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RÉSUMÉ

Le présent rapport fait état d'expériences sur le terrain effectuées sur des échantillons cylindriques et prismatiques orientés parallèlement et perpendiculairement à la couche de glace. On a fait varier la vitesse de déformation de 2×10^{5} s^{-1} à 5×10^{-4} s^{-1}; la charge et la déformation étaient contrôlées de façon continue. La résistance des échantillons verticaux de glace columnaire était environ trois fois plus grande que celle des échantillons horizontaux. Pour les deux échantillons, la résistance augmentait de la même façon lorsque la vitesse de déformation augmentait. Par contre, la déformation au point de rupture était similaire pour les deux orientations et ne dépendait pas de la vitesse de déformation. La rigidité du système d'essai a été mesurée et une technique de prévision des déformations est décrite. On se sert des valeurs mesurées de la résistance uniaxiale pour prévoir la résistance dans le cas d'une charge appliquée sous étreinte.

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ABSTRACT

Field experiments on cylindrical and prismoidal specimens oriented in the plane of the ice cover and perpendicular to it are reported. Nominal strain rate was varied from 2×10^{-5} s^{-1} to 5×10^{-4} s^{-1}; both load and strain were monitored continuously. The strength of vertical specimens of unaligned columnar-grained ice was about three times that of horizontal specimens. Both orientations showed similar increase in strength with increasing strain rate. On the other hand, strain at yield for both specimen orientations was similar and showed no dependence on strain rate. Test system stiffness was measured and a technique for predicting strains is described. The measured uniaxial strength results are used to predict strength under the confined loading condition.

INTRODUCTION

Knowledge of the mechanical properties of sea ice provides a basis for estimating design ice loads on offshore structures. When an ice cover impinges on any structure a complex stress field is set up within the ice, so that a failure criterion for ice under multi-axial loading is essential. Ralston (1) and Reinike (2) have demonstrated the application of a failure criterion, together with plasticity theory, to the estimation of ice loads for particular conditions. More recently, Timco and Frederking (3, 4) have determined strength for confined compression of both columnar-grained and granular sea ice and have evaluated the corresponding failure criteria.

Evaluating a failure criterion generally requires uniaxial strength data for specimens oriented in several directions in the ice cover as well as strength data from biaxial loading. Only limited biaxial loading data are available, however, because of the experimental difficulties of performing such tests. As a first approximation uniaxial compressive tests on vertical and horizontal specimens can give some indication of expected multi-axial strength. Test results of strength as a function of strain rate for vertical and horizontal specimens of first-year sea ice will be presented and applied to an estimation of the confined compressive strength.

The mechanical properties measured are a function of both the testing methods and the material characteristics of the ice. Two different loading systems and specimen configurations were used, the better to define their effect on measured strength properties. Loading system stiffness was measured in both cases. A technique for estimating specimen strain from the load-time history of the specimen and the loading system stiffness will be presented.

SPECIMEN ACQUISITION AND PREPARATION

During a field trip to the Beaufort Sea, 3-6 May 1982, a number of blocks and vertical and horizontal cores were cut from a large rafted piece of ice in the rubble field about 40 m west of Tarsiut Island, a caisson-retained island in the Beaufort Sea. Daytime maximum air temperatures were -5°C. The samples were packed in plastic bags and cardboard boxes and flown by helicopter to Tuktoyaktuk, where they were taken to a small laboratory and stored at a temperature of -11°C ± 1°C.

Both prismoidal and cylindrical specimens were made. The cylindrical ones were prepared by cutting the core samples to particular lengths. They had a diameter of 75 mm and preferred length of 250 mm, but some shorter specimens were cut to take advantage of the available pieces of core. The horizontal core samples (long axis parallel to the ice surface) were taken at a depth of 0.55 m, where the grain structure was columnar. Thin sections of these cores showed that the ice had random c-axis orientation in the horizontal plane, i.e. unaligned columnar grains, and an average grain size of 3 - 5 mm. The vertical cylindrical specimens were obtained from vertical cores (long axis perpendicular to ice surface) and comprised either granular or columnar-grained ice, depending on the depth from which they were taken in the ice cover. Thin sections of the granular ice showed that it had random c-axis orientation and grain size ranging from 1 - 2 mm. Prismoidal specimens were cut from the block samples with a band saw to nominal dimensions of 190 mm long, 100 mm wide, and 60 mm thick. The long axis of the vertical specimens was perpendicular to the ice surface and the long axis of the horizontal specimens parallel to it. The prism specimens were from a depth of 0.45 - 0.65 m and were unaligned columnar grained.

TEST PROCEDURE

A motorized, 60 kN capacity, screw-drive compression test machine (Tri-Test 50) was used for testing. Actuator rates were selected in the range 0.2 to 5 mm/min, producing nominal strain rates in the range 2×10^{-5} to 5×10^{-4} s^{-1}. "Maraset" compliant platens were used to eliminate the effect of irregularities and reduce radial stresses at the ends of the cylindrical specimens. For the cylindrical specimens the ends were cut with the band saw, with no further end preparation; two extensometers were fitted directly to each specimen and the output averaged for strain. The prismoidal specimens were loaded between steel platens and their ends finished with fine emery paper to provide a flat surface; strains were not measured.

Loading was monotonic to yield, when the specimen was unloaded. Typical stress-time and strain-time curves from vertical and horizontal cylindrical and prismoidal specimens under a nominal strain rate of 2×10^{-4} s^{-1} are presented in Fig. 1. In all cases the failure mode was ductile. Definitions of yield stress, σ_y, time to yield, t_f, strain at yield, ε_y, and strain rate at yield, $\dot{\varepsilon}_y$, are also shown. Average stress rate, $\dot{\sigma}_{av}$, is σ_y/t_f, and nominal strain rate, $\dot{\varepsilon}_{nom}$, is nominal machine speed divided by specimen length.

Testing was done at a temperature of -11°C ± 1°C. Specimen salinity varied from 3.2 to 4.5 ‰, with an average of 4 ‰.

TEST RESULTS AND DISCUSSION

Complete test results are tabulated in Tables 1 and 2 for cylindrical and prismoidal specimens, respectively. Strength versus average stress rate for all the tests is plotted in Fig. 2. The results fall into three categories: one for the horizontal specimens of columnar-grained ice, the second for vertical specimens of granular ice, and the third for vertical specimens of columnar-grained ice. Clearly the vertically oriented specimens of unaligned columnar-grained ice are about three times stronger than the horizontal specimens, similar to the earlier findings of Peyton (5). This can be related to the columnar-grain structure of the ice, in which the long axis of the columnar grains is parallel to the long axis of the vertical specimen. Compared on a stress rate basis, there is no significant difference between the strength of prismoidal specimens tested on steel platens and that of cylindrical specimens tested on compliant platens. This suggests that for field tests average stress rate can be used as an independent variable to compensate for differences in the stiffness of the loading system. As mentioned earlier, a number of the vertical specimens comprised granular sea ice, and results from these are also included in the plot. They fall approximately midway between the results for vertical and horizontal columnar-grained specimens. Also plotted is the regression line for the fit of a power law to strength results for horizontal specimens of granular ice (6). There is very little difference in strength for vertical and horizontal specimens of granular ice. Given the equiaxial grain structure and the near-random orientation of the symmetry axis of the grains, this is to be expected.

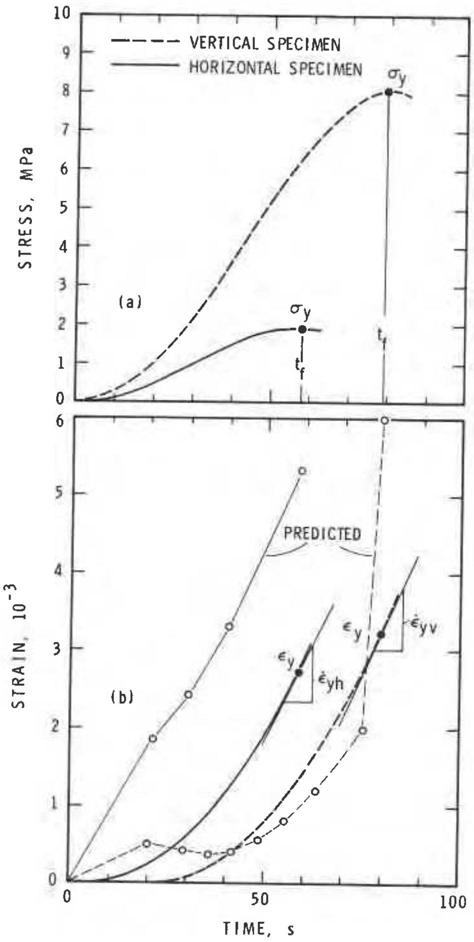

Figure 1. Stress-time and strain-time curves for vertical and horizontal cylindrical specimens of columnar-grained ice; $\dot{\varepsilon}_{nom} = 2 \times 10^{-4}$, test temperature = -11°C ± 1°C; $\dot{\varepsilon}_{yv} = 1.1 \times 10^{-4}$ s^{-1} (vertical specimen) $\dot{\varepsilon}_{yh} = 1.0 \times 10^{-4}$ s^{-1} (horizontal specimen)

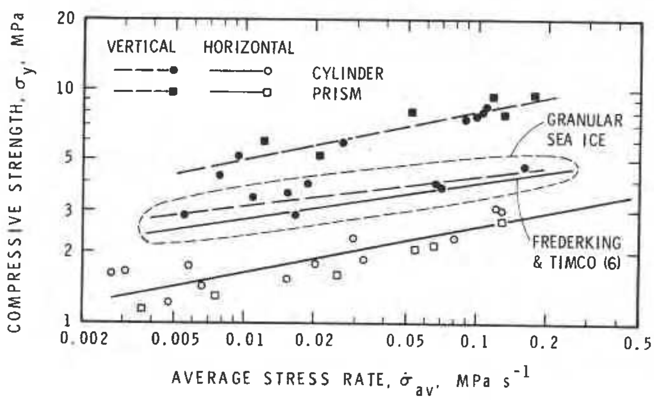

Figure 2. Strength of vertical and horizontal specimens of columnar-grained ice (except as noted) as a function of average stress rate at -11°C ± 1°C

A power function has been fitted to each set of strength versus average stress rate results. The resulting equations, with corresponding correlation coefficents, r, are as follows:

Columnar-grained ice - vertical specimens

$$\sigma_y = 13.9\ \dot{\sigma}_{av}^{\ 0.22}\ (r = 0.94) \qquad (1)$$

horizontal specimens

$$\sigma_y = 4.05\ \dot{\sigma}_{av}^{\ 0.20}\ (r = 0.86) \qquad (2)$$

Granular ice - vertical specimens

$$\sigma_y = 5.78\ \dot{\sigma}_{av}^{\ 0.13}\ (r = 0.84) \qquad (3)$$

horizontal specimens

$$\sigma_y = 5.85\ \dot{\sigma}_{av}^{\ 0.16}\ (r = 0.79) \qquad (4)$$

(The reader is cautioned not to extrapolate the preceding empirical expressions beyond the range of the experimental data.)

Although not plotted, the strength results were examined in terms of time-to-yield to verify the satisfactory performance of the test machine (7). All showed a trend towards increasing yield time with decreasing strength, confirming the satisfactory performance of this field test system.

From Fig. 1 it may be seen that although the tests were run at a constant nominal strain rate of $2 \times 10^{-4}\ s^{-1}$, strain rate is far from constant. Initially it is much less than the nominal rate, and only begins to approach the nominal strain rate at yield. There is undoubtedly some experimental measurement error at small strains. The average strain at yield for both the vertical and horizontal specimens was about 3×10^{-3}. A very weak trend towards increasing strain with increasing time-to-yield was apparent.

Measurements were made of the stiffness of both the test machine and the loading system; stiffness of the entire loading system can be quite different from that of the basic test machine owing to the separate effects of load cell, platens, alignment joints, etc. In this case the system stiffness was determined by loading a specimen of known constant elasticity and measuring load, movement of screw jack, and load frame deflection (6). The following expression was used to determine the loading system stiffness, $K_{\ell s}$,

$$K_{\ell s}(P) = \frac{\Delta P}{\delta_j - \frac{\Delta P\,\ell}{EA}} \qquad (5)$$

where ΔP is load increment, δ_j is the corresponding displacement increment of the jack, A is the cross-sectional area of the specimen, ℓ is length, and E elastic modulus. $K_{\ell s}$ was determined by loading a 75-mm diam by 200 mm long aluminum specimen. The resulting loading system stiffnesses derived from such tests on the Tri-Test 50 machine with compliant platens and steel platens are presented in Fig. 3. Loading system stiffness is not a constant, but a function of load, P. As expected, stiffness was greater for the steel platens than for the compliant platens. Jack speed was relatively constant at about 75% of the nominal rate. The basic frame stiffness of the machine is about 150 MN/m, which is substantially higher than the system stiffness.

Having determined loading system stiffness, it is possible to estimate the strain in a specimen of another material by transposing equation (5) to make E the dependent variable:

TABLE 1. Data and results of tests on cylindrical specimens (76 mm ϕ) at -11°C ± 1°C

Orientation	Specimen Length, mm	Jack Speed, mm/min	Yield Stress, MPa	Time to Yield, s	Strain at Yield, 10^{-3}
horizontal	248	1.5	1.84	93	3.8
"	224	4.5	2.25	28	3.2
"	225	0.5	1.22	258	3.6
"	170	2.0	1.90	58	2.5
"	206	0.6	1.44	222	2.3
"	205	0.25	1.66	550	3.9
"	206	1.8	2.36	82	2.7
"	205	5.0	3.22	27	2.5
"	157	5.0	3.17	25	2.7
"	153	1.2	1.55	102	2.4
"	145	0.5	1.77	312	4.8
"	140	0.2	1.62	606	4.0
vertical*	252	0.5	3.43	318	3.2
" *	251	1.5	2.89	177	6.3
" *	248	3.0	3.85	55	2.9
" *	250	5.0	4.75	30	2.3
" *	230	0.69	3.61	237	3.0
" *	250	0.30	2.89	528	2.8
" *	172	0.70	3.96	212	1.1
" *	179	1.6	4.00	60	2.5
"	178	1.6	8.03	80	2.8
"	179	1.6	7.74	87	5.3
"	179	1.6	8.29	78	2.9
"	178	1.6	8.71	80	1.3
"	192	0.25	4.29	549	-
"	191	0.25	5.23	570	-
"	186	0.6	6.02	228	-
"	192	0.6	3.24	210	-

*granular ice

TABLE 2. Data and results of tests on prismoidal specimens at -11°C ± 1°C

Orientation	Length, mm	Jack Speed, mm/min	Yield Stress, MPa	Time to Yield, s
horizontal	191	4.6	2.82	22
"	190	2.3	2.23	34
"	190	1.1	1.63	66
"	191	0.57	1.30	174
"	191	0.28	1.14	318
"	191	2.3	2.17	40
vertical	192	2.3	9.66	84
"	192	1.1	8.25	159
"	191	0.57	5.23	252
"	191	0.28	5.99	498
"	191	2.3	7.99	62
"	177	3.4	9.82	56

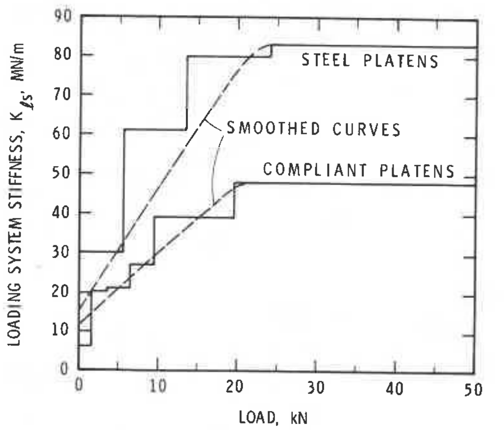

Figure 3. Loading system stiffness of Tri-Test 50 at 1 mm/min nominal actuator rate

$$E = \frac{\ell}{A\left\{\frac{\delta_j}{\Delta P} - \frac{1}{K_{\ell s}(P)}\right\}} \qquad (6)$$

Taking the jack displacement increment, δ_j, as equal to 75% of the nominal jack rate, $\dot{\delta}_j$, times a corresponding time increment, Δt, and substituting in equation (6) gives

$$E(P) = \frac{\ell}{A\left\{\frac{3}{4}\dot{\delta}_j\frac{\Delta t}{\Delta P} - \frac{1}{K_{\ell s}(P)}\right\}} \qquad (7)$$

From a load-time plot of a test on an ice specimen of known dimensions, modulus E can be determined as a function of load P (or stress). Strain can also be determined. Such a calculation was made for the two cases shown in Fig. 1.

The smoothed curves for loading system stiffness in Fig. 3 were used in the calculation. In a quantitative sense the correspondence of the predicted strain-time curves to the measured curves is not particularly close. The form of equation (7), with a difference in two small terms of the denominator, makes the modulus E(P) quite sensitive to any uncertainties in values for loading system stiffness and jack rate. Nevertheless, the predicted strains are an indication of actual strain at yield. In the two cases the predicted strain at yield is about twice the measured value.

It was pointed out in the introduction that strength measurements for vertically and horizontally oriented, uniaxial specimens can be used in estimating the confined compressive strength. This is not possible in a rigorous sense, but a qualitative estimate is possible. The simplest yield criterion for an anisotropic material, proposed by Hill (8), is assumed to be a quadratic in terms of the stress components

$$F(\sigma_y-\sigma_z)^2 + G(\sigma_z-\sigma_x)^2 + H(\sigma_x-\sigma_y)^2$$
$$+ 2L\,\tau_{yz}^2 + 2M\,\tau_{zx}^2 + 2N\,\tau_{xy}^2 - 1 = 0 \qquad (8)$$

This expression assumes similar yield stresses under tensile or compressive loading, and assumes also that hydrostatic stresses do not influence yield. Under the test conditions, i.e. low effective hydrostatic stresses and loading only in the compression-compression quadrants, these assumptions are acceptable. Taking x, y and z to be a right cartesian coordinate system, with x and y in the plane of the ice cover and z normal to it, and principal stresses to correspond to this coordinate system, F, G and H can be determined from the results of uniaxial compressive tests on specimens oriented in the three coordinate directions.

For an unaligned columnar-grained ice cover the structural and mechanical properties are usually isotropic in the plane of the ice cover. The uniaxial strength of a specimen oriented in the plane of the ice cover (horizontal) is $\sigma_x = \sigma_y = X$; for one oriented perpendicular to the plane of the ice cover (vertical) it is $\sigma_z = Z$. Substituting these values for uniaxial yield strength in equation (8) gives

$$F = G = \frac{1}{2Z^2}$$

and

$$H = \frac{1}{X^2} - \frac{1}{2Z^2} \qquad (9)$$

Having determined the constants F, G and H in equation (8), it is possible to estimate the yield strength for combined loading conditions. The loading case of frequent interest is confined compression in the plane of the ice cover, i.e., $\sigma_x = \alpha\sigma_y$, $\sigma_z = 0$. For ideal confined compression, $\alpha = 1$ and

$$\sigma_x = \sigma_y = \sigma_c \qquad (10)$$

where σ_c is the confined compressive strength. Substituting equation (9) in (8) for the loading condition of equation (10) gives the confined compressive strength.

$$\sigma_c = Z \qquad (11)$$

At a nominal strain rate of $2 \times 10^{-4}\ s^{-1}$ the uniaxial yield strengths from this test series were 8.4 and 2.65 MPa for vertical and horizontal specimens of columnar-grained ice, respectively. With these results, a confined compressive strength of 8.4 MPa would be the predicted value for biaxial loading in the plane of the ice cover. Results of confined compressive tests of columnar-grained ice under similar loading conditions gave an average confined compressive strength of 9 MPa (3).

CONCLUSIONS

1. On an average stress rate basis, the yield strength of the ice measured in these field tests is independent of the stiffness of the test system (compliant platens versus steel platens).
2. For unaligned columnar-grained ice, the uniaxial compressive strength of vertical specimens is slightly more than three times the uniaxial compressive strength of horizontal specimens.
3. For granular ice, the vertical strength is only about 10% greater than the horizontal strength.
4. With knowledge of the stiffness of the loading system, it is possible to estimate strain from the load-time results.
5. Uniaxial compressive strength results on vertical and horizontal specimens can be used in estimating confined compressive strength.
6. The strain at yield measured in these test for both vertically and horizontally loaded columnar-grained specimens is about 3×10^{-3}.

NOMENCLATURE

A	cross-sectional area of test specimen
E	elastic modulus
F,G,H,L,M,N	coefficients on yield function
$K_{\ell s}$	loading system stiffness
ℓ	specimen length
P	load
ΔP	load increment
t_f	time to yield
Δt	time increment
X	uniaxial compressive strength in plane of ice cover
Z	uniaxial compressive strength normal to plane of ice cover
$\alpha = \sigma_x/\sigma_y$	ratio of biaxial stresses in plane of the ice cover
δ_j	displacement increment of jack
$\dot{\delta}_j$	nominal jack displacement rate
$\dot{\varepsilon}_{nom} = \dot{\delta}_j/\ell$	nominal strain rate
ε_y	strain at yield
$\dot{\varepsilon}_y$	strain rate at yield
σ_c	confined compressive strength
σ_x, σ_y, σ_z	normal stress components
σ_y	uniaxial compressive yield strength
$\dot{\sigma}_{av} = \sigma_y/t_f$	average stress rate
τ_{xy}, τ_{yz}, τ_{zx}	shear stress components

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