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Experimental Results on the Buckling of Freshwater Ice Sheets

by G.W. Timco and N.K. Sinha

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RÉSUMÉ

Un ensemble d'essais a été mené afin d'étudier le comportement pendant la mise sous contrainte et la déformation de minces nappes de glace d'eau douce soumises à des contraintes entraînant ultimement la rupture sous l'influence du gauchissement. Les essais ont été effectués avec des taux de mise sous contrainte produisant des intervalles avant la rupture inférieurs à une demi-seconde. Il y a eu microfissuration importante de la glace. Des fléchissements importants, de l'ordre de la demie de l'épaisseur de glace, ont été mesurés à la rupture. Les charges et les profils de déformation de la glace sont présentés pour douze cas distincts de gauchissement.

EXPERIMENTAL RESULTS ON THE BUCKLING OF FRESHWATER ICE SHEETS

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ABSTRACT

A test series has been carried out to investigate the load and deformation behaviour of thin freshwater ice sheets loaded to ultimate failure in a buckling-type failure mode. The tests were conducted with loading rates giving failure times of less than one-half second. Considerable microcracking was observed in the ice. Large deflections, on the order of one-half the ice thickness, were measured at failure. The load and ice deformation profile are given for twelve different buckling events.

INTRODUCTION

The buckling of floating ice sheets is an important failure mode in many situations where a thin ice sheet impinges on a wide vertical-sided structure. To date there have been numerous theories developed to calculate the load and ice deformation behaviour during the buckling event (Sodhi and Hamza, 1977; Kerr, 1978; Wang, 1978; Sodhi, 1979; Nevel, 1980; Kerr, 1980; and Sjölind, 1984, 1985). These have been reviewed recently by Sodhi and Nevel (1980) and Sodhi (1986). Although there has been numerous theoretical treatments to this problem, there is a paucity of experimental data in this area. Sodhi (Sodhi, 1983; Sodhi et al., 1983; Sodhi and Adley, 1984) has been the principal investigator, measuring buckling loads for various geometries and loading rates under controlled conditions in an ice modelling basin. In his tests no information was collected on the deformation behaviour or damage processes of the ice sheet itself. This paper presents the results of a set of tests in which both the buckling load and ice deformation were measured throughout the whole buckling event. The tests were performed using thin sheets of freshwater ice, rather than model ice as used by Sodhi. The use of freshwater ice has two distinct advantages in tests of this type; firstly, the mechanical and rheological properties of freshwater ice are much better known than those of model ice. This aids in the interpretation and analysis of the test results. Secondly, freshwater ice is optically transparent, allowing observation of the cracking activity in the ice. The big disadvantage with freshwater ice relates to its higher strength - much higher loads are encountered in the tests and this restricts the range of experimental parameters. In these tests, the buckling loads and ice deformation of freshwater ice were measured over a range of aspect ratios from 30 to 50 for one nominal loading rate and two interface friction conditions.

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EXPERIMENTAL

The tests were performed in the ice tank in the Hydraulics Laboratory of the National Research Council in Ottawa (Pratte and Timco, 1981). In the tank, which is 21 m x 7 m x 1.2 m, thin sheets of freshwater ice approximately 1 cm thick were grown using a wet-seeding technique for nucleation. This method produces a fine-grained, columnar-structured ice with grain diameters of the order of 0.1 cm. The structure and mechanical properties of this ice have been measured and documented by Timco and Frederking (1982).

The model representation of a structure for these buckling tests was a 1.9 cm thick plywood sheet cut to a width of 30 cm and painted to a high gloss finish using Varathane paint. The board was used with this finish for one test series. It was covered with a thin (0.9 cm) sheet of rubber for a second test series. Previous tests by Timco (1984) using these finishes gave dynamic ice-structure friction coefficients of 0.02 and 0.07 for the Varathane (V) and rubber (R) finishes respectively*. The board was mounted onto a steel frame and attached to a six component dynamometer platform which, in turn, was attached to the main carriage of the ice tank facility. With this arrangement information on the three load and moment components on the structure are obtained.

* These values are based on tests measuring the ice load components on a wide inclined structure. Since they were determined using model ice and low confining pressures, however, these friction coefficients should be considered only as representative values for the present case.

To measure the deflection of the ice sheet in front of the board, an array of eight displacement gauges (DCDTs) was used. A bracket was constructed to hold the DCDTs at regular but adjustable spacings on the ice along the centre-line of the board but perpendicular to it. This bracket was mounted to the service carriage of the ice tank facility thereby making it completely independent of the main carriage. This procedure allowed measurement of ice deflection relative to a fixed, non-moving frame of reference. A schematic of the full test setup is shown in Figure 1.

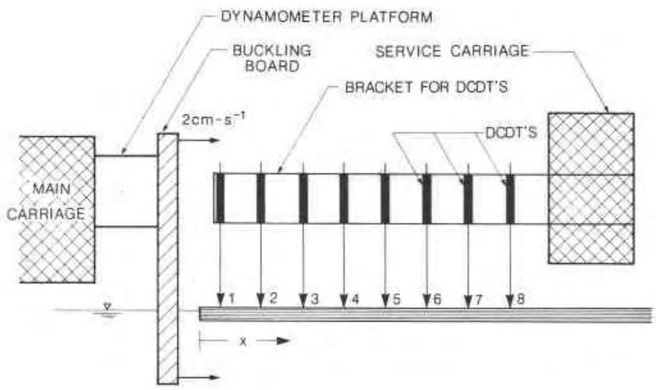

Figure 1 Schematic showing the experimental set-up for the buckling tests.

For the interaction event, a clean interface was cut in the ice sheet parallel to the plywood board across a 5 m width of the tank. The main carriage, which contained the buckling board, was then driven at a constant speed of 2 $cm\text{-}s^{-1}$ towards the ice edge. Although the carriage is capable of much higher speeds, the tests were confined to this lower speed range. Otherwise, damage to the displacement gauges could result due to the longer stopping distance of the carriage at higher speeds. The data acquisition system was started just before the board made contact with the ice sheet. All data channels were sampled at a rate of 100 Hz, digitized and stored for later analysis. The data were analysed such that load and relative displacement of the ice could be determined at any time during the loading event. From this information it was possible to get load-time curves, deflection-time curves, and load-deflection curves throughout the whole process. In this initial test series, six tests were performed for each of the two structure surface finishes (i.e. Varathane and rubber).

RESULTS AND DISCUSSION

Observations of the Ice Behaviour

Because of the relatively short time that the board was pushing against the ice sheet before failure of the ice, it was difficult to determine visually all the details of the buckling process. There were, however, several noteworthy events. As the board was pressing against the ice sheet, the sheet would start to deform and buckle with a wave which had a maximum amplitude either down into the water or up into the air. The direction varied from test to test but there was a propensity for it to buckle down into the water. With further increase in the load, numerous microcracks were formed in the ice in the region directly in front of the indentor, in a manner similar to that previously described by Timco (1986). The width of the cracks were of the order of 0.1 to 0.2 cm, comparable to the grain size of the ice, and the cracks extended through the full ice thickness. This microcrack density was highest close to the board. During the loading event this microcracking continued until there was a sudden and catastrophic failure of the ice when it shattered into numerous large pieces. Although the detailed pattern of cracks would vary from test to test, there were some common features observed in each case. For the tests using the Varathane-painted board, the ice would fail with a curved arc geometry similar to that shown in Figure 2 for test V-3. The length (L) of the arc was typically one and one-half to two times the width of the buckling board and it had a maximum width (w) at the mid-point of the board. The details of the cracking pattern outside this region differed from test to test, but there was always a mix of radial and circumferential cracks, with fractured ice extending typically two to four times the width (w) of the first circular arc. For the rubber-faced board, on the other hand, the larger cracking radius of the ice did not occur; instead the ice failure was much more confined to the region in front of the board. A typical failure pattern is shown in Figure 3. In this case, the ice pieces were much smaller and contained fewer microcracks. There were, however, a number of "grazing" cracks evident. These milky-coloured cracks meandered through the ice sample; however, there was no physical separation of the ice pieces along the fracture plane.

Although the loading time to failure was very short (<0.5 s) and the buckling event occurred very rapidly, it was observed that several of the large ice fragments were very highly deformed with a net permanent plastic deformation. This was especially evident for the ice in the Varathane test series. At first glance this result appears surprising since it could be argued that the loading time was so short that the whole event could be considered as an elastic, brittle failure. However, all of these pieces were "damaged", since they contained a large number of microcracks. The large deformation of the ice pieces was certainly caused by a mechanism of crack enhanced creep.

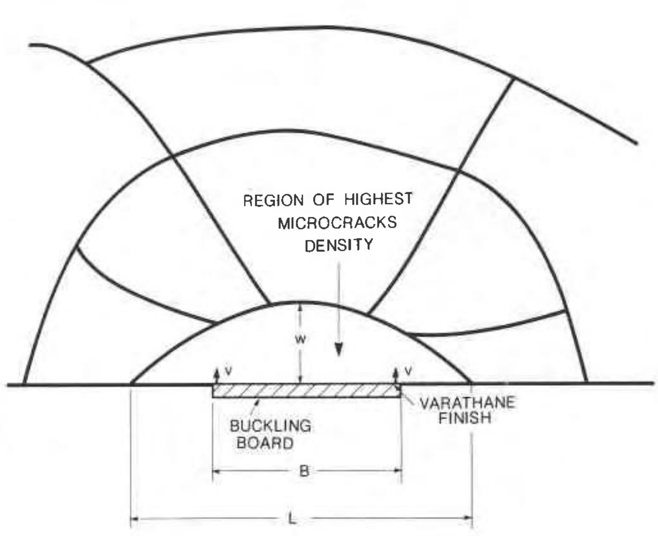

Figure 2 Schematic showing a typical failure pattern in the ice using the Varathane (V) covered buckling load.

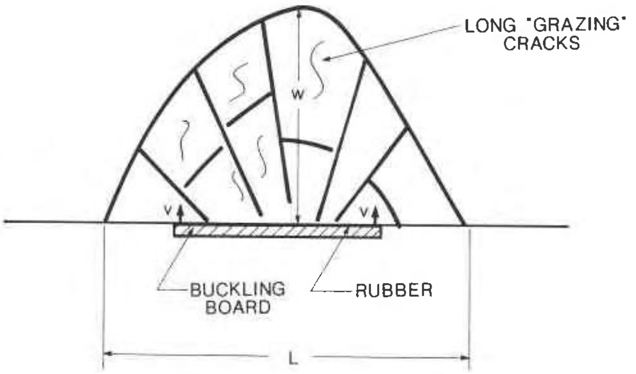

Figure 3 Schematic showing a typical failure pattern in the ice using the rubber (R) covered buckling board.

<u>The Load-Deflection of the Ice</u>

Using the load cell attached to the buckling board and the array of eight DCDTs resting on the surface of the ice, it is possible to quantify the behaviour of the buckling event. Figure 4 shows the load-time behaviour and deflection-time for each DCDT for the buckling event shown in Figure 2. Note that the position (x) of each displacement transducer is given relative to the edge of the original ice interface [see Figure 1]. In all cases, the load increased monotonically to failure, and the relative amount of deflection varied along the measuring axis. From these data it is possible to construct a picture of the progression of the ice deformation during the buckling event. Figure 5 shows the deflection of the ice in front of the board for four different times during one loading event. Note that the amplitude of the deformation increases with increasing time (or load). The "kinks" in the curve are due to the discrete measuring points on the ice surface; in analysis, each point was connected linearly with the neighbour, resulting in the sharp edges. In reality, the curvature of the ice would likely be continuous and smooth.

Knowing the ice thickness and the deflection at failure, it is possible to reconstruct the deformed shape of the ice sheet at the time when the ice shattered, (i.e. at failure). This reconstruction is shown for all six ice sheets in Figure 6 for the Varathane finish and in Figure 7 for the rubber finish. As previously discussed, the deflection of the ice can be up or down. Further, the maximum amplitude of the buckling wave can be quite large and, in these tests, up to one-half of the ice thickness. The position of the fracture of the first circumferential arc is shown by arrows in the Figures. It appears that this break occurs in a different region depending upon the surface finish of the buckling board. With the varathane board, the first circumferential crack occurred between the board and the peak displacement position whereas for the rubber-faced board, it occurred on the far side of the peak displacement.

A summary of all test results is given in Table 1.

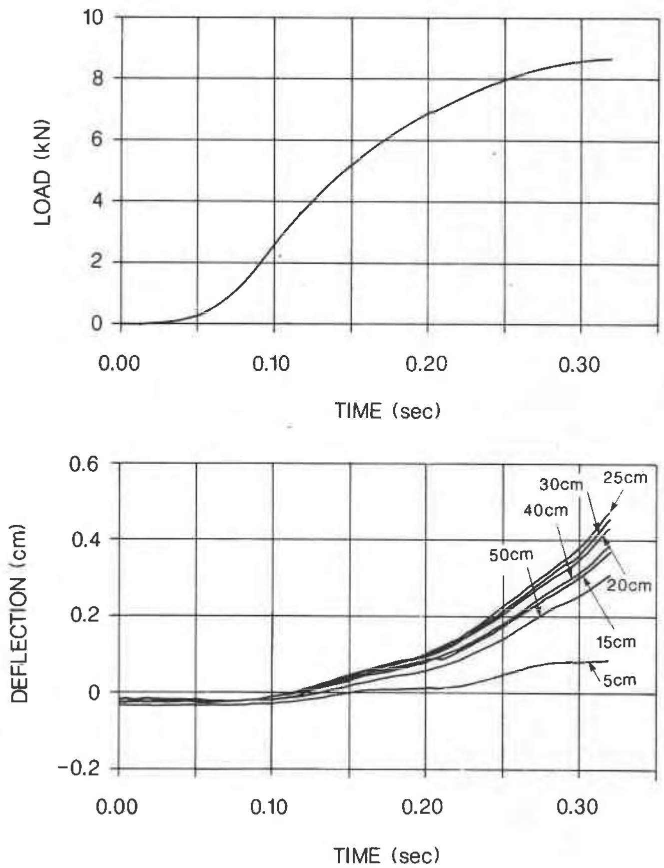

Figure 4 Load-time and deflection-time behaviour for one of the buckling tests (Test V-3).

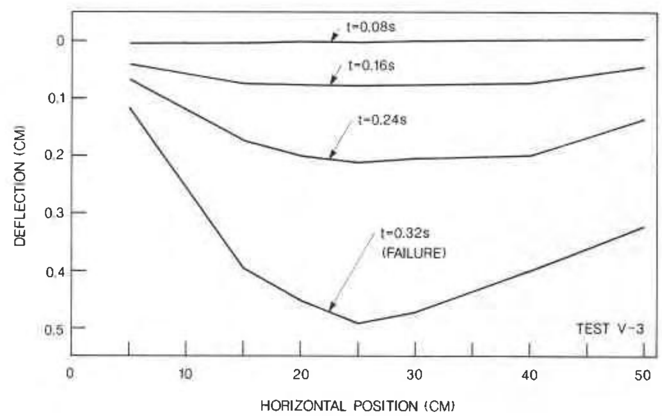

Figure 5 Deflection profile of the ice for four different times during the buckling event.

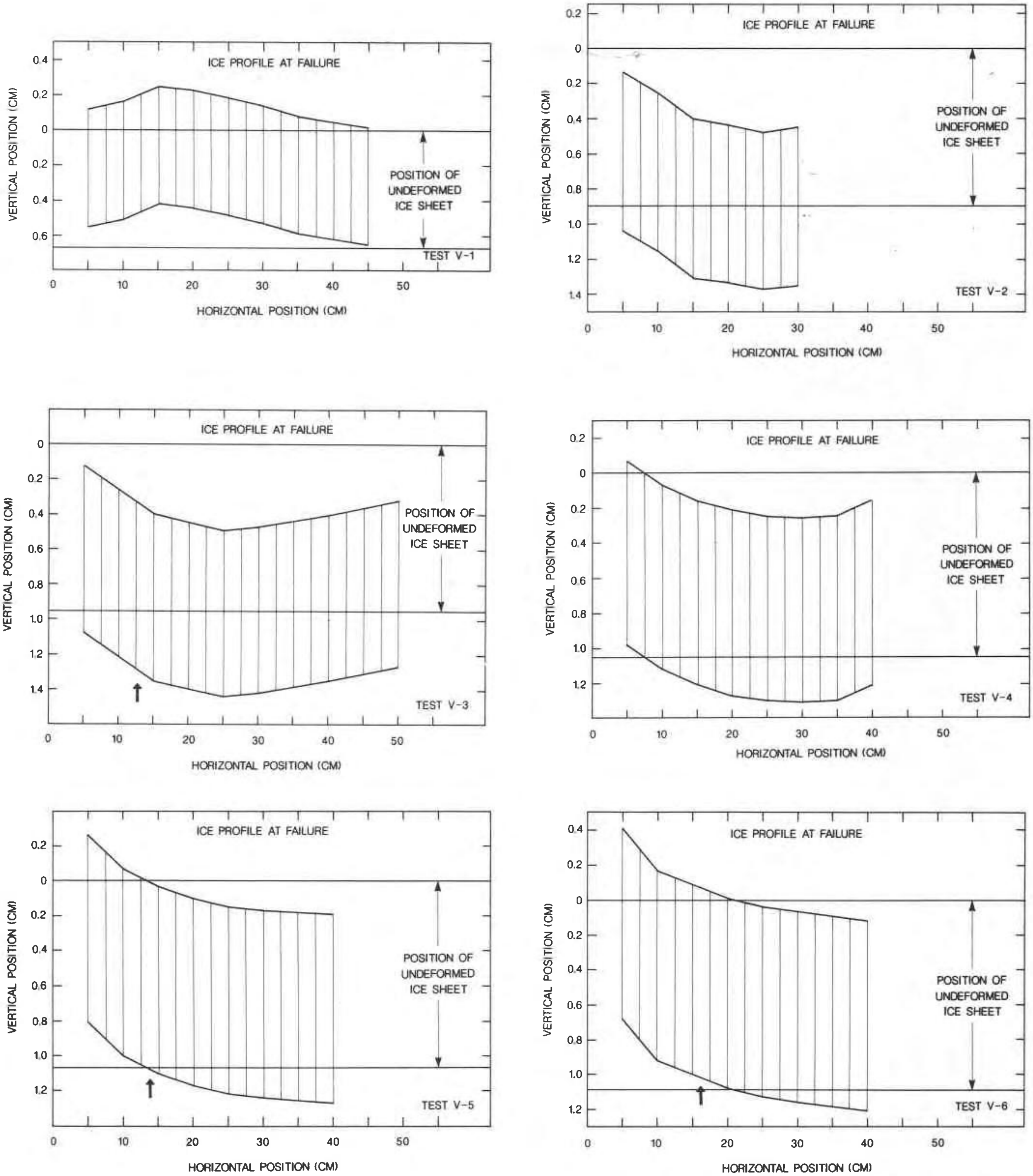

Figure 6 Deformation of the ice sheet at failure for each of the six tests using the Varathane finish buckling board.

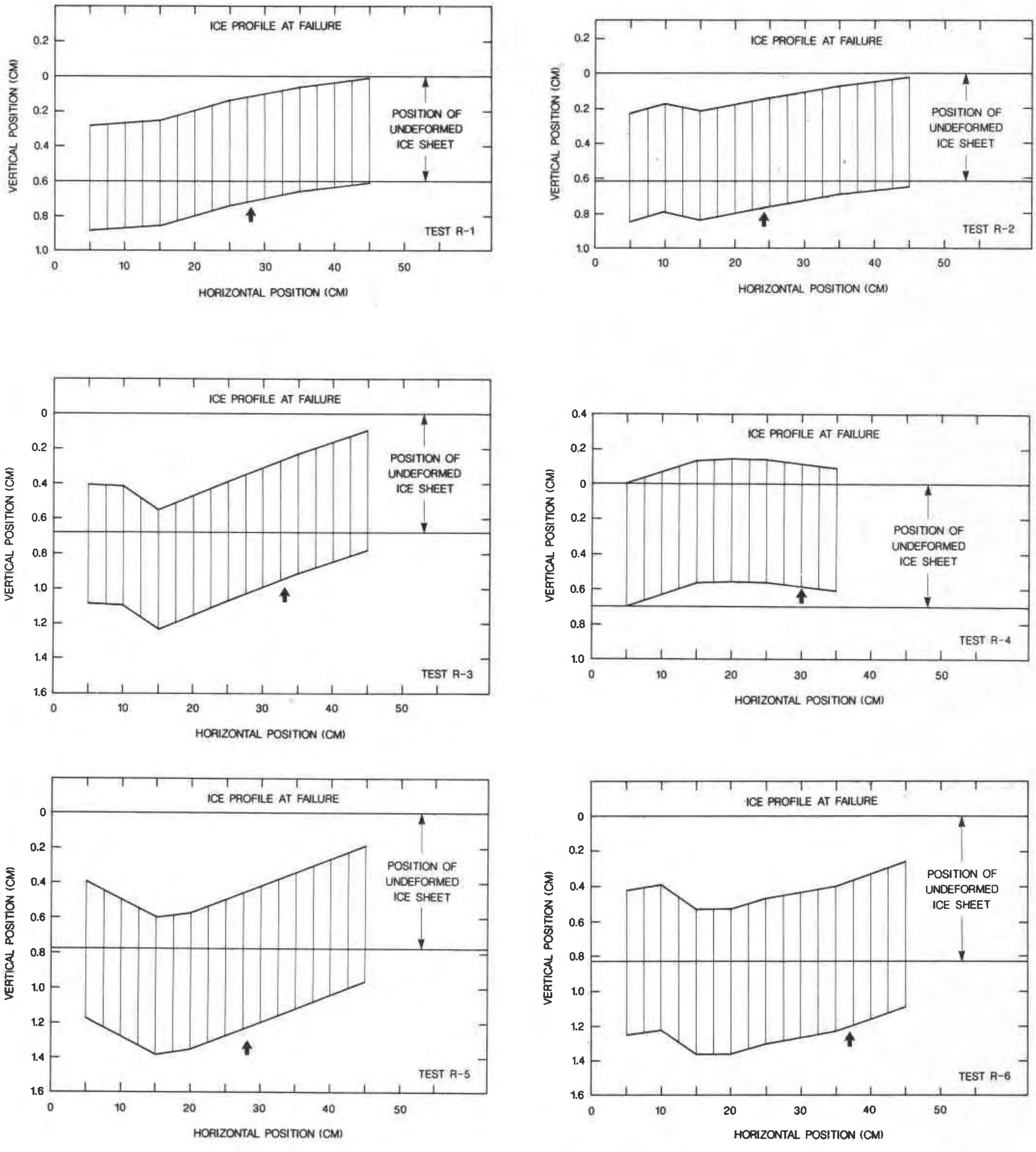

Figure 7 Deformation of the ice sheet at failure for each of the six tests using the Rubber finish buckling board.

Comparison of Results

Based on the measured peak loak (P_f), the width of the buckling board (B) and the ice thickness (h), the buckling pressure (σ_f) was determined as

$$\sigma_f = P_f/Bh \qquad (1)$$

The loading time to failure (t_f) was obtained from the load-time curve, and the average stress-rate in the ice was defined as

$$\dot{\sigma} = \sigma_f/t_f \qquad (2)$$

Figure 8 shows the peak pressure versus average stress rate for all of the tests. A rate effect in the buckling pressure can be seen only for the rubber-faced board. For the Varathane coated board, no rate effect is evident over the limited range of stress-rates of the tests. However, because there was some variation in the aspect ratio of these tests, the situation is more complex. Figure 9 shows the buckling pressure versus aspect ratio (B/h) for all of the tests. It can be seen that the lower buckling pressures tended to coincide with higher aspect ratios (i.e. the thinner ice sheets). These correspond to the lower stress-rates. Examination of Figures 6 and 7 show that the relative deformation at failure was greater for the thicker ice sheets (compare e.g. Figure 7-R2 for the thinner ice to Figure 7-R5 for the thicker ice). At comparable aspect ratios and loading stress-rates, the present data do not show any significant effect of surface friction on the buckling load.

In comparing the test results to current theory, the analysis by Sodhi and Hamza (1977) seems to be the most appropriate. They used a finite element analysis to study the buckling of a semi-infinite ice sheet loaded by a uniformly distributed load over a finite length of the straight boundary. The study assumed a frictionless boundary condition on the straight edge and fixed boundary conditions on the edges at infinity. These assumptions should give the lower limit of the buckling load. The results were presented in terms of non-dimensional buckling pressure ($P_f/Bk\ell^2$) versus B/ℓ where P_f is the buckling load, B the structure width, k the foundation modulus and ℓ the characteristic length (see Figure 10). The latter is related to the effective modulus (E) of the sheet by

$$\ell = \left[\frac{Eh^3}{12(1-\upsilon^2)k}\right]^{1/4} \qquad (3)$$

where υ is Poisson's ratio.

Sodhi and Hamza's (1977) analysis assumes a frictionless boundary condition and an increasing uniform load at the loading point along the free edge. In comparing the present test results with their analysis it should be kept in mind that neither of these conditions are met. In the experiments a uniform displacement was applied to the free edge of the ice sheet and not a uniform load. Second, the contact region of the structure is not frictionless as idealized in the theoretical treatment.

In order to compare the results of the present tests with Sodhi and Hamza's analysis, it is necessary to determine either the characteristic length or the effective modulus of the ice. Tests to measure these were performed using the "plate method" with an approach similar to that described by Sodhi et al. (1982). Values of the characteristic length were determined and the effective modulus was calculated using Equation (3), assuming a value for Poisson's ratio of 0.3. The characteristic length was a function of the ice thickness. The average value for the effective modulus was 9.0 GPa.

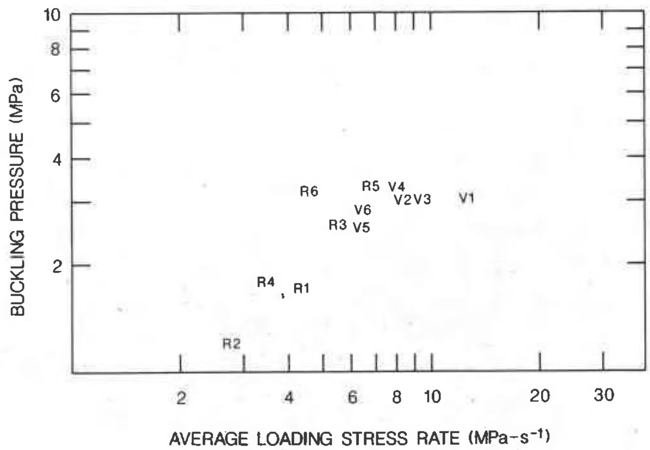

Figure 8 **Buckling pressures (at failure) versus average stress rate for all of the tests.**

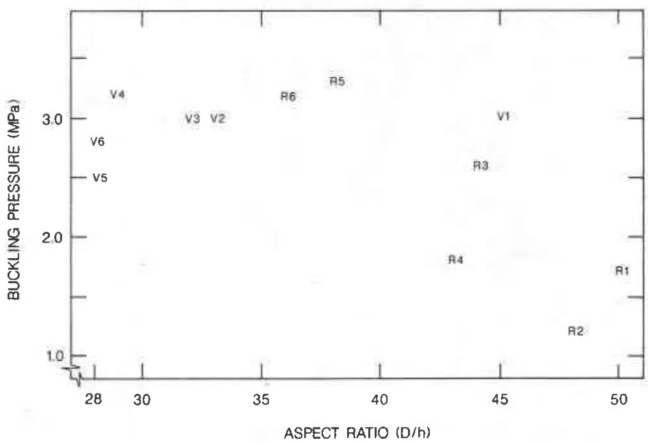

Figure 9 **Buckling pressure (at failure) versus aspect ratio for all of the tests.**

The present test results were analyzed using the non-dimensional approach discussed above. The results are shown in Figure 10. Because of the limited range of the test parameters, most of the data is clustered in one area. In all cases the measured values were higher than the calculated values. On average, the measured buckling load was about twice as high as Sodhi and Hamza's (1977) lower-bound value.

SUMMARY

This paper describes a test series investigating the buckling behaviour of thin sheets of fresh-

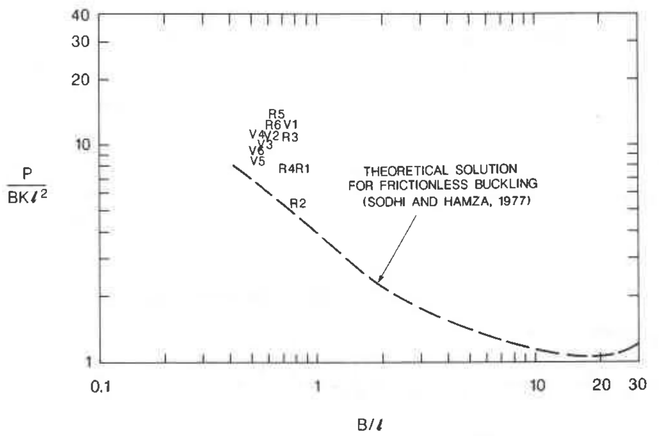

Figure 10 Non-dimensionalized buckling pressure analysis of the present tests. The theoretical curve for frictionless buckling is also shown.

water ice. The full results are presented in tabular and graphical form. The results clearly show that the ice can deform significantly before failure. Microcracking in the ice can lead to large permanent deformation of the broken ice pieces through a mechanism of crack enhanced creep. Buckling pressures ranged from 1.0 to 3.5 MPa depending upon loading stress-rate and/or aspect ratio.

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TABLE I

SUMMARY OF TEST RESULTS

Test Number	h Ice Thickness (cm)	Max. Load (kN)	t_f (sec)	B/h	w (cm)	L (cm)	σ_f (MPa)	$\dot{\sigma}$ ($MPa\text{-}s^{-1}$)
Varathane Interface (f = 0.02)								
V-1	0.67	6.1	0.24	45	40	-	3.0	12.5
V-2	0.90	8.1	0.36	33	50	-	3.0	8.3
V-3	0.95	8.6	0.32	32	53	13	3.0	9.4
V-4	1.05	10.2	0.40	29	54	-	3.2	8.0
V-5	1.07	8.1	0.40	28	51	14	2.5	6.3
V-6	1.09	9.2	0.44	28	68	17	2.8	6.4
Rubber Interface (f = 0.07)								
R-1	0.60	3.1	0.40	50	45	28	1.7	4.3
R-2	0.62	2.2	0.44	48	60	24	1.2	2.7
R-3	0.68	5.3	0.48	44	60	33	2.6	5.4
R-4	0.70	3.8	0.53	43	55	30	1.8	3.4
R-5	0.78	7.8	0.49	38	56	28	3.3	6.7
R-6	0.83	8.0	0.71	36	56	37	3.2	4.5

Structure width B = 30 cm; speed = 2 $cm\text{-}s^{-1}$

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