Cold Regions Science and Technology 65 (2011) 286–297

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Experimental studies on shear failure of freeze-bonds in saline ice: Part I. Set-up, failure mode and freeze-bond strength

Ada H.V. Repetto-Llamazares [a,*], Knut V. Høyland [a], Karl-Ulrich Evers [b]

[a] Norwegian University of Science and Technology (NTNU) Høgskoleringen 7A, 7491 Trondheim, Norway
[b] Hamburg Ship Model Basin (HSVA), Hamburg, Germany

ARTICLE INFO

Article history:
Received 27 May 2010
Accepted 2 December 2010

Keywords:
Saline iceFreeze-bond

ABSTRACT

The strength of freeze-bonds in thin saline ice has been investigated through two series (in 2008 and 2009) of experiments in the Hamburg Ship Model Basin (HSVA) as a function of the normal confinement (σ), the submersion time (Δt) and the initial ice temperature (T_i). The freeze-bonds were mostly formed in a submerged state, but some were also formed in air. The experimental set-up was improved in the 2009 experiments. In 2008 a ductile-like failure mode dominated (78%), whereas in 2009 the brittle-like dominated (93%). We suggest that this is a combined ice and test set-up effect. The 2009 experimental procedures allowed for careful sample handling giving higher strength and it was softer. Both these things should provoke a more brittle-like force–time response. The average freeze-bond strength in brittle-like samples was around 9 kPa while in ductile-like samples was around 2 kPa. The maximum freeze-bonds strength were measured for short submersion times, from 1 to 20 min, and reached a maximum value of 30 kPa.

A Mohr–Coulomb like failure model was found appropriate to represent the freeze-bond shear strength as function of the normal confinement. Saline freeze-bonds in saline water had cohesion/friction angle around 4 and 1.4 kPa/25° for the brittle- and ductile-like samples respectively, which fitted well with previously published data.

A bell-shape dependence for τ_c vs. Δt was found, which agreed with the predictions by Shafrova and Høyland (2007). We suggest that this is essentially a freeze-bond porosity effect and propose three phases in time with subsequent cooling, heating and equilibrium to account for this trend. Qualitative experiments showed that the submersion time and the initial ice temperature were strongly coupled.

To account for the connection between contact time, block dimensions and ice properties and the freeze-bond strength, dimensionless number were used. Fourier scaling was more appropriate than Froude scaling to scale freeze-bonds.

The freeze-bonding made in air developed fast (in less than 30 s) when the ice was cold and dry, but no freeze-bonding occurred for the same contact times when the ice was warm and wet.

1. Introduction

Ice ridges may represent the design load for ships, coastal, and offshore structures in many arctic and subarctic marine waters. When an ice ridge is formed, especially at a low air temperature, ice freeze-bonds may form between the broken pieces due to the internal cold energy stored in the ice. Freeze-bonds have been observed both in the sail and the keel of full scale ice ridges (Marchenko and Chenot, 2009). The mechanical properties of ice ridge keels are influenced by the freeze-bonding, and several authors argue that the initial failure of ice rubble is reached when the freeze-bonds fail (Ettema and Urroz, 1989; Surkov and Truskov, 1993; Surkov et al., 2001; Shafrova et al., 2004; Liferov, 2005). Moreover Liferov and Bonnemaire (2005) discuss that this initial failure of the rubble may correspond to the peak load observed during punch tests. Vershinin et al. (2005) presented a model of the mechanical properties of ridges based on the amount of freeze-bonds between the blocks.

The amount of previous publications specifically focused in freeze-bonds is not large. We found only four publications which deal with this topic specifically: Ettema and Schaefer (1986)—E&S—, Shafrova and Høyland (2008a)—S&H—, Marchenko and Chenot (2009)—M&C— and Vershinin et al. (2005). The three first papers present experimental data while the latter is focused on theoretical approaches. All the experiments consisted basically in the creation of artificial 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, and this complicates the comparison of the data. Ettema and Urroz (1989) found that parameters such as submersion

* Corresponding author. Tel.: +47 96820726.
E-mail address: ada.repetto@ntnu.no (A.H.V. Repetto-Llamazares).

0165-232X/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.coldregions.2010.12.001

time, normal confinement and water salinity influenced the strength of the freeze-bonds. Shafrova and Høyland (2008a) measured the strength of freeze-bonds formed in saline ice and they added the initial temperature of the ice to the list of contributing factors. Experimental observations from full scale ridges (Vershinin et al., 2005; Shafrova and Høyland, 2008b) show that horizontally oriented freeze-bonds exist in higher number than vertical freeze-bonds in ridge sails. Shafrova and Høyland (2008b) measured the orientation of freeze-bonds in ridge sails and found an average inclination angle to the horizon of 33°W.

Ice ridge–structure interaction has been often modeled numerically by assuming the consolidated layer to be a level ice-like feature and the rubble as an elastic plastic softening material with a Mohr–Coulomb yield or failure surface (Heinonen, 2004; Serré, submitted for publication). Rubble has also been modeled using pseudo-discrete continuum models (Shafrova et al., 2004; Liferov, 2005; Konuk et al., 2009) where contact or cohesive elements simulate the freeze-bonds between ice blocks.

This paper is the first of two papers that presents and discusses the results from experiments where the strength of artificially created freeze-bonds made from saline ice was tested on direct shear with the freeze-bond oriented horizontally. The main objective of the experiments was to gain insight into the freeze-bond failure process by studying the dependence of the freeze-bond shear strength on three main parameters: the initial temperature of the ice, the normal stress applied to the freeze-bonds while they were being formed and tested, and the submersion time available for the freeze-bonds to form. Part I of the set of papers presents the experimental set-up and experimental method used in the experiments, a description and characterization of the failure modes observed and the results from freeze-bond strength. Part II (Repetto-Llamazares et al., 2011, submitted for publication) presents the results of the ice–ice friction forces measured after freeze-bond failure and the results of the failure energies involved.

2. Experimental method

Experiments were done both in 2008 and in 2009 in the Hamburg Ship Model Basin (HSVA). In 2009 an improved experimental set-up was used and freeze-bonds formed in air were also tested.

2.1. Experimental set-up

2.1.1. 2008 experiments

Fig. 1 shows the direct shear testing device which was designed based on the experimental set-up proposed by Ettema and Schaefer (1986). It consists of two wooden frames that hold the freeze-bond sample from its top and its bottom. The bottom frame is fixed to a wooden table where a hydraulic piston is mounted. The piston pulls the upper frame at constant velocity until the ice specimen fails. There is a load cell connected to the piston (sensitivity 1 kN/mv/V, accuracy of 0.12 N and a range of 2 kN) that measures the tangential force (F_T) exerted on the sample and that is connected to an amplifier, analogue filter and AD converter. Data is recorded using DIAdem software as the computer interface. The hydraulic system was built by Friesecke and Hoepfner and allows a maximum load of 10 kN, maximum displacement of 100 mm and maximum velocity of 100 mm/s. The velocity used during the 2008 experiments was 7×10^{-4} m/s.

2.1.2. 2009 experiments

During 2008 experiments some drawbacks in the experimental set-up were identified (see Repetto-Llamazares et al., 2009 for details). The most important problem was the difficulty of fixing properly the bottom-frame movable-end and the tilting that the samples experienced for high freeze-bond strengths. A new bottom frame was designed with two fixing systems so that the bottom sample was fixed vertically in a better way (Fig. 2). The material in the frames was also changed from wood to plastic to avoid the expansion of the wood experienced by humidity and to make the fixing system smoother and easier to handle. The piston and the data acquisition system was the same as in 2008. The velocity of the piston was set to $(7.83\times10^{-4}\pm0.07)$ m/s, which was slightly higher than the one used in the 2008 experiments (7.00×10^{-4} m/s). Both the velocities used in 2008 and 2009 lie in between the velocities interval used by Ettema and Schaefer (1986) (4.4×10^{-4} and 8.4×10^{-4} m/s) in which they found no variation of shear strength of the ice.

2.2. Experimental procedure

The ice was saline columnar grained ice grown using the technique described in Evers and Jochmann (1993) from water of salinity 7 ppt. The ice was sampled, cooled down and treated as explained in the experimental procedure.

2.2.1. 2008 experiments

The experimental procedure is described in Fig. 3. Samples with dimensions around 160 by 160 mm in plane and with a thickness equal to the ice-sheet thickness (h_i) were cut from the ice-sheet using a hand saw, placed in plastic bags and put inside freezers that cooled the samples down to around −20 °C. Then the samples were taken out of the freezers and placed in shelves inside the cold-room until the ice was in thermal equilibrium with the cold-room air temperature, thus reaching the desired initial ice temperature (T_i). The ice thickness was between 31 and 34 mm with a few samples of 40 mm. The average ice salinity was around 3 ppt, and the average ice density was around 850 kg/m^3. The air temperature of the cold room (T_{air}) was set to be similar to T_i. When the samples reached T_i, they were cut with a band saw to the desired final size of 140 by 140 mm (the thickness was left untouched). The freeze-bonds were made by putting two ice pieces in contact (in the air), placing a wooden plate on top of them and adding metal weights until reaching the desired confinement (normal stress, σ). The complete set consisting of ice, plate and weight was immediately placed in a secondary basin containing water with similar salinity (S_w) and temperature (T_w) as in the large ice tank

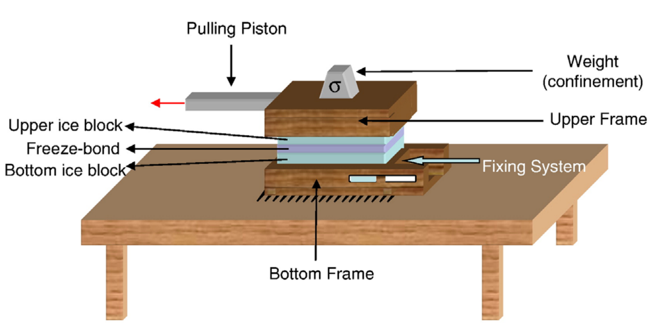

Fig. 1. Experimental set-up 2008. Basic design of the direct shear testing device used in 2008.

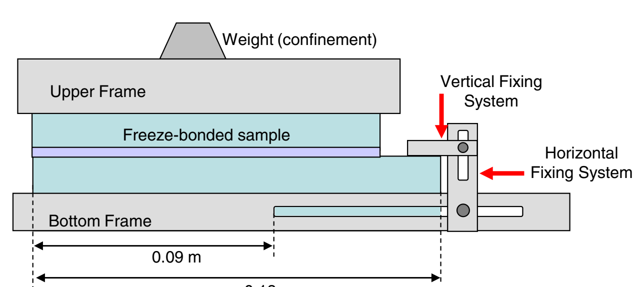

Fig. 2. Experimental set-up 2009. New bottom frame with improved fixing system designed to avoid tilting of the samples.