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THE FAILURE OF ICE

BY

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ICE SYMPOSIUM 1970
REYKJAVIK

THE FAILURE OF ICE

LA RUPTURE DE LA GLACE

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Information is presented on the cracking activity that occurs in columnar-grained ice during creep and constant rate of strain tests, when the load is applied perpendicular to the long direction of the grains. This cracking activity is responsible for the occurrence of tertiary creep or failure in uniaxial compression tests when the stress exceeds about 12 bars. The behaviour of ice around structures is discussed with reference to the results of the laboratory studies.

On présente des données sur la fissuration de la glace à structure colonnaire au cours d'essais de fluage et de déformations à taux constant lorsque la charge est appliquée perpendiculairement à la longueur des grains. La fissuration est responsable du fluage tertiaire ou de la rupture au cours des essais sous compression uniaxiale lorsque les contraintes excèdent 12 bars. On discute du comportement de la glace autour des structures en rapport avec les résultats obtenus en laboratoire.

The determination of the maximum force that ice can exert against a structure requires knowledge of the strength of ice under various conditions of loading. Failure of ice, under most design loads of interest to engineers, is due to a breakdown of its structure by the formation of cracks. A series of observations have been carried out on the factors controlling crack formation in ice, and the role that it plays in deformation and failure (1, 2, 3). These observations were made on columnar-grained ice, subjected to simple compression in the direction perpendicular to the long direction of the grains. There was a marked tendency for the crystallographic basal planes to be parallel to the long direction of each grain. This note presents some of the results of this study that are of significance for both laboratory and field investigations of ice pressures.

CRACK FORMATION DURING CREEP

Cracks were observed to form in ice when the constant compressive stress was greater than about 6 bars. The cracks were long and narrow, and usually associated with only one or two grains. The plane of the cracks tended to be parallel to the applied stress, with the long direction in the long direction of the grains. When the stress was less than about 10 bars, the cracking activity was confined mainly to the primary stage of creep.

A marked change in creep behaviour was observed over the stress range 10 to 12 bars. The secondary creep stage developed if the stress was less than 10 bars. If the stress was greater than about 12 bars, the tertiary or accelerating creep-rate stage developed directly from the primary stage within a creep strain of 0.25 per cent. Cracking activity for these loads was continuous in the tertiary stage, and many specimens developed fault zones approximately parallel to the planes of maximum shear. The cracking activity appeared to concentrate within the fault zones, as shown in figure 1.

The strain dependence of the average rate of cracking is shown in figure 2 for tests carried out at various stresses at a temperature of $-9.5 \pm 0.5°C$. The corresponding average creep behaviour is shown in figure 3. Similar cracking activity and creep behaviour was observed at temperatures of -4.8, -14.8 and -31.0°C.

The observations indicated that the onset of the tertiary stage of creep for stress greater than 12 bars, was due to the breakdown of the structure by cracking activity. The crack density observed at the beginning of the secondary creep stage for stress of 10 bars, was about 1.4 per cm^2. It was about 1.6

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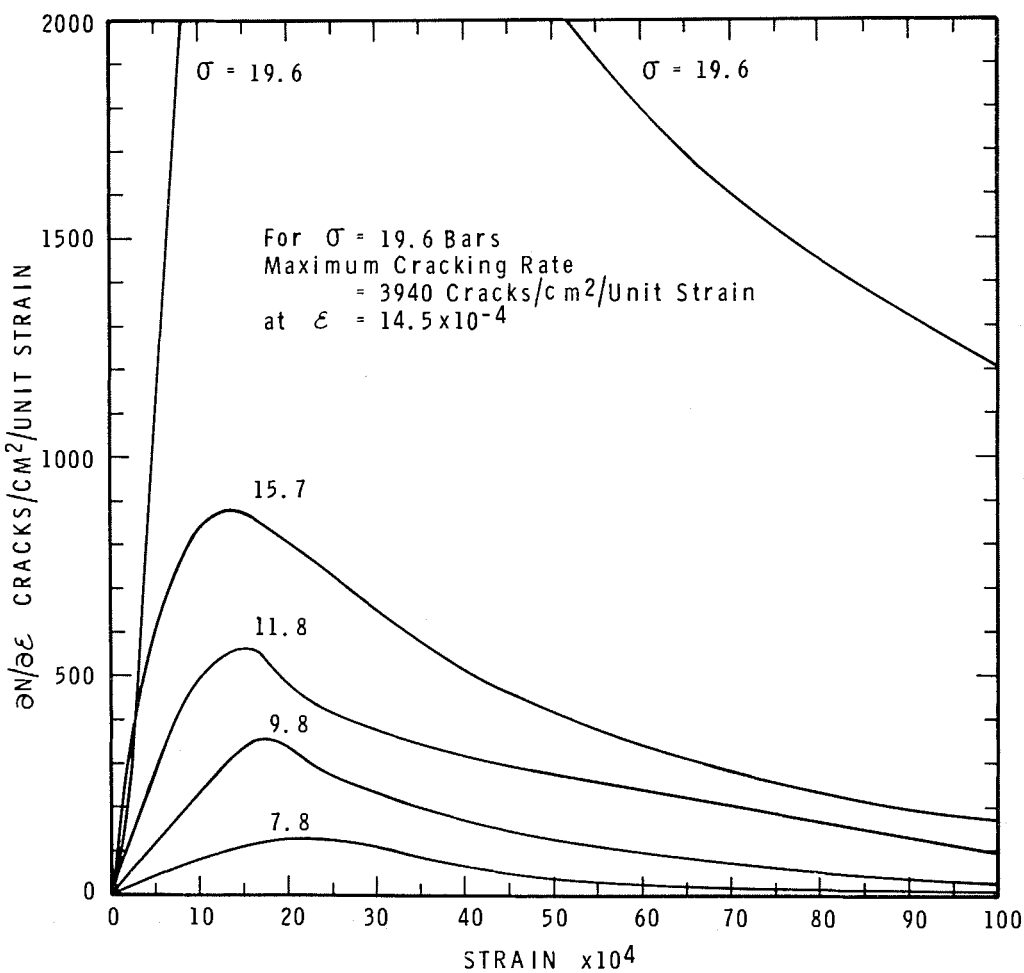
Fig. 1. Crack formation in columnar-grained ice deformed 1 per cent; stress = 19.6 bars. Temperature = -9.5°C.

Fig. 2. Strain dependence of cracking rate, $\frac{\partial N}{\partial \epsilon}$, for given stress σ, bars. Temperature = -9.5°C.



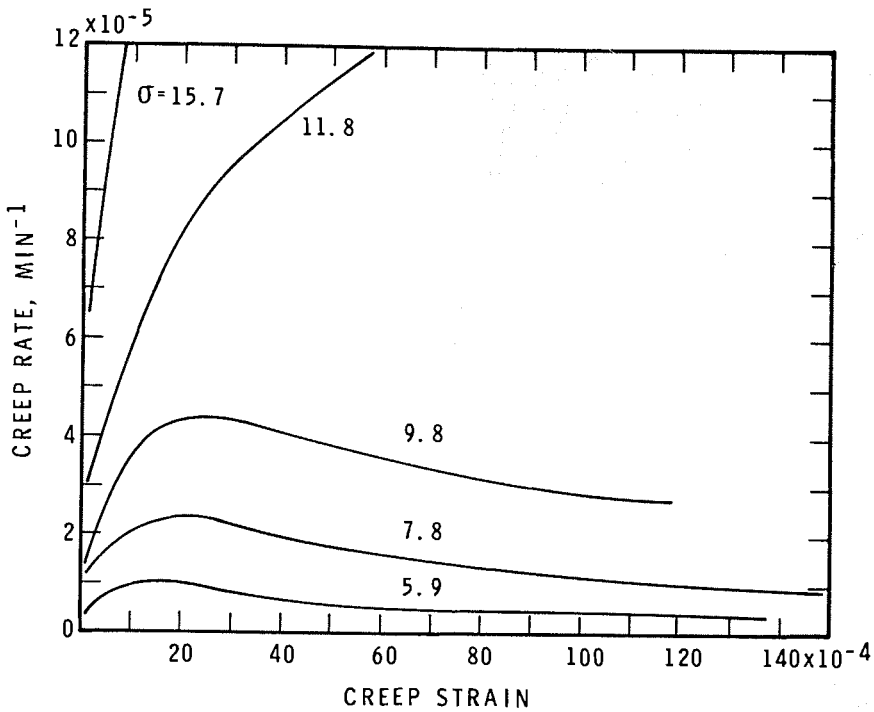


Fig. 3. Strain dependence of average creep rate for given stress. Temperature = -9.5°C. (Note the transition in behaviour in the stress range of 10 to 12 bars.

per cm^2 at the onset of the tertiary stage for stress of 11.8 bars , and about 0.5 per cm^2 for the same condition when the stress was 15.7 bars.

CRACK FORMATION DURING CONSTANT RATE OF STRAIN

Observations have also been made on the behaviour of columnar-grained ice under conditions of constant rate of cross-head movement of the testing machine. As in the constant-load tests, loads were applied perpendicular to the long direction of the grains. The stress developed had a maximum in the range of strain of 5×10^{-4} to 15×10^{-4} (i.e. an upper yield stress). A second upper yield stress was observed for strain rates in the same range as those associated with constant compressive loads of less than 10 bars The second maximum in the stress occurred in the strain range of 1 to 2 per cent; this range is about the same as that associated with the transition of the secondary creep stage to the tertiary stage for constant compressive loads.

The strain rates that were applied covered the range of 1.2×10^{-7} sec^{-1} to 1.7×10^{-4} sec^{-1}. A ductile-to-brittle transition was observed for strain rates of about 8.3×10^{-5} sec^{-1}. The yield stress in this range of strain rate was 70 to 100 bars.

Crack formation occurred when the strain rate exceeded about 10^{-7} sec^{-1}, a rate that is about equal to that associated with a constant compressive stress of 6 bars. There was very considerable cracking activity prior to and during yield for strain rates giving an upper yield stress greater than 12 bars.

Cracking activity prior to yield in the constant strain rate tests, and prior to the tertiary stage in the creep tests, appeared to be distributed relatively uniformly throughout the specimens. Yield in the constant-strain rate tests appeared to be associated with the development of fault zones in the same way as for the tertiary stage during creep (see figure 1). These observations demonstrated that the structural instability associated with failure was induced by the breakdown of the structure by cracking activity. This fact has implications for the failure behaviour of ice around structures, and the use of laboratory results on the strength of ice for predicting the maximum forces that can occur.

IMPLICATIONS FOR LABORATORY AND FIELD TESTS.

Almost all information concerning the strength of ice has been obtained from unconfined compression tests. The behaviour of columnar-grained ice for this condition of loading is such as to cause the strain during deformation and failure to be primarily perpendicular to the long direction of the grains. This strain behaviour would be inhibited under most field conditions because of the biaxial stress state that would be induced. Such a biaxial stress would also inhibit the type of cracking activity causing failure in the case of unconfined compression. For the case of complete lateral constraint, for example, crushing failure would require crack formation perpendicular as well as parallel to the long axis of the columnar-grains if the failed ice is to be displaced to the upper and bottom surfaces of the ice cover. Crushing strengths for complete lateral constraint would be greater than those observed in unconfined compression.

There appears to be little evidence that the relatively large stresses required to fail ice in the laboratory are induced near structures. From a design point of view, however, the possibility of such large stresses under some field conditions cannot be ruled out at this time. Ice covers would probably develop their maximum load on a structure when moving relative to it at a speed causing a rate of strain in the ductile-to-brittle transition range. A serious load condition might develop, for example, at an isolated structure frozen into the ice cover, if the cover is suddenly subjected to a significant lateral displacement.

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Discussion by B. Ross on paper by L.W. Gold.

Are the cracks observed in the tests noted to occur in the central regions of the specimens or are they initiated at the loading heads of the test machine?

Reply to question by B. Ross.

The cracks that are formed prior to the onset of the failure condition are uniformly distributed throughout the central region of the specimen. It was clear that the constraints imposed by the loading platens affected the distribution of the cracks near the ends of the specimens. Some evidence was also obtained of an edge effect (i.e. the crack density was smaller near the edge than in the central region). The observations on the carcking activity were made over the central portion of each specimen where the cracking activity appeared to be uniform.

Discussion by G. Frankenstein on paper by L.W. Gold.

Did the cracks occur along the Grain Boundries?

Reply to question by G. Frankenstein.

We observed both transcrystalline and grain boundary cracks. The relative proportion of these two types of cracks appears to depend upon the strain rate and associated stress.

Discussion by S. Hanagud on paper by L.W. Gold.

In your paper you mentioned that cracks are initiated under tensile loading at a stress below the level at which complete failure would take place. I would like to know the stress at which these cracks are initiated are their size. Is there any effect of these cracks?

Also I shall appreciate if you can elaborate on the failure stress under stream rate.

Reply to question by S. Hanagud.

In tensile tests, cracks were observed to form for stress equal to 4 kg/cm^2. These cracks were small, usually less than 1 mm by 1 cm in area. Some cracks were observed to degenerate into a plane of small cavities with continued deformation. The cracks did not appear to participate in the final failure event, although this occurred so rapidly that it was not possible to state positively that failure was not due to the propagation of a pre-existing crack.

All of our tests at constant rate of strain have been carried out in compression. In the ductile range of behaviour, the maximum yield stress increased with rate of strain according to a power law relationship. This dependence was found to be the following:

$$\sigma_{uy} = 203\ \dot{\varepsilon}\ 0.25\ kg/cm^2$$

where $\dot{\varepsilon}$ is in $min.^{-1}$. We have not extended our observations far enough in the brittle range of behaviour to determine the strain rate dependence of the brittle strength.

Discussion by C. Cochard on paper by L.W. Gold.

Can you tell me if the cross-sectional dimension of the crystals has an influence on the number and the repartition of the cracks?

Reply to question by C. Cochard.

Most of our studies have been carried out on ice with grain size of 1 to 3 mm. As the cracks are associated with either one or two grains, it would be expected that as the grain size increased, the number of cracks per unit area would decrease and their size increase. This appeared to be the case for specimens that we prepared from natural columnar-grained ice of larger grain size.