Ice Sample Production Techniques and Indentation Tests for Laboratory Experiments Simulating Ship Collisions with Ice

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ABSTRACT

This paper summarizes a pilot study conducted in the fall of 2010 and winter of 2011 for the multi-party research program entitled Sustainable Technology for Polar Ships and Structures or STePS^2 at Memorial University of Newfoundland, Canada. The work investigates laboratory production techniques of cone-shaped ice specimens and further examines the brittle behavior of them when crushed against a flat steel plate. The influences of ice temperature, cone geometry and ice type, resulting from various production techniques, is examined.

KEY WORDS: Ice; ship; collision; laboratory; indentation; cone; experiments

NOMENCLATURE

E (J)	Energy of the crushing process
F (N)	Force
T (°C)	Temperature
c_σ (−)	Crushing strength coefficient
v (mm/s)	Impact velocity
x (mm)	Penetration depth
α (°)	Cone angle
ρ (kg/m3)	Ice density

INTRODUCTION

The present paper summarizes a pilot study conducted in the fall of 2010 and winter of 2011 for the multi-party research program entitled Sustainable Technology for Polar Ships and Structures (STePS^2) at Memorial University of Newfoundland (MUN), St. John's, Canada. The work investigates laboratory production techniques of cone-shaped ice specimens, opposed to cylindrical samples, in order to prepare for full-scale ice impact tests for 1STePS2. Further their brittle behavior when crushed against a flat steel plate is examined representing natural ship-ice encounter situations. The influences of ice temperature, cone geometry (angle) and ice type, resulting from various fabrication techniques, is of interest.

Ice under load may respond variously as a brittle solid or as a visco-elastic ductile material depending on loading conditions, ice morphology and composition, and, the ambient physical state under which the loading occurs. The mechanical properties of pure ice are fairly well known at the laboratory scale, at least the ductile range of responses have been sufficiently examined to enable reasonably accurate engineering analysis for most practical circumstances. The case for brittle failure is less clear and analysis even for general engineering applications requires careful consideration, judgment and cautiously conservative approaches. Further, the confidence with which engineers analyze structural responses to sea ice – as an extension of pure ice behaviour – is further reduced because of the influence of natural salts on the physical properties of water and ice and the vast range of sea ice phenomena encountered. The result of this situation is that a combination of theoretical and empirical analytical approaches is often employed when investigating important design questions involving the fracture of ice.

METHODS

For STePS2 investigations ice is variously produced using saline and degassed purified freshwater, employing a range of ice crystal seed sizes for the latter. Ice specimen temperature at test-time ranges from −30 °C to 0 °C and cone angles of 20 °, 25 °, 30 ° and 35 ° (140 ° – 110° tip angle) are fabricated. All ice specimens are grown in a chest freezer modified to permit vertical suspension of cylindrical moulds into the cold space. Equipped with removable covers, allowing expansion of ice, these moulds provide easy access for filling and free-surface temperature regulation. The base of the moulds is exposed to subfreezing temperatures while side walls are insulated to enable directional freezing. A specimen with the least amount of internal stresses results from the control of freezing direction. (Cammaert and Muggeridge, 1988) Integral to the moulds are steel rings of 250mm internal diameter into which the ice becomes embedded. These rings facilitate specimen handling in both a newly designed apparatus for machining cone shapes, and an existing cold room compression test frame. The experiments include a total of 33 specimens in which the ice (tip-first) is penetrated by a raw, flat and unpainted steel plate normal to the right axis of the cone. These tests are conducted at a penetration rate of 100mm~s (scale 1 4), bearing typical full-scale ice-structure interaction velocities of 0.1m~s . . . 1.0m~s mentioned by Schulson (1999) in mind. The height of remaining uncrushed ice is kept constant, thus the penetration depth varies between 20mm and 63mm. Axial force and displacement is measured at sampling frequencies of 2 048 Hz. High speed videos for all tests are recorded, orthogonal thin sections from 2 each test specimen are also obtained for grain analysis.

Ice Specimen Preparation

For ice crushing tests conducted in a laboratory it is essential to control certain properties of the ice samples for a good comparability of single experiments or data sets. Most important parameters are crystal size and orientation as well as ice density and homogeneity. Considering ice sample fabrication techniques described by Cole (1979) moulds are filled with diversely sized seeds and flooded with degassed and purified water; see Figure 1. Before flooding moulds are shaken to minimize the entrapped air volume in the compact. According to Michel (1978) crystallization is induced with seeding a supersaturated solution with small particles of the material to be crystallized, a mechanism comparable to snow falling into water. Ice forms from the existing crystals, which gives control over crystal size and size distributions.

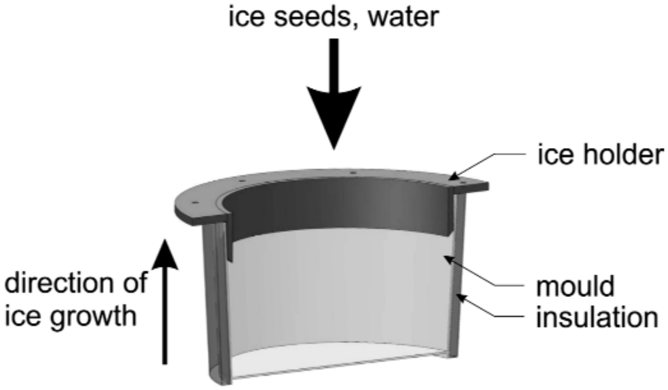

Figure 1. Schematic illustration of the ice growing setup within the freezer

Harvested snow and ice chips produced with an ice auger are used for the preparation of compacts. Figure 2 and 3 show the produced chips and their crystal size distribution. Ice blocks ordered from a third-party company serve as raw material for chips fabrication. As snow is only available in the winter specimens seeded with ice auger chips are preferred, also their seed sizes are consistent. Other seed types, such as ice cubes and handmade chips 5 . . . 10mm or > 10mm of size, have been discarded due to unwanted inhomogeneity of the specimens' morphology. Frozen test specimens are machined in the pottery-wheel style cone shaping apparatus shown in Figure 4. The samples are mounted on the apparatus' base plate rotating at about 300 rpm and shaped with a planer blade to cone angles between 20 ° and 35 °. According to Lieu and C. D. Mote (1984) cutting force components are approximately independent of cutting speed, thus the rotational speed is chosen arbitrarily. The sharpness of the blade is the more important influencing factor. After machining the specimens are stored at their testing temperature to cool down or warm up respectively.

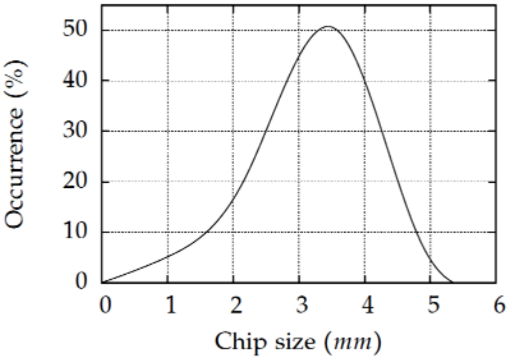

Figure 2. Size distribution of chips produced with ice auger

Figure 3: Ice auger chips

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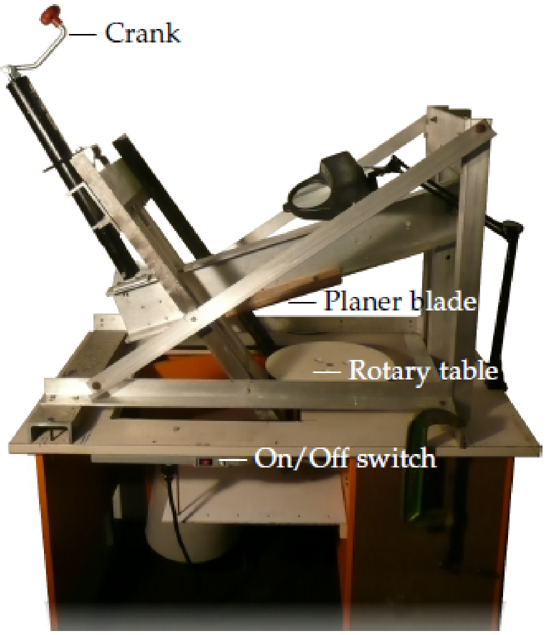

Figure 4. Ice cone shaping apparatus

Testing

Experiments conducted in the thermal laboratory at MUN are divided into two series of tests. The first series focuses on the significance of different ice types on impact experiments; in the second series the influence of cone angle and ice temperature is examined. Figure 5 shows the experimental setup for all tests.

Series 1

Seventeen samples are tested varying the ice type and keeping the following parameters constant:

- Ice temperature $T = -10$ °C
- Ice cone angle $\alpha = 30$ °
- Impact velocity $v = 100 mm/s$
- Penetration $x_{max} \approx 50 mm$

All ice types are tested in respect to their reproducibility and the specimen's suitability for impact experiments.

Series 2

Fifteen samples are seeded with ice auger chips, one with snow. The impact velocity is kept constant at 100mm~s; the following parameters are varied:

- Ice temperature $T = -30$ °C . . . 0 °C
- Ice cone angle $\alpha = 20$ ° . . . 35 °
- Penetration $x_{max} \approx 20 mm \ldots 63 mm$

Figure 5. Test setup

ANALYSIS AND RESULTS

The energy of the crushing process E is calculated as follows:

$$E = \int_0^{x_{max}} F(x)dx \qquad (1)$$

x is the penetration depth and F the measured force. A non-dimensional coefficient C_σ is introduced for the comparability of samples:

$$C_\sigma = \frac{E}{v^2 x^3 \rho \tan(\alpha)} \qquad (2)$$

The density ρ is calculated with the mass of the ice sample and its known volume. v is the impact velocity.

Ice type investigations

Samples with cone angles between 25° and 35° tested to examine the influence of the ice cone angle on their impact behavior show slight differences in their average strength coefficient ($C_\sigma \approx 1 \cdot 10^6$ for 35° cones; $C_\sigma \approx 4 \cdot 10^6$ for 25°). The ice cone with an angle of 20° shows an exceptional strength coefficient of $C_\sigma = 18.7 \cdot 10^6$ (see Figure 6).

Figure 7 shows the outcome of temperature variation tests. Ice temperature does not have a major influence on the strength of the tested samples. This corresponds to literature describing that the compressive strength of ice increases with decreasing temperature, but is not very sensitive to temperature variations at high strain rates. (Cammaert and Muggeridge, 1988) The crushing strength coefficient C_σ is in the range of = $1.4 \cdot 10^6 \ldots 2.1 \cdot 10^6$.

Although the average strength does not vary a lot with temperature, the peak force increases with decreasing sample temperature. This trend is shown in Figure 8.

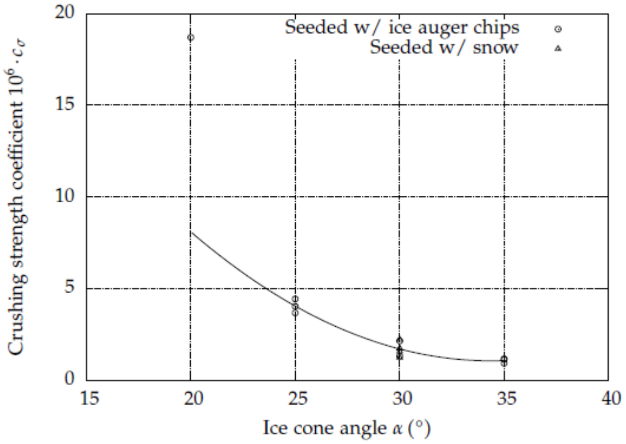

Figure 6. Crushing strength coefficient versus ice cone angle, T= -10°C

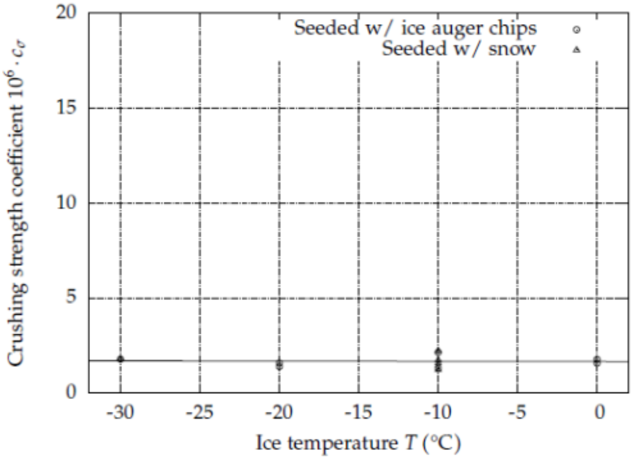

Figure 7. Crushing strength coefficient versus ice temperature, α= 30°

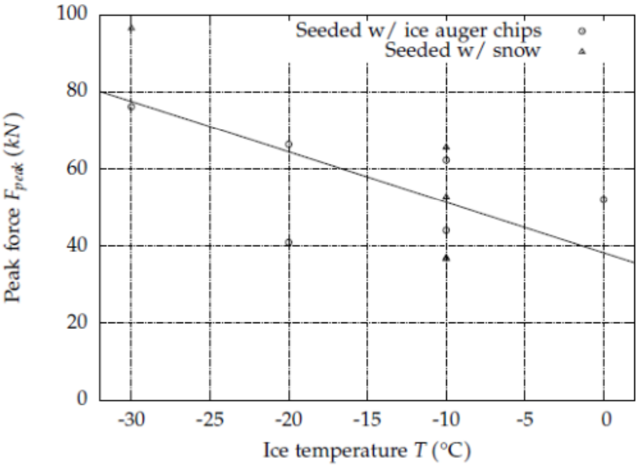

Figure 8. Peak force versus ice temperature for all snow and ice auger chips seeded specimens, α= 30

CONCLUSION

The conducted experiments show the specimens insensitivity to temperature variations between −30 °C and 0 °C concerning their strength. With regard to planned STePS^2 experiments to be conducted at room temperature the ice is to be as cold as possible for a longer durability at warm temperatures. However samples at −30 °C are sensitive to cracking when handling them, why ice temperatures of −20 °C are recommended for experiments. Test specimens with cone angles between 25 ° and 35 ° do not show significant differences in their crushing strength. Further experiments examining ice cones with angles of 20 ° and 40 ° (cone shaping apparatus modifications required) would be interesting. In addition the variation of specimens' geometries could be examined, in particular truncated cones as well as ice cylinders (0 ° cones) using the existing ice holders. Advantage of the geometries described would be their known contact area in the beginning of impact tests.

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