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Ice: A Future Structural Material of the North?

La glace: un matériau futur de construction pour le Nord

Eis: ein zukünftiger Baustoff für den Norden?

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SUMMARY
A nonlinear 3-dimensional constitutive model describing the behaviour of ice, including its three creep stages, its strain softening at constant strain rate and its tensile brittleness, is briefly reviewed. The properties of reinforced ice, with spun fibreglass yarn as reinforcement, are sketched and a possible use for it in constructing reinforced ice domes indicated.

RÉSUMÉ
Cette contribution décrit une loi tridimensionnelle et non-linéaire du comportement de la glace, en incluant les trois phases de fluage, la relaxation sous l'effet d'un raccourcissement à vitesse constante et la fragilité en traction. Sont également décrites les caractéristiques de la glace armée de fibres de verre et une application pour la construction de coques en glace.

ZUSAMMENFASSUNG
Ein kurzer Überblick über ein nichtlineares dreidimensionales Stoffgesetz für Eis wird gegeben, der dessen Materialeigenschaften, einschließlich der drei Kriechenphasen, des Dehnungserweichens unter konstanter Dehngeschwindigkeit und der Zugsprödigkeit beschreibt. Die Eigenschaften von mit Glasfaserzwirn bewehrtem Eis werden beschrieben und eine mögliche Anwendung für Eisschalenbau aufgezeigt.

1. INTRODUCTION

The demand for improved performance characteristics of common structural materials under increasingly stringent/hostile environments has resulted in research and development work leading to completely new structural materials or to significant improvements in their mechanical, chemical, electrical or transmissivity properties. For example, mechanical alloys have been produced which have ultimate/yield strength characteristics far superior to those produced by traditional thermal/chemical processes. Fibre reinforced plastics and resins, new and improved ceramics and various other new or improved materials are increasingly used in the latest products of microelectronics and other branches of technology.

The need for more economical and improved materials also forces us to look at traditional materials available abundantly in nature to see whether they can be used and/or their use increased. One abundant material in cold regions is ice which has been studied extensively by engineers and physicists, establishing its crystal structure and its physical properties [1-3]. Less attention has been paid to its mechanical/strength characteristics and its behavioural features which affect its use as a structural material [7,8].

This paper briefly sketches a constitutive model which describes the characteristic features of ice behaviour [4-6], including the three-stage creep under constant stress, strain-softening under constant strain-rate, and its brittleness. Stress-strain nonlinearities and hereditary effects are also included. Next properties of reinforced ice are briefly reviewed. The reinforcing is spun fibreglass yarn. As a possible application of ice as a structural material, the construction of reinforced ice domes, using a novel construction/erection technique whereby water is sprayed onto an inflatable [7-9], is sketched.

The aim of the paper, thus, is to give a brief review of information available on this abundant and potentially important material thereby, hopefully, fostering further research and bringing about its acceptance as a common structural material with an accompanying substantial increase in its use. Is this a 'challenge' for structural engineers during the last decade of this millennium and the first years of the 21st century?

2. A UNIFIED CONSTITUTIVE MODEL FOR ICE

From a structural viewpoint ice exhibits the full range of features characteristic of structural materials, the most important of which are elasticity, viscosity and brittleness. Experiments indicate that the effects of viscosity manifest themselves in strain hardening during the primary creep stage, strain softening at advanced stages of deformation and partial recovery after unloading. A well-known property of ice is its brittleness in tension leading to stress-anisotropy at advanced stages of deformation. The constitutive model sketched here simulates all of these significant features of ice behaviour. It is of the hereditary type and is chosen with two primary objectives in mind: 1. The number of material parameters contained in the model must be 'reasonable' and 'determinable' from experimental data; 2. A resulting theory using this constitutive model must be 'tractable' and 'calculable' by means of some reasonable effort.

In view of these objectives each of the material parameters used in our constitutive law should have specific physical meaning. The stress-anisotropy/brittleness feature is handled by introducing a damage function which is assumed to be tension stress dependent and is intended to simulate internal microcracking. The Volterra-type integrals are treated approximately by means of a nonlinear Kelvin body with some imposed similarity conditions [6].

On the basis of experimental data from tests on 'laboratory' ice, the following general characteristics are assumed in modelling ice behaviour: 1. A linear instantaneous response, typical of the behaviour of linearly elastic isotropic materials. 2. Material isotropy, extending and being acceptable for some range into the viscous deformation, including the primary and secondary creep stages. 3. Isotropy terminating with the appearance of microcracking at some advanced stage of deformation, a stage which can be related to the start of the accelerating/third phase of creep. 4. The accelerating creep stage for compression may be rather long while for tension this stage may disappear almost completely, leading to very rapid fracture. All of these features are indicated schematically on Figure 1 for uniaxial tests in tension and compression.

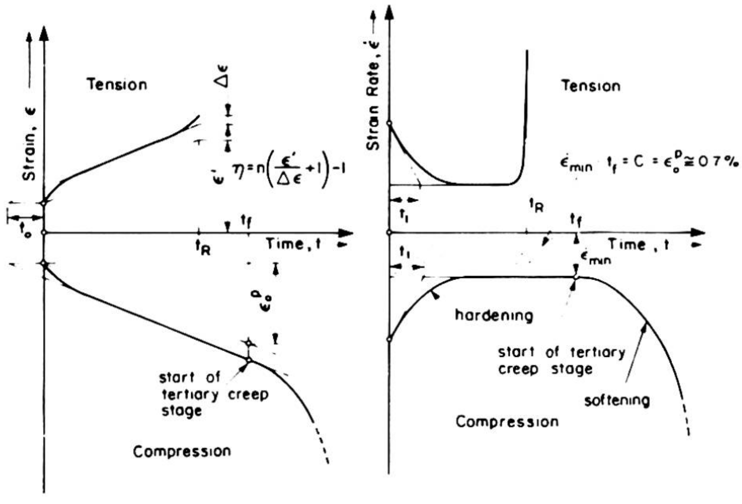


Fig 1 Some Characteristic Features for Tension and Compression Creep Test Curves of Ice

2.1 The Constitutive Model

Starting from a general uniaxial strain/stress relation for time-dependent materials, a three-dimensional nonlinear constitutive law, simulating the above-listed characteristic features of ice, was derived in [6], expressing the strain rate, $\dot\varepsilon_{ij}$ in the form

$$\dot\varepsilon_{ij}(t) = \dot\varepsilon^e_{ij} + \dot\varepsilon^r_{ij} + \dot\varepsilon^p_{ij} \qquad (1)$$

where the elastic, reversible and permanent viscous strain rate portions $\dot\varepsilon^e_{ij}$, $\dot\varepsilon^r_{ij}$, $\dot\varepsilon^p_{ij}$ are given, respectively, by

$$\dot\varepsilon^e_{ij} = \frac{1}{E_o}[(1+\mu)\dot\sigma_{ij} - \mu\dot\sigma_{kk}\delta_{ij}]; \quad \dot\varepsilon^p_{ij} = \frac{1}{\nu_2}\left[\frac{\tilde\sigma_{ij}(t)}{1-\omega(t)}\right]^n \cdot \left\{1+\alpha\left[\frac{\varepsilon^p_{ef}(t)}{\varepsilon^p_o} - 1\right]^a\right\} \qquad (2a,b)$$

$$\dot\varepsilon^r_{ij} = \frac{1}{\nu_1}\frac{d}{dt}\int_0^t [\tilde\sigma_{ij}(\tau)]^n . j(t-\tau)d\tau; \quad \frac{dj}{dt} < 0; \quad j(0) = 1; \quad j(t)\Big|_{t\to\infty}\to 0 \qquad (2c)$$

and where E_o and μ are Young's modulus and Poisson's ratio, respectively, n, ν_1, ν_2 and the function $j(t)$ are used in describing the first two stages of creep, with the latter (function) being (approximately) characterized by the stress-independent parameters t_o and t_1 (see Fig. 1) while α, a and ε^p_o are material constants chosen to help define the tertiary compressive creep phase. The 'effective' viscous stress, $\tilde\sigma_{ij}$, is given in terms of the stress deviator, s_{ij} and its second invariant S, by

$$\tilde\sigma_{ij} = s_{ij}\left\{\frac{3}{2}\left|\frac{S}{s_{ij}}\right|^{n-1}\right\}^{1/n}; \quad s_{ij} = \sigma_{ij} - \frac{1}{3}\sigma_{kk}\delta_{ij}; \quad S^2 = \frac{3}{2}s_{ij}s_{ij} \qquad (4ab,c)$$

where δ_{ij} denotes the Kronecker delta and where $\varepsilon^p_{ef}(t) = [\frac{2}{3}\varepsilon^p_{ij}\ \varepsilon^p_{ij}]^{\frac{1}{2}}$.

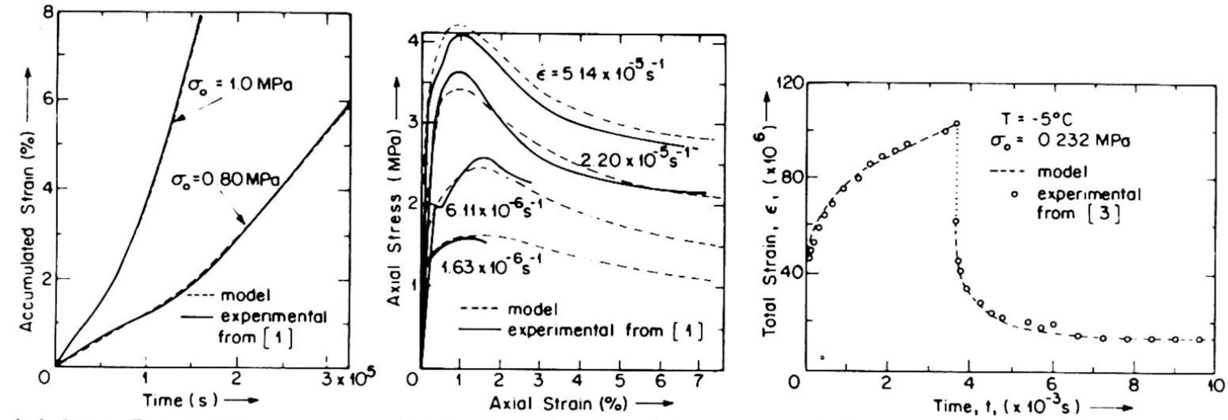
The damage function, $\omega(t)$, is assumed to be tensile stress dependent so that the damage rate, $\dot\omega(t)$, assumed to be a function of the 'true' stress and the current damage, can be written in the form [6]

$$\dot\omega(t) = K\left|\frac{\sigma_{max}}{1-\omega}\right|^\Gamma \cdot \frac{1}{(1-\omega)^{\eta-\Gamma}} \qquad (5)$$

where K, Γ and η are three material parameters required in defining the tensile tertiary creep stage and where σ_{max} denotes the largest tensile stress and is assumed to be zero for compression. From Fig. 1 we note that η represents the ductility of ice at/near brittle failure. For $\sigma_{max} = \sigma_o$ = const, one can integrate Equ. (5) to obtain an expression involving the rupture time, t_R, (for which $\omega = 1$) in the form $(1+\eta)Kt_R\sigma_o^{\Gamma} = 1$, which allows determination of K and Γ from a log-log plot of t_R vs σ_{max}.

Note that this constitutive law was derived by assuming, 1) the viscous nonlinearity of the material in the form of a power law (Norton's law), defined by n; 2. microcracking/anisotropy affects only the permanent and not the reversible viscous strain rate. Note also that $\dot{\varepsilon}^e_{ij}$ and $\dot{\varepsilon}^p_{ij}$ are functions of the current stress rate, $\dot{\sigma}_{ij}$, and the current stress, σ_{ij}, respectively, while $\dot{\varepsilon}^r_{ij}$ is a function of the entire stress history. Equ. (1) can be obtained, formally, by postulating the existence of a scalar functional, $P(\sigma_{ij})$, with the physical meaning of a complementary power potential [6].

Reducing our constitutive law, Equ. (1), to the uniaxial case and using numerical values for the thirteen material parameters, as given in [6], we simulated the behaviour of ice under constant stress (creep), under constant strain rates and under loading/unloading conditions and compared our predictions with experimental data, as shown on Fig. 2. As one can see, this constitutive model



(a) Creep Test Results (b) Constant Strain Rate Data (c.) Creep and Recovery Data

Fig. 2 Comparison of Model Predictions with Experimental Data for Ice

simulates the characteristic behavioural features of ice, including creep at advanced stages of deformation, strain softening and recovery upon unloading, quite well. The model can also be used in formulating a von Kármán-type nonlinearly viscous plate theory which was used to predict the time-deflection-strain-stress behaviour of a long ice plate undergoing cylindrical bending and subjected to uniform compressive stresses applied along its longitudinal edges [6] (see Fig. 3).

3. REINFORCED ICE AND A POSSIBLE USE

If ice is to become a widely used structural material its tensile and flexural strength, like that of concrete, will have to be enhanced by suitable/economical reinforcement. Unfortunately, there is no commonly known/adopted reinforcing material for ice at the present time. When we first thought of reinforcing ice [7-9] various materials, including wire and nylon string were considered. In the end, we decided to use spun fibreglass yarn (#ECG 150-4/8) with an average diameter of 0.87 mm and a specified average breaking strength of 570 N. This material was used in all reinforced ice samples and in the construction of reinforced ice domes. Results from tensile tests on 3 pieces of spun fibreglass yarn are shown in Fig. 4a. The load-strain curve is initially very flat but becomes linear at higher loads with a modulus of elasticity (approximately) of 42 GPa when the nominal diameter of the yarn is used in calculating stress.

The yarn was used to reinforce tensile test specimen formed in a specially fabricated mold. The test series included 15 specimens with different amounts

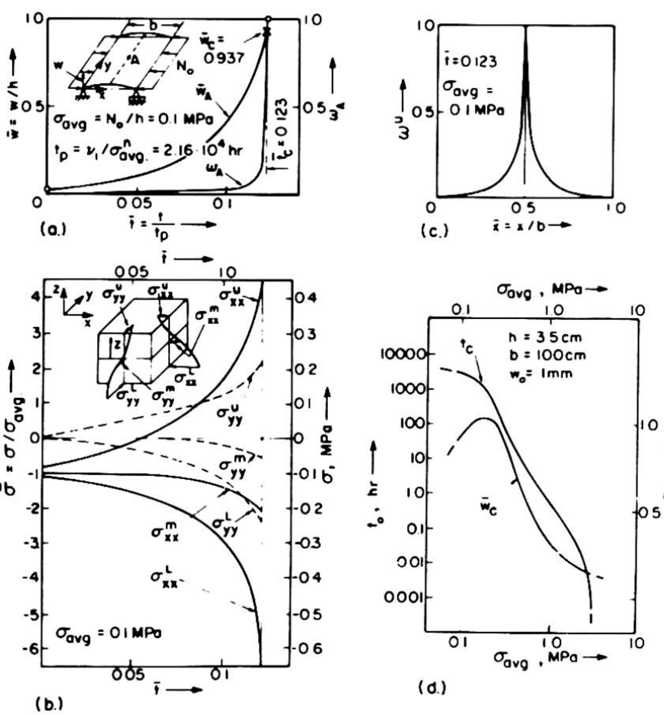
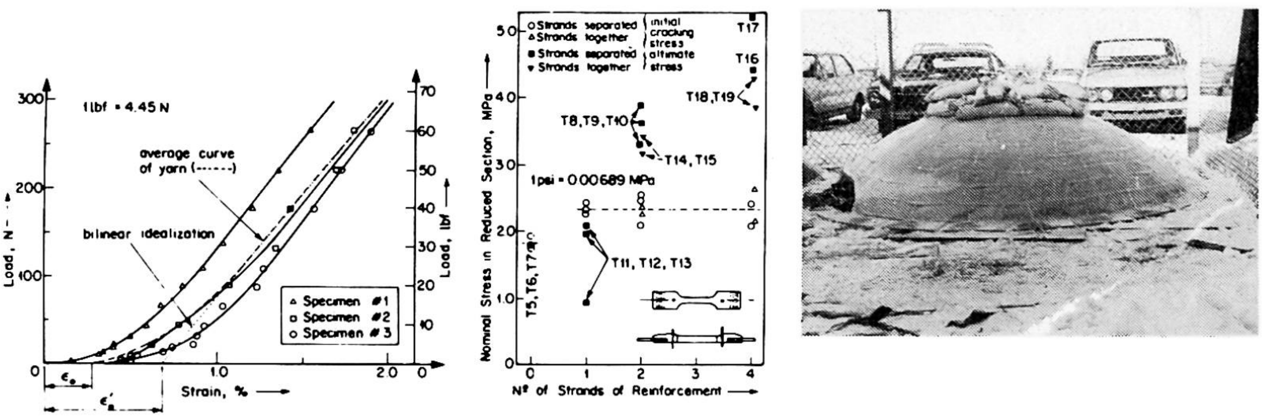


Fig. 3 Some Numerical Results for Ice Plate

of yarn. As one can see (Fig. 4b), for plain ice the 'initial cracking stress' was also the ultimate stress, while for the reinforced specimen, the reinforcement inhibited initiation/propagation of cracking, as a result of which the initial tensile cracking stress was increased by approximately 25% as compared to that for the unreinforced specimen.

A possible area of application of reinforced ice is in the construction of temporary and semi-permanent enclosures for shelters, storage areas, repair and workshops along pipeline right-of-ways, and/or enclosures at mining and exploration sites. Reinforced ice domes may even be suitable for covering/enclosing recreational areas in northern communities. Since cold regions are often rather inaccessible, a construction/erection procedure was suggested [7-9] whereby water is sprayed onto an inflatable, below



(a.) Load Strain Curves for Three Specimen of Spun Fiber-Glass Yarn [9]

(b.) Some Tensile Test Results [9]

(c.) Ice Dome N° 2

Fig. 4 Some Test Data on Reinforced Ice and the Ice Dome

freezing temperature, to form a reinforced ice dome. A number of model ice domes were constructed at The University of Calgary using this erection technique [9]. A network of spun fibreglass yarn was used as reinforcement to inhibit thermal cracking.

Dome #2 is shown in Fig. 4c partially loaded. The useful life-span of such domes, naturally, depends not only on the state of stress in the structure, but also on any imperfections present and on the environmental conditions, particularly the temperature.

4. CONCLUSIONS

From our analytical and experimental studies to date, it is apparent that reinforced ice can become a useful structural material for cold regions. Spun fibreglass yarn may have potentials as reinforcement for ice. Further tests are required to determine the properties of the composite and the effectiveness of the reinforcement which may be enhanced by pretensioning.

Tests on small-scale reinforced ice domes indicate that spraying water onto an inflatable may be a practical and economical erection technique for such structures.

Before ice is accepted as a common structural material, more tests and analytical investigations will have to be carried out in order to gain a better understanding of its behaviour, particularly its response to multi-axial stress and to temperature variations.

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