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# INFLUENCE OF VELOCITY ON ICE-CONE INTERACTION

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## Abstract

A series of upward breaking cone tests was conducted at NRC/IMD's ice tank in level ice using EG/AD/S correct density model ice. Cone angles of  $45^\circ$  and  $60^\circ$  were tested. The effect of ice draft velocity in the range 0.005 to 0.5 m/s was studied for ice thicknesses ranging from 35 to 110 mm. The mean peak forces in both horizontal and vertical directions were measured and found to be almost independent of Froude Number below 0.02, but increased significantly at higher Froude Numbers. The effect of speed for upward breaking conditions was found to be less than similar conditions for downward breaking cones.

## 1. Introduction

For many structures, a conical form at the water line is superior to a cylindrical form or vertical flat surfaces, since this configuration reduces ice loads by causing the ice to fail in bending. Observations from early experiments show that bending failure is dominant under interaction at low structure inclination angles from the horizontal ( $10^\circ$  to  $60^\circ$ ), low ice-cone friction coefficients, low ice thickness, and low ice speeds. With increasing inclination, roughness of the cone surface, and ice thickness, the dominated failure mode can change gradually from bending to shear or crushing. At higher speeds, the failure mode also changes abruptly from bending to shear or crushing due to dynamic effects (Lau *et al.*, 1999; Wessels, 1984; Sodhi, 1987). The speed at which the transition of failure modes takes place was found to increase with an increase in the inclination angle (Haynes *et al.*, 1983). The influence of shear stresses on determining failure modes becomes more important with increasing ice thickness and predominates for thick ice covers (Lau *et al.*, 1999; Maattanen, 1986). Observation of actual fracture patterns in thin ice reveals that pure bending occurs when circumferential cracks form at distances slightly greater than the characteristic length. With an increase in ice thickness, the average length of broken pieces decreases, which may indicate a combination of bending and shear failures (Lau *et al.*, 1999 and 1991a).

Model tests with conical structures in level ice have been carried out in the ice tank at the Institute for Marine Dynamics (Lau *et al.*, 1988; Lau and Williams, 1991a and 1991b; Lau *et al.*, 1993, Spencer *et al.*, 1993). A recent experiment has extended previous model test results by expanding the range of ice thicknesses and speeds. This paper presents the influence of model speed on ice loads and associated failure modes for velocities between 0.005 and 0.5 m/s.

## 2. Scaling Issues

It has been shown (Atkins and Mai, 1985) that for the case of geometrically similar linear elastic structures under monotonic loading:

$$\sigma_p = \left[ \frac{1}{\sqrt{\lambda}} \right] \sigma_m \left[ \frac{K_{Cp}}{K_{Cm}} \right] \quad (1)$$

where  $\sigma$  is the strength,  $\lambda$  is the geometric scaling factor,  $K_C$  is the critical stress intensity factor, and the subscripts  $m$  and  $p$  refer to model and prototype respectively. Then, by equating inertia and cracking forces they obtained:

$$\frac{V_p^2 \rho_p L_p^{1/2}}{K_{Cp}} = \frac{V_m^2 \rho_m L_m^{1/2}}{K_{Cm}} = I_n \quad (2)$$

where  $I_n$  is a new “Ice Number” introduced by Atkins (1975),  $V$  is the velocity,  $\rho$  is the density, and  $L$  is the length. If we use Froude’s law, which arises from equating inertia and gravity (wave-making) forces, for velocity scaling,  $V_p = \sqrt{\lambda} V_m$ , then we obtain:

$$\frac{K_{Cp}}{K_{Cm}} = \frac{\rho_p}{\rho_m} \lambda^{3/2} \quad (3)$$

and hence from equation (1) above:

$$\sigma_m = \frac{1}{\lambda} \frac{\rho_m}{\rho_p} \sigma_p \quad (4)$$

Equation (3) is the condition for scaling ice toughness at Froude speeds. Equation (4) is the rule by which model ice strength should be scaled in order to satisfy both Froude’s law and the cracking law given by equation (1). Since in most ice tanks  $\rho_m = \rho_p$  (or any difference is ignored) it is seen that the tank ice strength should be reduced directly as the linear scaling factor. This is the normal approach taken by ice tanks in testing ships and structures in ice and it works quite well. Unfortunately, equation (3) is not well obeyed since the model ice is not stiff enough and not sufficiently brittle (Timco, 1986).

The main reason for this work was to determine if the forces on a conical upward breaking structure were dependent on velocity. If they were, Froude scaling (or something similar) would be important; if not, Froude scaling, which works well for ships tested in water, might be unnecessary for icebreaking ships/structures. Another reason for this work was to obtain data to compare with centrifuge modeling results (Barrette *et al.*, 2000).

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### 3. Model Tests

The experiments were carried out in CD-EG/AD/S (Correct Density – Ethylene Glycol/Aliphatic Detergent/Sugar) model ice developed by Spencer and Timco (1990). With inclusions of air bubbles into the growing ice sheet, this model ice significantly improves scaling of ice density, elastic and fracture properties. The anisotropy associated with the columnar crystal structure of the model ice provides a suitable representation of the three dimensional distributions of stress in the prototype ice and gives a good ratio of shear to flexural failure stresses. The percentage concentrations of EG/AD/S for the present test series were 0.39/0.27/0.0<sup>1</sup> and the ice density was about 870 kg/m<sup>3</sup>.

The model ice area was 12 m x 76 m. For each ice sheet, flexural strength  $\sigma_f$  and shear strength  $\sigma_s$  were measured frequently throughout the test period. The values reported at test time are interpolated from the strength versus time curves for the ice sheet. Flexural strength was measured using in-situ cantilever beams. A set of 4 or 5 beams with proportions of thickness:width:length of 1:2:5 was tested at each location in either upward or downward loading directions. Shear strength measurement was performed immediately after the flexural strength test to provide index values for comparison with the measured flexural strengths. For the shear tests, an ice sample was positioned on a horizontal plate with a 38 mm diameter hole in it and a metal punch with a diameter of 32.5 mm was forced through it. The 5.5 mm difference in diameter ensured that failure occurred along the grain boundaries of the columnar EG/AD/S ice as opposed to through the individual crystals. The ratio of shear strength to upward breaking flexural strength varied from 1.6 to 2.6. The reported ice thickness,  $h$ , is the average over approximately 65 measurements for the ice sheet along the test path. The procedures for producing and characterizing level ice sheets are described in more detail in Jones (1993).

While a 45° cone was used for most of the tests, a number of tests were conducted using a 60° cone to assess the effect of cone angle. The models were mounted rigidly to the towing carriage through a six-component force dynamometer (Lau *et al.*, 1993). The model dimensions are shown in Figure 1. The models were towed at constant speeds through a fixed ice sheet. The transducer outputs were sampled digitally at 500 Hz, and filtered at 100 Hz to capture the possible high frequencies at high speed due to shearing and crushing failure. The model surface was finished to a friction coefficient of 0.15 with Dupont's Imron paint. Five

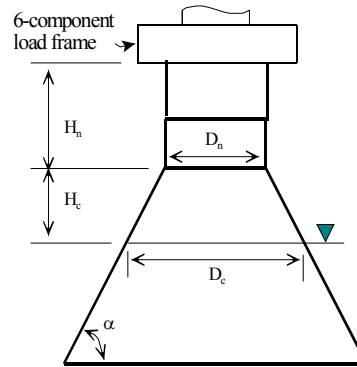


Figure 1. Schematic of the test set-up showing the 6-component load frame and the cone models with the following dimension:

Model	$\alpha$ (°)	$D_c$ (m)	$D_n$ (m)	$H_c$ (m)	$H_n$ (m)
1	45	1.23	0.6	0.546	0.5
2	60	0.94	0.6	0.315	0.6

<sup>1</sup> The solution contained a minute quantity of sugar.

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video recordings were made of each test: one on the starboard side, one looking down ahead of the model, one ahead of the model near the ice surface, and two underwater cameras looking up ahead of the model.

The test matrix for the experimental program is given in Table 1. The 45° cone was tested at 1.23 m diameter waterline and ice thicknesses of 33.8, 52.1, 80.1 and 115.1 mm. The 60° cone was tested at 0.94 m diameter waterline, and ice thicknesses of 33.9 and 116.9 mm. Each ice sheet was tested over a velocity range of 0.005, 0.01, 0.05, 0.1, 0.25 and 0.5 m/s. Ice strength varied from sheet to sheet with upward breaking strength ranging from 34 to 43 kPa. The variation in ice strength within each sheet during these tests was kept within 2.5 kPa. The cones were also towed in open water over the same range of velocity and the forces were measured.

Table 1. Matrix of the experimental program

Cone Angle, $\alpha$ (°)	45	60
Cone Waterline, $D_c$ (m)	1.23	0.94
Ice Sheet Thickness, $h$ (mm)	34, 52, 80, 115	34, 117
Upward Breaking Flexural Strength, $\sigma_f$ (kPa)	34 – 43	
Ice Velocity, $V$ (m/s)	0.005, 0.01, 0.05, 0.1, 0.25, 0.5	

## 4. Test Results

### 4.1. 45° CONE

The interaction process with the 45° cone was similar to that observed from previous tests with sloping structures in the range of velocity tested. The failure mechanism was typically governed by the flexural stresses induced in ice in both the radial and circumferential directions by the bending of the ice sheet, as shown in Figure 2. Figure 3 gives the time record of a typical test with the 45° cone illustrating the cyclical nature of the loading. Figure 4 shows the increase of mean peak forces with ice velocity. “Mean peak force” is the mean of the icebreaking peaks over the steady-state portion of the ice-cone interaction. The increase in force was negligible for velocities less than 0.2 m/s but it increased substantially for velocities greater than 0.25 m/s. The increase was greater for thicker ice as shown in Figure 5, in which the ice force increase over that measured at 0.005 m/s is plotted against ice thickness.

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Figure 2. Photograph showing a typical ice interaction with the 45° cone: ice thickness equal to 115 mm and ice velocity equal to 0.01 m/s.

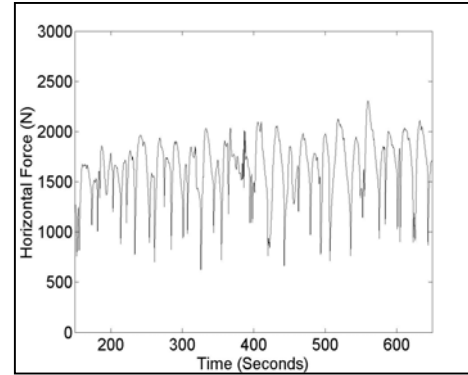


Figure 3. Typical force time records for tests with the 45° cone: ice thickness equal to 115 mm and ice velocity equal to 0.01 m/s.

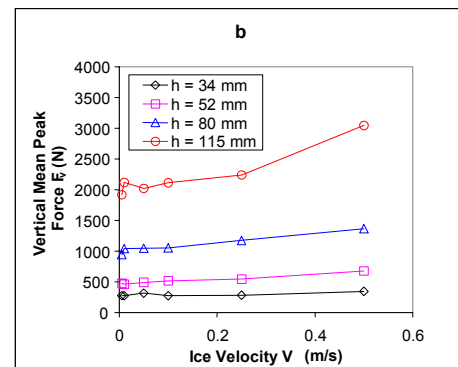
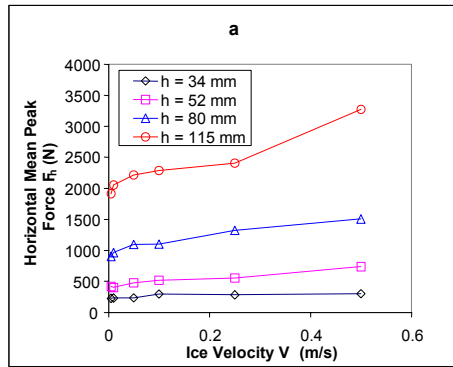


Figure 4. Mean peak forces versus ice velocity for 45° cone in various ice thicknesses: (a) horizontal force and (b) vertical force.

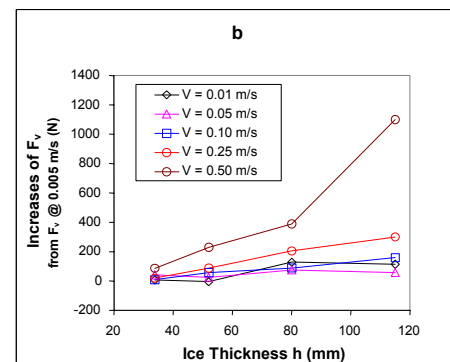
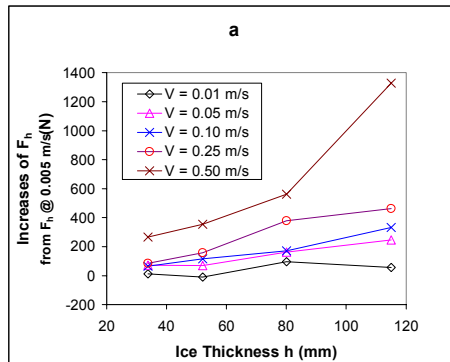


Figure 5. The increase of ice force over ice force measured at ice velocity equal to 0.005 m/s versus ice thickness for the 45° cone: (a) horizontal mean peak force and (b) vertical mean peak force.

#### 4.2. 60° CONE

A similar trend was observed for the 60° cone in thin ice. However, for ice thickness equal to 117 mm, the failure mode changed abruptly to shear at velocities greater than a transitional velocity of about 0.15 m/s (Figure 6). Shearing of the ice edge along the grain boundaries of the columnar model ice occurred before any circumferential crack could form, resulting in small columnar ice chips with cross-sectional dimensions less than 15 X 10 mm<sup>2</sup> (Figure 7) and a high frequency cyclical loading (Figure 8). The distance between circumferential cracks was about 130 mm prior to the change of failure mode. The contact surface after failure was very rugged resulting in non-simultaneous failure along the cone/ice contact. The channel formed by the model's passage appeared very regular at the approximate width of the waterline diameter (Figure 7). The ice chips rode up and cleared around the cone with a lesser amount of ride-up as shown in Figure 6b. Figure 9 shows the influence of ice velocity on the horizontal and vertical



Figure 6. Photographs showing 117 mm ice interaction with 60° cone at velocity below (left plate: ice velocity of 0.1 m/s) and above (right plate: ice velocity of 0.25 m/s) the transitional speed.



Figure 7. Photograph showing small columnar ice chips left at the wake of the 60° cone tested at high speed (ice velocity of 0.25 m/s)

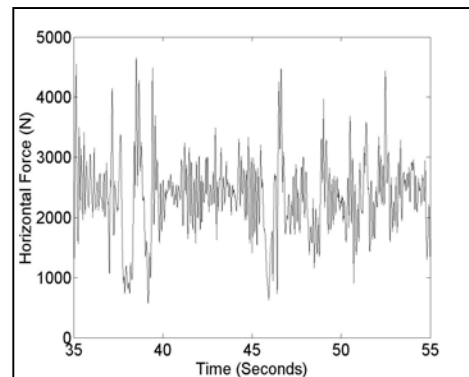


Figure 8. Typical force time records for tests with the 60° cone tested at high speed (ice velocity of 0.25 m/s)

mean peak forces for the 60° cone. There was a larger increase in ice force with increase of ice

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velocity up to the transitional speed when compared with the 45° cone (Figure 4) for the same ice thickness. Again, the increase was greater for the thicker ice. For the 117 mm thick ice, the force increased rapidly with velocity until a transition velocity was reached, and after which the ice force dropped to an almost constant level, when shearing of the ice edge predominated.

The data from this test series suggest that thicker ice and a steeper cone angle accentuate the influence of ice velocity on ice load and lead to a change in failure mode. The increase in ice load on both cones was more than 1 kN with the thicker ice for an ice velocity of 0.5 m/s. Water resistance contributed less than 50N to these increases as estimated from the open water resistance data.

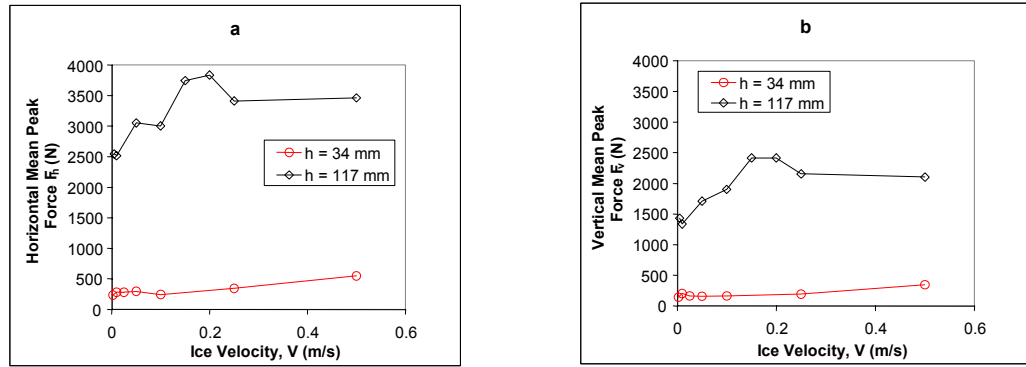


Figure 9. Mean peak forces versus ice velocity for the 60° cone in two ice thicknesses: (a) horizontal force and (b) vertical force.

## 5. Comparison with Downward Breaking Cones

Figure 10 shows the non-dimensional horizontal mean peak force versus Froude Number for all data presented in this paper. The non-dimensional force was the actual force divided by the force measured at 0.01 m/s in the same ice sheet, where the velocity effect is negligible. The Froude Number was calculated as  $V/(gh)^{0.5}$  where  $g$  is the gravitational constant. The solid symbols are for the 45° cone and the hollow symbols are for the 60° cone. A previous set of data obtained with the same cones tested in the inverted orientation (downward breaking) was

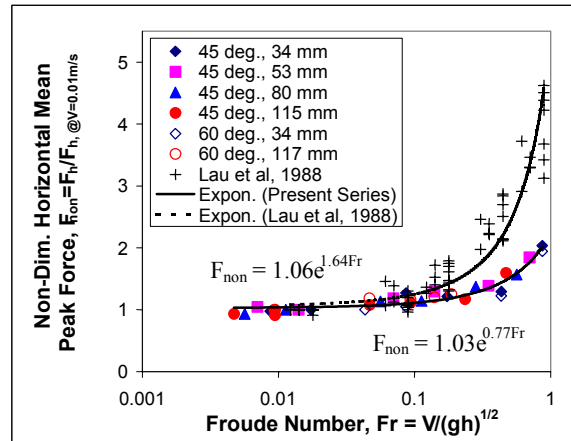


Figure 10. A plot of non-dimensional horizontal mean peak force versus Froude Number showing the effect of ice velocity. The crosses are for the inverted cones and the other symbols are for the present test series.



plotted on the figure (the crosses) for comparison. Figure 10 shows a dependency of the ice force ratio on Froude Number, despite the scattering of data. For Froude Numbers less than 0.02, the velocity was negligible. The forces increased with increasing Froude Number for Froude Numbers greater than 0.02. The effect of velocity is greater with the inverted (downward breaking) cones, because the broken ice fragments have to move through the water in the downward breaking configuration, and hence are subjected to water drag and added mass.

The Froude Number is a ratio of inertia and gravity forces and is used in momentum transfer in general. Maintaining this ratio is important for modeling ships in ice where the hydrodynamical similitude is required. Figure 10 gives an assessment of the degree of importance this number had in ice-cone interaction modeling. The Confederation Bridge between PEI and New Brunswick uses piers with upward breaking cones. At the bridge, level ice thickness can reach 1 m, velocities have been measured up to 1 m/s, giving a Froude Number of 0.3. From the curve of Figure 10, the increase in force due to velocity is then approximately 30% for an upward breaking cone. If ice velocity reaches 1.5 m/s, the increase is 45%.

## 6. Conclusions

The results from a series of tests of 45° and 60° upward breaking cones in level ice are presented. This experiment has extended previous model test results by expanding the range of ice thicknesses and speeds. The mean peak force in both horizontal and vertical directions was found to be almost independent of velocity below 0.2 m/s, but increased significantly at higher velocities. The data suggest that thicker ice and a steeper cone angle accentuate the influence of ice velocity on ice load and lead to a change in failure mode. The effect of speed was found to be less than that for tests conducted with downward breaking cones under similar conditions. The results suggested that Froude scaling will be important in ice-cone interaction modeling, if the Froude Number of the models exceeds 0.02.

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