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Experiments on Anisotropic and Rate Sensitive Strain Ratio and Modulus of Columnar-Grained Ice

by N.K. Sinha

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RÉSUMÉ

On a étudié les caractéristiques d'anisotropie et de sensibilité au taux du rapport de la déformation latérale à la déformation axiale, ainsi que le module effectif de sensibilité au taux pour de la glace d'eau douce et de la glace de mer à grains prismatiques de l'Arctique. Des essais ont été réalisés à -20°C dans des conditions de non-microfissuration sous des charges uniaxiales (perpendiculaires à la longueur des grains) dans la plage de taux de contrainte de $1 \times 10^{-3} \text{ MN}\cdot\text{m}^{-2} \text{ s}^{-1}$ à $1 \times 10^2 \text{ MN}\cdot\text{m}^{-2} \text{ s}^{-1}$, soit une variation équivalente du taux de déformation de $1 \times 10^{-7} \text{ s}^{-1}$ à $1 \times 10^{-2} \text{ s}^{-1}$. Dans le cas d'augmentation du taux de contrainte, le rapport est passé d'environ 0,2 à 0,3 dans le plan parallèle aux prismes, tandis qu'il est passé d'environ 0,65 à 0,3 dans le plan normal. On a utilisé un appareil d'essai fonctionnant en boucle fermée associé à des jauges à feuille mince montées directement sur l'éprouvette. Pour évaluer la justesse des jauges à feuille mince, on s'est servi d'une jauge de déplacement clipsable.

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EXPERIMENTS ON ANISOTROPIC AND RATE SENSITIVE STRAIN RATIO AND MODULUS OF COLUMNAR-GRAINED ICE

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ABSTRACT

Anisotropic and rate sensitive characteristics of the ratio of lateral strain to axial strain in addition to the rate sensitive effective modulus for columnar-grained freshwater ice and sea ice from the Arctic, have been investigated. Tests were carried out at -20°C , for conditions of no microcracking under uniaxial loads (normal to the length of the grains) in the stress rate range of $1 \times 10^{-3} \text{ MN}\cdot\text{m}^{-2}\text{s}^{-1}$ to $1 \times 10^2 \text{ MN}\cdot\text{m}^{-2} \text{ s}^{-1}$ or an equivalent strain rate range of $1 \times 10^{-7} \text{ s}^{-1}$ to $1 \times 10^{-2} \text{ s}^{-1}$. With increase in stress rate, the ratio increased from about 0.2 to 0.3 in the plane parallel to the columns whereas it decreased from about 0.65 to 0.3 in the plane normal to the columns. A closed-loop controlled test system in association with foil gauges, mounted directly on the specimen, was used. A clipon displacement gauge was used to evaluate the accuracy of the foil gauges.

INTRODUCTION

A measure of three dimensional deformation in a material is given by the Poisson's ratio. This is defined as the ratio of the lateral strain to the longitudinal strain in a homogeneous material for a uniaxial elastic loading condition. It is a manifestation of the factors that play a central role in three dimensional constitutive formulations for materials including ice.

Poisson's ratio in the range 0.31 to 0.37 for freshwater ice was tabulated some years ago by Gold (1). Lin'Kov's (2) in-situ seismic determinations for ice ranged from 0.36 to 0.39. Both Peschansky (3) and Langleben and Pounder (4) reported dynamic values of 0.29 for sea ice. There is little discrepancy in the dynamically obtained data, irrespective of the ice type. Statically determined values, on the other hand, show great variability in the results reported by different investigators.

For transversely isotropic, columnar-grained, freshwater ice loaded perpendicular to the columns, Gold's static experiments indicated values in the

range of 0.31 to 0.54 for the ratio of transverse to longitudinal strains (1). Corresponding to this, Wang (5) reported a range of 0.8 to 1.2 for sea ice, however, he obtained values in the range of 0 to 0.2 when the load was applied in the direction parallel to the length of the columns. Saeki et al (6) also studied deformation along the length of the columns in sea ice but reported a rather complex response, the ratio increasing from 0.02 to 0.48 with increase in stress rate from 0.01 to $0.5 \text{ MN}\cdot\text{m}^{-2} \text{ s}^{-1}$. In the same stress rate range and for the direction normal to the columns at -5°C , Murat and Lainey (7) reported the ratio decreasing from 0.48 to 0.38. Moreover Saeki et al (6) reported that the ratio increased with decrease in temperature whereas an opposite temperature effect was observed by Murat and Lainey (7). While examining the rate sensitivity of the compressive strength of congealed frazil sea ice, Sinha (8) observed that the strain ratio depends not only on rate of loading but also on stress or strain level and the state of damage (microcracking) of the material.

The variability observed in the statically determined values of the ratio between the lateral strain and the axial strain indicates the complex mechanical response of ice. The complexities arise primarily because working temperatures with ice are very close to its melting point, T_m , and are usually greater than $0.9 T_m$ where the temperature is given in Kelvin scale. At high temperatures, $> 0.4 T_m$, polycrystalline deformation is greatly affected by intergranular sliding mechanisms and grain boundary embrittlement processes in addition to the intergranular deformation due to the elastic distortion of the lattice and mobility of lattice dislocations. Constitutive equations for ice therefore must give consideration to these mechanisms. A micromechanically based rheological model was proposed (9) to show that the material response, however complex, is reasonably predictable. This model also pointed out the dire need for reliable experimental data on three dimensional deformation of ice with known fabric, texture, grain size and damage state, and obtained

under well described experimental conditions such as temperature, stress and stress rate, strain and strain history. The present paper describes an effort towards this goal and presents some results on strain ratio and effective modulus of columnar-grained fresh- water and sea ice over a wide (over five orders of magnitude) range of loading rates for conditions with no detectable microcracking activities. The maximum stress was kept below that required to form microcracks.

ICE CHARACTERISTICS AND SPECIMEN PREPARATION

Investigations were primarily carried out on laboratory made transversely isotropic columnar-grained freshwater, S-2 type ice, with load applied in the plane of isotropy, that is, at right angles to the long axis of the columns. The ice was transparent with no air bubbles and had a density of $917.8 \text{ Kg}\cdot\text{m}^{-3}$, at -10°C , which was the same as that of single crystal density. The cross sectional grain sizes varied in the range of 2 to 3 mm. Grain structure in the mid-plane of one of the specimen (L83) tested is shown in Figure 1. Note the uniformity in the cross sectional grain sizes through the entire 250 mm long specimen. Details of grains are given in Figure 2. In this thin section, 1498 grains were counted in an area of $90 \text{ mm} \times 100 \text{ mm}$, giving an average grain area, a , of 6.01 mm^2 which gives an equivalent grain diameter, d ($d = 2\sqrt{a/\pi}$), of 2.77 mm. The corresponding average grain size obtained from the intercept method, using ten randomly selected lines over the same observation area, was 2.33 mm. This is 16% lower than that given by the first method. If all the grains are assumed to be square in cross section, then 6.01 mm^2 area is equivalent to a square with sides of 2.4 mm which agrees well with the size given by the intercept method.

Experiments were performed inside a cold room kept at $-20^\circ\text{C} \pm 0.1^\circ\text{C}$ on specimens with final dimensions of $50 \text{ mm} \times 100 \text{ mm} \times 250 \text{ mm}$, having the $100 \text{ mm} \times 250 \text{ mm}$ faces at right angles to the length of the columnar-grains. They were machined with a milling machine and a lathe inside an adjacent cold room at -15°C . Cutter marks on the surfaces were removed with fine sandpaper on a flat granite block. Final finish was given by wiping with a tissue slightly moistened with alcohol. The samples were then stored at -20°C within the experimental cold room in individual bags until they were tested within a few days. It should be pointed out here that for the chosen orientation of the grains, rectangular geometry of the specimen is more compatible than the cylindrical specimen. Though obvious, this fact is overlooked by most investigators.

A few tests were also carried out at -20°C on a specimen of first-year columnar-grained sea ice with preferred c-axis orientation in the horizontal plane (S-3 type). The specimen had the final dimensions of $100 \text{ mm} \times 100 \text{ mm} \times 250 \text{ mm}$ with the long dimension parallel to the preferred c-axis orientation in the plane normal to the columns. This sample was made from an ice block sampled in May 1986 from Admiralty Inlet near Baffin Island. The salinity (5°oo) and microstructure of this ice was similar to that reported in Nakawo and Sinha (12) for sea ice from Eclipse Sound, Baffin Island.

FIGURE 1. Horizontal (a) and vertical (b) thin sections of test specimen L83, made after completing the test series.

FIGURE 2. Mid-plane thin section of test specimen L83 exhibiting no grain-boundary distortions, small angle boundaries and cracks.

TEST METHODS

A commercial closed-loop, servohydraulic test machine, with a design load capacity of 1 MN for the frame (MTS) and situated inside the cold room near an observation window, was used. The controls, pumps, and recording systems were kept outside the cold room. The loading train consisted of two 152 mm diameter compression platens (one at the top and one at the bottom of the specimen), a spherical seat, a 250 kN capacity load cell and a 250 kN capacity actuator. The lower platen was attached to the actuator and the upper platen reacted against the load frame through the spherical seat and the load cell. The lower platen was specially designed with a liquid circulation system to maintain it at the cold room air temperature and thereby prevent it from any warming effect from the oil in the actuator. Compressive

loads were applied parallel to the long axis of the specimens and hence normal to the length of the columnar grain (See Figure 3). Axial load rate and hence stress rate was maintained constant during a test by the feedback system. Tests were conducted over a wide range of stress rates from 1×10^{-3} $\text{MN}\cdot\text{m}^{-2} \text{ s}^{-1}$ to 1.25×10^2 $\text{MN}\cdot\text{m}^{-2} \text{ s}^{-1}$.

Earlier experiments (10), carried out on columnar-grained ice, showed that microcracks, about the size of the grain facets, form when the stress exceeds about $1.2 \text{ MN}\cdot\text{m}^{-2}$ for stress rates greater than $1 \times 10^{-3} \text{ MN}\cdot\text{m}^{-2} \text{ s}^{-1}$. It was decided to keep the peak stress, σ_{10} , well below cracking level to avoid any effects due to the cracks. The system was programmed to apply the load up to an equivalent stress level of about $0.75 \text{ MN}\cdot\text{m}^{-2}$ and then to unload rapidly to zero stress. A long incubation time was given after each tests during which the specimen strains were monitored in order to be certain that the specimen was at an equilibrium state before loading again. Stress rates were chosen randomly to avoid any effect due to microstructural change that could occur during the tests and systematically influence the results. To avoid specimen to specimen variation, it was planned to do as many tests as possible on the same specimen. However, an accident occurred during handling and the first test specimen (designated as L81), after several tests, broke into small pieces when it slipped and dropped on the floor. A second specimen (L83) was then used. Tests were terminated on this specimen after several days of testing when two foil gauges came off the specimen during storage over a weekend. This specimen showed no cracks after all the tests. Microstructural examination of this specimen was then made and are shown in Figures 1 and 2. Tests on the sea ice specimen (L82) were terminated when it was damaged during handling.

For the chosen maximum stress level of $0.75 \text{ MN}\cdot\text{m}^{-2}$, the total loading time is 0.0075 seconds at the intended maximum stress rate of $1 \times 10^2 \text{ MN}\cdot\text{m}^{-2} \text{ s}^{-1}$. In order to record a reasonably continuous history of loading, there should at least be 100 data points during the loading phase. This means that data should be collected at a rate of $1.3 \times 10^4 \text{ s}^{-1}$. Availability of a six channel transient recorder, capable of recording all the channels simultaneously up to $2 \times 10^6 \text{ s}^{-1}$ proved ideal. It was imperative that the axial load and the deformation of essentially the entire specimen, given by the 200 mm long MTS displacement gauge (Figure 3) mounted directly on the specimen, be recorded. This procedure allowed only four channels to be used for other measurements. All the electronic equipment was kept outside the cold room.

Four commercially available constantan alloy grid foil strain gauges, with active gauge length of 12 mm, were mounted on the specimen at the test temperature of -20°C as shown in Figure 3 following the method described later. Longer gauges, though preferable, were not used because of difficulties of mounting them uniformly. These gauges provided independent measurements of both axial and lateral strains on two surfaces, one parallel to the length of the columnar grains and the other normal to it. The gauges were excited by a commercial signal conditioner and the gauge outputs were amplified before recording. An excitation voltage of 7 volts, for the 350-ohm strain gauges, was found satisfactory without showing any adverse effect due to heating.

Experiments were conducted with two types of foil gauges. No differences were noted in their

1, 2, 3, 4 - FOIL GAUGES
5 - DISPLACEMENT GAUGE
⊙ - ANCHOR ICE

FIGURE 3
EXPERIMENTAL ARRANGEMENT FOR THE GAUGES
ON A SPECIMEN

response. Both were integral lead type with a constantan alloy grid and active gauge length of 12 mm. The gauge length is large enough to cover several grains, yet small enough to freeze uniformly on the specimen surface. Two types of "off the shelf" Micro Measurement Inc. gauges were used: (model number CEA-06-500UW-350) which were completely encapsulated in a flexible polyimide coating, and (model number EA-06-500-BL350W), which were open faced with only a polyimide backing. In both cases the lead wires were cleaned and carefully soldered onto the tabs. The active gauge portion of the open faced gauges was then waterproofed by coating first with a thin layer of Dow Corning 3140 RTV followed by a thin layer of Micro Measurements nitrile rubber coating, model M. The open ends of the lead wires and the tabs were also waterproofed for both types of gauges by the two layer technique. The encapsulated gauges were preferred and used in the main part of this study.

Several methods, including that described by Murat (11), were tried inside the experimental cold room for mounting the strain gauges on the specimen surfaces. The simplest and yet satisfactory method may be described as follows. After selecting the desired location and positioning the gauges, about 10 mm of the lead wires, at a distance of about 50 mm from the active portion, was frozen to the specimen using an eye dropper and two or three drops of water from a container maintained at about 0°C . These drops acted as the anchors and isolated the gauges and the joints from any pulling action of the lead wires during further handling. Moreover, they also protected the gauges from any vibrational strain induced by the lead wires that were often seen to vibrate during the experiment when the load was applied suddenly for the rapid tests or due to the air circulation inside the cold room during the slow tests. With the lead wires secured solidly at the

anchor, the gauge was lifted slightly, and two drops of cold water were applied to the area where the gauge was to be mounted. The gauge was then quickly and accurately pressed into place, using a flat rubber pad, and held until freezing of the water was complete. The pad was then removed. After inspection, to ensure overall freezing and flatness, a thin layer of water was placed over the gauge and a small portion of the lead wires, for protection against sublimation. Needless to say, a great deal of practice was required before the gauges could be properly mounted. The common problem was the partial freezing and wrinkling of the gauges. It should be mentioned here that the use of water at about freezing point was found necessary to avoid microcracks on the specimen surface due to thermal stress. Examination under a microscope revealed that even one drop of water at 20°C (usual warm room temperature) damages the ice surface at -20°C.

RESULTS AND ANALYSIS

Two questions were examined during the tests (a) how well the machine performed and whether stress rates were maintained constant and (b) how well the deformations were measured.

For axial stress rates from $1 \times 10^{-3} \text{ MN} \cdot \text{m}^{-2} \text{ s}^{-1}$ to about $2 \times 10^1 \text{ MN} \cdot \text{m}^{-2} \text{ s}^{-1}$, the system was found capable of loading the specimen at the intended constant stress rates and of unloading it

FIGURE 4
STRESS AND STRAIN HISTORIES FOR A SLOW TEST

rapidly after reaching the peak load σ_{1p} , as may be seen in Figures (4) and (5). Although the stress rate was constant during the major part of the loading cycle, the lack of constancy in the load rate during the beginning and the end of the cycle, was evident at rates, $\dot{\sigma}_1 > 20 \text{ MN} \cdot \text{m}^{-2} \text{ s}^{-1}$ (Figure 6). These were rather rapid tests and involved load rise time, t_r , less than 40 milliseconds or frequency, $f_r (= 1/2 t_r)$ greater than about 10 Hz. An average stress rate, $\dot{\sigma}_1 = \sigma_{1p}/t_r$, was thought to be appropriate for describing the loading rates at these high rates.

Figure 4 shows that the axial strains measured by the foil gauges, 1 and 3, agree well with that given by the displacement gauge 5. Consideration is given to the fact that the strain levels were extremely small and that even a slight rounding of the edges of the load bearing end surfaces (50 mm $\times$ 100 mm) would significantly affect the surface strain of the side surfaces. It should be noted that both axial and lateral strains increased linearly with time giving indications of a linear dependence of strain on stress. Time dependence of the strain recovery and total recovery after unloading were indicated by both the foil gauges and the displacement gauge; permanent strains, if any, were therefore beyond the accuracy of the measurement. This type of total recovery was

FIGURE 5
STRESS AND STRAIN HISTORIES FOR A MEDIUM RATE TEST

observed in all the loading cycles. Total accumulated permanent strain in a specimen at the end of all the tests was less than about 3×10^{-5} and therefore negligible. Evidence of little permanent change in the specimen L83, after 23 tests, is provided in Figure 2. Note that the

FIGURE 6
STRESS AND STRAIN HISTORIES FOR A RAPID TEST

grain boundaries have no irregularities and no small angle boundaries can be seen in any grains.

A new phenomenon in the response of the foil gauges was observed as the rate of loading increased. The gauges recorded not only lower axial strains, with increase in stress rate, than that given by the displacement gauge but also showed a significantly damped response (Figures 5 and 6). The output from the displacement gauge was noted to be in phase with the stress at all stress rates but the corresponding peak response in the foil gauges occurred after a significant lapse of time. Results summarized in Figure 7 for three sets of measurements show that (a) phase lag in the foil gauges occurs at about $\dot{\sigma} > 3 \text{ MN} \cdot \text{m}^{-2} \text{ s}^{-1}$ and (b) foil gauges could give acceptable strain data for $\dot{\sigma} < 0.1 \text{ MN} \cdot \text{m}^{-2} \text{ s}^{-1}$.

The generalized Hooke's law relating strain, ϵ_i , to stress σ_j is given by

$$\epsilon_i = S_{ij} \sigma_j ; i, j = 1, 2 \dots 6 \quad (1)$$

where S_{ij} denotes the compliances. For columnar-grained ice with the assumption of x_1 and x_2 axes in the horizontal plane or the plane of the ice cover (also the plane of isotropy for S-2 ice) and x_3 along the longitudinal axis and hence the growth direction of the columnar grains (see Fig. 3), the usual concern is with the compliances S_{11} , S_{22} and S_{33} ; the principal stresses are usually in x_1 and x_2 directions for most engineering situations. In case of uniaxial stress, σ_1 ,

FIGURE 7
STRESS RATE DEPENDENCE OF THE RESPONSE OF THE FOIL GAUGES

applied along x_1 , the lateral compliances of concern are S_{21} and S_{31} , and the major strain ratios are given by

$$\mu_{21} = -S_{21} / S_{11} = -\epsilon_2 / \epsilon_1$$

and (2)

$$\mu_{31} = -S_{31} / S_{11} = -\epsilon_3 / \epsilon_1$$

The histories of ϵ_2 and ϵ_3 for the test corresponding to Figure 4 are presented in Figure 8 which shows that the lateral strains in the plane of isotropy and normal to it differed significantly from each other but both maintained a linear relationship with the axial strain. Similar observations were made in all the tests including those on S-3 sea ice. Thus the strain ratios do

FIGURE 8
DEPENDENCE OF LATERAL STRAIN ON AXIAL STRAIN RECORDED BY THE FOIL GAUGES

not depend, at least not significantly, on the stress or strain level within the experimental ranges investigated. Dependence of μ_{21} and μ_{31} on stress rates, using the peak strains recorded by the two pairs of foil gauges are presented in Figure 9. A continuity in the rate sensitivity of the strain ratios is evident here. Note that this continuity extends from low rates at which foil gauges are reliable to high rates where their response is questionable. The two ratios approaching a common dynamic value at high rates are also physically understandable. This observation indicates that the damping effect on the foil gauges affected the total output without influencing their response relative to each other. Since the axial and lateral strains on the two orthogonal surfaces were measured separately using pairs of foil gauges, the reliability in the measurement of strain ratios with these gauges could perhaps be extended significantly to higher stress rates than the limiting rate of about $0.1 \text{ MN}\cdot\text{m}^{-2} \text{ s}^{-1}$ discussed earlier. Independent tests are required to verify this point.

Figures 4-6 show that the strain rates were more-or less constant during loading in all the tests. The test results therefore could also be presented in terms of constant strain rates such as shown in Figure 10 in which the strain rates represent those measured by the 200 mm gauge length displacement gauge (No. 5). A systematic variation in μ_{21} and μ_{31} is again noted.

Stress rate dependence of the effective modulus, $E_{\sigma} = \sigma_{1p} / \epsilon_{1p}$, where ϵ_{1p} is measured by the displacement gauge, is presented in Figure 11. A complementary illustration would be Figure 12 exhibiting the strain rate dependence of the effective modulus.

DISCUSSION

Complete strain recovery after unloading demonstrates clearly the elastic nature of the deformation processes involved. The time dependent recovery indicates that at least two processes are involved for the loading conditions used. This type of response was termed as "elasto-delayed elastic" (ede) by this author (9). The "regime" of "ede" response is essentially limited to transient stage of polycrystalline behaviour when the strains are small and the deformation is homogeneous. In this regime, grain-boundary shear in freshwater ice or interplatelet sliding in sea ice, contributes significantly to the total strain in addition to the intragranular elastic strain. These processes influence both effective elastic modulus and strain ratio unless very high frequency loadings are involved.

Intragranular elastic strain, due to the distortion of the lattice, involves volumetric change and a measure of this change is given by "Poisson's" ratio. Intergranular grain-boundary sliding or delayed elastic process, in the absence of any cracking activity, would be isotropic and would involve no appreciable volumetric change (9), for all practical purposes. Thus in the ede regime, strain ratio depends significantly on the degree of contribution of delayed elastic strain to the total strain. A theory has been proposed for isotropic polycrystalline material and discussed in (9). This theory has been extended to predict the anisotropic behaviour of columnar-grained ice but will be presented elsewhere because of the space limitations here. However, the solid lines in

FIGURE 9
STRESS RATE DEPENDENCE OF STRAIN RATIO

FIGURE 10
STRAIN RATE DEPENDENCE OF STRAIN RATIO

Figures 9 and 10, obtained using this theory for columnar-grained ice of average cross-sectional grain diameter of 2.5 mm, grain length to grain diameter ratio (aspect ratio) of 20 and material constants given in (9, 13) give indications that material response, however complex, is reasonably predictable. The theory also clarifies some of the variabilities in statically determined strain ratios presented earlier in the introduction of this paper. Wang (5) reported values of 0.8 to 1.2 for μ_{21} and Saeki et al's (6) observations on μ_{31} , increasing from 0.02 to 0.48 with stress rate, were certainly due to the effect of microcracking activities as the stress levels involved in these experiments were high (up to $6 \text{ MN}\cdot\text{m}^{-2}$).

Direct experimental observations on the dependence of the effective modulus on strain rate, for conditions of no cracking, are available up to a strain rate of $4 \times 10^{-4} \text{ s}^{-1}$ as can be seen in Traetteberg et al, 1975 (14). The present results

FIGURE 11
STRESS RATE DEPENDENCE OF EFFECTIVE MODULUS

FIGURE 12
STRAIN RATE DEPENDENCE OF EFFECTIVE MODULUS

(Figures 11, 12), therefore, extend the availability of experimental data to a significantly higher loading rate. The solid lines in Figure 11 show the results calculated for effective modulus, $E_\sigma = \sigma_{lp} / \epsilon_{lp}$ using the theory and material constants described in (13) for ice with grain diameter of 2.5 mm. The same results are presented in Figure 12 as a function of the calculated average strain rate. Again, it can be seen that the experimental results are reasonably predictable.

CONCLUSIONS

For stress rates in the range of 1×10^{-3} to $1.2 \times 10^2 \text{ MN}\cdot\text{m}^{-2} \text{ s}^{-1}$ or strain rates in the range of 1×10^{-7} to $1 \times 10^{-2} \text{ s}^{-1}$, for stress levels up to $0.75 \text{ MN}\cdot\text{m}^{-2}$ or strain levels up to 1.5×10^{-4} at a temperature of -20°C and for loads applied in the

plane normal to the length of the columns, the lateral strains in columnar-grained ice maintain a linear relationship with longitudinal or axial strains during loading in the plane parallel to the length of the columns as well as the other normal to it. The lateral strain, normal to the length of the columnar grains, is about 3 times larger than that parallel to the columns at a stress rate of $1 \times 10^{-3} \text{ MN}\cdot\text{m}^{-2} \text{ s}^{-1}$ or strain rate of $1 \times 10^{-7} \text{ s}^{-1}$. The strain ratio, μ_{21} , in the loading plane, decreases monotonically from about 0.7 at a strain rate of $1 \times 10^{-7} \text{ s}^{-1}$ to about 0.3 at $1 \times 10^{-2} \text{ s}^{-1}$. However, the strain ratio, μ_{31} , corresponding to the plane parallel to the length of the columns, increases from about 0.2 to about 0.3 for the same range of loading rates. Both freshwater ice and sea ice shows similar anisotropic response.

Since the response of the foil gauges is poor at the high end of the loading rates investigated, the data obtained on the strain ratios in the dynamic loading ranges, though apparently reasonable, are of questionable value. Independent tests are required to verify these measurements.

The stress/strain ratio or the effective modulus increases monotonically from $4 \text{ GN}\cdot\text{m}^{-2}$ at a strain rate of $1 \times 10^{-7} \text{ s}^{-1}$ to about $9.5 \text{ GN}\cdot\text{m}^{-2}$ at $1 \times 10^{-2} \text{ s}^{-1}$. These results fill the gap in the data available in the literature, in the load frequency range of 3 to 100 Hz and are in agreement with the theoretical predictions made earlier.

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