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REVIEW IN EXPERIMENTAL STUDIES ON FREEZE-BONDS

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ABSTRACT

This paper reviews and compares the existing literature on experimental studies of freeze-bonds. A summary of the procedures and main parameters shows that the methods used to make and test the freeze-bonds differed considerably. The impact of the different parameters on the freeze-bond strength is discussed in order to define how the different experiments can be compared. The discussion is focused on how the freeze-bond strength depends on normal confinement, contact time, initial ice temperature, sample size and ice properties. The discussion covers freeze-bonds of saline ice in saline water, saline ice in air and freshwater ice in freshwater. The reported freeze-bond shear strengths, defined as the peak shear stress in the freeze-bond, ranged from 0.2 to 195 kPa. However, when taking the normal confinement into consideration, a linear pressure dependent failure criterion (Mohr-Coulomb type of model) gave a reasonably good description of the mechanical behaviour of the freeze-bonds.

INTRODUCTION

Sea ice ridges are formed by compression or shear in the ice cover and in many Arctic and sub-Arctic marine areas they give the design ice action on offshore and coastal structures. The calculation of ice action from first-year ridges involves a description of the unconsolidated layer (ice rubble). Ice rubble consists ideally of sea ice blocks and pores with seawater. The bonding between the ice blocks is called freeze-bonds and is often considered to be a key feature in a physical description of ice rubble deformation (Liferov and Bonnemaire, 2005).

This paper has two main objectives: to summarize what has been done within the topic and to compare the results from the different investigations. We found only five publications which deal with this topic specifically: Ettema & Schaefer (1986) –E&S-, Shafrova and Høyland (2008) -S&H-, Marchenko and Chenot (2009) -M&C-, Repetto-Llamazares et al. (2011) -RL- and Vershinin et al. (2005). The four first papers present experimental data while the latter is focused on theoretical approaches. We expand on the brief review of RL and focus our analysis in the comparison between the four experimental investigations (E&S, S&H, M&C and RL).

The experiments were partly done in the laboratory and partly in the field. All the experiments consisted basically in the creation of freeze-bonds by placing two ice blocks together, waiting certain time for the freeze-bond to develop and subsequently testing it. However simple this may sound, there are several parameters affecting the results, and different sets of parameters and testing methods were used by different authors. This complicates the comparison of the data.

EXPERIMENTAL METHODS AND SET-UPS

The type of ice, initial boundary conditions, experimental method and experimental set-up of the tests done by each author were different, so the comparison of the data is not straightforward. Table 1 presents the main characteristics of the different experiments. We classified the type of experiment into three categories: Freeze-bond strength (FB-σ), heat transfer in submerged blocks (HT) and freeze-bond growth (FB growth). In this paper we will mostly focus on freeze-bond strength tests.

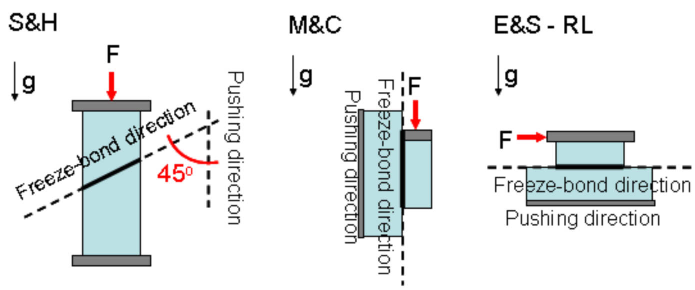

Figure 1. Experimental set-ups used in the reviewed papers.

The type of ice was classified as freshwater ice (FWI), natural sea ice (SI) and laboratory made saline ice (referred just as saline ice from now on). The ice physical properties: initial ice temperature (T_i) -, ice salinity (S_i) – and ice density (ρ_i) - are described in the table when the information was available in the original publications. The initial ice temperature was one of the control parameters in our own experiments (RL) and thus it is of high interest in our analysis. However, not all the authors reported this value so in Table 1 we made the two following assumptions: a) E&S does not explicitly say that the ice was at -10^{o}C when the freeze-bonds started to form, but since -10^{o}C was the temperature at which the ice blocks were formed, we assumed this was the initial temperature of the ice, b) M&C reported only the ambient air temperature, but since they worked only with freeze-bonds made in air, we assumed that the initial ice temperature was the same as the air temperature.

The fluid surrounding the ice blocks as the freeze-bonds were forming is referred as *surrounding fluid* and it was either air, distilled, tap and fresh water (salinity around 0 ppt) or saline water with varying salinities. When water was the surrounding fluid, the temperature (T_w) and salinity of the water (S_w) are important parameters to consider. The air temperature (T_{air}) is not only important when the air is the surrounding fluid but also when the freeze-bonds were made in water, since the mechanical tests were performed in air in most of the publications. In these cases, T_{air} is probably a parameter that does not have a great impact in the freeze-bond mechanical behaviour, but it is still interesting to have it in mind.

The time that the ice blocks were left in touch to develop the freeze-bond (Δt_c), also referred as contact time, or submersion time when the freeze-bonds were made in water, was another control parameter in our experiments (RL) and it differed greatly between different authors. E&S worked with very short Δt_c (between 10 seconds to 4 minutes), while M&C and S&H worked with long Δt_c (from 1 to 3 days) and RL used intermediate Δt_c (between 1 minute and 20 hours).

The normal confinement used while the freeze-bonds were being formed, and while mechanical testing took place are in principle two independent variables. During RL and E&S tests, both confinements were the same, but they were different in S&H and M&C tests. In S&H the confinements during freeze-bond formation were between 250 and 600 Pa and during testing it was gradually increased until failure (around 10 to 100 kPa). In M&C the confinement during freeze-bond formation was around 350 Pa and during testing around 0 Pa. Nevertheless, no special analysis was done regarding the difference between these parameters in any of the publications and we will refer to the pressure applied during testing (σ) as the normal confinement. In addition, Table 1 distinguishes between constant normal confinement during testing (as used by E&S, RL and M&C) and continually increasing normal confinement while testing, as used by S&H.

The dimensions of the ice blocks will influence the energy balance between the surrounding fluid and the ice, so a characteristic length (L_b) and block thickness (h_b) are presented in the table. The contact area between the blocks (A_c) will give the "amount of freeze-bond" that might grow between the blocks, while the ratio between the contact area and the sample volume ($\underline{Vol}$), A_c/Vol, is a measure of the available cold energy to form the freeze-bond (Vol) and the "amount" of freeze-bond that has to be grown (A_c). The quality of the ice surface will certainly affect the freeze-bond strength, but the roughness of the ice surface prior to freeze-bonding was not studied in detail by any of the researchers. However, in most of the papers it is mentioned briefly; E&S used a heated plate to smooth the ice surfaces, S&H mostly used natural sea ice but the roughness in the freeze-bond surface was probably defined by the saw used to cut the ice pieces. M&C reported gaps of thickness around 1 mm between the ice surfaces. RL did not pay particular attention to the roughness and classified it as random.

The set-ups used to measure the freeze-bond strength are sketched in Figure 1. In three of the papers (E&S, M&C and RL) the force was applied along the freeze-bond whereas S&H applied it 45° to the freeze-bond. The angle between the applied force and the freeze-bond is referred in Table 1 as the *set-up angle*, while the expression *pushing direction* is used about the pushing force direction relative to the gravity (g) (vertical, when pushing is in the same direction as g, and horizontal when the pushing is transversal to g, See Figure 1). As the mechanical behavior of ice depends on the strain-rate, the freeze-bond behaviour can also be expected to depend on the strain-rate. The strength tests were all performed by using a piston at constant velocity as given in Table 1. E&S reported that no significant change in freeze-bond strength was found when varying the velocity between 0.44 mm/s and 0.84 mm/s. The velocity used in RL experiments was within this range, while the velocity used by S&H was slightly lower and M&C did not report this parameter. In general we can say that the velocities were similar and we do not expect this parameter to be of much relevance when comparing the results from the four authors. The number of samples used to determine one experimental point (n) is shown in Table 1 as well as the maximum strengths recorded by each author.

RESULTS

In order to make the comparison of the data easier, data points published by the different authors were extracted from the corresponding figures by using the free software WinDig2.5 and plotted together.

Table 1. Experimental characteristics of the procedures used in the reviewed papers.

Author	**E&S**	**S&H**	**M&C**	**RL**
Experiment	FB-σ	FB-σ and HT	FB-σ - HT - FB growth	FB-σ
Ice type	Freshwater	Natural sea ice - Saline ice	Natural sea ice - freshwater	Saline Ice
T_i [˚C]	-10	(-7.2 to -1.8)	(-15 to -1)	-14 to -1.0
S_i [ppt]	0	(4.47 to 7.16)	---	(1.1 to 3.2)
ρ_i [kg/m^3]	----	(859 to 910)	---	(795 to 930)
Surrounding	Air - Distilled	fresh water - Sea water	Air - Sea water	Saline water – Air
T_{air} [˚C]	0	(-15 to -1.8)	(-15 to -2)	(-12 to -1)
T_w [˚C]	0	-1.5 to -1.7	freezing point sea ice	-0.85 to -0.5
S_w [ppt]	3 & 12.5 & 25	34	34	(7 to 13)
Δt_c	(0 to 4) min	(24 to 60) hr	few days	1 min to 20 hr
σ [Pa]	Constant	Increasing	Constant	Constant
L_b [m]	~ 0.1	0.24	~ 0.1	0.14
h_b [m]	~ 0.05	0.24	0.04	0.03
A_c [m^2]	(5 to 20) 103	0.081	~0.024	0.0196
A_c/Vol [1/m]	1-10	6	20	14
Ice surface	Smoothed	saw	gaps ~ 1mm	rough, random
Pushing	Horizontal	Vertical (Uniaxial)	Vertical	Horizontal
Set-up angle	0	45	0	0
Velocity	0.84 & 0.44	0.175	-----	0.7 - 0.8
N	> 10	1	1	3 & 7
$\tau_{c\ max}$ [Pa]	6 000	450 000	70 000	30 000

The variation of the freeze-bond strength (= the peak applied shear stress on the freeze-bond plane, τ_c) as a function of the normal confinement (σ) was only explicitly studied by E&S and RL, but information of the normal confinement during testing can be found in all the publications. Figure 2 (a) (also presented in Repetto-Llamazares et al., 2011) presents the results of τ_c vs. σ. In the tests of S&H the normal confinement (the normal stress perpendicular to the failure plane) increased proportionally with the shear stress on the same plane. In their paper they used *freeze-bond strength* about the peak uniaxial compressive stress (σ_{max}), whereas the others have reported the peak shear stress on the freeze-bond plane as the freeze-bond strength. In Table 1 we have converted the reported compressive capacity by S&H (σ_{max}) to the peak applied shear stress on the FB-plane (τ_c), so that

$$\tau_c = \sigma_{45} = \sigma_{\max} / 2 \quad (1)$$

where σ_{45} is the normal stress on the freeze-bond plane (=the normal confinement)

M&C experiments were performed without applying any normal confinement, so all the points are situated in a vertical line at σ ~ 0 Pa in Figure 2 (a).

The variation of the freeze-bond strength (τ_c) as a function of the contact time (Δt_c) was studied by E&S, S&H and RL and their data is presented in Figure 2 (b).

The freeze-bond strength as a function of temperature was studied by S&H, M&C and RL, and Figure 2 (c) give summarizes these data. Points corresponding to E&S were also included for the single initial temperature used (-10 C).

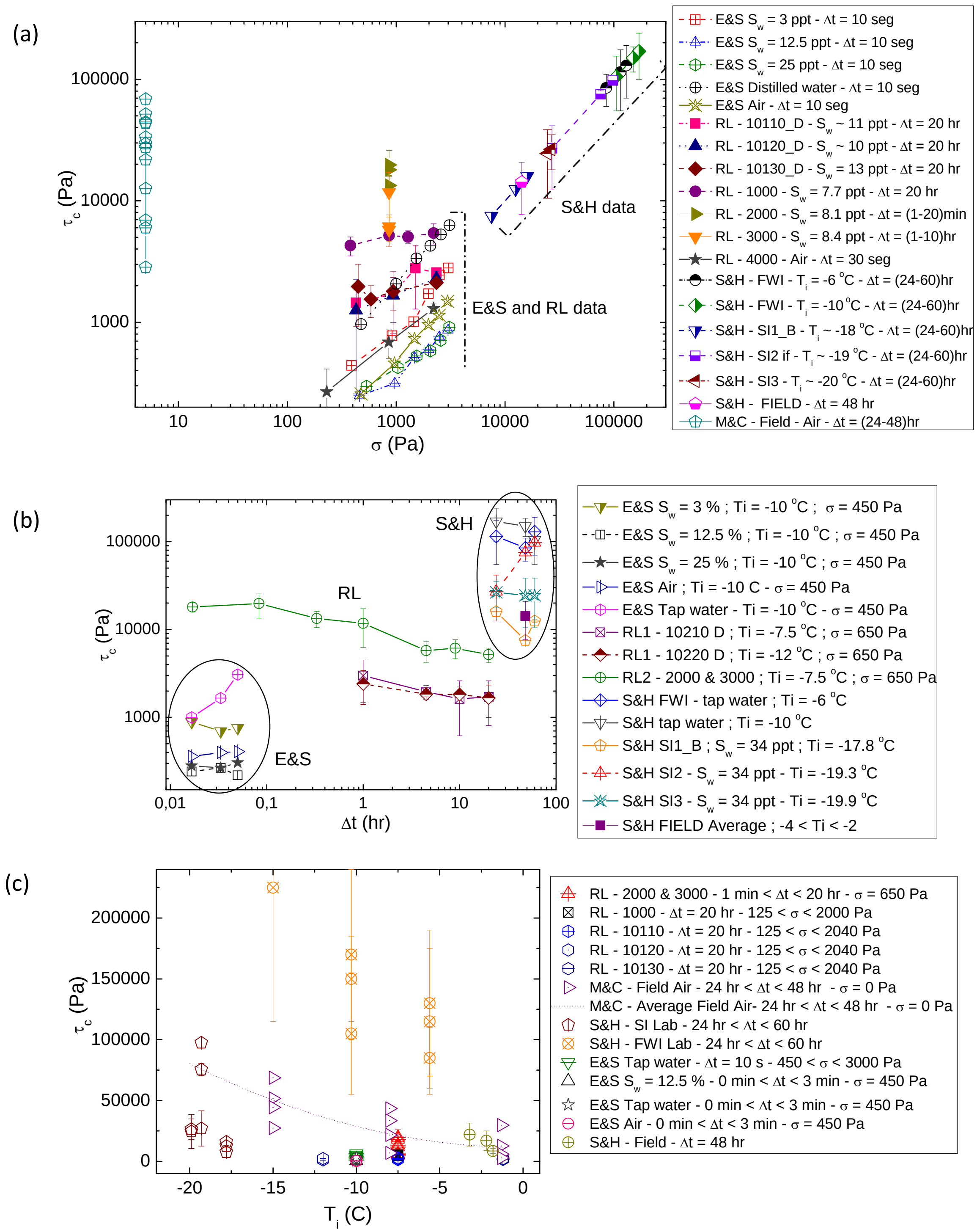

Figure 2. The measured strength as a function of a) confinement (τ_c vs. σ), b) contact time (τ_c vs. Δt_c) and c) Ice temperature (τ_c vs. T_i), Figure 2 a) is taken from RL.

DISCUSSIONS

The measured freeze-bond strength (τ_c) depends on several parameters. In addition to the parameters already discussed in so far, the oceanic conditions (temperature, salinity and velocity of the surrounding water) will determine the development of the freeze-bonds. Given the variation in the parameters during the different experiments, the relatively large span in τ_c (from less than 1 kPa and up to 195 kPa can be expected.

Dependence on the normal confinement

Saline ice in saline water

The Mohr Coulomb model proved to be an appropriate description of the τ_c vs. σ relation. As shown in RL, the extrapolation of the brittle-like model proposed by RL fitted relatively well to the data obtained by S&H.

RL discusses the possibility of the freeze-bond strength approaching the strength of ordinary ice after a long enough submersion time. S&H who had the highest values of τ_c still get a cohesion about one order of magnitude les than that of ordinary ice (Repetto-Llamazares et al., 2011). However, recent field tests (April 2011) indicate that the strength of old freeze-bonds are similar to that of the surrounding ice. More work is necessary to understand how both long term (several weeks) and short term (less than one minute) contact time govern the freeze-bond strength.

Saline ice and freshwater ice in air

Both E&S and RL worked with freeze-bonds made in air with freshwater and saline ice (respectively) under similar experimental conditions. The results of τ_c vs. σ of the freeze-bonds made in air are shown in Figure 2 (a) with starred-dots. Even though RL measured slightly higher strengths their results are numerically comparable with those obtained by E&S. The contact times and the initial ice temperatures used in both experiments were similar (10 s in E&S and 30 s in RL, and -10^{o}C in E&S and -7.5^{o}C in RL). Consequently, the difference between the two strengths may be explained by either the lower air temperature used during RL tests (-7.5^{o}C in RL tests and 0^{o}C in E&S), by the higher asperities or by the higher ice salinity in RL ice.

M&C worked in the field and measured saline ice freeze-bonds made in air. Even though their tests were done with almost zero confinement, their strengths were substantially higher than the ones measured by E&S and RL in air and comparable with submerged freeze-bonds (Figure 2 a). The vital difference is the different contact times: M&C used from 20 to 48 hr while E&S and RL used less than 4 minutes.

Freshwater ice in freshwater

S&H and E&S both performed experiments with freshwater ice submerged in freshwater, with similar initial conditions: T_i around -10°C and air temperature when testing around -1°C. Figure 3 shows the data from each author. E&S worked with different normal confinements and derived a cohesionless Mohr-Coulomb model (the dotted line in Figure 3) for freshwater ice in distilled water (friction angle 63.5°). The results from S&H lay below this model when extrapolated to the high normal confinements used by S&H.

The difference in the submersion times used by both authors (24 hr to 60 hr in S&H and 4 min in E&S) can explain the difference in their results: shorter submersion times mean that the freeze-bonds will be colder and thus stronger than freeze-bonds with long submersion times. It could also be that the large span in confining pressure goes beyond the range of a constant friction angle so that a decreasing angle is reasonable.

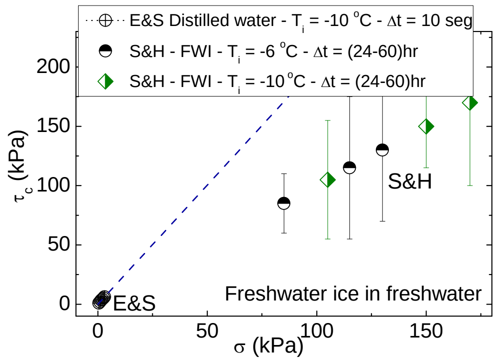

Figure 3. Freeze-bond strength vs. normal confinement of freshwater ice in freshwater.

Dependence on the submersion time / contact time

Saline ice in saline water

The bell-shape dependence of τ_c vs. Δt for saline ice in saline water was predicted by S&H and found by RL experimentally. With increasing submersion time the freeze-bond strength should increase fast, reach a peak and decrease more slowly. RL defined three phases and suggested that the observed strength-submersion time effect is essentially a strength-porosity effect ($\tau_c(\eta_{FB})$). The first phase is dominated by freezing and the freeze-bond temperature (T_{FB}) decrease (=decreasing $\eta_{FB} \Rightarrow$ increasing τ_c). When T_{FB} becomes equal to the temperature of the surrounding ice, the second phase starts. Here the freeze-bond is heated and brine is drained, but RL argue that heating dominates. The third phase starts when there are no more temperature or salinity gradients in the system of surrounding fluid-ice-freeze bond. With out these gradients any kind of process slows down considerably.

Freshwater and saline ice in air

For freeze-bonds made in air, the strength will probably be sensitive to the air temperature during formation. Assuming a constant air temperature, lower than the melting point of the ice, the development of the strength will probably increase continuously in time. However there are no experiments to confirm this hypothesis.

Freshwater ice in freshwater

The curve of τ_c vs. Δt will probably have a bell-shape similar to the one found for saline ice in saline water. However, since there is no brine to be expelled, the process will entirely be driven by thermal processes and thus the duration of each stage will be different. S&H were the only authors studying the freeze-bond strength variation of freshwater ice in freshwater and they worked with long submersion times (20 hr to 60 hr) where the trends were not clear. We suspect that for that long submersion times, the sample is in the third stage of the curve, where it has already flattened so the effects of the submersion time are not clearly observed.

Dependence on the initial ice temperature

Saline ice in saline water

Neither RL nor S&H found clear trends for the variation of freeze-bond strength as function of the initial temperature of the saline ice. The lack of consistency is probably associated to the strong coupling that joins the effects of the initial ice temperature with the submersion time and the ice properties. RL proposed that T_i can have two effects of on τ_c. On the one hand lower T_i will give colder and thus stronger freeze-bonds. On the other hand, lower T_i will produce faster ice growth thus producing more porous ice (locks in more brine) and weaker freeze-bonds. Which effect that dominates under which circumstances is not clear from the experimental data.

From the qualitative RL experiments it is clear that the initial ice temperature influences the freeze-bond strength strongly for short submersion times, while it does not play a major role for long submersion times. S&H experiments were all performed for long submersion times (from 24 hr to 60 hr) where the influence of the initial ice temperature is possibly small and this can be a reason of the absence of a clear trend in the data. Note that what are long and short submersion times will depend on the scale of the system, in particularly the size and ice properties.

Saline ice in air

MC found a clear decreasing trend with increasing temperature, but this is probably mostly an effect of freeze-bond temperature at the time of testing and not an effect of the initial temperature.

Freeze-bond strength dependence on sample size and ice properties

The ice properties are important in the development of freeze-bonds and its mechanical properties. The ice salinity, temperature and porosity give the thermal conductivity, the specific heat capacity and the diffusivity of the ice. None of the authors performed any systematic study on how the freeze-bond strength varied with the ice properties. However, although the ice samples in S&H were not made with predefined ice properties, they measured the ice density, salinity and temperature and then analyzed its impact in the freeze-bond strength. They found that the freeze-bond strength is highly influenced by the relation of air to brine volume. They observed that samples taken from the ice foot (SI2 if, Figure 2 (a)) were stronger than samples taken from the adjacent floe ice (SI3, Figure 2 (a)). They concluded that the higher air volume from the ice foot gave both a lower thermal conductivity and more possibilities for brine to drain away from the freeze-bond. A lower thermal conductivity increases the insulation and reduces the effect of the oceanic flux, and this leaves more available energy for freezing. The more efficient the brine drains from the freeze-bond the lower the salinity and the porosity so the freeze-bond should become stronger. In other words, both these effects from a high air fraction should increase the freeze-bond strength.

The size of the samples is important in at least two ways. Firstly the A_c/Vol is important as it gives the available energy to create the freeze-bond (minus the oceanic flux) so that a bigger sample has bigger thermal potential for creating a freeze-bond. The area is also interesting in itself as the brine that needs to drain from the freeze-bond may drain into the ice blocks or along the freeze-bond. In other words a small (areal wise) freeze-bond may become stronger than a larger one. Experiments performed by Strub-Klein (2010) showed the importance of the drainage along the freeze-bond plane. Moreover S&H observed that samples taken from the interior of the ice blocks were weaker than samples from the exterior, which shows the importance of both the brine drainage in the freeze-bond plane and the influence of this process in the freeze-bond strength.

In general, the freeze-bonds made from natural sea ice were stronger than the freeze-bonds made from saline ice by RL. The submersion times used in S&H and in RL experiments were similar (24 and 48 hours, and 20 hours, respectively). On the other hand, the ratio A_c/Vol in S&H experiments was around **6** while in RL experiments was around **14**. That means that there was more cold energy available to produce the freeze-bonds in S&H experiments and it gives a possible explanation for their higher values.

Coupled effect of the contact time, initial ice temperature and ice properties

The effect of the initial ice temperature on the freeze-bond strength proved to be strongly coupled with the submersion time in the qualitative experiments performed by RL. RL experiments showed that the initial ice temperature had a strong influence in the freeze-bond strength for short submersion times, whereas it was almost insignificant for longer submersion times.

These observations fit well with the assumption about phase 1 and 2 in the τ_c vs. Δt curve (increase and decrease in τ_c respectively) being basically thermally driven. This means that the width and height of the bell will be influenced by the initial ice temperature (the type of ice and of ice block geometry will also affect the bell-shape, as it will be discussed later). Another example of the coupling effect between the initial ice temperature and the submersion time is presented in Figure 4. The figure was built using results from S&H and shows two plots. In the upper part the uniaxial compressive strength (σ_c) is plotted vs. the submersion time, and in the lower part the ice temperature (T_{ICE}) vs. the submersion time is given. The measurements were not done for freeze-bonds, but we believe that the results can be extended easily. The initially colder ice required more time to warm to a temperature close to the melting temperature and was initially stronger than the warmer ice. However for a submersion time of 60 hr the difference in the ice temperature and the ice strength was almost inexistent.

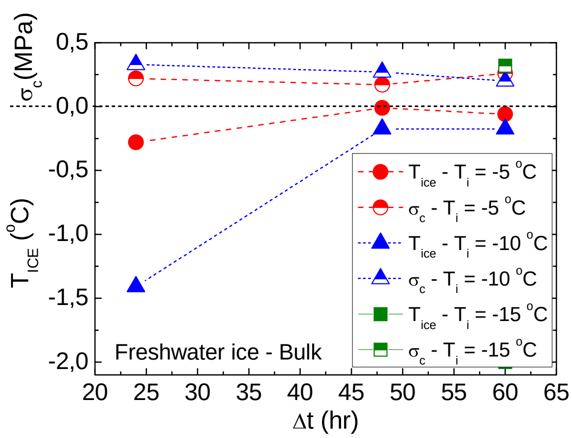

Figure 4. Uniaxial compression strength of the ice (σ_c) as function of the submersion time (Δt) – upper part. Ice temperature (T_{ICE}) as function of the submersion time (Δt) – lower part.

If we now think about saline ice in saline water, then the degree to which the initial ice temperature influences the freeze-bond strength will be related with the thermal properties of the ice (mostly determined by salinity, temperature and density), with the block dimensions and with the oceanic conditions. An example of the coupling effect between initial ice temperature and ice properties is found in the measurements from S&H using ice from an ice foot. After the 24 for 60 hours of submersion, the ice from the ice foot had a temperature between -2.5°C and -3.2°C (mostly around -3°C), well below the freezing point of the surrounding water. On the other hand, the ice from the floe ice tested in the same conditions (same container and initial temperatures) was warmer, between -1.8°C and -2.5°C. Thus it is clear that time scale was affected by the different type of ice used in the tests.

In order to quantitatively account for the coupling effect RL presented a study of dimensionless numbers. They considered experiments from S&H to be representative of full scale conditions and experiments from RL as model scale conditions and found that Froude scaling is more appropriate to scale freeze-bond problems than Fourier scaling.

Freeze-bond strength dependence on water salinity

The thermodynamics of saline ice in saline water are complex but as long as the ice is submerged in the same water in which the ice was grown and at the freezing point of the system, we are in a familiar experimental situation where the freeze-bond strength will be influenced by the salinity of the water mainly due to the brain drainage processes occurring inside the freeze-bond during its formation. However the situation is different when the ice is submerged in water of different salinity from which the ice was grown. That is the case in E&S experiments, where they submerged freshwater ice in saline water of variable salinities at a temperature of 0^oC. We do not give any theoretical description of this phenomenon, but we want to point out its complexity. Shestov (2009) performed experiments with freshwater ice close to 0^oC in saline water of different salinities at temperatures between its freezing point and 0^oC and observed melting of the ice. His experiments showed that freshwater ice in saline water melted even though the temperature of the water was lower than the melting point of the ice. The phenomena occurs due to the solid having less enthalpy than the liquid (Marchenko, 2009, Feistel and Hagen, 1998).

CONCLUSIONS

We have reviewed and compared results from the available experimental studies on freeze-bonds, that is the papers by Ettema and Schaeffer (1986) –E&S-, Shafrova and Høyland (2008) – S&H-, Marchenko and Chenot (2009) – M&C - and Repetto-Llamazares et al. (2011) –RL-.

A summary of the procedures and main parameters used by each author was done. The methods used to make and test the freeze-bonds differed considerably, and the freeze-bond shear strengths (= the peak measured shear stress during a test) covered a wide range of values, varying from 0.2 to 195 kPa.

The normal confinement affects the freeze-bond strength to a great extent. The experiments performed by S&H gave the highest strengths but they were also subjected to the highest normal stresses. A Mohr-Coulomb type of model gave a good representation of the freeze-bond strength as a function of the normal confinement. This kind of model fitted well the data of E&S and RL for saline ice in water and the mathematical expression found by RL to fit their brittle-like data fitted well the data from S&H for saline ice in saline water. Moreover, the data of E&S and RL for freeze-bonds made in water were also successfully fitted by a Mohr-Coulomb type of model with similar values of cohesion and angle of internal friction.

The bell-shaped curved of freeze-bond strength (τ_c) vs. submersion time (Δt) predicted by S&H and found experimentally by RL contains the information from the thermodynamic and geometric factors that influence the freeze-bond strength: initial ice temperature, submersion time, oceanic flux, ice properties and block geometries. From the data of the different authors it is clear that the effect of all these parameters are coupled and that they will give, in a coordinated way, the shape of the bell, i.e., the duration of each stage and the peak value. When comparing results from different authors, the safest place to make the comparisons is in the third stage of the curve of τ_c vs. Δt where the freeze-bond strength is stabilized. These values are probably useful when thinking about its possible application to first year ridges late in the season. On the other hand, the maximum of the τ_c vs. Δt can be of importance when thinking about extreme design loads. We think that further studies of this curve are needed both in full scale and model scale since it can provide the key to proper scaling of freeze-bonds.

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APPENDIX

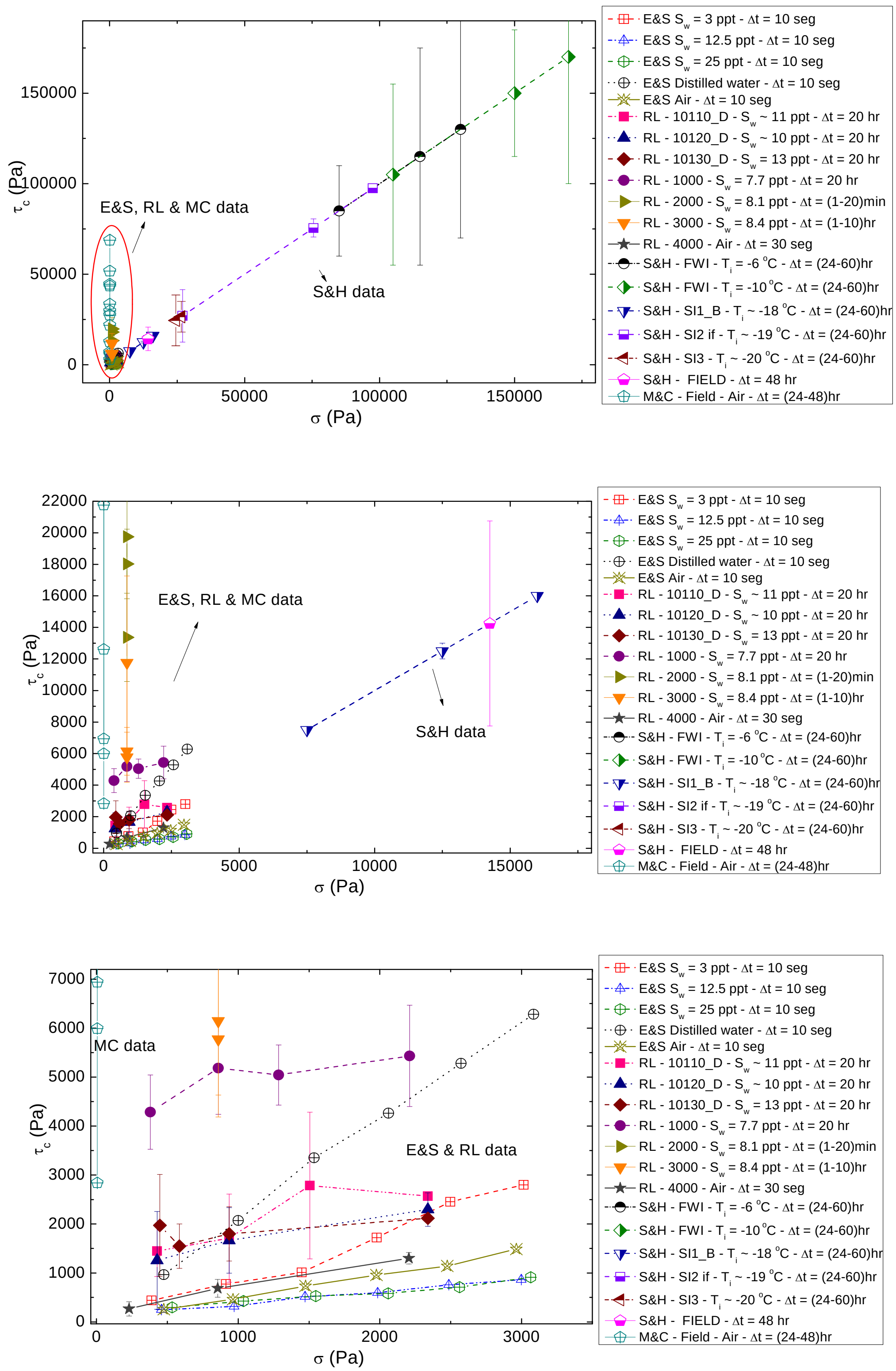

Figure A.1 Strength (measured peak shear stress) vs. confinement for three different zooms.