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Recovery of Strength in Thermally Cracked Freshwater and Salt-Water Ice

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Abstract. The integrity of ocean and lake ice covers is increasingly threatened by climate change, which reduces ice extent and promotes breakup. In addition to thinner ice and larger waves, thermal cracking may also contribute to ice cover failure. This study investigates the impact of thermal cracking on the flexural strength of freshwater and sea ice. Laboratory experiments show that when a narrow region of ice is thermally shocked, the flexural strength of both freshwater and sea ice initially decreases but subsequently recovers completely. In contrast, when the entire surface is thermally shocked, strength recovery is only partial in freshwater ice, while sea ice again fully recovers its strength. Repeated cycles of cracking followed by healing do not affect the recovered flexural strength. Additional experiments involving creep demonstrate that compressive stress enhances healing, highlighting the role of ice sintering in strength recovery. The differing behavior between localized and full-surface cracking is attributed to residual compressive stresses that develop during healing when only a narrow region is shocked. Rapid healing observed in sea ice is likely facilitated by its porous structure and the presence of brine, suggesting that natural sea ice may retain significant mechanical integrity even after thermal cracking.

1 Introduction

The structural integrity of ocean and lake ice covers faces a growing threat (Filazzola et al., 2024; King et al., 2026; Kwok and Rothrock, 2009; Stroeve et al., 2011). Understanding the mechanical characteristics of ice covers, for example in the Great Lakes, is essential for ensuring the safety and design of infrastructure (Bruce Martin and Cott, 2016; Millerd, 2011; Timco and Weeks, 2010). The ongoing reduction in ice cover extent due to climate change (e.g., NSIDC, 2022), coupled with the simultaneous factors of thinner ice and the presence of larger waves due to increased fetch (Li and Du, 2016; Thomson et al., 2018), makes the remaining ice cover more susceptible to fragmentation. The potential consequences of this situation are negatively affecting wave attenuation (Squire, 2007), coastal erosion (Jones et al., 2009; Overeem et al., 2011), shipping (Stewart et al., 2007), albedo (Perovich et al., 2001; Pistone et al., 2014; Zhang et al., 2019), and rate of ice melting (Rampal et al., 2009). One of the processes that could contribute to ice cover breakup is thermal cracking which generates defects of varying lengths, from submeter to several kilometers (Evans and Untersteiner, 1971). The cracks concentrate stress that originates from deformation induced by wind and ocean currents. This stress concentration from smaller cracks can lead to the development of large-scale cracks (Schulson and Duval, 2009) that imperil the integrity of the cover.

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The issue of thermal cracks in ice has been addressed in previous studies (Barrette and Charlebois, 2018; Barrette and Jordaan, 2002; Bazant, 1992; Colbeck, 1986; Fisher, 2005; Fransson, 1991; Gold, 1961, 1963; Milne, 1972; Yang et al., 2018). However, to the best of our knowledge, there has been no comprehensive study exploring the long-term impact of thermal cracks on ice strength and their influence on ice behavior under dynamic loading.

To obtain some insight into how thermal cracks impact structural integrity, we recently conducted a preliminary study to investigate how thermal cracks affect flexural strength of both sea ice and freshwater ice at temperatures from -78° C to -3° C (Murdza et al., 2022a). In that study, small beams of ice were thermally shocked by spraying liquid nitrogen across a narrow band in the middle of one of their largest faces. Afterwards, the cracked ice was bent to failure under four-point loading, ensuring that the cracked surface experienced tensile stresses. The cracks initially weakened the materials, in accord with the dictates of fracture mechanics, but not for long. Within a short period of time, typically of the order of minutes, the flexural strength recovered completely: the cracks had healed. In most instances, after the ice had healed, terminal fracture occurred outside the area of remnant scars that marked the pre-cracked region, suggesting that the healed region may have been as strong as or stronger than the surrounding pristine ice. If thermal cracks heal rapidly, their long-term impact on the mechanical integrity of ice covers may be significantly smaller than previously assumed.

A limitation of the previous investigation (Murdza et al., 2022a) was its focus on cracking a narrow band on the ice surface – a scenario less common in real-world applications. Here we consider the more common scenario where the entire surface of the ice is thermally cracked. Specifically, the present study aims to explore how thermal shock and subsequent healing impact the flexural strength of both freshwater ice and sea ice. Applying thermal shock to a larger area provides more relevant insights for situations where cracking occurs due to rapid air temperature fluctuations. It is relevant not only to fractures occurring in sea ice but also to any ice cover, terrestrial or extraterrestrial (Goldreich and Mitchell, 2010; Hirata et al., 2022).

In addition, this study explores several related aspects of the healing process, including whether healing can restore or even enhance the strength of previously cracked regions relative to pristine ice, whether repeated cycles of cracking and healing lead to cumulative strengthening, and the role of contact stresses at points of contact (asperities) during thermal expansion in promoting healing.

To address these questions, we conducted a new series of experiments where we sprayed with liquid nitrogen the whole sample surface, instead of a narrow band only. We conducted these experiments on both freshwater ice and first-year sea ice. In addition, to further investigate the role of pressure on the healing process we conducted creep experiments on thermally shocked ice. In the sections to follow, we describe our observations and discuss the processes responsible for strength recovery.

As will become apparent, the results indicate that strength recovery in thermally cracked ice may occur through two distinct processes. First, healing may occur when opposing crack surfaces come into contact, allowing sintering across the crack interface; the presence of a liquid-like layer at crack surfaces may further facilitate this process,

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particularly in sea ice where brine and porosity enhance mass transport. Second, even when crack surfaces remain separated and cannot sinter, strength recovery may occur through creep-assisted blunting of crack tips. The relative importance of these processes depends on temperature and loading conditions.

2 Materials and Methods

We studied the behavior of three types of ice: S2 laboratory-grown freshwater ice (i.e., salt-free), laboratory-grown saline ice and first-year sea ice, as previously investigated (Murdza et al., 2020, 2021c, 2022a, 2023; Schulson et al., 2022). The freshwater and saline ice were produced in the laboratory through a standard procedure, involving the unidirectional solidification of either local tap water (Golding et al., 2014; Smith and Schulson, 1993) or local tap water that had been salted with the commercial product "Instant Ocean" to a salinity of 17.5 parts per thousand (Golding et al., 2014). The sea ice was collected as submeter-sized blocks from the Beaufort Sea's ice cover during the winter of 2020 and stored at -30°C in Dartmouth's Ice Research Laboratory. All types of ice were polycrystalline aggregates, characterized by columnar-shaped grains oriented with their long axes parallel to the growth direction, Fig. 1. They exhibited the S2 crystallographic growth texture, with grain c-axes primarily within the horizontal plane but oriented randomly within that plane. The grain size (column diameter) of the freshwater ice was 5.5 ± 1.3 mm, with a density of 914.1 ± 1.6 $kg \cdot m^{-3}$. The laboratory-grown saline ice had a grain size of 3.8 ± 0.9 mm, with a density of 878 ± 11 $kg \cdot m^{-3}$ and a salinity of 3.0 ± 0.9 ppt. The first-year sea ice had a grain size of 2.7 ± 0.4 mm, a density of 906 ± 4 $kg \cdot m^{-3}$, and a salinity of 3.0 ± 0.3 ppt.

Grain size was measured manually from horizontal thin sections prepared from tested ice beams. For each thin section, five horizontal and five vertical lines were drawn and the mean grain diameter was estimated using the linear intercept method by dividing the total line length by the number of grain boundaries intersected by the line. Approximately 500 grains were measured for each ice type. Density was determined from rectangular prism-shaped specimens cut and milled from tested ice beams. The dimensions of each specimen were measured using calipers and the mass was measured using a digital balance. The density was then calculated from the measured mass and volume. To improve accuracy, relatively large specimens were used whenever possible. Reported uncertainties in density represent propagated measurement uncertainty based on repeated measurements of mass and dimensions. Salinity of saline and sea ice was measured by melting individual samples and measuring the salinity of the meltwater using a digital conductivity meter. Reported salinity uncertainties represent standard deviations from measurements of multiple samples.

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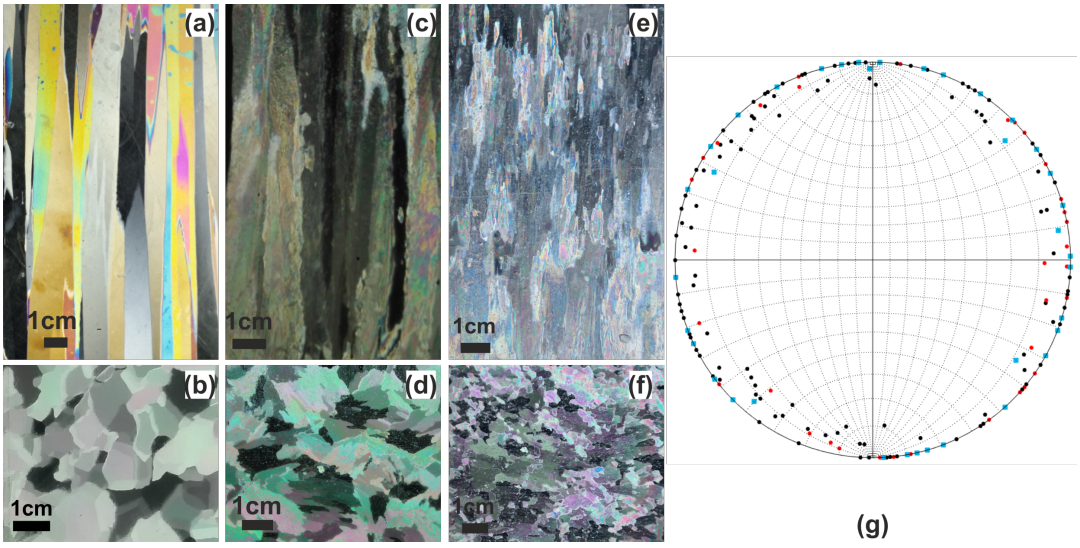

Figure 1. Photomicrographs of ice microstructure: vertical (a) and horizontal (b) thin sections of freshwater ice, vertical (c) and horizontal (d) thin sections of saline ice, vertical (e) and horizontal (f) thin sections of sea ice, and stereographic projection plot of crystal c-axis {0001} orientations freshwater (in black), saline (in red) and sea ice (in blue) (g).

From these materials, test specimens were machined and milled into thin beams with final dimensions: thickness h = 13 mm (along the columns), width w = 75 mm, and length l = 300 mm. To explore the effect of temperature on kinetics and hence to gain some insight into the physical mechanism underling healing, the specimens were tested at either -78 °C, -28 °C, -10 °C or -3 °C. Each specimen was oriented such that its long axis was perpendicular to the direction of loading upon bending, ensuring that the ice was loaded across the columnar-shaped grains, analogous to the natural loading of an ice cover (Iliescu et al., 2017; Murdza et al., 2021a, b, 2022b). After achieving thermal equilibrium, the beams were subjected to thermal shock by briefly spraying them with liquid nitrogen, either across a narrow (~20 mm) band in the middle of one of the largest faces or across the complete surface of one of the largest faces. The thermal shock created a network of randomly oriented, grain-sized thermal cracks, both intergranular and transgranular, that partially penetrated the beam to about one-fourth to one-third of its thickness, as in the previous studies (Murdza et al., 2022a, 2023). The cracks in the sea ice vanished rapidly, typically within less than 10 seconds, at least as far as the naked eye could discern. For ease of reference to our earlier work, Fig. 1 in Murdza et al. (2022a) shows cracks in the salt-free ice and the video in supporting information of that reference shows them in the sea ice where they vanished quickly.

The present manuscript combines newly acquired experimental results with selected previously published datasets (Murdza et al., 2022a, 2023) to investigate and understand the processes responsible for healing in thermally cracked ice. The narrow-band thermal cracking experiments are summarized from Murdza et al. (2022a) for comparison (number ii below), whereas the full-surface thermal cracking, repeated cracking–healing, compressive-creep, and sea-ice cyclic-loading experiments are newly reported here. Some cyclic-loading results from Murdza et al. (2023) are also reinterpreted in the context of creep-assisted crack-tip blunting. The experimental sets are described below.

(i) *Healing after full-surface thermal cracking*. Some freshwater and sea ice beams were subjected to thermal shock, ensuring complete coverage of one of the largest faces of the sample, which induced cracking of the whole surface. The experiments were performed at -10 °C. The cracked specimens were allowed to heal for a period of up to 12 hours by placing them in sealed plastic

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bags inside a foam box in a cold room at the same temperature of -10 °C. Afterward, the cracked beams were placed in a 4-point loading frame and then bent to failure such that the cracked surface was loaded in tension.

(ii) *Healing after narrow-band thermal cracking*. Some freshwater, saline and sea ice beams were thermally shocked across a narrow (~20 mm) band and then subjected to failure under 4-point loading, after varying the time elapsed between shocking and bending from 0 to ~20 hrs. These experiments were conducted at temperatures of -78 °C, -28 °C, -10 °C or -3 °C.

(iii) *Repeated cycles of cracking and healing*. Some of the freshwater ice beams underwent a process involving five cycles of cracking of the entire surface followed by subsequent healing before they were subjected to bending. In these tests, the intervals of healing between thermal shocks ranged from 1 hour to 3 days, with the same interval applied consistently throughout all five cracking-cum-healing cycles for each specific sample. For instance, a five-cycle test with healing intervals of 3 days was performed over a period of 15 days. These experiments were performed at -10 °C.

(iv) *Effect of compressive stresses on healing*. Some freshwater ice beams were subjected to full-surface thermal shocking and then immediately after shocking were subjected for 1 hour to a creep load that generated an outer-fiber compressive stress on the cracked surface of 1 MPa. Subsequently, the samples were bent to failure with the cracked surface under tension. These experiments were performed at -10 °C.

(v) *Creep-assisted crack-tip blunting.* To investigate the effect of thermal shock and creep assisted crack-tip blunting on the behavior of freshwater ice under non-reversed cyclic flexing, we introduced the thermal shock during the first cycle to a narrow (~20 mm) band. Cycling of cracked specimens was done by flexing under 4-point loading at either -10 °C or -28 °C. In order to eliminate the potential for opposing crack surfaces to come into contact, we cycled specimens in a non-reversed manner such that the shocked region was always under tension. In these experiments, the minimum outer-fiber stress, defined below, was either 0.3 or 0.5 MPa, while the maximum outer-fiber stress was initially 0.6 MPa and then was gradually increased up to 1.1 MPa to reach higher outer-fiber stress amplitudes during cycling, in the manner described earlier (Murdza et al., 2020). Eventually, samples were cycled in tension between either 0.3 MPa and 1.1 MPa or 0.5 MPa and 1.1 MPa for an additional number of cycles ranging from 50 to ~20,000, and then monotonically brought to failure, again, such that the cracked surface was under tension. In this case, stress amplitude, which is defined as one-half of the difference between the maximum and the minimum outer-fiber stress, was either 0.4 or 0.3MPa, while the mean stress, which is defined as one-half the sum of the maximum stress and the minimum stress, was either 0.9 or 0.8 MPa, respectfully. In a few experiments, instead of cycling, we crept the sample at 0.8 MPa for ~10,000 sec.
Similar experiments on crack-assisted blunting were also performed on first-year sea ice at −10 °C. In these tests the specimens were cycled between outer-fiber tensile stresses of 0.5 and 0.7 MPa for either 10,000 or 20,000 cycles, with thermal shock applied to the surface that would subsequently experience tensile stress.

During both bending and cycling, the samples were loaded across the columns at a constant outer-fiber center-point strain rate of ~10^{-4} s^{-1}, always taking care to ensure that the cracked face was under tension (Murdza et al., 2023). The flexural strength σ_f was obtained from the load at failure, P, using the four-point loading relationship:

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

where L = 254 mm is the distance between the outer pair of load lines and b and h denote the width and thickness of the beam, respectively.

3 Results

Including our earlier experiments (Murdza et al., 2022a) a total of 213 flexural strength measurements were made across all experimental conditions. Fewer tests were conducted on sea ice owing to the limited availability of the material. Results for each experiment are available in the data repository. The results are categorized based on the types of experiments as outlined in the previous section.

(i) *Healing after full-surface thermal cracking*. After thermally cracking the whole surface, freshwater samples underwent a single 12-hour healing period, while sea ice samples were allowed to heal for 1 hour. Subsequently, the flexural strength of the healed freshwater ice was 1.3 ± 0.1 MPa; similarly, the strength of the sea ice was 1.3 ± 0.3 MPa. For reference, the strength of the as-cracked ice (i.e., zero elapsed time since thermal cracking) was ~ 0.7 MPa for both the salty and the salt-free materials (Murdza et al., 2022), in keeping with the dictates of fracture mechanics; the strength of pristine, non-cracked freshwater and sea ice was 1.67 ± 0.22 MPa and 1.40 ± 0.07 MPa, respectively. In other words, both materials recovered to nearly twice their as-cracked strength, which for sea ice was comparable to the strength of intact sea ice.

(ii) *Healing after narrow-band thermal cracking*. Figure 2 illustrates the effect of the elapsed time on flexural strength. These results are discussed in detail in Murdza et. al. (2022). In brief, for each material and at each of the three temperatures explored, immediately after the thermal shock the flexural strength of ice was significantly reduced in accord with fracture mechanics, but then rapidly recovered completely and reached the strength of non-cracked ice. At the same temperature, the healing time was greater in the freshwater ice than in the sea ice.

(iii) *Repeated cycles of cracking and healing*. Following five cycles of thermal cracking of the entire surface and subsequent healing of freshwater ice, the flexural strength was measured as 1.28 ± 0.08 MPa. This value is comparable to the strength obtained after a single cracking–healing event (1.3 ± 0.1 MPa), indicating that repeated cycles of cracking and healing do not lead to further strengthening of the material.

In one additional experiment, after completing five cracking–healing cycles with healing intervals

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of 3 days, a specimen was subjected to bending while thermal shock was applied simultaneously. In this case, failure occurred at 0.56 MPa, a value consistent with the strength of ice that is thermally cracked and loaded immediately after shocking. This observation further indicates that repeated cracking-cum-healing *does* not increase the inherent resistance of the material to thermal cracking.

(iv) *Effect of compressive stresses on healing*. In this set of experiments where the thermally cracked surface of freshwater ice was crept under compression before being bent to failure under tension, the measurements yielded a flexural strength of 1.56 ± 0.13 MPa. This value approaches the strength of pristine freshwater ice (1.67 ± 0.22 MPa), indicating that compressive stress during healing significantly enhances strength recovery.

(v) *Creep-assisted crack-tip blunting.* Figure 3 shows the effect of cycling on the recovery of strength. At −10 °C, the strength of freshwater ice recovered completely after ~10,000 cycles, approaching the strength of pristine ice, whereas at −28 °C recovery remained incomplete even after ~20,000 cycles, with the strength reaching only 1.23 ± 0.12 MPa. Similarly, following approximately 10 hours of creep at 0.8 MPa (equivalent to the duration of the cycling experiments) at −10 °C, the flexural strength of the freshwater ice also exhibited complete recovery. Several freshwater specimens failed during the early stages of cycling at −10 °C while being loaded (Fig. 3), indicating relatively low strength prior to full recovery.
In similar experiments on first-year sea ice conducted at −10 °C, the strength recovered completely after ~10,000 cycles, reaching 1.32 ± 0.22 MPa, which is comparable to the strength of pristine sea ice (1.40 ± 0.07 MPa).

To demonstrate that the observed recovery of strength in freshwater ice cannot be explained solely by the warming of the thermally shocked beam, we compared the time scales of temperature recovery and strength recovery, finding that the surface temperature recovers much more rapidly than the strength. Figure 2 shows the effect of elapsed time on flexural strength of freshwater ice and salt-water ice at different temperatures (Murdza et al., 2022a). The recovered strength was normalized by dividing by the maximum strength recovery

$$\frac{\sigma - \sigma_{t=0}}{\sigma_0 - \sigma_{t=0}}, \tag{2}$$

where $\sigma_{t=0}$ is strength of ice immediately after thermal shock, σ_0 is strength of pristine non-cracked ice). This figure additionally illustrates the normalized ice surface temperature change of the thermally shocked surface immediately following the shock

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$$\frac{T(t) - T_N}{T_o - T_N}, \tag{3}$$

where *T(t)* is the surface temperature of the ice as a function of time *t*, T_N is the temperature of the liquid nitrogen (-196°C), and T_o is the temperature of the cold room (see Supporting Information). It is worth noting that in freshwater ice the surface temperature recovers significantly faster than strength; the majority of the temperature recovery takes place within the initial 4 seconds (from -196°C to -40°C), whereas strength predominantly recovers over approximately 100-300 seconds. In contrast, in salt-water ice the recovery time of strength is comparable to the time scale of temperature recovery, suggesting that the mechanisms governing healing in saline ice may differ from those in freshwater ice.

Taken together, these results demonstrate that thermally induced cracks in ice can heal through multiple processes, and that the rate and extent of strength recovery depend on temperature, loading conditions and the geometry of the cracked region.

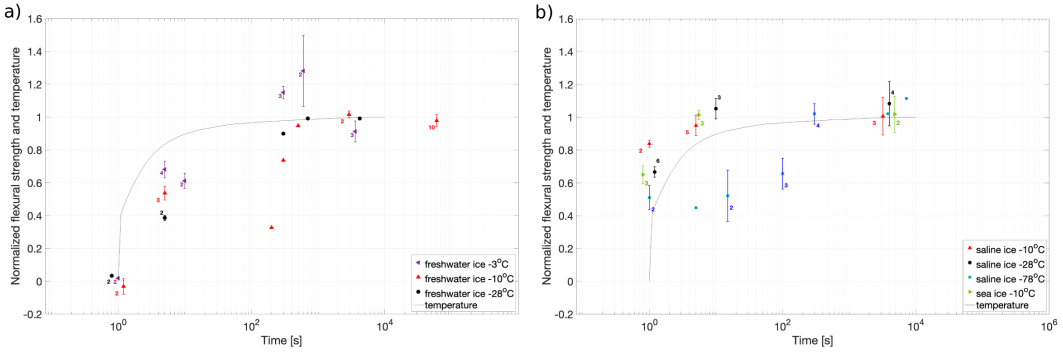

Figure 2. Flexural strength recovery of cracked and healed freshwater ice (a) and salt-water ice (b), normalized by the maximum strength recovery, plotted against time since thermal cracking at various temperatures. Error bars indicate standard errors with the number of samples indicated by the number next to the point. The solid line illustrates the normalized surface temperature at the center of the beam, with respect to the temperature of the cold room. Modified after (Murdza et al., 2022a).

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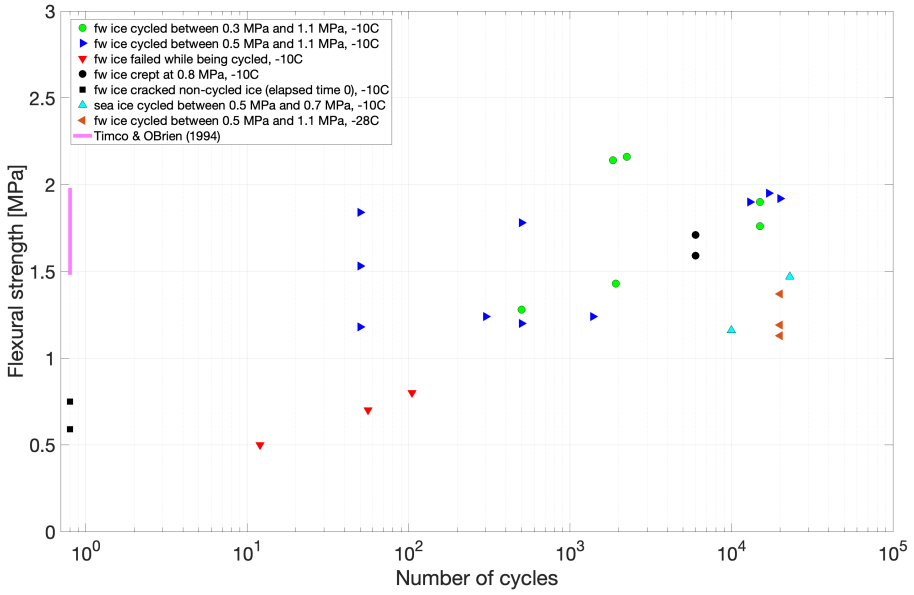

Figure 3. Flexural strength of cracked freshwater ice at −10°C as a function of number of cycles during non-reversed cycling. The solid pink line indicates the average flexural strength of non-cracked non-cycled freshwater ice plus and minus one standard deviation, that is, 1.73 ± 0.25 MPa (Timco and O'Brien, 1994).

4 Discussion

The primary objective of the present study was to investigate the effect of thermal shock on the flexural strength of both freshwater ice and sea ice and to identify the processes responsible for strength recovery. Based on the experimental observations, we propose that strength recovery occurs through two primary processes. The first involves healing through contact between opposing crack surfaces, where sintering via surface diffusion and the presence of a liquid-like layer promote the formation of bonds across the crack interface (Nguyen et al., 2021). This process can be significantly enhanced when compressive stresses increase the real area of contact between crack faces. The second process involves creep-assisted blunting of crack tips, a thermally activated mechanism that reduces stress concentration and allows recovery of strength even when crack surfaces remain separated. The relative importance of these processes depends on temperature, loading conditions and whether opposing crack surfaces are able to come into contact.

When the entire surface of a freshwater ice sample is subjected to thermal cracking, the initial flexural strength decreases to approximately 0.7 MPa, consistent with the expectations of fracture mechanics (see analysis in Murdza et al., 2022a). After a healing period of approximately 12 hours, the strength recovers to approximately 1.3 MPa. In these experiments, terminal fractures always propagated along at least one of the original thermal cracks, suggesting that the healed cracks still represented relatively weak regions within the ice structure. We therefore attribute the

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observed partial strength recovery to healing processes occurring at the crack surfaces, primarily through the combination of sintering and of the transformation of the liquid-like layer (Asakawa et al., 2016; Dash et al., 1995; Elbaum and Schick, 1991; Faraday, 1860; Petrenko and Whitworth, 1999; Szabo and Schneebeli, 2007) into solid ice.

Experiments involving repeated cycles of cracking of the entire surface followed by healing indicate that this process restores strength but does not lead to progressive strengthening of the material. After several cracking–healing cycles, the measured flexural strength remained comparable to that of specimens that experienced a single cracking event, suggesting that the healing mechanisms primarily restore the original strength rather than enhance it.

A different behavior is observed when only a narrow band of the ice surface is thermally shocked. In this case, although the initial strength again decreases to approximately 0.7 MPa, the flexural strength recovers completely within a relatively short period of approximately 300 s (Murdza et al., 2022a). The faster and more complete recovery is likely due to the presence of compressive stresses generated during the warming of the thermally shocked region. Immediately following thermal shock, the surface layer contracts due to rapid cooling and cracks form. As the shocked region subsequently warms, thermal expansion occurs while the surrounding material constrains this expansion. This constraint generates compressive stresses within the cracked region. These stresses increase the real area of contact between opposing crack faces and promote healing through creep and sintering (Schulson et al., 2016; Schulson and Fortt, 2013).

Consistent with this interpretation, in the majority of narrow-band experiments (22 out of 25 tests) the final fracture after healing propagated outside the thermally shocked region (Murdza et al., 2022a). This observation suggests that the healed region may be as strong as, or even stronger than, the surrounding pristine ice. One possible explanation is that the compressive stresses and creep deformation occurring during healing lead to plastic deformation along the crack surfaces and to potentially dynamic recrystallization, resulting in locally finer grain sizes. Since the tensile strength of ice is known to increase with decreasing grain size (Schulson and Duval, 2009), this microstructural change could locally enhance strength. Whether such recrystallization actually occurred remains to be determined. However, an alternative explanation is also possible. If the healed region has the same strength as the surrounding material, fractures may occur more frequently outside the shocked region simply because the cracked region occupies a smaller area within the beam section between the loading spans. Therefore, statistically, fractures are more likely to happen in the larger area.

When the entire surface of the ice specimen is thermally shocked, the situation differs because the shocked region is not confined by surrounding non-cracked material during subsequent warming (although there may still be some internal pressure as the ice warms up). As a result, the generation of compressive stresses is significantly reduced. The absence of substantial confinement limits the extent to which opposing crack faces are forced into contact, and consequently the ability of the material to regain strength is reduced. In these experiments the strength recovered only partially, from approximately 0.7 MPa to approximately 1.3 MPa after a healing period of 12 hours. This

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contrast between narrow-band and full-surface cracking highlights the important role of confinement and compressive stresses in promoting healing.

Further evidence for the role of compressive stresses is provided by comparing the time required for thermal equilibration with the time required for strength recovery. If healing occurred solely through the transformation of the liquid-like layer into solid ice as the cracked region warmed, strength recovery would be expected to occur on the same timescale as temperature recovery. In this case, the transformation is expected to occur almost instantaneously, possibly within the same time frame as the Debye relaxation time. However, numerical calculations show that the temperature of the thermally shocked ice recovers rapidly, within approximately 4 s, whereas the recovery of flexural strength requires significantly longer times, typically 100–300 s (Fig. 2). This difference suggests that additional time-dependent processes contribute to healing. The fact that strength recovery continues well after thermal equilibration indicates that creep deformation and the development of contact between crack surfaces play an important role.

In the previous study of narrow-band thermal cracking (Murdza et al., 2022a), the healing rate exhibited Arrhenius behavior with an apparent activation energy comparable to that associated with surface diffusion on ice. That observation led to the tentative interpretation that crack healing was primarily controlled by sintering via surface diffusion. In light of the present results, however, the apparent activation energy likely reflects the combined contribution of more than one process, including sintering at contacting crack surfaces and creep-assisted crack-tip blunting. The presence of multiple processes operating simultaneously may therefore contribute to the uncertainty in the activation-energy estimates obtained in the earlier analysis.

The increase in strength produced by compressive creep, resulting in a flexural strength of 1.56 ± 0.13 MPa, which is statistically indistinguishable from the strength of pristine ice (1.67 ± 0.22 MPa; $p = 0.3$), can be understood in terms of the geometry and deformation of asperities that protrude from opposing crack surfaces and interact at points of contact. When two rough surfaces are brought into contact, the real contact area is typically much smaller than the apparent area because contact occurs only at asperity tips. This concept, originally proposed by (Bowden and Tabor, 1950), implies that the actual contact area increases gradually as asperities deform. In the present case, creep deformation under compressive stress increases the real contact area between opposing crack faces, thereby promoting sintering and bond formation. The kinetics of strength recovery can be described by an Avrami-like relationship (Avrami, 1939; Porter et al., 2009):

$$\frac{\sigma_r}{\sigma_0} = 1 - \exp\left(-kt^n\right), \tag{4}$$

where σ_0 is the initial strength of crack-free material, σ_r is the recovered strength, t is the healing time, and k and n are kinetic parameters. Assuming that ${}^{\sigma_r}/_{\sigma_0} = {}^{A_r}/_{A_0}$, where A_r and A_0 denote the real area and the apparent area

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which is constant. Assuming that the recovered strength is proportional to the ratio of real to apparent contact area and following the analysis of (Schulson et al., 2016), the recovered strength can be expressed as

$$\frac{\sigma_r}{\sigma_0} = \sigma_h B^{-1} t^n \exp\left(^{-nQ}/_{RT}\right), \quad (5)$$

where B is a material constant, σ_h is the compressive creep stress during healing, Q is an activation energy, R is the gas constant and T is a temperature. Using parameter values reported by (Schulson et al., 2016), namely an activation energy $Q = 50 \pm 6$ kJ mol^{-1}, a material constant $B = 0.027$ MPa s^n, and a stress exponent $n = 0.33$, and taking $T = 263$ K and $R = 8.31$ J mol^{-1} K^{-1}, we obtain that for 1 hr of creep at the effective bending stress of $\sigma_h = 0.5\ MPa$, $\sigma_r = 0.24\ MPa$.

This model predicts an increase in strength of approximately 0.24 MPa after one hour of creep at an effective compressive stress of 0.5 MPa. In the present experiments, the observed increase in strength was 1.56 MPa − 1.3 MPa = 0.26 MPa, which agrees well with the predicted value. Because the applied bending stress varies linearly through the thickness of the specimen, the effective compressive stress acting on crack faces is approximately half of the outer-fiber stress, which supports the assumption used in the calculation. This interpretation is consistent with previous observations (Murdza et al., 2023), where strength recovery was enhanced when cyclic loading permitted compressive contact between crack faces.

4.1 Creep-assisted blunting

Even when crack surfaces remain separated and cannot sinter, strength recovery can still occur through creep-assisted blunting of crack tips. In the present experiments (v) this mechanism was examined by cyclically loading thermally cracked specimens under non-reversed bending, ensuring that the cracked surface remained under tension and that opposing crack faces did not come into contact. Under these conditions healing by sintering is suppressed. Nevertheless, at −10 °C the flexural strength recovered completely after approximately 10,000 seconds (Fig. 3), whereas at −28 °C only partial recovery was observed. This temperature dependence indicates that the process responsible for recovery is thermally activated and consistent with creep-assisted crack-tip blunting.

In the competition between crack growth and crack blunting, blunting dominates as strength increases over time and most likely tips of the cracks are getting blunted. Generally, according to the model proposed by (Renshaw and Schulson, 2001), and crack blunting dominates crack growth when the size of the creep zone r_c ahead of the crack tip exceeds the size of the elastic zone r_e, i.e. $r_c > r_e$. The size of the elastic zone can be estimated using Irwin's approximation (Anderson, 2017; Irwin, 1957):

$$r_e = \frac{1}{6\pi}\left(\frac{K_I}{\sigma_e}\right)^2, \quad (6)$$

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where K_I is the stress intensity. Assuming $\sigma_t = K_{Ic}/Y\sqrt{c}$, where K_{Ic} is the critical stress intensity factor (for both freshwater and sea ice $K_{Ic} \approx 0.1\ MPa\sqrt{m}$ and depends on temperature, grain size, and loading rate; e.g., Schulson and Duval., 2009; Rist et al., 2002; Weber and Nixon, 1996; Nixon and Schulson, 1988) and Y denotes a geometrical factor, that we take to be of order unity, the elastic zone size becomes

$$r_e = \frac{c}{6\pi}. \tag{7}$$

For the cracks observed in the present experiments this yields $r_e \approx 0.1$ mm.

When the ice is loaded slowly, creep occurs rapidly enough to prevent K_I from reaching K_{Ic}, therefore, promoting macroscopically ductile behavior (Anderson, 2017; Broek, 1986; Schulson and Duval, 2009). The creep zone is defined as the region within which creep strain exceeds elastic strain. The creep zone size can be estimated from the Riedel–Rice model of creep zones around non-interacting cracks (Schulson and Duval, 2009):

$$r_c = \frac{{K_I}^2}{2\pi E^2}\left(\frac{(n+1)^2 E^n B t}{2n\zeta^{n-1}}\right)^{2/(n-1)} F\,, \tag{8}$$

where F denotes an angular function of order unity, ζ is a dimensionless factor.

Using material parameters for ice, this analysis yields r_c = 5 mm. Since $r_c \gg r_e$, creep deformation occurs rapidly enough to blunt the crack tip before the stress intensity reaches the critical value for crack propagation. Dislocation activity ahead of the crack tip therefore absorbs energy during the loading and partial unloading portion of the load cycle that would otherwise drive crack growth. A similar phenomenon of crack-tip blunting and arrest of fatigue crack growth during non-reversed 4-point cyclic loading of freshwater ice was previously observed by (Weber and Nixon, 1997).

Sea ice exhibits different behavior from freshwater ice. In both narrow-band and full-surface thermal shock experiments the flexural strength of sea ice recovered completely within a short period. In addition, the thermally induced cracks disappeared visually within a few seconds after the shock (a video recording of the rapid disappearance of the cracks in the sea ice is provided in the Supporting Information of Murdza et. al (2022a)). We attribute this rapid healing to the microstructural characteristics of sea ice, particularly its porous structure and the presence of brine. Brine rapidly wets newly formed fracture surfaces and can refreeze quickly, facilitating rapid healing. Furthermore, cracks propagating through sea ice frequently encounter pores and brine channels that act as natural crack arresters, limiting crack length. The rapid disappearance of cracks and the quick recovery of strength indicate a strong self-healing capability of sea ice associated with its microstructure. However, the present results also suggest that healing kinetics may be strongly temperature dependent. At much lower temperatures, such as those relevant to extraterrestrial icy environments, healing may occur significantly more slowly. For example, in our

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earlier experiments at −78 °C the characteristic healing time of saline ice increased substantially compared with the few seconds observed at −10 °C. Whether thermal cracks in saline ice can heal rapidly under such extremely cold conditions therefore remains an open question and warrants further investigation. However, because the number of sea-ice experiments was limited and the associated uncertainties were relatively large, the apparent complete recovery of strength should be interpreted cautiously.

The extent to which the present laboratory observations scale to natural ice covers remains an open question. Processes such as sintering between contacting crack surfaces, liquid-like layer-assisted bonding, and creep-assisted crack-tip blunting are expected to operate across scales because they are governed by material-level thermodynamic and creep processes. However, their relative importance in natural environments may depend strongly on crack geometry, confinement, thermal gradients, pore structure, brine transport, and loading history. In particular, the compressive stresses generated during healing of narrow-band thermal cracks in laboratory specimens may be more difficult to achieve in large-scale natural ice covers, where crack opening displacements and thermal gradients are more heterogeneous. Similarly, the rapid healing observed in sea ice may depend on local brine connectivity and pore structure, which vary substantially in natural environments. Nevertheless, the present experiments provide insight into physical mechanisms that may contribute to strength recovery in thermally damaged ice.

If the behavior observed in laboratory-scale experiments reflects processes occurring at larger scales, the implications for natural ice covers may differ between freshwater and sea ice. In freshwater ice, large regions subjected to thermal cracking may not heal rapidly because the development of compressive stresses and confinement may be limited. In contrast, sea ice may retain a greater capacity for rapid healing due to the presence of brine within pores. However, the behavior of saline ice at extremely low temperatures remains uncertain and requires further investigation.

Conclusions

Systematic experiments were conducted on the flexural strength of S2 columnar-grained freshwater, saline, and first-year sea ice that were thermally cracked using liquid nitrogen and subsequently allowed either to heal at rest or under cyclic loading at temperatures between −78 °C and −3 °C. The results demonstrate that thermally induced cracks do not necessarily lead to permanent weakening of ice. Instead, the flexural strength of cracked ice can recover substantially, and in some cases almost completely, through two primary processes. The first involves healing by contact between opposing crack surfaces, where sintering through surface diffusion and the presence of a liquid-like layer promote the formation of bonds across the crack interface. This process is strongly enhanced by compressive stresses that increase the real area of contact between crack faces. The second process involves creep-assisted blunting of crack tips, a thermally activated mechanism that reduces stress concentration at the crack tip and allows partial or complete recovery of strength even when crack faces remain separated.

The relative importance of these processes depends on temperature, loading conditions, and crack geometry. When compressive stresses develop—either due to thermal expansion or externally applied loads—healing by contact

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dominates. When crack surfaces remain separated, strength recovery can still occur through creep-assisted crack-tip blunting, particularly at higher temperatures where creep processes are more active. In sea ice, healing occurs particularly rapidly, likely due to the presence of brine and the porous microstructure, which facilitate rapid wetting and refreezing of crack surfaces.

These findings suggest that thermally induced cracking may not permanently compromise the mechanical integrity of natural ice covers, as healing processes can restore strength over timescales ranging from seconds to hours. Understanding these processes is therefore important for predicting the mechanical behavior and stability of ice covers in natural environments.

Code and data availability

The datasets supporting this study are publicly available through the Arctic Data Center repository:

- Murdza, A., Schulson, E., & Renshaw, C. (2024). *Study on creep-induced blunting of thermal cracks in laboratory-produced freshwater ice and sea ice collected from the Beaufort Sea under cyclic loading and creep, 2022–2024.* doi:10.18739/A2HT2GD4Z.
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Author contributions

AM, ES, and CR designed the experiments, and AM carried them out. AM prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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