PRELIMINARY OBSERVATIONS OF THE CREEP BEHAVIOUR OF IN SITU SEA ICE BEAMS

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ABSTRACT

The spring break-up of Antarctic sea ice is influenced by the cyclic loading of the ice due to ocean waves. An interest in this fatigue behaviour of sea ice has motivated in situ experiments on cantilever beams of first year sea ice. These creep experiments were performed immediately after a period of variable stress loading that produced some damage, as evidenced by concurrent acoustic emissions. An empirical approach, employing a standard anelastic model, has been applied to the bending of a beam to model the strain under the varying stress period and the constant stress loading. A second model however is believed to provide a better description of strain development, modelling the anelastic strain as a function of time to the power of 0.3.

INTRODUCTION

Many models have been used to describe the creep of both freshwater and sea ice. Creep processes have been examined by, for example, Glen (1955), Barnes et al. (1971), Sinha (1979), Duval et al. (1983), Weertman (1983), Schapery (1997), Abdel-Tawab and Rodin (1997), Cole (1993), and Derradji-Aouat et al. (2000). Frequently the form of the models is similar to models developed for engineering materials (for example see Skrzypek, 1993), an indication that the mechanical behaviour of ice is similar to other materials and that the results obtained from the deformation of ice might have broader applications. That said, with its regular array of brine inclusions, brine drainage channels and the frequent occurrence of a c-axis orientation, sea ice has a unique structure, which likely limits the extension of specifically developed models to other materials. Modelling of ice is a complicated process for a number of reasons. One particular example is that strong anisotropies develop during the deformation of isotropic ice because both the crystallographic and the flow properties are time dependant (Budd and Jacka, 1989).

The fatigue mechanisms of first year sea ice are of interest for a number of reasons, in particular its contribution to the break-up of sea ice in late spring. Fatigue is influenced by the number of dislocations and these numbers can be inferred from the delayed elastic strain. The delayed elastic strain, itself a product of dislocation motion, is usually measured by observing the strain resulting from the application of a constant

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load, normally called a creep relaxation experiment. The experiments described in this paper are somewhat different because a half sinusoid load is applied to the ice immediately prior to the constant load. A combination of creep loading, interspersed with the application of relatively lower amplitude cyclic stress, has been used previously in laboratory tests on sea ice samples (Cole and Durell, 2001). The present experiments differ from these in two ways: our experiments involve large scale testing of sea ice samples in situ, and our tests are performed with large cyclic amplitudes (300 kPa) followed by small creep stresses (50 kPa).

**EXPERIMENTAL DETAILS**

The creep experiments examined in this paper were performed on sea ice about one kilometre offshore from Cape Evans, in McMurdo Sound, Antarctica. This is a region with reasonably high winds and very low snowfall, although windblown snow was present, which results in predominantly snow free ice. The ice in this region is first year, fast ice approximately 2 m thick. Cracks are present, however there were large (approximately 100 m × 100 m) regions of unbroken ice from which beams were cut.

Creep experiments were performed on two in situ cantilever beams composed of first year sea ice of approximately uniform thickness. The application of a series of half sinusoids of increasing amplitude created the recent load history of the ice (see figure 1). The loading was always in a downward direction at the free end of the beam, producing tension at the upper ice surface. At the end of each half cycle the beams were held for a short time at a creep stress of approximately 50 to 100 kPa, with the upper surface of the beam in compression. Such stress levels will produce viscous strain rates of less than $3 \times 10^{-8}$ s$^{-1}$ (Cole and Durell, 2001). Given the short time scales of these experiments, the viscous component of the creep strain is negligible. The half cycle of loading produced some damage within the ice, as evidenced by the occurrence of acoustic emission events. The purpose of the experiment was to examine the delayed elastic strain exhibited by the beams after some damage had occurred within the ice.

![Figure 1: Plot of experiment entitled beam 3.](image1.png)

The two stress regimes are referred to throughout this paper as *varying stress* and *constant stress*. The term *period* has been used to denote the time of loading during either of these stress regimes. This should not be confused with the term commonly associated with cyclic behaviour to denote the time for one cycle.

Records of three loading sequences are available for beams 3 and 4, with the loading sequence being denoted by a, b and c. Unfortunately a fourth record for a preliminary
loading of beam 4 was lost due to power failure, and beam 4a is a repeat of the lost load form. Beam dimensions are presented in Table 1. The stresses and strains are calculated at the hinge of the cantilever beam at the upper ice surface.

<table>
<thead>
<tr>
<th>Beam</th>
<th>l (m)</th>
<th>w (m)</th>
<th>h (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 3</td>
<td>11.42</td>
<td>0.96</td>
<td>1.80</td>
</tr>
<tr>
<td>Beam 4</td>
<td>10.82</td>
<td>0.95</td>
<td>1.83</td>
</tr>
</tbody>
</table>

Table 1: Delayed elastic strain beam dimensions where $l$, $w$, and $h$ denote the length, width, and height of the beams respectively.

Load was applied to the free end of the beam using a hydraulic system attached to the ice sheet with specially designed ice screws (Haskell and Robinson, 1994). Displacement information was obtained using two linear variable differential transformers, one being placed at the hinge end of the beam, the other at the free end with a lever system amplifying the movement of the beam. Stresses and strains were calculated using the equations presented by Kerr and Palmer (1972) for a cantilever with a vertical variation in properties (such as that in figure 2). Further experimental details are available in Haskell et al. (1996) since the experimental apparatus used for these experiments was the same as that used for the cyclic loading of sea ice described in that paper. To provide an indication of material damage, two acoustic transducers were used to locate the source and the relative magnitude of acoustic emissions during a portion of the varying stress period.

![Figure 2: Void fraction, salinity, temperature, and density versus depth. For salinity and temperature, the solid circles and × marks are measured values and solid lines are fitted curves.](image)

Samples were removed from adjacent ice to obtain characteristic density and salinity profiles for the ice sheet. An approximately linear temperature profile was observed through the ice. These results are displayed in figure 2, as is the calculated (from Cox and Weeks, 1982) void fractions that are presumed to be typical of the sea ice sheet, and consequently the beams tested.

**MODELLING**

An empirical approach was taken to understanding the behaviour of the beams, assuming that a standard anelastic solid (Nowick and Berry, 1972) describes the anelastic sea ice behaviour at least under short creep loading periods. A limitation of this model is that it does not account for the relaxation time distribution of the anelastic straining. Equation 1, which describes the creep relaxation period, has been derived
Figure 3: Horizontal thin section obtained at 1 m depth. The grid markings are at 10 mm spacing.

assuming an initial varying stress described by \( \sigma(t) = \sigma_0 \sin(\omega t) \) for \( 0 \leq t \leq \pi/\omega + \xi \) and \( \sigma(t) = \sigma_{\text{creep}} \) for \( t \geq \pi/\omega + \xi \). Here, \( t \) is the time, \( \sigma_0 \) is the stress amplitude, \( \omega \) is the angular loading frequency, and \( \xi \) is the small time required to attain the creep loading stress, \( \sigma_{\text{creep}} \), after crossing the stress zero value. Strain superposition is assumed, although the short duration of these experiments means the viscous strain component can be assumed insignificant.

\[
\varepsilon(t) = J_u \sigma_{\text{creep}} - \frac{\delta J \sigma_0}{1 + (\omega \tau)^2} \left[ \sin \alpha - \omega \tau \cos \alpha - \tau \exp(-\frac{\alpha}{\omega \tau}) \right] \exp \left( -\frac{t_{\text{creep}}}{\tau} \right) +
\]

\[
\sigma_{\text{creep}} \delta J \left( 1 - \exp(-\frac{t_{\text{creep}}}{\tau}) \right)
\]

\[
\varepsilon(t) = J_u \sigma_0 \sin(\omega t) + \delta J \sigma_0 \left[ \frac{\tau \omega}{1 + (\omega \tau)^2} \exp(-\frac{t}{\tau}) + \frac{\sin(\omega t) - \tau \omega \cos(\omega t)}{1 + (\tau \omega)^2} \right]
\]

In equations 1 and 2 the expression \( J_u \) represents the unrelaxed compliance, \( \delta J \) the relaxation of the compliance, \( \alpha = \pi + \xi \omega \), is a dimensionless time and \( t_{\text{creep}} \) represents the time elapsed since the stress was held constant. \( \tau \) is the relaxation time. Under cyclic stress the strain behaviour can be described by equation 2, as discussed in Gribble (2002). The model for a standard anelastic solid subjected to a zero mean stress cyclic loading strongly resembles a theoretical model describing the motion of dislocations and incorporating the relaxation time distribution (Cole, 1995; Cole et al, 1998; Cole and Durell, 2001). Drawing an analogy between these two descriptions, comparison of like terms indicates that \( \delta J \) is proportional to the dislocation density. Consequently changes in \( \delta J \) will reflect changes in the number of dislocations.

Alternatively the strain observed during a creep experiment can be partially modelled by an equation describing delayed elastic strain initially published by Sinha (1979). Any unknown parameters have been obtained by fitting to our data although, where applicable, parameters determined by Sinha have been used. For our experiments the use of Sinha’s (1979) equation requires the use of equation 2 to calculate the theoretical strain at the time of constant load initiation.

RESULTS

Figure 3 provides an example of a horizontal thin section and displays the crystal alignment characteristic of mid-depth in the sheet. The mean c-axis was approximately coincident with the long axis of the beam: that is, if pure bending is assumed, the axis of loading is approximately coincident with the crystal c-axes.
When subjected to constant stress, the ice relaxed. Since the compliance is frequency dependent it is not surprising that no parameters common to equations 1 and 2 satisfactorily describe the strain during both the constant stress period and the varying stress period. Consequently, the varying stress and the constant stress periods were modelled separately. Both the unrelaxed compliance, $J_u$, and the relaxation of the compliance, $\delta J$, obtained from the varying stress period were larger than those observed for the constant stress period.

The use of equation 1 enables the generation of parameters that can be compared to cyclic experiments on ice with similar characteristics. Figure 4 provides an example of the results obtained for a creep stress of 50 kPa after two prior loading periods, with equation 1 fitted to the data and compliances displayed in table 2. However, it can be seen (figure 5) that a better description is obtained using Sinha’s (1979) expression for the delayed elastic strain. In this case the relaxation of the compliance, $\delta J$, is found to decrease from the first to the second constant stress period applied to each beam (see table 2).

<table>
<thead>
<tr>
<th></th>
<th>3a</th>
<th>3b</th>
<th>4a</th>
<th>4b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_u$ (Pa$^{-1}$)</td>
<td>$1.9 \times 10^{-10}$</td>
<td>$0.9 \times 10^{-10}$</td>
<td>$1.7 \times 10^{-10}$</td>
<td>$1.6 \times 10^{-10}$</td>
</tr>
<tr>
<td>$\delta J$ (Pa$^{-1}$)</td>
<td>$0.4 \times 10^{-10}$</td>
<td>$0.6 \times 10^{-10}$</td>
<td>$1.0 \times 10^{-10}$</td>
<td>$0.8 \times 10^{-10}$</td>
</tr>
<tr>
<td>Sinha's equation</td>
<td>$2.9 \times 10^{-10}$</td>
<td>$2.6 \times 10^{-10}$</td>
<td>$3.4 \times 10^{-10}$</td>
<td>$2.4 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Table 2: Parameters derived from fitting the equations 1 and 2 to the stress-strain data of the experiments described in the text. Also displayed are the compliance relaxations inferred from Sinha’s model.

Unfortunately, the behaviour of the compliances in subsequent loading cycles was not consistent for either stress regime when modelled using the standard anelastic solid. The initial loading cycle produced a larger $J_u$ for beam 3 than observed in the subsequent loading. Similarly, an increase in $\delta J$ from beam 3a to 3b is not reproduced.
for beam 4. An increase in dislocation density has been observed after the application of a creep stress (Cole and Durell, 2001), and we might therefore have expected such an increase in $\delta J$. However Cole and Durell (2001) discuss the existence of a threshold stress for dislocation multiplication, and the lack of evidence of this multiplication for our low levels of creep stress (0.05 to 0.1 MPa) is consistent with this premise. Nevertheless it is interesting that the large amplitude of the varying stress (0.3 MPa) did not produce a reproducible change in compliance.

This lack of consistency may be due to our use of models that do not allow for cracking. Acoustic emissions were observed during each of the variable load cycles (see figure 6), with events of greatest magnitude occurring during the third loading. On the assumption that all events occurred at the upper ice surface, the source of these emissions was calculated using cross correlation between the signals received by two transducers situated at the surface of the ice. The source of these emissions was determined to be the failure plane, verifying that microcracking occurs near the ice-air interface. After failure, striations were observed on the fracture face of one of the beams. The repeated emission of acoustic signals from the same location, coupled with the observed striations, probably indicates that crack propagation was, at least initially, stick-slip.

**CONCLUSIONS**

Constant stress loading periods were applied to in situ cantilever beams of natural sea ice immediately after the application of variable load. The aim of these experiments was to look for trends in material behaviour that would act as a proxy for dislocation multiplication in large, in situ samples.

An empirical approach was taken to understanding the behaviour of the beams, using a standard anelastic solid as the model. Both the relaxation of the compliance and the unrelaxed compliance was found to be lower when estimated from the period of constant stress rather than from the period of varying stress. No convincing trends arose from this analysis. The use of a dislocation-based model with a proper account of the relaxation time distribution would be complicated for cantilever beam with a gradient in properties. However such a model may be necessary to provide consistent results. Further, there is evidence of cracking close to the ice-air interface and it may not be possible to ignore this in the modelling.

Evidence of stick-slip crack propagation during the variable stress loading was inferred from acoustic emissions originating from the region of final failure, with further indication provided by the striations observed on the crack face of one of the beams.

![Figure 6: Relative magnitude of acoustic emission events with respect to their position on the beam. The origin is the hinge, and positive directions are along the axis of the beam.](image-url)
ACKNOWLEDGEMENT
The authors are grateful for the considerable assistance of Dr T. Haskell, S. Gibson, D. Cochrane of Industrial Research Ltd, and J. Downer of Otago University; for the logistical support of Antarctica New Zealand; and for the financial support of the New Zealand Foundation for Research, Science and Technology. Dr D. Cole of Cold Regions Research and Engineering Laboratory, USA is thanked for his comments.

REFERENCES