of failure of the sea ice cover on the Arctic Ocean. Improved understanding of sea ice behavior will result in improvements in the safety of ships operation, offshore structures and coastal infrastructure.

In this work, new experiments are described and preliminary results are discussed.

## 2. Experimental procedure

Though our ultimate goal is to characterize sea ice behavior under cyclic loading, we studied freshwater ice in this work for two reasons. Firstly, freshwater ice is a simpler material to start with our study and it forms a basis for a comparison. Secondly, sea ice comprises ≅95% by volume of freshwater ice, within which there is almost no solubility of salts (Weeks and Ackley, 1986). The remainder is a mixture of air and brine.

Freshwater ice was produced in the laboratory. Tap-water was frozen unidirectionally from top to bottom in the manner described elsewhere (Smith and Schulson, 1993). The ice generally was bubble-free, columnar-grained with the S2 growth texture. The c-axes were randomly oriented within the horizontal plane of the ice and confined more or less to that plane. The average column diameter was 5.5±1.3 mm and the length exceeded 50 mm.

Specimens were manufactured from the ice blocks in the form of thin plates of dimensions $h$ ~13 mm in thickness (parallel to the long axis of the grains), $b$ ~ 75 mm in width and $L$ ~300 mm in length. We flexed the plates up and down under 4-point loading, using a servo-hydraulic loading system to which we attached special apparatus designed and built on site (see Iliescu and others (2017) and Murdza and others (2018) for details). During cyclic experiments, the hydraulic actuator was driven up and down at a displacement control manner of the piston and its motion was load-limited by MTS loading system in both directions. Upward and downward motion of hydraulic actuator was done symmetrically with respect to the neutral axis of the ice plate. The resulting displacement of the top surface of the ice plate was measured using a calibrated LVDT gauge.

The experiments were performed in a cold room at temperatures of -3ºC, -10°C and -25ºC and at an outer-fiber center-point displacement rates of 0.01, 0.1 and 1 mm $s^{-1}$ which resulted in an outer-fiber stress rate in the range from 0.1 MPa $s^{-1}$ to 5 MPa $s^{-1}$ and frequencies in the range from 0.03 to 2 Hz. However, most of the tests were conducted at a frequency of ~0.1 Hz which is approximately the frequency of ocean waves (Collins and others, 2015). The outer-fiber stress $\sigma_f$ was calculated from Equation [1] below:

$$\sigma_f = \frac{3PL}{4bh^2} \qquad [1]$$

where $P$ is the applied load.

## 3. Results and observations

### 3.1. Flexural strength of non-cycled freshwater ice

The flexural strength of non-cycled freshwater ice was measured at -3ºC, -10ºC and -25ºC 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 at -3ºC , -10ºC and -25ºC are 1.42±0.16, 1.67±0.21 and 1.89±0.01 MPa, respectively. These values compare favorably with the value of 1.73±0.25 MPa reported by Timco and O.'Brien (1994) for freshwater ice at temperatures below -4.5°C. This fact raises our confidence that our lab-grown freshwater is analogues to natural and other lab-grown ice.

### 3.2. Flexural strength of reversed cycled freshwater ice

In the beginning of this work we started to cycle freshwater ice samples at stress amplitudes lower than the flexural strength of non-cycled ice and we expected to observe weakening of the material as the number of imposed cycles increases. However, after we tested a few samples, none of them failed during cycling; moreover, after applying a final unidirectional monotonic load until failure occurred, all the samples showed strengthening compared with non-cycled samples. This result was rather surprising as it contradicts two earlier reports of cyclic weakening of ice (Nixon and Smith, 1987; Haynes and others, 1993). More tests, performed in a systematic manner, confirmed cyclic strengthening.

Figure 1 shows the flexural strength versus the cycled stress amplitude. The figure shows unambiguously a positive effect of cycling on flexural strength. A linear relationship between the flexural strength $\sigma_{fc}$ and cycled stress amplitude $\sigma_a$ is observed:

$$\sigma_{fc} = \sigma_{f0} + k\sigma_a;$$

where $\sigma_{f0} = 1.75$ MPa is the flexural strength of non-cycled ice, $k = 0.68$.

Points on Figure 1 with a cycled stress amplitude above 1.6 MPa were pre-conditioned either through step-cycling at progressively higher stress amplitude levels (see Iliescu and others (2017) for details) or through gradual increasing of stress amplitude at every cycle. After pre-conditioning, samples generally were cycled for ~ 2000 cycles. Separate set of experiments showed that there is no significant difference in the results obtained using these two pre-conditioning procedures.

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 ice plates that were broken after cycling. This important observation is discussed in the "Discussion" section below.

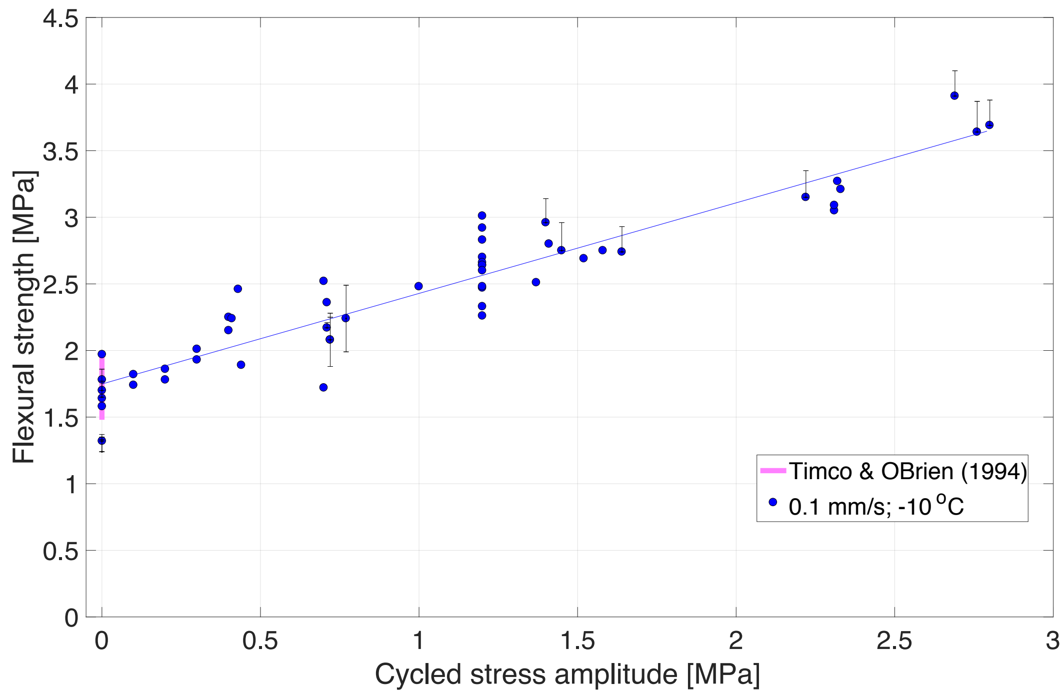


*Figure 1. Flexural strength of freshwater ice as a function of reverse-cycled stress amplitude. Solid pink line indicates the average flexural strength of non-cycled ice plus and minus one standard deviation, i.e. 1.73±0.25 MPa (Timco and O'Brien, 1994). Blue points represent tests which were conducted at -10ºC and 0.1 mm $s^{-1}$ rate. During all depicted tests the ice did not fail during cycling and was broken by applying one unidirectional final monotonic load until failure occurred.*

### 3.3. Flexural strength as a function of reversed cycles

Does the number of cycles influence the flexural strength? We did not raise this question initially since in the tests leading to Figure 1 the ice was generally cycled more than 300 times and it seemed that there was no detectable effect.

To answer that question, we performed a series of experiments on freshwater ice cycled at -10ºC at an outer-fiber center-point displacement rate of 0.1 mm $s^{-1}$ at four levels of stress amplitude: 0.4 MPa, 0.7 MPa, 1.2 MPa and 1.5±0.1 MPa. For stress amplitudes 0.4 MPa, 0.7 MPa and 1.5±0.1 MPa the number of cycles that were imposed before the plate was monotonically bent to failure varied from ~300 to ~16,000.

Figure 2 shows the results for three stress amplitudes. The results indicate that, while generally increasing with stress amplitude, the flexural strength of the cycled ice is essentially independent of the number of cycles imposed over the range explored (>300).

For the stress amplitude of 1.2 MPa fewer cycles were imposed (from 10 to ~7,000) before the plate was monotonically bent to failure. The results are presented on Figure 3. It seems that strength saturates after ~ 300 cycles though it is not clear due to the high degree of scatter. These results are consistent with the results from Figure 2, where data only beyond 300 cycles are presented.

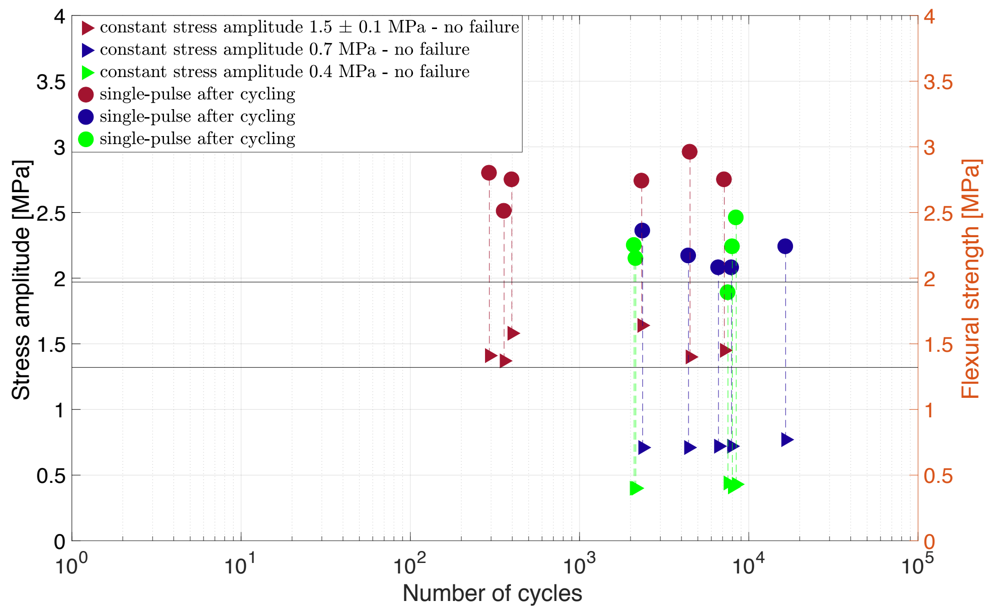


*Figure 2. Flexural strength of freshwater ice as a function of number of cycles for different cycled stress amplitudes. Solid triangles of different colors show different cycling stress amplitudes (left-hand-side ordinate) for different numbers of cycles. None of these samples broke during cycling. Solid circles of the same colors denote the flexural strength of the same specimen of ice tested after cycling (right-hand-side ordinate). Two horizontal solid black lines depict the range of flexural strength of non-cycled freshwater ice.*

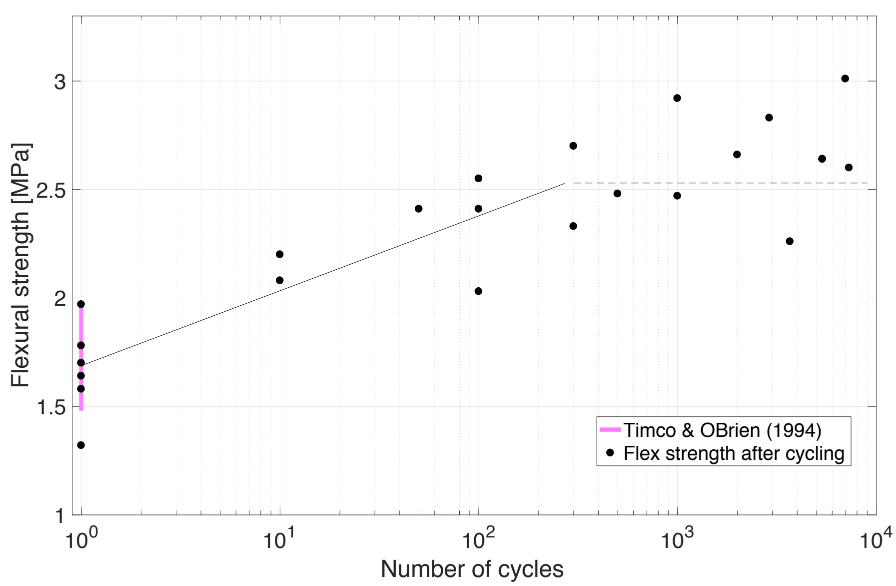


*Figure 3. Flexural strength of freshwater ice as a function of number of cycles at 1.2 MPa cycling stress amplitude (according to the loading procedure I). All the data points represent an outer-fiber center-point displacement rate of 0.1 mm s$^{-1}$ and temperature -10ºC. Black solid line is a line fit of tests for cycles ≤ 300. Black dotted line represents the expected saturated flexural strength after cycling (~2.5 MPa) according to data from Figure 1.*

### 3.4. Displacement Rate effect

Figure 4 shows data obtained from experiments performed to determine whether the displacement rate of cycling of outer-fibers at the midpoint of the specimen (0.01 to1 mm $s^{-1}$) affects the flexural strength.

Samples were cycled at different displacement rates but constant during one experiment for ~2000 cycles each. However, for the final monotonic one-directional bend, displacement rate of 0.1 mm $s^{-1}$ was used for all tests. This was done in order to be able to compare results with the flexural strength of non-cycled ice which was obtained at -10°C and 0.1 mm $s^{-1}$ displacement rate. In other words, we are trying to see whether the strength depends upon displacement rate.

Statistical analyses resulted in a *p*-value equal ~0.06 (for both hypothesis that the slope for samples cycled at 0.7 MPa and 0.4 MPa is zero). Therefore, we question whether there is an effect of displacement rate on the flexural strength. If there is, the data suggest that the effect is a small one, over the range explored.

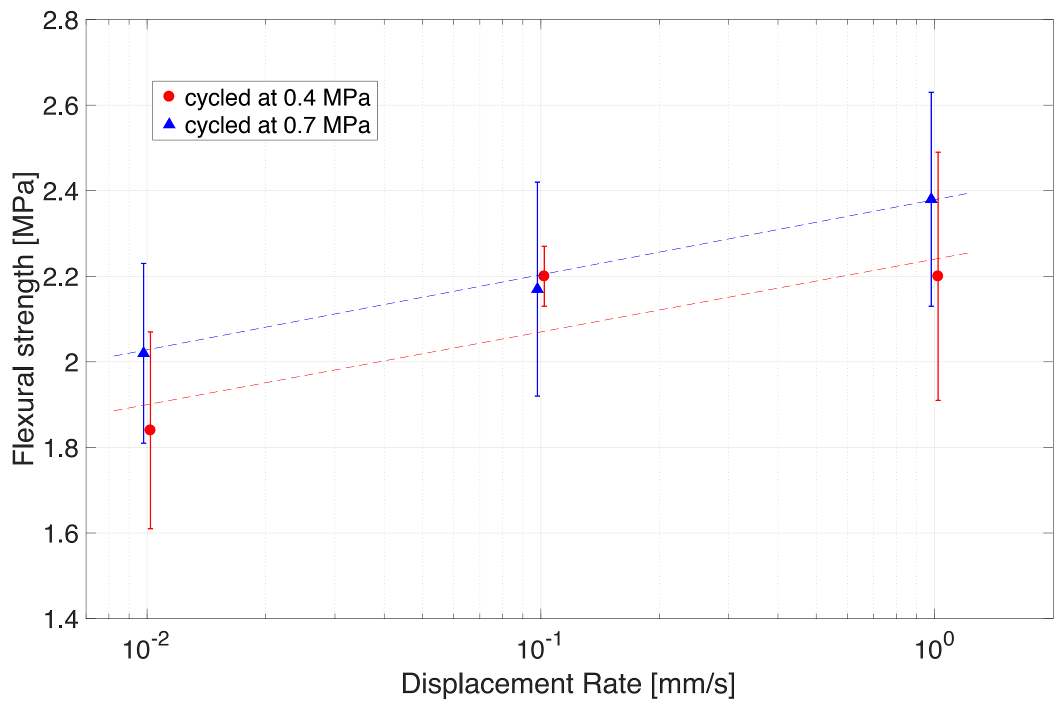


*Figure 4. Effect of displacement rate on flexural strength of freshwater ice tested at - 10°C. Red lower data points and corresponding line fit (in red) describe effect of outer-fiber center-point displacement rate on flexural strength for samples cycled at 0.4 MPa; blue upper data points and corresponding line fit (in blue) describe effect of outer-fiber center-point displacement rate on flexural strength for samples cycled at 0.7 MPa. Error bars represent standard deviations. All samples were cycled at 0.01, 0.1 and 1 mm $s^{-1}$ outer-fiber center-point displacement rates.*

### 3.5 Temperature effect

Figure 5 shows the results from experiments performed to determine whether temperature of cycling (-25ºC to -3ºC) affects the flexural strength. Although few in number, the data suggest that the flexural strength increases only slightly with deceasing temperature, for both non-cycled ice (lower curve on Figure 5) and for ice cycled at 0.7 MPa and at 2.3 MPa (middle and upper curves on Figure 5).

For the tests with varying temperature the same approach as for varying displacement rates (observe whether ice properties change by a different amount while cycling at different temperatures) cannot be used since it is impossible in practice to change temperature of the material instantaneously before the final monotonic bend. As a result, obtained flexural strength may depend on both cycling and failure conditions. Therefore, it was decided to apply final monotonic one-directional bend at the same temperature at which the sample was cycled and hereafter compare obtained values with the flexural strength of non-cycled ice at the same temperature. Thus, following the described procedure we can separate the magnitude of strengthening only due to the cycling at a certain temperature. The actual magnitude of strengthening during cycling is the difference in ordinates at the same abscissa. As one can see, three dotted lines have about the same slope. Hence, we may conclude that temperature does not affect the magnitude of strengthening over the range examined.

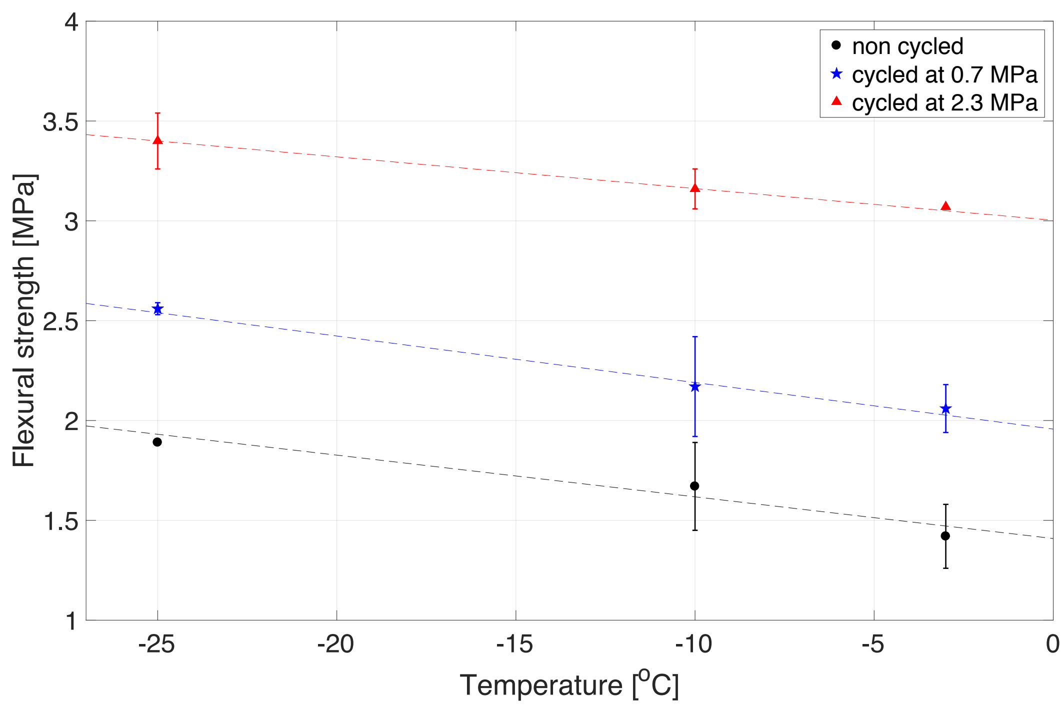


*Figure 5. Effect of temperature on flexural strength of freshwater ice tested at 0.1 mm s$^{-1}$ outer-fiber center-point displacement rate. Lower data points and corresponding line fit (in black) describe temperature dependency of flexural strength of non-cycled ice; middle data points and corresponding line fit (in blue) describe temperature dependency of flexural strength of the material which was cycled at 0.7; upper data points and corresponding line fit (in red) describe temperature dependency of flexural strength of the material which was cycled at 2.3 MPa. Error bars represent standard deviations.*

## 4. Discussion

To summarize, the experiments show:

1. *Frequency of cycling effect.* As apparent from the results, higher frequency does not lead to ice weakening; moreover, Figure 4 suggests that magnitude of strengthening might increase with increase of cycling frequency (though this statement cannot be made at 5% significant level).
2. *Temperature effect.* As was noted in Iliescu and others (2017), temperature should not play the leading role in the difference of behavior. This statement is confirmed by Figure 5 in the present work over the range of temperatures examined.
3. *Stress amplitude effect.* Cycling stress amplitude has a great effect on the flexural strength of freshwater ice, where flexural strength increases linearly with increase of cycling stress amplitude.

What is the origin of ice failure in our experiments? Owing to the higher value of compressive strength of ice compared with a 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 with the results obtained by Carter (1971), who provided measurements on tensile strength of laboratory grown cylindrical ice samples. Our flexural strength values, if divided by 1.7 (Ashby and Jones, 2013), are very similar to the Carter's data.

What governs tensile strength? Depending on the grain size, either crack propagation or crack nucleation controls the tensile strength (Schulson and others, 1984). If grain size is larger than a critical size, crack nucleation governs the tensile strength as stress to nucleate cracks greater than stress to propagate cracks. This is suggested by the absence of remnant cracks (which is consistent with the observation in section 3.2), which are generally of grain-size dimension in ice (Cole, 1988; Schulson and Duval, 2009) within the parts of broken sample. Hence, we may conclude that nucleation of the first crack is followed by immediate propagation and creation of the fracture surface.

What is the nucleation mechanism in tension? According to Schulson and Duval (2009), either dislocation pile-ups or grain boundary sliding may be responsible for the nucleation of cracks in ice. It was hypothesized in Iliescu and others (2017), that strengthening upon cycling might be the result of grain boundary decohesion development. Presumably, the reason is that cycling lessens the effectiveness of localized internal stress concentrators, such as facets and ledges (Liu and others, 1995; Baker, 2002) which are located at grain boundaries. These sites also may allow strain to be accommodated. We also imagine that during cycling due to the grain boundary sliding dislocations are created near grain boundaries and then migrate, thus, creating an internal dislocation substructure. Dislocations that are sent out from grain boundaries interact with each other and create a "back stress" which opposes an applied stress. In other words, this is a process that might be referred to as hardening. As a result, the applied stress to nucleate a crack increases which lead to increase of flexural strength.

Returning to the observations noted in the introduction, why did ice failed in the field under the wave action, but strengthened upon cycling in the laboratory? We report a clear evidence of ice strengthening while cycling for the first time. In addition, essentially we do not know the process through which the ice sheet has failed in the field and it is probably more complicated than simply flexural failure. How many cycles was this ice cover imposed to? It is also very likely that floating ice sheet has thermal cracks (Evans and Untersteiner, 1971), while our samples do not have any microcracks. Therefore, we need to do more work not only on saline ice, but also on ice containing microcracks for better understanding of ice behavior under cyclic loading.

## 5. Summary

- The flexural strength of columnar-grained freshwater ice loaded across the columns at −10°C and cycled in a reverse manner at a frequency of ~0.1 Hz can be increased by as much as a factor of two or, perhaps, more.
- The rate of loading has little or no detectable effect on the strengthening.
- The temperature has no detectable effect on the magnitude of strengthening within the range examined (from -3ºC to -25ºC).
- The fatigue life of freshwater ice does not obey classical S-N behavior.

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