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THE FATIGUE BEHAVIOR OF FRESHWATER ICE

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RESUME

Des expériences de fatigue ont été faites sur la glace d'eau douce soumise à la flexion alternée. On a élaboré une technique pour prendre des répliques des surfaces de fracture; on a examiné ces répliques pour mesurer la porosité et pour chercher les signes d'une croissance cyclique des fissures. On a trouvé quelques striations, mais la contribution relative de la déformation plastique et des mécanismes de clivage reste incertaine. Il faut un examen supplémentaire pour découvrir si les fissures croissent immédiatement à partir des défauts existants ou s'il y a un délai important d'initiation. On a démontré que le temps de fatigue dépend de la porosité, de la déformation imposée et de la température.

ABSTRACT

Cyclic loading (fatigue) tests have been performed on freshwater ice subjected to reversed bending. A technique has been developed to take replicas of the fracture surfaces, which have been examined to measure porosity and to seek evidence of cyclic crack growth. Some striations have been found, but the relative contributions of plastic deformation and cleavage mechanisms remain unclear. Further investigation is needed to see if cracks grow immediately on cyclic stressing from existing defects or if there is a significant initiation period. A dependence of fatigue life on porosity, applied strain range and temperature has been demonstrated.

INTRODUCTION

The study of the fatigue behavior of ice is of interest for several practical reasons. First, ice is a ceramic which can be tested at high homolous temperatures ($T > 0.95$ Tm) with relative ease and studying ice behaviour may thus yield information relevant to the behaviour of ceramics under such conditions. Second, much natural ice suffers fatigue loading through wave or tidal action. Third, when ice is used for structural purposes the loading may be repetitive. That ice in nature does suffer cyclic loading is clear from field measurements [1,2]. A recent theoretical investigation by Vinogradov and Holdsworth [3] predicts oscillating bending strains for a floating glacier tongue excited by water waves.

The fatigue behavior of ice has attracted surprisingly little interest. The earliest work was performed by Kartashkin [4] who made compressive fatigue tests (i.e., the load was compressive through the whole cycle) on large blocks of freshwater ice. Similar tests were performed by Tabatha and Nohguchi [5] and also by Mellor and Cole [6]. Goodman [2] reports some unsuccessful fatigue tests and it may be that the deficiency of data arises from the inherent experimental difficulties involved in performing such tests.

EXPERIMENTAL METHODS

Rig Design

To avoid the effect of creep deformation, it was decided to use a rotating bending specimen in a Wöhler type rig (see Fig. 1), a classic type of fatigue test originally designed to mirror the loading on railway axles. The test rig consisted of a drive shaft mounted through two bearings on an aluminium frame and driven by a belt. The speed of rotation, whilst controllable to a limited extent directly by the pneumatic motor, was mainly varied by the use of different sized pulley wheels. The whole rig was placed inside a freezer box which had been adapated to give temperature control accurate to ± 0.5°C.

Specimen Design and Preparation

Connections between the ice specimen and the load and the drive systems were made by the use of inserts, so as to avoid excessive stress concentrations. The driving insert consisted of a stainless steel shaft with wooden "paddle wheels" fitted on one end. Some water penetrated the wood prior to freezing, thus giving particularly good bonding between ice and wood. A similar loading insert was made entirely of wood. The load was applied through a bearing attached to the shaft of the insert with wood screws.

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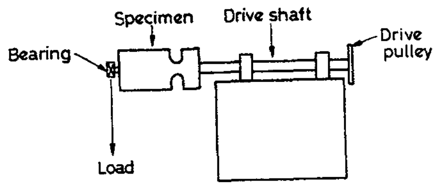


Fig.1. Schematic diagram of fatigue rig

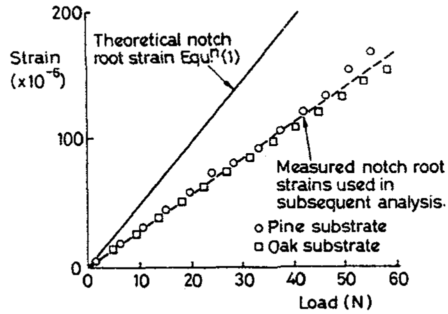


Fig. 3. Results of strain gauge experiments on fatigue specimen.

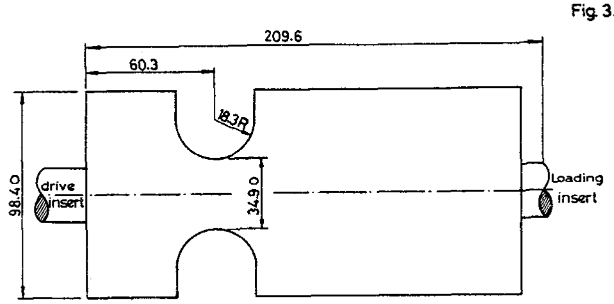


Fig. 2 Fatigue specimen dimensions (mm)

To localise failure, the specimen was waisted from 98.4 mm diameter down to 34.9 mm diameter (see Fig. 2). The mould used to construct the specimen was also a jig which ensured correct placement of the two inserts. Two pieces of Tufnol were used as end plates of the mould with central holes to hold the inserts. So that the loading insert was not displaced during freezing, the ice was frozen from the botton (the drive end) upwards, with the aid of a heating ring placed at the top of the mould. This heating ring allowed the rate of specimen freezing to be controlled. Solidification time was between 24 and 48 hours.

Stress analysis was made of the specimen by treating it as a built in cylindrical beam and applying a stress concentration factor [7]. This analysis showed that the maximum elastic surface stress at the root of the notch is given by:

$$\sigma_s = \frac{32\ K_T\ P\ d}{\pi\, e^3} \tag{1}$$

where K_T is the stress concentration factor (= 1.26), P the load, d the distance from the notch root to the plane of loading, and e the diameter of the specimen at the notch root. To test this stress analysis, strain gauges were attached to the specimen, and the strain at the root of the notch was measured under load. The gauges were mounted on 0.5 mm thick slivers of wood 18 mm long by 5 mm wide. These were frozen into each of two specimens, one on the tension surface of the notch and one on the compressive surface. One set of gauges was mounted on a pine substrate, the other on oak. Figure 3 shows the results of the strain gauging experiments. As can be seen, the two sets of results are in good agreement, suggesting that the type of wood substrate used has little effect on the strain readings. To give an idea of the accuracy of this method of strain gauging the specimens, the strain reading were compared with theoretical values calculated from equation (1). The value of E used in these calculations was 9.33 GPa [8]. The measured values of strain were some 25% less than those predicted. This discrepancy probably arose because the diameter/length ratio of the cylinder was too large for simple beam theory to be strictly applicable and because the strain gauges, being 12 mm long, were measuring the average strain across the bottom of the notch which would be less than the peak strain at the root of the notch. The values of measured strain are used in the presentation of experimental results.

A series of static strength tests were performed at three levels of porosity, qualitatively designated clear, bubbly and very bubbly. No significant difference in static strength could be found between the three porosities. The results of these tests are summarised in Table 1. In order to ascertain what part creep might play in any fatigue failure, two constant load creep tests were performed. The inflection points on the displacement/time curves for these tests occured after 180 hours and 600 hours (± 10 hours) for end loads of 39.8 N and 26.4 N respectively.

Porosity

Since natural ice almost always has pores or brine pockets it seems sensible to try and investigate the effects, if any, of varying degrees of porosity on the fatigue life of ice. In order to do this, specimens had to be manufactured with different and controlled porosities, and further, the porosity had to be measured in some quantitative way. The first of these requirements was met by varying the rate of freezing with a heating ring. A slower rate of freezing reduces porosity because oxygen has more time to diffuse away from the ice water interface. It also leads to larger grain sizes, the variation in grain size from very bubbly to clear being from 3 to 8 mm. Thus it may be that the variation of fatigue life with porosity that was observed was due to changes in grain size, but the magnitude and sense of the variations as compared with other grain size effects in ice [9,10] suggest not.

Table 1: Static Tests on Fatigue Specimens

Specimen No.	Time to Fail (s)	Failure End Load (N)	Porosity p%	Porosity Type*
SA1	20 ± 0.5	88 ± 5	2.89	B
SA2	2 ± 0.5	54 ± 5	2.79	B
SA3	15 ± 0.5	94 ± 5	1.29	C
SA4	16 ± 0.5	84 ± 5	0.98	C
SB1	30 ± 0.5	86 ± 5	1.12	C
SB2	20 ± 0.5	66 ± 5	4.51	VB
SB3	27 ± 0.5	82 ± 5	4.25	VB
SB4	24 ± 0.5	80 ± 5	5.98	VB
SB5	30 ± 0.5	93 ± 5	3.42	B

The porosity of the specimens in the working section was measured by taking silicon rubber replicas of the fracture surfaces. To avoid melting the fracture surface, the silicon rubber was cooled to sub-zero temperatures after mixing with the setting catalyst. These replicas produced good negatives of the fracture surface. Porosity was measured by inspection of the replicas under a binocular microscope at low magnification. The pore diameters were found to lie between 0.01 mm and 1 mm. The number and size of the pores were measured in four 154 mm^2 areas on each replica, thus allowing the mean reduction in area due to porosity to be found. To check the accuracy of the sampling technique, two replicas were given an examination over the whole surface. The porosities found from these total examinations were within 3% of those found by the sampling method. The pores were cylindrical in shape, with lengths of up to 5 mm. In general, the pores were oriented nearly parallel to the axis of rotation of the specimens. Three different porosities were defined in terms of the percentage reduction in area due to porosity (p). These were "clear" ($0\% < p < 2\%$), "bubbly" ($2\% < p < 3.5\%$), and "very bubbly" ($3.5\% < p < 5.5\%$).

RESULTS

Initial Measurements

This study was intended as a preliminary investigation of the fatigue behavior of ice under fully reversed loading. As well as generating basic stress-life data, the intention was to investigate how the fatigue behaviour changed when temperature, porosity and loading frequency were varied. A considerable degree of scatter was expected in the results both because of the large scatter inherent in fatigue testing and because of the brittle nature of ice which led to a number of handling problems.

The first series of tests were conducted at -13°C with bubbly ice to establish a "standard" strain/life curve to which all other data could be compared. Figure 4 shows this"standard" curve together with data for clear and bubbly ice at the same temperature (-13°C). These results are tabulated in Table 2. Three things are particularly notable. First, loads of 40% of the static failure load produced very short lives (≈500 cycles). Second, porosity had a considerable effect on the lifetime at a given load. Third, small reductions in load produced significant increases in the number of cycles to failure.

The fracture surface replicas were examined under a scanning electron microscope (see Figs. 5a and 5b). Difficulties were experienced in coating the replicas, which meant that high acceleration voltages could not be used. However, a small number of replicas did coat well and two of these, from specimens having 491 and 505 cycles to failure, showed marking which might be indicative of striations (see Fig. 5b). Striation spacing was approximately 10 µm and the total crack length at failure was about 5 mm, giving a lifetime of 500 cycles, gratifyingly close to the observed lifetime for these two specimens. The striation markings were not particularly clear and have not been found on specimens with longer life-times. Such striations have been observed in other brittle materials [11] and if striations arise from plastic deformation at the crack tip then in ice, where such deformation is small and some crack advance may be by cleavage, one would not expect particularly clearly defined striations. However, there were no obvious cleavage facets visible, though the porosity may mask such effects, and it should be noted that the striations are markedly different from Wallner lines observed in some brittle fractures.

Table 2: Fatigue Tests at -13°C

Frequency: 2.8 ± 0.2 HZ

End Load, P	Cycles to Failure	Porosity p%[2]
35.3	491	3.47 B
35.3	505	2.12 B
33.1	1,505	2.88 B
33.1	3,091	2.01 B
26.4	37,050	2.13 B
26.4	11,989	3.28 B
17.5	1,110,000[1]	2.29 B
39.8	73,600	0.56 C
39.8	66,640	0.65 C
35.3	879,700	0.52 C
26.4	1,130,000[1]	0.24 C
26.4	2,760	456 VB
17.5	9,850	4.79 VB
13.0	901,200	3.91 VB

1: These tests were considered to be runouts

2: C = Clear (p less than 2%)
B = Bubbly (p between 2 and 3.5%)
VB = Very Bubbly (p above 3.5%)

Table 3: Effect of Temperature on Fatigue Tests of Bubbly Ice

Frequency: 2.8 ± 0.2 Hz

Load N	Cycles to Failure	Temperature °C
39.8	10,000	-30
39.8	15,628	-30
35.3	491	-13
35.3	505	-13
33.1	792	-7
33.1	1550	-13
33.1	3091	-13
33.1	66,000	-18
33.1	34,940	-18
33.1	148,700	-30
33.1	73,900	-30
33.1	80,929	-30
30.8	600,000	-18
26.4	11,000	-7
26.4	20.520	-7
26.4	37,050	-13
26.4	25,360	-13
17.5	1,500,000[1]	-7
17.5	830,000	-7
17.5	1,110,000[1]	-13

1: These tests were considered to be runouts

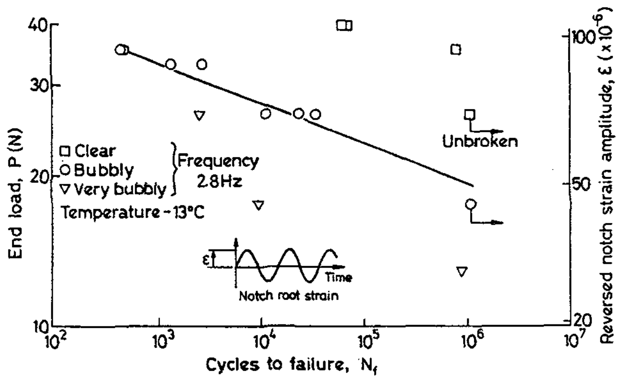


Fig.4 Fatigue tests at -13°C : Results

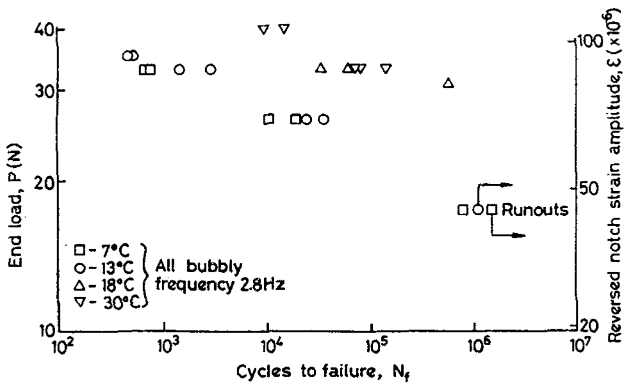
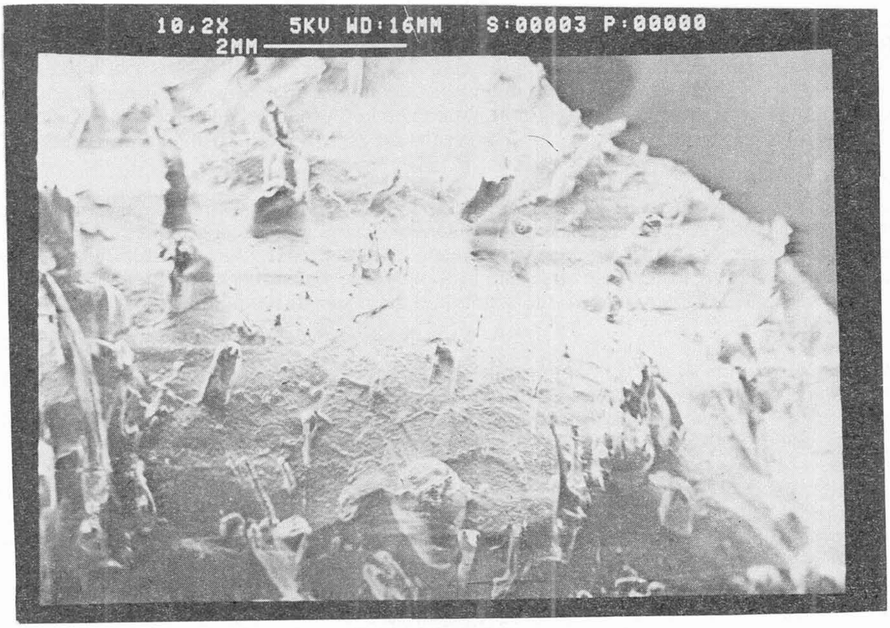
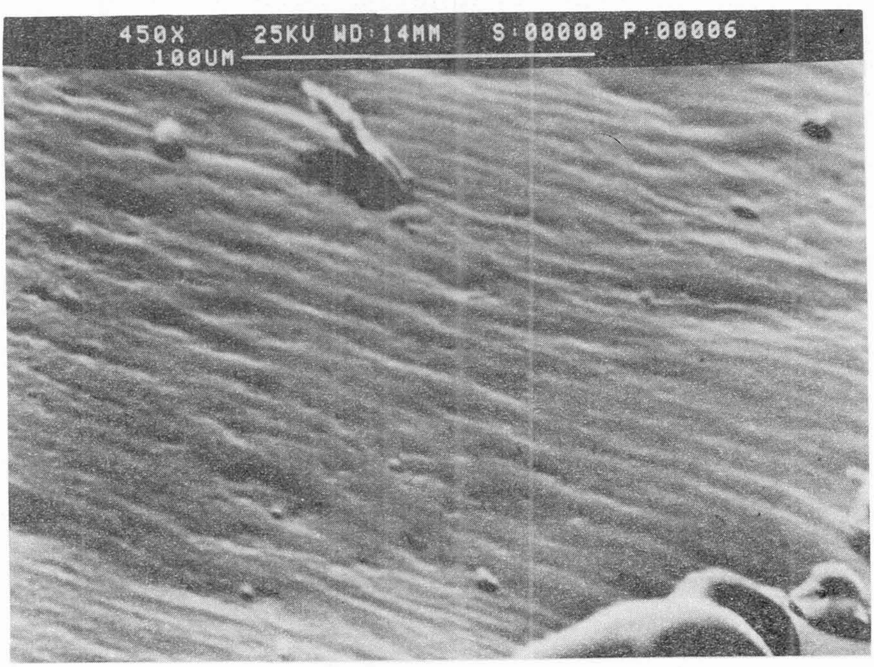


Fig. 6 Fatigue tests, all temperatures: Results.



(a) Showing Pores



(b) Showing Striations

Fig. 5: Replicas of Fracture Surface

Variations of Temperature

Tests were performed at four temperatures; -7°C, -13°C, -18°C, -30°C. A number of practical difficulites were encountered at -30°C when the metal shaft in the loading inserts exhibited a tendency to pull out. This was avoided by strengthening the wood-metal bond in the insert. Fatigue life at a given load increased as temperatures decreased though the difference in lifetime between tests at -7°C and -13°C was negligible for lives greater than 10^4 cycles. The results are shown in Fig. 6 and summarised in Table 3.

Variation of Frequency

Six tests were performed at a frequency of 0.28 - 0.30 Hz as a preliminary investigation into frequency effects on fatigue. Low frequency effects are of particular interest in the fatigue of ice because natural fatigue loading occurs at frequencies between 0.01 and 0.2 Hz. A major difficulty in these tests is the long times required to accumulate large numbers of cycles. To limit testing time, high load levels were used. There was considerable scatter in the results and three specimens failed by drive shaft pull-out.

DISCUSSION

The results in Figure 4, clearly demonstrate that fatigue of ice is an important failure mechanism. At fatigue loads of approximately 40% of the monotonic failure load, specimens failed in a few hundred cycles. On further decreasing this load, more cycles were needed to cause failure. The significance of these results for cyclically loaded structures is extremely important. Safety factors for the design of ice structures must be large enough to accommodate this previously ignored mode of failure.

The mechanisms of fatigue failure in ice need much further consideration. Figure 4 demonstrates that the greater the number of defects in the sample, the shorter the fatigue life at a given strain level. Presumably this is because the "very bubbly" specimens were more likely to contain a bubble (defect) in the high stress surface region. The temperature dependence results shown in Figure 6, indicate longer lives with lower temperatures.Since these tests were performed under conditions giving rise to deformation by power law creep [12] this result might have been anticipated. The frequency tests in our experiments were inconclusive, but we expected that lower frequencies might cause enhanced (cyclic) growth rates, because creep processes would have more time to contribute to the deformation.

It has been noted that striations were observed on one fracture surface and an argument has been produced to show that, in that case, the whole of the fatigue process was dominated by crack propagation. We are unable to generalise from this result, but clearly in large scale practical applications, both in fresh and sea-water ice, defects of considerable size will be present. In these cases, experiments of the crack propagation type would be more appropriate than the type of fatigue test in this present study.

In conclusion, apart from a short communication of our preliminary results [13], these are the only unambiguous fatigue results for ice of which we are aware. It has been shown that fatigue can cause failure in ice; it therefore behoves designers to take this into account when considering ice structures subjected to cyclic loading. Fatigue may also play an important role in problems of "natural cyclic" loading: for example sea-ice breakup, or the flexure of floating ice tongues.

ACKNOWLEDGEMENTS

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COMMENTS

E. GAFFNEY

What is the length dimension used to determine loading rate (i.e., grain diameter, sample diameter, sample length, etc...).

Answer :

The appropriate length dimension to use in calculating K, the loading rate, is the crack length.

R.GAGNON

One would think that bubbles should hinder the propagation of cracks in a stressed sample. Why do you think this has not been evident in your experiments ?

Answer :

I feel that bubbles are most important in the initiation of fatigue cracks, and that the marked effect of porosity on fatigue life that we observed arises from a reduction in the number of cycles to initiate a fatigue crack as the porosity is increased.

A.J.GOW

In the initial slide of your presentation your indicated relevance of your work to the Arctic. Your interest in the Arctic must surely involve sea ice.Results you presented here were concerned solely with freshwater ice, a very different material compared to sea ice, both structurally and in terms if its mechanical and rheological properties. It would be virtually inpossible to relate your present results to sea ice. My question : Do you intend to conduct similar tests on sea ice samples ?

Answer :

I would very much like to perform fatigue tests on saline ice. Of particular interest is the effect which brine will have on the crack growth process.

P. CAMP

Have you any evidence which would suggest that fatigue effects anneal out of your samples at higher temperatures ?

Answer :

At a given load and porosity, the number of cycles to fracture decreased as temperature increased, up to - 7°C. Thus there is no evidence that fatigue effects "anneal" out at high temperatures.