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EXPERIMENTAL STUDY OF EDGE LOADING OF ICE PLATES

BY

R. FREDERKING AND L. W. GOLD

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Experimental Study of Edge Loading of Ice Plates

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The interaction of an ice cover and a fixed narrow structure was modelled by edge loading large rectangular (0.4 m × 0.5 m) plates of columnar-grained ice. The plates were set on one of the long edges and the load was applied to the opposite edge by means of indentors of widths varying between 12 and 150 mm. Ice plates 25 to 100 mm thick were used. Observations were made of the dependence of the indentation load on indentor width and ice thickness. All loading was within the range of ductile behavior of the ice. The study indicated that the indentation pressure was a function of the width of the indentor, but not of the thickness of the ice plate. The mode of deformation was observed to be primarily two dimensional. The results of this study are in contrast to observations under field conditions, from which it is concluded that the indentation pressure depends on the ratio of the width of the indentor to the thickness of the ice cover. This suggests the presence of an effect which must be given attention in the development of modelling techniques for the ice pressure problem.

On étudie sur modèles l'interaction d'un champ de glace et d'un ouvrage mince et fixe au moyen de charges appliquées au bord de larges placques rectangulaires (0.4 m × 0.5 m) de glace à structure colonnaire. Les plaques reposent simplement sur un de leurs bords longitudinaux et la charge est appliquée sur le bord opposé au moyen de pénétrateurs de 12 à 150 mm de largeur. L'épaisseur des plaques de glace varie de 25 à 100 mm. On observe la charge de pénétration en fonction de la largeur du pénétrateur et de l'épaisseur de la glace. Le chargement se situe toujours dans les limites de comportement ductile de la glace. L'étude indique que la pression de pénétration est fonction de la largeur du pénétrateur, mais non de l'épaisseur de la plaque de glace. La déformation est essentiellement à deux dimensions. Les résultats de cette étude s'opposent à des observations *in situ*, indiquant que la pression de pénétration est fonction du rapport entre la largeur du poinçan et l'epaisseur du champ de glace. Cela suggère la présence d'un effet dont il faut tenir compte dans la mise au point des modèles servant à étudier la pression de la glace.

The force that a floating ice cover can exert on a fixed structure still cannot be adequately predicted. This is due to lack of information in the following three key areas: (1) the strength and deformation behavior of ice; (2) characteristics of the ice cover associated with the design condition; and (3) the interaction between the ice and the structure.

Knowledge is furthest developed in the area of the strength and deformation behavior of ice. Investigations have indicated that ice is anisotropic, nonhomogeneous, and viscoplastic. Its strength is dependent upon strain rate, ice type, and temperature.

The characteristics of the ice cover associated with the design condition have to be determined by site investigations. In cases where background information on ice conditions is meager these investigations might have to extend over several seasons.

The interaction between ice and structures can be studied by field measurements, mathematical modelling, or physical modelling. Field measurements of ice forces have been undertaken by several investigators, *e.g.* Neill (1972), Croasdale (1974), Schwarz (1970), and Atkinson *et al.* (1971). This type of measurement is necessary but it is expensive, time consuming, and limited by the conditions that nature produces. Mathematical modelling, *e.g.* Tryde (1973), Frederking and Gold (1971), Assur (1972), is an attractive alternative, which, with a good physical model and reasonable assumptions, allows parametric studies to be undertaken. Such parametric studies can easily encompass broad ranges of variables and yield an insight into the relative importance of various factors. Mathematical modelling also provides a framework for the conduct and analysis of field measurements. A number of investigators, including Michel (1970), Lavrov (1969), Schwarz and Hirayama (1973), and Afanas'yev *et al.* (1972), have undertaken physical modelling. By suitable

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Can. Geotech. J., 12, 456 (1975)

scaling of dimensional parameters (ice grain size, ice thickness, structure size, etc.) and ice physical properties (density, deformation behavior, strength, coefficient of friction, etc.), ice–structure interaction can be modelled, at least approximately. Exact geometric similitude can be achieved but strict kinematic similitude is virtually impossible to achieve except at a 1:1 scale ratio. A wide range of parametric variations, however, can be studied by means of physical models and empirical relations developed.

Most investigations do not fall neatly into one of the areas previously mentioned. The work reported in this paper is relevant to both physical modelling and the deformation behavior of ice. It was undertaken to investigate the effect of plate thickness and indentor width on the maximum force that develops during the ductile deformation of columnar-grained ice plates subject to edge loading. The results of the investigation relate to physical modelling of ice–structure interactions, the strength and deformation behavior of ice, and the plastic indentation of an anisotropic material.

Indentation Theory

Theoretical studies by Assur (1972) and Tryde (1973) of the ice–structure indentation problem showed that the nominal stress on the structure is a function of the dimensionless ratio of ice plate thickness to structure width. Their results are based on an assumed plastic behavior related to the maximum shear stress developed on planes at 45° to the surface of the ice cover.

Another theoretical approach, by Nadai (1963), is that of a rigid indentor pressing on a perfectly plastic half space. This is analogous to the two-dimensional hardness test and indicates no size effect, provided the depth of material beneath the indentor is more than $4\frac{1}{2}$ times the indentor width. The failure stress for this case is $(1 + \pi/2)$ times the uniaxial compressive strength.

The results of the experiments reported herein will be examined in the light of these theories.

Description of Model Tests

The ice from which the rectangular plates were machined was grown in a tank in the laboratory. By controlling water temperature and seeding with powdered snow, it was possible to produce columnar-grained ice with grain diameter perpendicular to the long direction of the columns in the range of 2 to 5 mm. The ice produced was type S-2, as described by Michel and Ramseier (1971), *i.e.* random orientation of the crystallographic symmetry axis in the horizontal plane. Each tank of ice was checked for uniformity of grain size and ice type. Using deaerated water allowed ice thicknesses of up to 150 mm to be attained before air bubbles appeared.

The ice was grown at a temperature of −10 °C and all machining operations were done at the same temperature. Special milling procedures had to be developed to permit the production of large rectangular ice plates. As shown in Fig. 1, the 400 mm × 500 mm surfaces were machined parallel to each other. The upper and lower loadbearing edges were then machined parallel to each other and perpendicular to the large machined surface. The 400 mm long edges were not machined. Plates of thickness of 25 to 100 mm, with a uniformity of ±0.15 mm, were fabricated. Usually the top 20 mm of ice were discarded so that grain size was reasonably uniform through the thickness of the specimen. The long axes of the columnar grains were normal to the plane of the plate.

Tests were performed in a 100 kN capacity screw drive test machine. Figure 1 illustrates the test setup. The indentor was moved downwards at a nominally constant rate of movement. It was loaded through a ball and socket

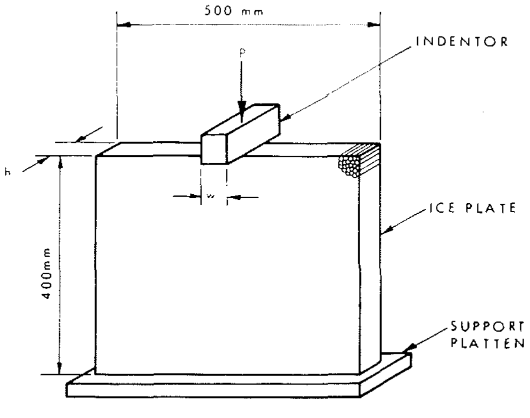

FIG. 1. Schematic of edge loading of ice plates.

TABLE 1. Test conditions and results for edge loading of columnar-grained ice plates

Test No.	Specimen No. / Edge No.	Indentor width (mm)	Ice thickness (mm)	Nominal strength (kN/m^2)	Indentation rate (mm/s)
E-1	1/1	100	50	1980	8.3×10^{-5}
E-2	1/2	100	50	—	8.3
E-3	2/1	50	50	2710	8.3
E-4	2/2	50	50	2680	8.3
E-5	4/1	75	50	2060	8.3
E-6	4/2	75	50	2280	8.3
E-7	7/1	150	50	1580	8.3
E-8	7/2	25	50	3430	8.3
E-9	8/1	150	50	1690	8.3
E-10	8/2	25	50	3660	8.3
E-11	8/1	25	50	3390	8.3
E-12	9/1	100	50	2130	8.3
E-13	9/2	75	50	2640	16.7
E-14	11/1	100	50	2050	8.3
E-15	11/2	150	50	1670	8.3
E-16	12/1	75	50	2870	16.7
E-17	12/2	75	50	3280	33.3
E-18	11/1	38	50	2920	8.3
E-19	13/1	75	50	3630	33.3
E-20	11/2	13	50	4580	8.3
E-21	14/1	75	62	2510	8.3
E-22	14/2	75	62	2340	8.3
E-23	14/1	25	62	3280	8.3
E-24	14/2	13	62	4460	8.3
E-25*	12A/2	75	50	1930	8.3
E-26*	12A/1	50	50	2520	8.3
E-27*	12B	50	25	2690	8.3
E-28	15/1	75	38	2320	8.3
E-29	15/2	75	38	2330	8.3
E-30	16/1	75	25	2320	8.3
E-31	16/2	75	25	2300	8.3
E-32*	15A/1	25	38	3350	8.3
E-33*	15B/1	25	38	3600	8.3
E-34	17/1	75	98	2070	8.3
E-35	17/2	75	98	2350	8.3
E-36	18/1	75	82	2310	8.3
E-37	18/2	75	82	2350	8.3

*Half-size specimen (250 mm × 400 mm).

and thus had some freedom of rotation. All rotations, however, were less than 0.005 rad. No lateral restraint of any sort was placed on the specimens.

The time dependence of the load, P, and the relative displacement between the indentor and the support platten were recorded. The majority of the tests were conducted at an indentation rate of 8.3×10^{-5} mm/s although some were done at 1.7×10^{-4} and 3.3×10^{-4} mm/s. At the higher rate (3.3×10^{-4} mm/s) the failure mode tended to be brittle. The test program was restricted to indentation rates resulting in ductile behavior.

As the tests took an hour or longer the specimens were wrapped with polyvinyl film to inhibit sublimation. Each specimen was tested twice, once on either loadbearing edge. This double usage of specimens did not appear to affect the results.

Results and Discussion

A total of 37 edge loading tests were carried out and the results and test conditions are presented in tabular form in the Table 1. In the first series of tests the plate thickness was fixed at 75 mm and indentor width varied from 12 to 150 mm. In the second series the indentor

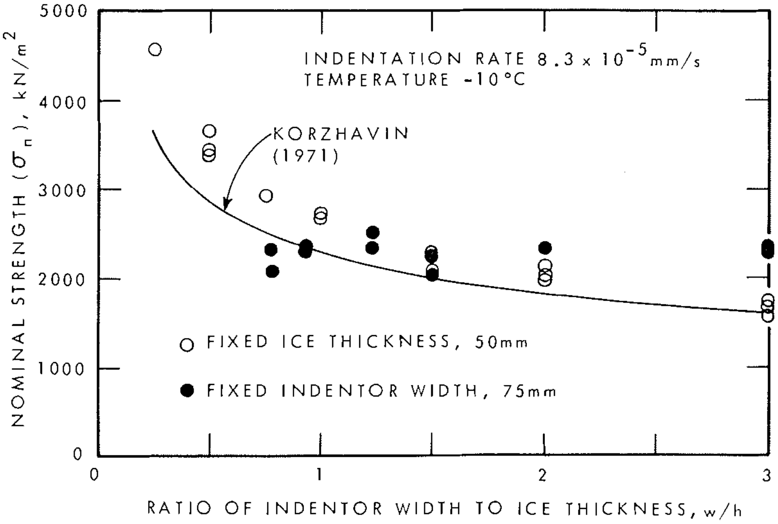

FIG. 2. Dependence of nominal strength σ_n, on ratio of indentor width to ice thickness, w/h.

width was fixed at 75 mm and ice thickness varied from 25 to 100 mm. In Fig. 2, the nominal strength (stress of yield) for both series, measured at an indentation rate of 8.3 × 10^{-5} mm/s, is plotted against w/h. Nominal strength is defined by

$$[1] \qquad \sigma_n = P/wh$$

where P is the maximum force on the indentor during a test, w is indentor width, and h is ice thickness.

Examination of the plotted data indicates there is a size effect on the nominal strength, but that for fixed indentor width the nominal strength is independent of the ice thickness. This is in general agreement with the model test results of Schwarz *et al.* (1974) which indicated that the effect of thickness on nominal strength was only to the power 0.1, but not in agreement with the theoretical predictions of Assur (1972) and Tryde (1973) for an isotropic material.

A typical deformation–time and load–time measurement is plotted in Fig. 3. In this test, time to yield was 120 min and indentation at yield was about 0.3 mm. Indentation at yield for all tests varied from 0.25 to 1.9 mm with no apparent relation to indentor width or ice thickness. The drop-off in indentation force after yield was very gradual. Over a 24 h period there was a 5 to 10% decrease from the maximum force. This behavior indicates that for the conditions of the tests, the ice could be considered as an elastic, ideally plastic solid.

Nominal strength, σ_n, at an indentation rate of 8.3 × 10^{-5} mm/s and ice thickness from 25 to 100 mm is plotted *versus* indentor width in Fig. 4 on a full logarithmic graph. The best fit line through the observations had the equation

$$[2] \qquad \sigma_n/\sigma_0 = (w/B)^{-0.4}$$

where w is the indentor width, B is specimen width (500 mm), and σ_0 is nominal strength at an arbitrarily selected indentor width. The correlation coefficient on the exponent is 0.98. If indentor width is extrapolated to the width of the specimen (B = 500 mm), a nominal strength, σ_0, for uniaxial compression of 1050 kN/m^2 is indicated for a strain rate of 2 × 10^{-7} s^{-1} (*i.e.* indentation rate 8.3 × 10^{-5} mm/s divided by specimen height, 400 mm). Uniaxial compression tests on the same type of ice and at the same strain rate, carried out at −10 °C on specimens 50 mm × 100 mm × 250 mm indicate a uniaxial compressive strength of 950 kN/m^2 (Gold and Krausz 1971). For indentor widths less than 25 mm, the grain size of the ice starts to become signifi-

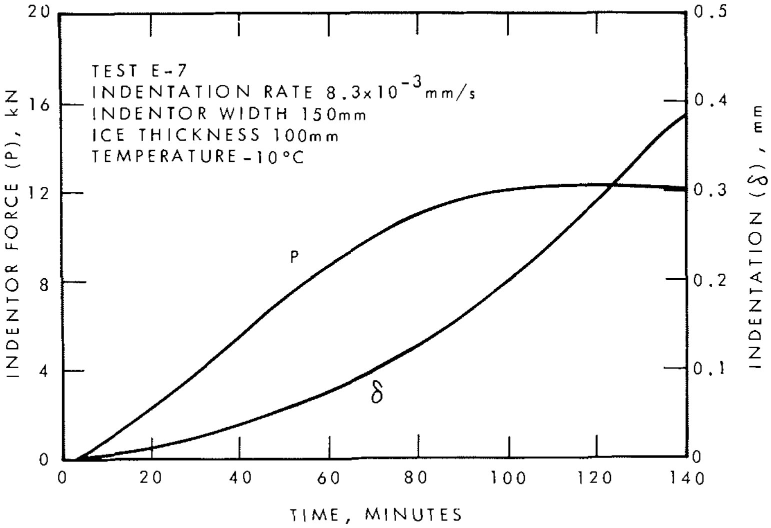

FIG. 3. Typical deformation–time and load–time behavior.

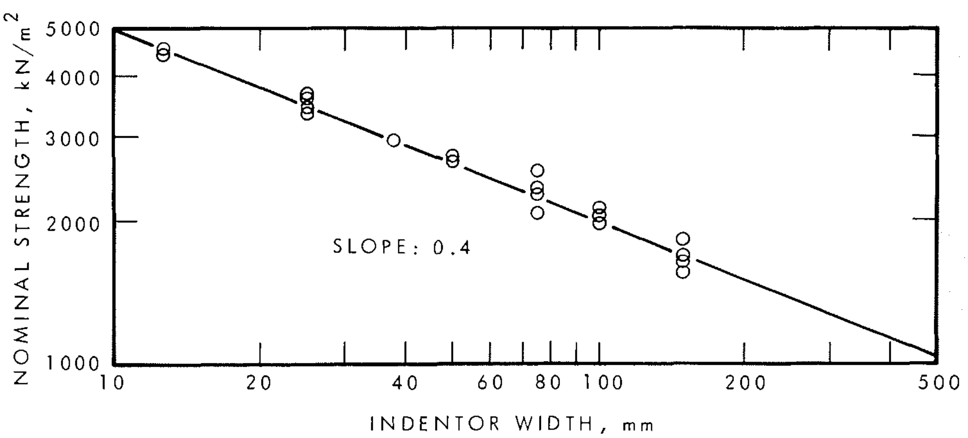

FIG. 4. Dependence of nominal strength σ_n, on indentor width.

cant with respect to the width of the indentor, and this effect could influence the results. However, there is no evidence of this in Fig. 4.

Test results for a 75 mm indentor, 50 mm thick plates, and several indentation rates are presented on a full logarithmic graph in Fig. 5. The plotted points lie along a straight line represented by

$$[3] \qquad \sigma_n = 1050\left(\frac{\dot{u}}{10^{-5}\,\mathrm{mm/s}}\right)^{0.35} \mathrm{kN/m^2}$$

where $\dot{u}$ is indentation rate in mm/s. This expression indicates a power law dependence of nominal strength on indentation rate, with an exponent of 0.35. Uniaxial compression tests on similar ice at −10 °C give a value of 0.32 for the exponent in the power law dependence of strength on strain rate. Note that Eqs. [2] and [3] apply only to the range of ductile behavior of the ice.

An earlier analytical study by Frederking and Gold (1971) of the interaction of an ice cover and pile structure indicated an expression of the form

$$[4] \qquad \sigma_n = N(\dot{u}/d)^{\alpha}$$

where $\dot{u}$ is indentation rate, d is pile diameter (analogous to indentor width w), and α is the exponent of the power law relating ice strength to strain rate. Comparing Eqs. [2], [3], and [4]

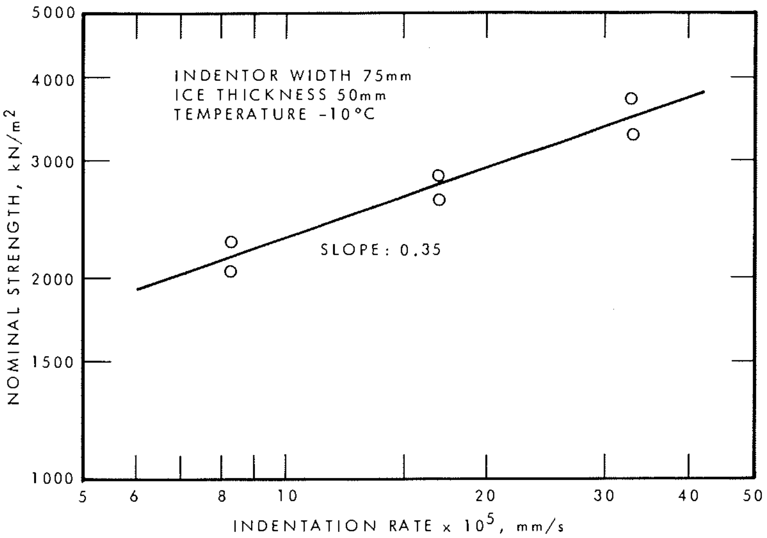

FIG. 5. Dependence of nominal strength σ_n, on rate of indentation.

indicates that factors other than penetration rate affect the dependence of nominal strength on width of indentor. The second factor is probably some sort of 'shoulder' effect (Williams 1965), *i.e.* the stress concentration at the edge of the indentor and the width dependence of its contribution to the measured nominal stress.

Korzhavin (1971) conducted a series of indentation experiments from which the following empirical expression was developed

$$[5] \qquad \sigma_n = \sigma_0(w/B)^{-0.33}$$

where σ_0 is the uniaxial compressive strength, B is specimen width, and w is indentor width. This equation is essentially the same as Eq. [2] except for the value of the exponent. The difference in the values of the exponents may be due to the differences in temperature and indentation rate (Korzhavin's observations are for a temperature of 0 °C and an indentation rate of 0.3 mm/s). Korzhavin's empirical expression (Eq. [5]) is plotted in Fig. 2, for $\sigma_0 = 1050$ kN/m² and $B = 500$ mm and $w = 50$ mm.

In general there was only a small amount of cracking activity by the time yield had occurred. Figure 6a illustrates the crack pattern at yield for test E-6 (indentor width 75 mm, ice thickness 50 mm, indentation rate 8.3×10^{-5} mm/s). The indentation at yield was 1.77 mm. It can be seen that crack formation tended to be concentrated in an ellipsoidally shaped band. This band extended about 125 mm into the specimen. The nominal spacing of the horizontal lines scribed on the specimen is 10 mm.

No cracks are present in the triangular zone directly beneath the indentor. This zone would be analogous to the 'dead metal' zone in plastic indentation under a rough punch. The apex angle of the zone of crack activity is less than 90°, suggesting that ice is a material with an internal friction angle greater than zero. Although it is not clear from this photograph, most of the cracks tended to be vertically oriented and to propagate parallel to the longitudinal axis of the columnar grains. By the time the yield point had been reached some cracks had also formed in the plane perpendicular to the long axis of the columnar grains.

Figure 6b shows the same test specimen, when the indentation was 7.8 mm. There are still relatively few cracks in the 'dead metal' zone, and the cracked zone (plastically deformed zone) now extends 160 mm beneath the indentor. Examination of the specimen after unloading revealed some plate-like cavities at either edge of the indented surface, oriented perpendicular to the long axis of the columnar grains.

Figure 7 is a photograph taken with polarized light of a thin section cut from the center of the ice plate 18/2 directly beneath the in-

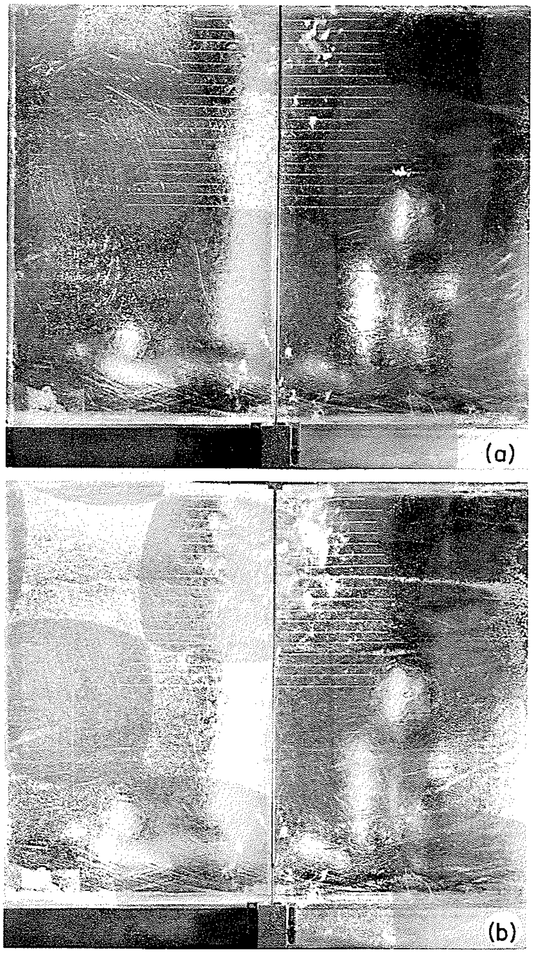

FIG. 6. Cracking activity; test E-6, indentor width 75 mm: (a) yield, 1.77 mm indentation and (b) plastic deformation, 7.80 mm indentation.

dentor immediately after testing. Test E-37 was conducted under the same conditions as test E-6. Nominal strengths for each test were within 1% of each other. In this case the indentation at yield was 1.9 mm and the total indentation was 6.75 mm. Large grains to either side of the indented area and in the triangular zone beneath the indentor indicate areas that underwent little if any plastic deformation. The plastically deformed zone is evident from the irregular smaller grains, low angle boundaries within grains, *i.e.* banded features, and otherwise distorted crystal structure.

The lack of dependence of the nominal strength on the ice thickness, as demonstrated by the results presented in Fig. 2 for fixed indentor width of 75 mm, indicates that for the columnar-grained ice used in the experiments, plastic shear does not occur on planes at 45° to the surface of the plane as would be expected from the reasoning of Assur (1972) and Tryde (1973) for isotropic plates. It is considered that this is due to the anisotropic deformation and strength properties of columnar-grained ice, which effectively force the plastic strain beneath the indentor to be essentially two dimensional. This behavior must be taken into consideration when attempting to model the ice–structure interaction using thin ice sheets. Unless special precautions are taken to ensure the formation of granular ice, such ice sheets will tend to have grains that are columnar because of conditions associated with the freezing process. In addition, even if the ice is granular, there may not be sufficient grains through the thickness to ensure isotropic behavior.

The theory of the two-dimensional hardness test (Nadai 1963) indicates that, for an isotropic ideally plastic material, the normal pressure on the indentor at yield is $(1 + \pi/2)$ times the uniaxial compressive strength and independent of the indentor width. The test results, however, show a very strong dependence on indentor width. Only for indentor width of about 50 mm did the nominal strength equal that predicted by this plastic theory. This theory, therefore, is not suitable for explaining the edge loading test results.

Conclusions

The tests showed that for edge loading of columnar-grained ice plates, ductile deformation is essentially one of plane strain and that the yield stress depends on the width of the indentor but not on the ice thickness. This finding is in general agreement with that of Schwarz *et al.* (1974) for model tests on ice near the melting point. It seems reasonable to explain this behavior in terms of a strain rate effect and the stress concentrations at the edges of the indentor. Extrapolation of the results to an indentor width equal to the specimen width gives a nominal strength about equal to that obtained in unconfined compression tests on the same ice, and at the same temperature and rate of strain. It is recognized that for large indentor widths (greater than or equal to 150 mm) the specimen width could

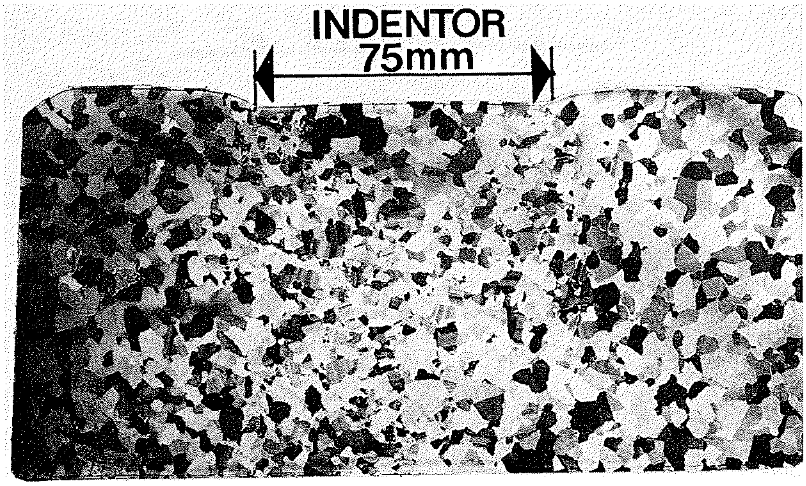

FIG. 7. Thin section of deformed ice; test E-37, indentor width 75 mm, 6.75 mm indentation.

affect the results. Future investigations will be directed toward exploring this effect.

Acknowledgments

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