Ice Mechanics

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Ice Mechanics

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Acknowledgment

This special issue of *Applied Mechanics Reviews* is based on papers first presented at the Sixth (annual) International Symposium on Offshore Mechanics and Arctic Engineering (OMAE) held at Houston TX, 1–5 Mar 1987. The Symposium was organized by the International Council on Offshore Mechanics and Arctic Engineering and the American Society of Mechanical Engineers, Offshore Mechanics and Arctic Engineering Division.

The Guest Editor and the authors would like to acknowledge that a part of this effort for international presentation at the technical sessions of the Symposium and the Ice Mechanics Workshop was supported by the National Science Foundation Grant No MSM-8701368 administered by the Colorado School of Mines.

Except for the paper by Schwarz, which is entirely new here, the papers (as presented at the Symposium) were previously published in the proceedings volume "Advances in Ice Mechanics 1987," ASME Book No I00218 (1987), and revised for this issue except the paper by Sodhi and Cox. The original version of the paper by Hallam and Sanderson had none of the illustrations published here.

Introduction

Not surprisingly, "offshore structures" is classified under "solid mechanics" in *Applied Mechanics Reviews*. In industry, interdisciplinary approaches are generally used in solving design problems. Certainly, the integration of various engineering disciplines with branches of applied mechanics has been needed in the development of technologies for the design of complex offshore structures.

One of the very important emerging disciplines for the design and operation of arctic offshore structures and systems is ice mechanics and engineering. For the last 20 years significant advances have been made in ice mechanics and its engineering applications, mainly by experimental means. Earlier research had been conducted primarily to aid navigation of vessels such as the Exxon tanker "Manhattan." More recently, research and development interests have been directed toward petroleum drilling and production technology in the Arctic offshore. Although much of the recent work has concentrated on the Arctic offshore, some research results have been emerging on the Antarctic offshore.

One of the research areas of great interest to many in the industry is the mechanics of sea ice and its engineering applications (ice forces on offshore structures and ships, icebreaking, and under-the-ice-systems). Recent progress was summarized by leading international researchers from the United Kingdom, Finland, Canada, Federal Republic of Germany, and the United States at a Workshop on Ice Mechanics held at the Sixth International Symposium on Offshore Mechanics and Arctic Engineering (Houston TX, Mar 1987). The papers published in this issue of *Applied Mechanics Reviews* were written not only for those engaged in ice mechanics research, but also for both engineers in this field and general applied mechanicians interested in ice mechanics.

Hallam and Sanderson review the progress made in both experimental and theoretical research on Arctic and Antarctic ice in the United Kingdom. The review includes flow laws for ice, fracture processes in ice, morphology of ice, physical scale models of ice behavior, and engineering applications. Although details are proprietary, British Petroleum's field research projects for engineering applications on the Canadian and American Arctic offshore are highlighted.

Määttänen reviews Finnish progress made in ice research toward engineering applications, including the Manhattan tanker projects of the 60s. His review includes ice monitoring and statistics, ice forecasting, mechanical properties of ice, icebreaker testing, navigation, theoretical modeling, and offshore applications, focusing on scale-model and recent valuable full-scale lighthouse experiments.

Schwarz provides a review of the progress made in experimental research of basic ice mechanics and ice forces at the Hamburgische Schiffbau-Versuchsanstalt (HSVA). The review includes a history of the development of the HSVA ice model basin from the small one in 1958 to the large one in 1984. Schwarz cites computational methods and basic microscopic physical approaches to the study of ice properties, and gives an engineering formula to determine the effective pressure of level ice.

Sinha, Timco, and Frederking provide a comprehensive review of ice mechanics in research and engineering on a broad front in Canada. The review provides a balanced treatment of both theoretical and experimental work in physical properties of ice (structure, strength, and rheology), ice forces, and ice as construction material. The review places a strong emphasis on both Arctic and Hibernia offshore.

Sodhi and Cox review progress in ice mechanics and ice forces made in the United States with an emphasis on ice forces related to the offshore petroleum development. The review covers mechanical properties of ice, ice–structure interactions, modeling of ice drift, and the US petroleum industry research activities on the basis of the published literature. Although this research has been conducted by both academic and industrial groups, it is the petroleum industry that has made the most significant contributions; US universities have entered this field only recently.

In the United Kingdom, Finland, Germany, and Canada, research on ice mechanics and engineering is based on relatively well-balanced cooperation among government research organizations, industry, and universities. In the US, polar research has been conducted mainly in the basic sciences. Recently, research on arctic engineering and ice engineering is becoming a issue of interest to government. Much of the US petroleum industry research on site-specific problems remains proprietary, however, and only the published literature has been cited in the references here.

NEED FOR FUTURE SEA ICE MECHANICS RESEARCH

During the Workshop, the authors and ten other participants held lively discussions on the priority needs for future sea ice mechanics research. They were among some 60 symposium participants who are currently engaged in ice mechanics and engineering research and who represent most of the major petroleum industry, university, and government research organizations from the United States, Canada, Norway, Finland, the United Kingdom, Federal Republic of Germany, Denmark, France, Japan, Korea, and China.

The agreed-upon list of priority topics for research needs was the following:

- local and global scale effects and explanations of them
- shape effects and aspect ratio
- constitutive equations for multiyear sea ice
- brittle to ductile transition
- brittle fracture mechanisms: crushing, spalling, and flexure
- fracture mechanics and mechanisms or damage mechanisms
- ice–structure interactions, its effects at resonance
- ice forces and pressure distributions

A strong consensus among the participants quickly established scale effects as the top priority in research needs. They also agreed that in the long run, a research intiative on constitutive equation for multi-year sea ice would be necessary. The last four topics in the above list were deemed to be of more immediate interest for engineering purposes.

Additional topics emphasized by individual speakers included ridge formation, statistical approach, ice storage effects, three-dimensional effects, computational methods, expert system, buckling, microfracturing model, failure load, ice impact hydrodynamics, and high strain rate indentation.

Jin S Chung

Advances in ice mechanics in the United Kingdom

S D Hallam and T J O Sanderson

BP Petroleum Development, London, United Kingdom

The United Kingdom has made substantial contributions during the last few years to the field of ice mechanics and ice forces on offshore structures. Experimental studies have been carried out in the field and in the laboratory, and significant advances have been made in theoretical understanding. This paper summarizes the most recent contributions.

INTRODUCTION

Research on ice mechanics in the United Kingdom falls into five natural categories:

(1) flow laws for ice,
(2) fracture processes in ice,
(3) morphology of ice,
(4) physical scale models of ice behavior, and
(5) engineering applications.

These areas are each considered in turn in the following.

FLOW LAWS FOR ICE

These consist of experimental and theoretical investigations into the continuum rheology of ice.

C S M Doake (British Antarctic Survey, Cambridge) has made an analysis of field data for Antarctic ice caps and ice shelves [1] and shows that the data are consistent with an index of $n = 1$ in Norton's flow law. This suggests that at low strain rates ($< 10^{-10}\ s^{-1}$) diffusional flow is the dominant deformation mechanism, whereas at higher deformation rates it is power law creep. The data are not yet conclusive, and the subject is being debated [2, 3].

M F Ashby (University of Cambridge) and P Duval have developed constitutive equations for polycrystalline ice [4] which provide improved understanding of primary creep (also referred to as delayed elastic strain). The equations they present are similar in form to those developed by Sinha [5], but show more satisfactory dimensional dependence. Figure 1 shows how the theoretical equation fits experimental creep data.

J W Glen and R W Whitworth (University of Birmingham) with colleagues have performed experiments on dislocation motion in ice [6–9]. Their work is concerned with the theory of the obstacle presented to dislocation motion in ice by proton disorder. They have studied dislocation motion using synchrotron radiation x-ray topography, which is a new development and a substantial advance on more conventional techniques of topography. The quality of this work is illustrated by Figure 2 which shows the operation of a Frank–Read dislocation source viewed by this method. The current position is summarized in Ref. 10. There are still unresolved problems about the nature of the rate-limiting process for dislocations in ice.

L W Morland (University of East Anglia) has approached the rheology problem from the standpoint of an applied mathematician [11–14]. He has investigated the most general mathematical way in which the flow law for ice can be expressed and the degree to which available data allows it to be constrained and simplified.

J F Nye (University of Bristol) has developed theoretical considerations relating to singular isotropic points (known as "monstars") on glacier surfaces [15].

A R S Ponter (University of Leicester) has applied time-dependent finite element modelling techniques to ice, in order to model the creep of ice in complex geometric and stress states. This work has not all been published, but some of the results have been used to calibrate the reference stress method [16].

FRACTURE PROCESSES IN ICE

W A Nixon and R A Smith (University of Cambridge) have performed new experiments on the fatigue behavior of polycrystalline ice [17]. To date, experiments on fatigue of ice have been for repeated compressive loading, and suffer from effects of permanent creep deformation. To overcome this, Nixon and Smith's experiments use an end-loaded rotating cantilever beam specimen, in which the loading is truly cyclic and negligible permanent deformation occurs. Their experiments show that the fatigue process results from crack growth from defects. Figure 3 shows a summary of their results of fatigue life (cycles to failure) as a function of applied load (P). The fatigue life is considerably reduced by an increase in ice porosity.

S A F Murrell and P Sammonds (University College) have recently completed a triaxial testing machine and aim to study in particular the triaxial fracture strength of ice. The vast majority of triaxial tests to date have been conducted at ranges of confining pressure, temperature, and strain rate where the creep deformation is dominant.

M F Ashby (University of Cambridge) and S D Hallam (British Petroleum) have developed a theory of crack growth in ice (or any other brittle material) under compressive stress states [18]. Cracks in an elastic solid can interact with a compressive stress field in a way which causes new cracks to grow from them. If these cracks extend to a sample surface, or if they interact so that they grow unstably, then a macroscopic failure

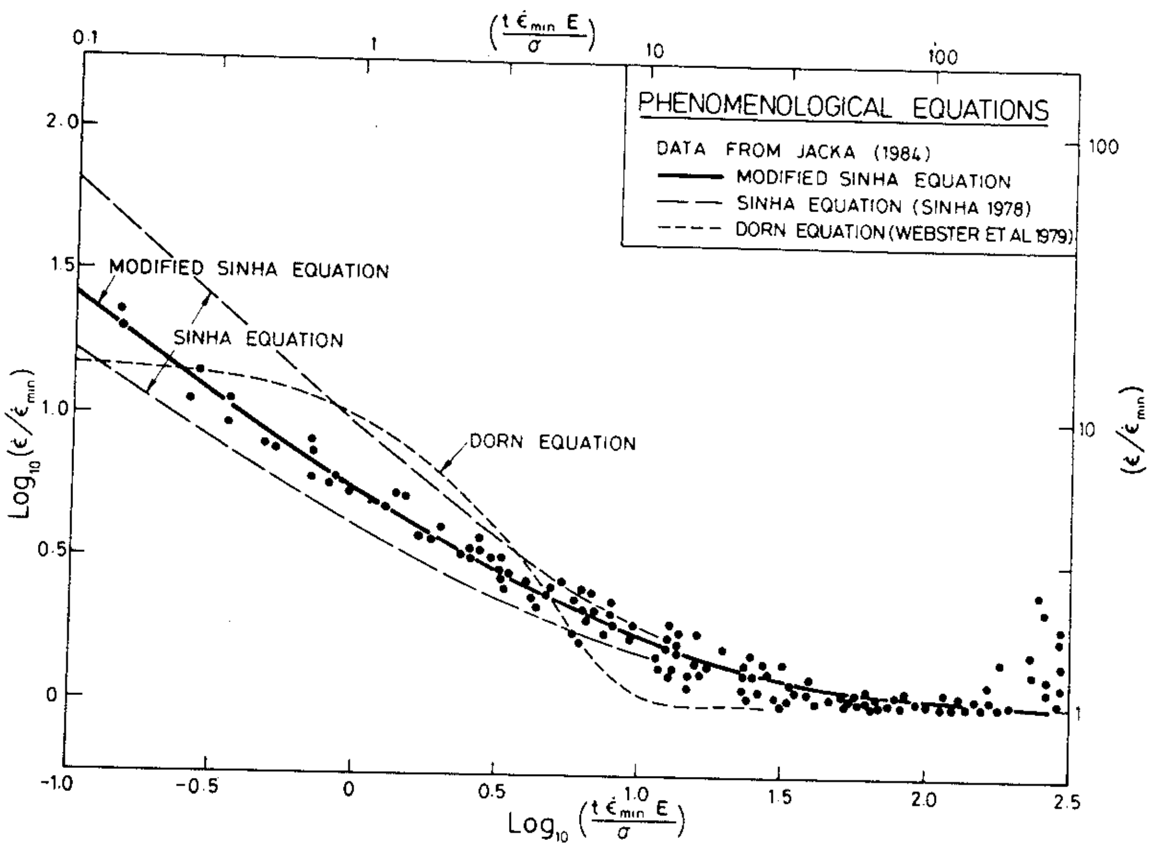

FIG. 1. Ashby and Duval phenomenological equations for the creep of polycrystalline ice (from [4]).

may follow. Figure 4 illustrates how confining pressure influences the brittle failure. Simple axial or radial compression, shown at (a) and (d), cause one or a few cracks to propagate and combine to give failure on planes parallel to the maximum, compressive stress ("slabbing"). A modest confining pressure prevents this unlimited crack growth; failure then occurs by the interaction of cracks to give the macroscopic shear failure shown at (b). Larger confining pressures limit the growth of individual cracks even further and the sample deforms in a pseudo-ductile way with large scale deformation taken up by many short, homogeneously distributed microcracks, shown at (c). S D Hallam (née Cooksley) has used some of this work to predict a compressive fracture surface for ice under confining pressures and shown how the failure mechanism depends on the confining pressure, temperature, and strain rate [19].

S D Hallam (British Petroleum) has considered the effect of ice thickness irregularities on the strength of ice showing how induced bending moments cause tensile stresses and how failure

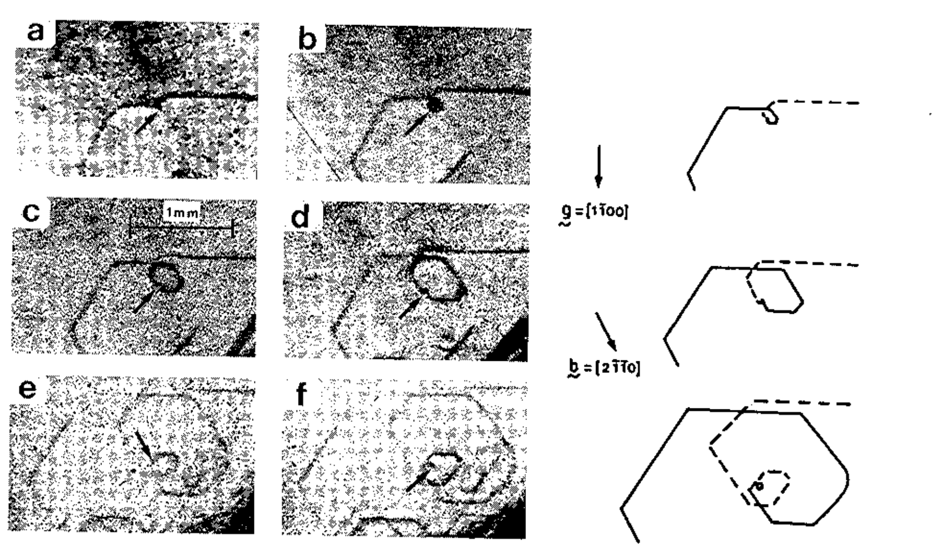

FIG. 2. Ahmad et al Frank–Reid source in ice viewed by synchrotron radiation x-ray topography (from [8]).

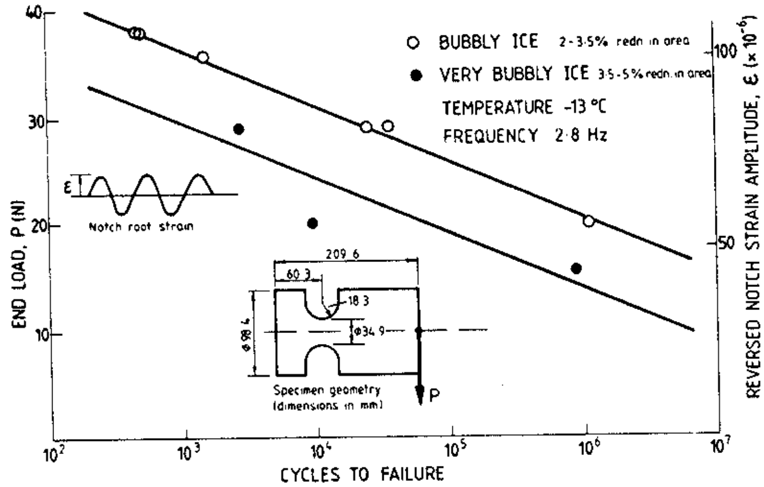

FIG. 3. Nixon and Smith fatigue life of freshwater ice (from [17]).

occurs when new flaws nucleate in these areas [20]. Figure 5 illustrates the dramatic way in which a thin section in an ice sheet can affect the ice sheet strength. Another piece of work considers the role of fracture in limiting ice forces on offshore structures [21]. In this paper the fracture surfaces derived in Ref. 19 are described and plotted. Essentially, the brittle fracture or crushing strength of ice is highly pressure sensitive and increases linearly with confining pressure and provides a limit to the strength of ice.

T J O Sanderson (British Petroleum) has collated and reviewed a large body of indentation failure data to produce a pressure area curve for ice [22]. This provides evidence that the maximum failure strength of ice is scale-dependent; ice indented over a contact area of up to about 1 m^2 fails at a maximum indentation pressure of about 10 MPa, while over a contact area of 100 m^2 or more the maximum indentation pressure is typically 1 MPa or less. Figure 6 shows the collection of data and the trend is clear. It should be noted that a vast volume of data can be found at any pressure level below the upper bound but there is no evidence of any data significantly above it. The origin of this trend is far from well understood and most of the candidate theories are discussed in the paper.

T J O Sanderson and A J Child (British Petroleum) have investigated loading rates encountered in natural sea ice [23]. If failure is controlled by fracture initiation, then a delayed elastic strain criterion [24] helps explain the low failure stresses observed during natural interaction with structures.

M D Thouless (University of Cambridge) has studied and extended the understanding of edge cracking and spalling of brittle plates [25].

MORPHOLOGY OF ICE

P Wadhams (Scott Polar Research Institute, University of Cambridge) has studied directional wave spectra near ice edges and found that the spectra becomes almost isotropic within a few kilometers of the ice edge [26, 27] and that the attenuation can be described by a simple scattering model [28]. Other studies include: the measurement of sea ice drift and deformation in the marginal ice zones of the Bering and Greenland Seas using radar transponders including the study of bands and eddies [29, 30], and measurement of the response of Antarctic tabular icebergs to ocean waves [31].

J R Potter, J G Paren, and M Pedley (British Antarctic Survey, Cambridge) have studied the effects of Antarctic ice shelves on tidal behavior and spectrum [32, 33].

P J Langhorne (Scott Polar Research Institute, University of Cambridge) has performed laboratory tank experiments on

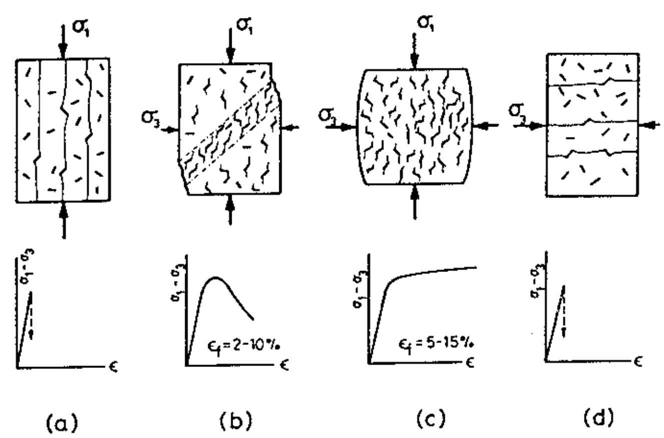

FIG. 4. The influence of confining pressure on the britle failure of materials containing a population of microcracks from Ashby and Hallam (from [18]).

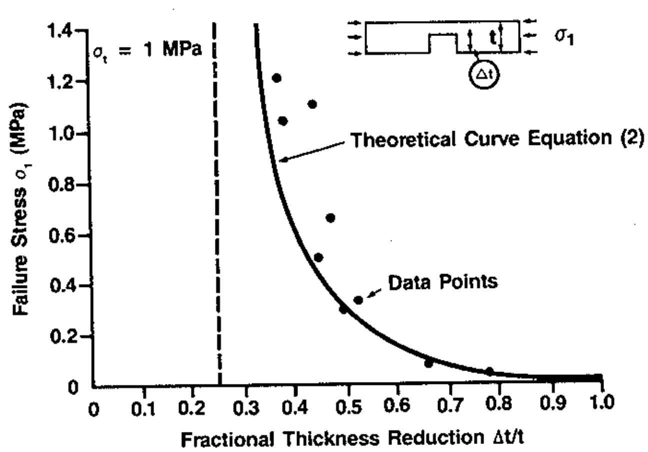

FIG. 5. Isolated thin sections in ice sheets can cause premature flexural failure at low stress levels from Hallam et al (from [20]).

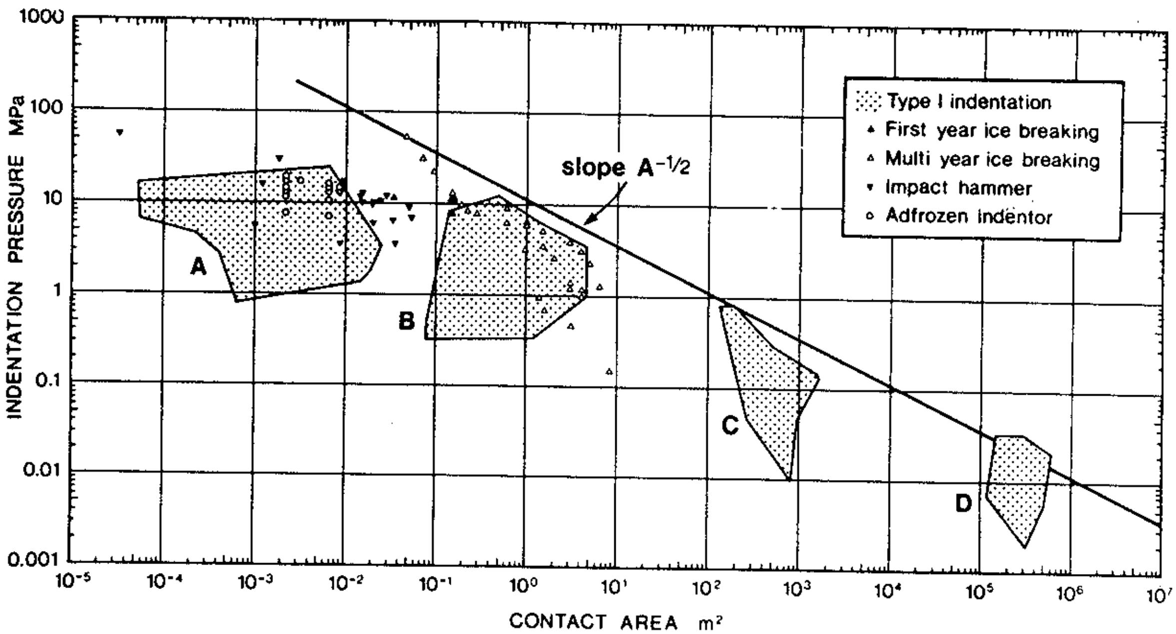

FIG. 6. Sanderson pressure-area curve for ice (from [22]).

c-axis orientation in columnar ice [34, 35], and has established that the existence of preferred orientation is due to water current direction during the growth process.

PHYSICAL SCALE MODELS OF ICE BEHAVIOR

M S Lovell and A N Schofield (Scott Polar Research Institute and the University of Cambridge) have developed a system for growing and failing floating ice sheets in a geotechnical centrifuge [36]. The ice grown in this has a very fine structure similar to that of first-year ice but at a much smaller scale. The high gravitational forces used in the experiments allow more appropriate modelling of the water buoyancy forces during the ice failure. Tests to date have concentrated on vertical loading of the ice plates. Horizontal loading of an ice sheet will proceed when a new drum centrifuge, at present nearing completion, becomes available.

P J Langhorne (Scott Polar Research Institute, University of Cambridge) has studied the effect of gravitational forces on the growth of ice crystals and shows that an increase in force of gravity generally leads to smaller crystal size [37]. This observation may be of use in manufacture of fine-grained ice for scale model experiments.

N Jones (University of Liverpool) has investigated the principles behind scale modelling of ice dynamics and has introduced a new dimensionless number to characterize the scaling [38]. This allows ice failure to be correctly modelled when the influences of fracture and gravitational forces both need to be accounted for. The dimensionless number is given by:

$$J_n = \rho g L \left(\frac{b}{EG_c} \right)^{1/2},$$

where ρ = density, g = acceleration of gravity, L = characteristic length, b = crack length, E = Young's modulus of elasticity, and G_c = toughness, or energy absorbed per unit area of crack.

ENGINEERING APPLICATIONS

V A Squire (Scott Polar Research Institute, Cambridge) has conducted experiments to measure the dynamic response of lake and sea ice to moving loads [39]. The existence of a critical velocity at which the strain is resonant was identified. Other work [40, 41] has concentrated on the break-up of an ice edge by wave action. The break-up is associated with flexural failures induced by the magnitude of the vertical displacement of the ice sheet.

D S Aldwinckle (Lloyd's Register, London) has been involved in updating offshore classification standards to include detailed specification of multi-year ice loading levels [42]. Other work has involved finite element analysis of impact of icebergs on steel hulls [43].

The British Petroleum Company has been engaged in intensive studies over the period 1981–1986 to quantify the risks involved in installing offshore structures in Arctic waters. Efforts have been concentrated on large-scale field experiments, laboratory experiments and theoretical understanding; the principal projects are summarized below. Some of the work is still proprietary, but most is expected to become public before 1990.

Field programs

Tarsiut Island (Canadian Beaufort Sea): Two programs were carried out, in 1982 and 1983 [44, 45], to measure strain rates and deformation processes in winter first-year ice surrounding an artificial island. The 1983 program supplied direct measurements of strain during slow build up of stress as a result of wind action, and monitored strain during failure. The strain rates were used to estimate maximum stresses sustained at failure.

Mobile Ice Laboratory (Alaskan Beaufort Sea): A specially constructed mobile refrigerated laboratory was used offshore Prudhoe Bay, to establish whether storage of ice cores has any significant effect on mechanical properties. A closed loop testing machine was used to perform uniaxial compression tests on samples of ice within hours of coring from the ice cover. Results were then compared with twin cores transported back to UK and tested in the laboratory [46].

Hans Island 1983 (Kennedy Channel, Canadian High Arctic): As part of the 1983 Hans Island multi-year impact joint industry research program, operated by Dome/Canmar, BP carried out an experiment to measure linear and rotational deceleration of vast multi-year floes during impact with an island [47]. The technique used fast-tracking EDM equipment.

Multi-Year Ice Sampling Program 1984 (Buckingham Island, Queen Elizabeth Islands, Canada): A 30 cm diameter core barrel was used to take a series of closely spaced deep cores from a multi-year floe. The aim was to identify flaws within the ice cover and investigate their effect on ice strength. Almost 2 tons of cored ice was transported back to London for testing.

Katie's Floeberg Experiment 1985 (Alaskan Beaufort Sea/Chukchi Sea): Stress measurements were made in multi-year ice failing against Katie's Floeberg, offshore Point Barrow [48]. Stresses were measured using specially designed stress sensors frozen into the ice cover at up to 0.5 m depth. Measurements were obtained of the static stress present in ice close to an active compression ridge which formed in an undeformed multi-year floe.

Mukluk Program 1986 (Alaskan Beaufort Sea): A continuous record of ice stresses and the response of Mukluk island (a gravel island) was made over a period of about 5 weeks during March/April 1986. The island was surrounded by landfast first year ice subject to predominantly thermal stresses.

Hans Island 1986 (Kennedy Channel, Canadian High Arctic): A program has been carried out to measure stresses during break-out of multi-year ice from around Hans Island at the end of the landfast winter ice season. In addition detailed measurements have been taken of short range variations in ice thickness on floes of average thickness some 8 m.

Theoretical work

A series of intensive meetings of academic specialists have been held over the years 1981–1985 to investigate fresh approaches to the problem of ice loading on structures. The three meetings were held in Cambridge, and have become known as the "Garden House Meetings," after the hotel in which they were held. The meetings each lasted a week without interruption. The aim was to involve a small number of specialists in fields which are peripheral to that of ice engineering, in order to encourage cross-fertilization. Four papers have resulted directly from these meetings, treating: reference stress methods applied to ice [16]; propagation of radial fractures [49]; spalling fracture [50]; and nonsimultaneous failure [51].

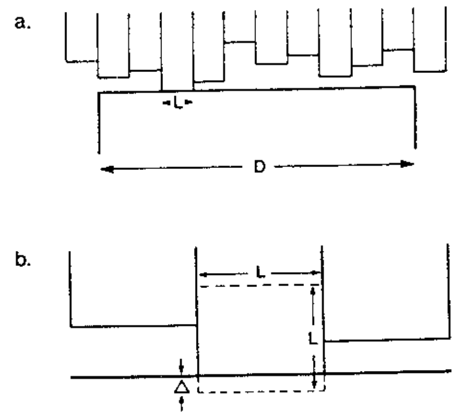

FIG. 7. Nonsimultaneous failure modelling, zones of dimension *L* interacting with a structure of diameter *D* (a) fail a distance L away from the contact surface (b) (from [22]).

The most significant piece of work is the last one. Tests were carried out on a brittle ceramic foam to investigate the process of nonsimultaneous failure. The process can be modelled as in Figure 7(a) where the foam was divided into discrete cells or zones only some of which were in contact with the indentor at a particular point in time. At a critical local stress level each zone fails and when it does so it fails a distance away from the indentor illustrated by Figure 7(b). The statistical averaging of such a process gives a failure pressure inversely proportional to the square root of area (a relationship observed for ice) except where the contact area is smaller than the size of one zone (which provides a maximum strength as a function of area). This work has been applied to ice by Sanderson [22] for failure zones of a fixed area and of the total ice sheet thickness times a fixed length. The result of the latter is shown in Figure 8 as a function of ice thickness (t).

Several other papers treating the theory of ice loading on structures have been produced, and a series of review papers [52–55].

Laboratory work

A program of laboratory experiments on uniaxial compressive strength of ice has been in progress since 1981. Tests have been performed on freshwater ice, first-year ice, and multi-year

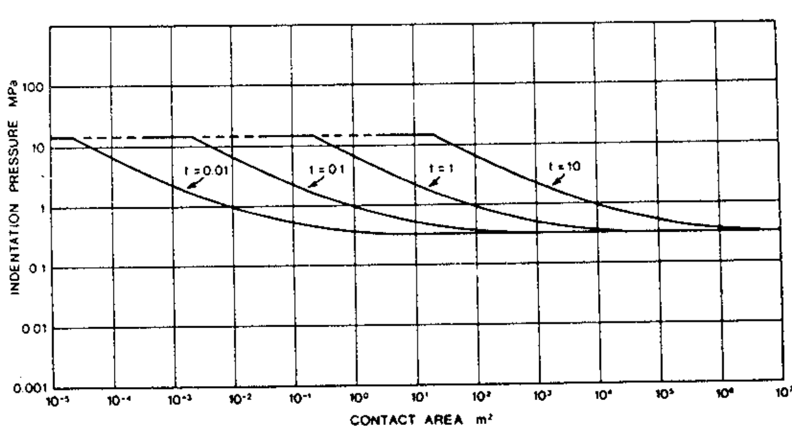

FIG. 8. An example of theoretical pressure-area curves for ice of varying thickness from Sanderson based on Ashby et al (from [22]).

ice, and vertical and horizontal loading directions have been employed.

Experiments have also been performed on a variety of brittle materials undergoing impact, in order to gain a broad understanding of brittle fracture processes. The results have been used to place bounds on methods for extrapolation of full-scale multiyear ice impact data [56].

CONCLUSIONS

The United Kingdom has produced a wide variety of recent advances in the field of ice mechanics. Advances have been made in the understanding of ice flow laws both at the low strain rates associated with glacier movements and the higher rates appropriate to ice loading on offshore structures. Observations of the mechanisms of dislocation motion have been made.

Fracture processes are important in breaking up of ice covers and in limiting ice loads on offshore structures. The United Kingdom research has concentrated on the understanding of the failure mechanisms (such as crushing, flexure, spalling, etc), nonsimultaneous failure and scale effects, and the fatigue strength of ice.

Studies have been made of the response of icebergs and ice sheets to waves; *c*-axis orientation in columnar ice has been related to current effects.

A method of growing and failing model ice with a fine grained structure in a centrifuge has been developed.

A substantial number of field and laboratory studies have been carried out in order to understand and quantify the magnitude and nature of ice forces on offshore structures.

ACKNOWLEDGMENTS

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Advance in ice mechanics in Finland

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In Finland, 110 years of winter navigation has been a natural initiator of ice mechanics research. It has brought with it sea ice monitoring and statistics, ice forecasting, the testing of mechanical properties, ship and icebreaker model testing and full-scale trials, ice resistant aids-to-navigation, and theoretical modelling and numerical simulations. Lately, a lot of ice mechanics research has been devoted to arctic offshore applications. A summary of the major developments is given in this paper.

INTRODUCTION AND HISTORY

Finland is the only country in the world with a sea coast with all her harbors blocked by ice every winter. The necessity of developing winter navigation has created a demand for ice research. Actually, this year is the 110th anniversary of the beginning of winter navigation from Finland to Sweden in 1877. The first icebreaker started operation in 1890. Since then, winter navigation has continued each winter with the number of icebreakers, ships reinforced against ice and winter harbors increasing. From 1970 onwards, all the main harbors have been kept open.

The development of efficient bow shapes for ice breakers and self-sufficient ships reinforced against ice required a lot of model testing in addition to field trials. The first ice model tank was put into operation in 1969. It was replaced by a new one in 1983. Model testing included model ice development, testing of the mechanical properties of ice, theoretical models and comparisons with in-field full-scale measurements for design refinements.

Together with winter navigation, ice monitoring techniques were being developed. Information on ice thickness, ice formations, ice extent and duration was compiled. Systematic ice map production started in 1918. However, it was relatively late in the 1950/60s when work on the mechanical properties of ice in the Northern Baltic was started. Ice forecast methods were developed in the 1970s.

To improve winter navigation safety, ice resistant aids-to-navigation were developed. Caisson lighthouses were built to replace the lightships that could not stay on their location while the ice was moving. In the 1970s cost effective lightweight steel aids-to-navigation were developed to allow more closely spaced channel markings in winter navigation routes.

The potential of arctic oil and gas resources also motivated research on arctic offshore structures in Finland in the early 1980s. This further stimulated the existing well-established ice-structure interaction research on ice resistant ships and aids-to-navigation.

RESEARCH FACILITIES AND RESOURCES

Ice tanks and cold rooms

The best known research facility is WARC (Wärtsilä Arctic Research Centre). Wärtsilä specializes in the construction of icebreakers and ice reinforced ships. Coöperation with Exxon in the Manhattan project brought with it the realization of the first ice model tank in the western countries, WIMB (Wärtsilä Ice Model Basin), in 1969. This enabled the comparison of the effects of design parameters before the final design was completed. By comparing model test results to subsequent full-scale trials, the accuracy of scale model testing could be gradually improved (Fig. 1).

Success in many cases further increased the demand for scale model ice testing so that a new, more efficient ice tank, WARC, was built and put into use in February 1983. It is now the backbone of all ice tank testing in Finland. The government financed 20% of the facility in order to ensure equivalent testing time for Finnish universities and state research organizations. The main dimensions of the new WARC ice tank are given in Table I. Most of the work, so far 85%, has been ship model ice testing but lately the share of testing model offshore structures in ice has increased.

There are no other privately owned ice mechanics research facilities in Finland. The normal practice of private industry is to conduct their own in-field studies or to utilize the WARC ice tank or the laboratories of state research organizations. Also, model tests in foreign ice tanks have been conducted.

The Technical Research Centre of Finland (VTT) substantially increased its research in arctic technology in the early 1980s. A new cold room for heavy static or dynamic testing down to −60°C was completed in 1984. An ice tank (VTT in Table I) for the main purpose of arctic offshore structure testing was put into operation at the end of 1986. One special feature not found elsewhere will be an arrangement to simulate earthquake loads in offshore structures by shaking the foundation platform with hydraulic actuators.

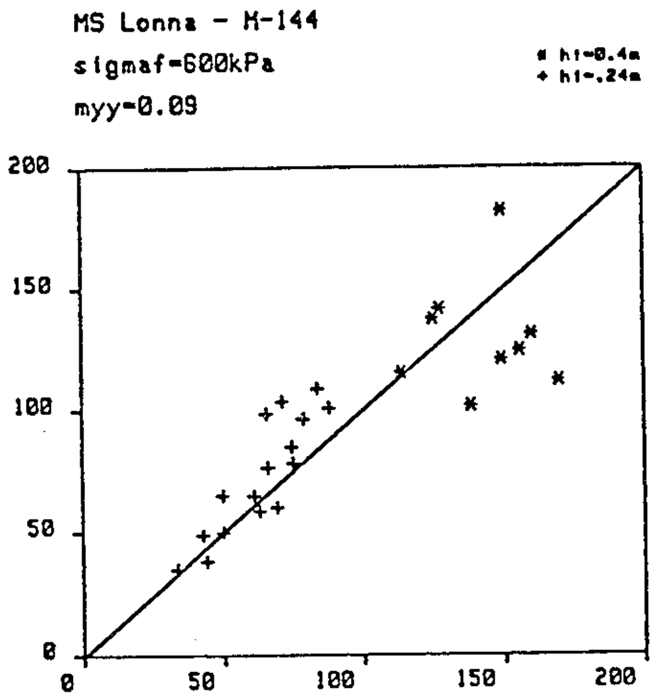

FIG. 1. MS Lonna ice resistance (kN) predictions from scale model data versus full-scale measurement results.

In universities, research organizations, and industry, there are several small cold rooms in which basic ice property research and structural testing can be carried out. The University of Oulu, which started ice mechanics research in 1971, has a cold room in which static and dynamic loadings can be simulated at temperatures down to −55°C. A micro ice tank is used for initial testing before more comprehensive tests in WARC are started. The Institute for Marine Research has provisions to simulate ice accretion in a wind tunnel [17].

The Shipbuilding Laboratory at the Helsinki University of Technology (HTKK) has completed the design for converting an existing 40 × 40 m ship model maneuvering basin into an ice maneuvering basin with additional capability for offshore structure model testing. This ice tank (HTKK in Table I) is scheduled to start operation at the end of 1987. The maneuvering ice model tank complements the WARC ice tank, which has only limited maneuvering test capability. In offshore ice model testing, larger models can be used than in either the WARC or Technical Research Centre tank.

Personnel

The number of personnel working in the ice mechanics field depends on definitions. Both in WARC and in the Technical Research Centre there are about 25 people, and in other state research organizations about 15 employees solely devoted to ice related research. If all the assistant personnel and those who are working in the arctic applications field were included, the above numbers would be quadrupled. In industry, excluding WARC, there is no reliable estimate on the number of workers in the ice mechanics field.

TABLE I. ICE TEST BASINS IN FINLAND.

	WARC	VTT	HTKK
Year	1983	1986	1987
Length (m)	60	15	40
Width (m)	6.5	3.2	40
Depth (m)	2.3	1.4	3.0
Max. speed (m/s)	3.0	0.5	3.0

Other resources

Nature herself is one resource in ice mechanics research. Waters around Finland are ice covered from 3 up to 7 months annually. Temperatures fall down to −40°C. Maximum level ice thickness at sea can reach up to 1.3 m. In addition, there are all kinds of first year ice features, rafted ice over 1.5 m thick, broken ice fields and pressure ridges with sails over 3 m, and keels down to 28 m. Beyond the landfast ice zone there is frequent ice movement. This natural laboratory is found everywhere near habitation and airports so that logistics for offshore operations is easy. This gives many possibilities for full-scale field work. A good example is the test cone project in which an existing caisson lighthouse was used as a base to measure ice loads against a conical structure [6, 29]. Prompted by the good data recovery in variable ice conditions, proposals have been made to test other structural shapes at the same location.

Another asset is university policy to give free computer time for thesis and postgraduate studies regardless of whether the research topic is from university or industry. This has encouraged the development of various numerical simulation algorithms in the ice mechanics field.

RESEARCH TOPICS

Ice forecast

Related to early winter navigation, the first ice research reports [7], as well as ice maps starting from 1918, are on ice formation, extent, thickness, movement, etc [21]. They were and still are used for planning winter navigation operations, ship design, and for making calculations on cost effectiveness. In the 1970s more effective methods for ice monitoring were developed. Sponsored by the Finnish–Swedish Winter Navigation Research Board, a computational ice forecast model was developed [20]. It is based on arctic ice dynamics models and is adjusted to a finer mesh in the Baltic Sea. Taking prevailing ice conditions and the weather forecast as a starting point, a prediction on the amount of ice and its movement in the Baltic Sea is calculated. The prediction, in addition to ordinary ice maps, is telefaxed to icebreakers and ships for navigation route planning. Present developments aim for a mesh of 4 × 4 km^2 and to double the length of the forecast period up to 3–4 days.

Winter navigation

The flagship of winter navigation is an icebreaker. Its evolution to its present form, lasting over a century, was slow at the beginning, mostly concentrating on increasing the icebreaker's power and only little by little shaping the hull. In the 1970s the utilization of ice tank testing made it possible to compare different hull shapes, propulsion, and other details to make the progress of an icebreaker easier in ice [1]. The systematic experimental research including in-field verifications resulted in modern bow and hull shapes, a reduced risk of broken ice floes hitting the propellers, low ice-friction painting, and air bubbler systems.

For example, an icebreaker from 1986 uses about 20% less energy to proceed with the same speed in the same ice conditions when compared to a 10 year older model with a 4% narrower beam. This is achieved by modelling more carefully ice breaking patterns, the pushing away of broken ice floes, friction between the hull and ice, and by searching for an overall optimum. To determine the contribution of different parameters, both scale model tests and full-scale trials are performed in such a way that the effect of a certain parameter can be distinguished, e.g., by sawing the ice sheet in pieces so that ice breaking component can be eliminated [2].

Icebreaker technology is also utilized in the design of ice reinforced ships. The optimum design is now different from icebreakers since in most cases most of the navigation is done in open water. However, by utilizing ice model tanks and normal towing tanks the hull shape can be optimized in such a way that the open water penalty is only about 1% while the reduction in ice resistance is 40% for the case of the bulk carrier M/S Finncarrier. This type of ice reinforced ship can proceed most of the time without icebreaker assistance.

Currently there are active research projects on ship resistance and maneuvering in various types of ice including level ice, broken channels, and multiyear ice [10, 13, 32], ice impact and loads against ships [11, 16, 41, 46, 47], ship dynamics in ice [15, 22], propulsion dynamics [8, 9, 14], and ice mechanical properties related to winter navigation [12, 38, 39, 45].

Aids-to-navigation

Accurate positioning in winter navigation shipping channels requires fixed aids-to-navigation. To reduce cost a simple bottom-founded steel structure was developed in the 1970s to replace conventional caisson type lighthouses and other channel markers. However, at the beginning, ice mechanics research was needed to prevent adverse ice-induced vibrations that caused structural failures [25]. Theory for ice-induced self-excited vibrations [26] was used to design vibration isolated steel lighthouses that are free from superstructure vibrations [28, 31] (Fig. 2).

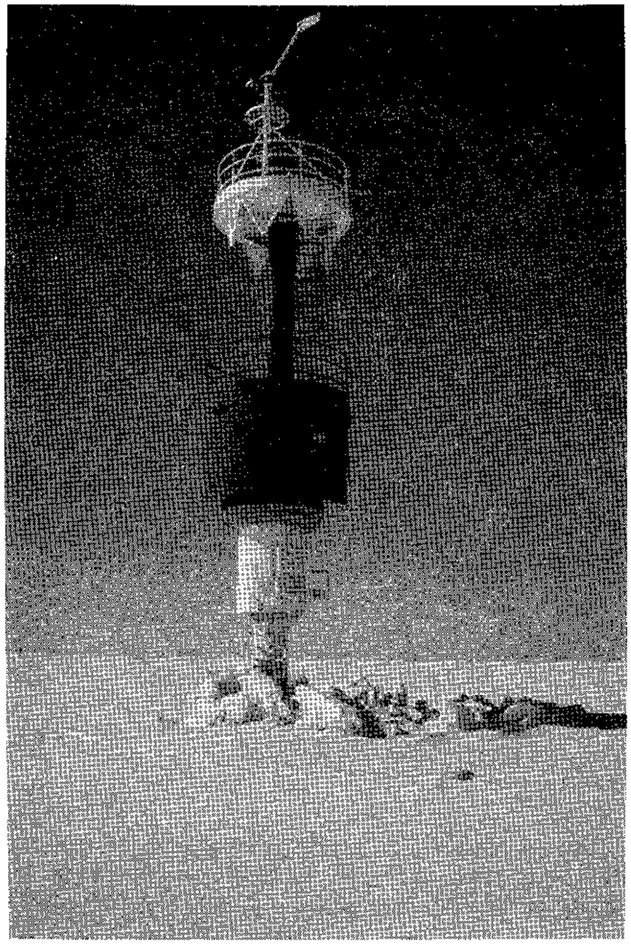

FIG. 2. The Kemi 2 steel lighthouse with the vibration isolation system.

For the continuous monitoring of the performance of vibration isolated lighthouses and their ice forces, a telemetry system [19] was developed. Also ice pressure transducers and total ice load sensing instrumentation have been developed. In order to eliminate structural dynamic effects from the ice force measurement data, a transfer function and deconvolution approach has been used. A large amount of full-scale data on static and dynamic ice forces with sheet ice thickness up to 1.3 m has been gathered [31] (Fig. 3).

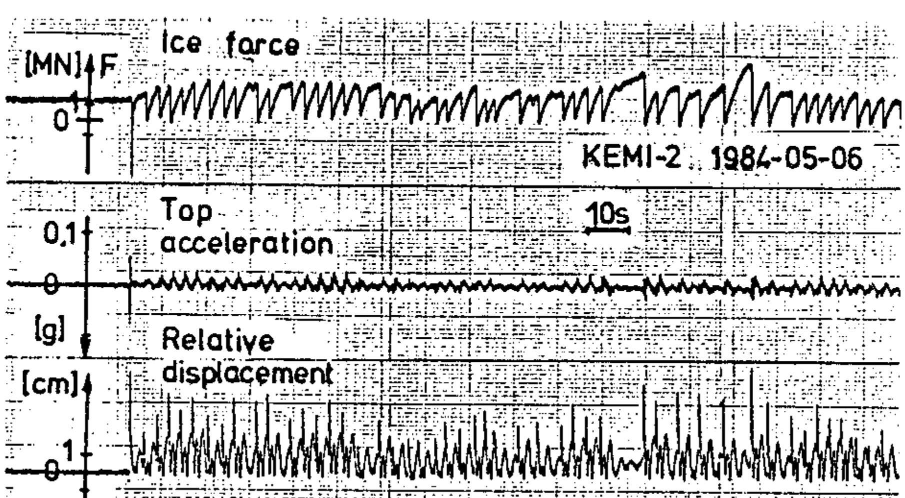

FIG. 3. Telemetry data from the Kemi 2 lighthouse. Ice force, and superstructure response versus time [31].

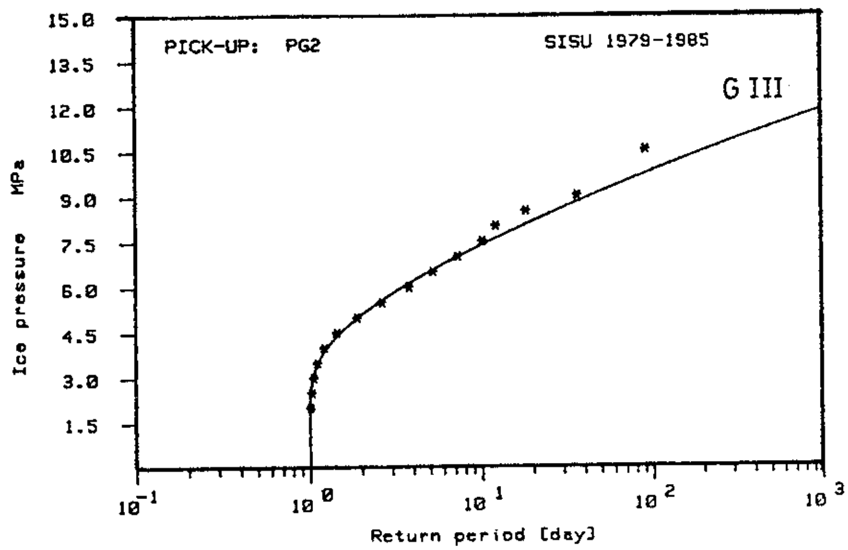

FIG. 4. Measured propability of ice pressure against the hull of icebreaker "Sisu" [16].

For fixed aids-to-navigation without the whole superstructure vibration isolation system, local ice-induced vibration isolation for lights and driving instrumentation have been developed. Ice resistant large plastic spar buoys with a diameter up to 1.6 m have been developed by using scale model tests and analytically predicting ice impact stresses.

FIG. 5. Ice action against the test cone on the Kemi I lighthouse.

Full-scale testing in field

The majority of full-scale tests have been ice trials of ships and icebreakers. Comprehensive tests have been run on ship resistance in level ice, in ice clogged channels, in pressure ridges, and in ship maneuvering [1, 2, 10]. Local ice pressures against ship hulls have been measured and statistical distributions of ice pressures and ice loads have been collected [8, 9, 11, 16, 22, 41] (Fig. 4). *In-situ* ice beam bending tests have been used to measure the flexural strength of the brackish water ice in the Baltic [12, 24]. By using large root radius with cantilever test beams a notch sensitivity of about 50% for the ice was verified [24]. Ice forces against lighthouses have been measured since 1973. Numerical models on ice drift have been compared to full scale ice drift measurements in the Gulf of Bothnia [20]. The applicability of linear elastic fracture mechanics for sea ice with loading rates higher than 7 kPa m/s has been verified by in-field tests [45].

The Kemi-I test cone is so far the largest project involving full-scale measurements of ice forces against offshore structures [6, 29] (Figs. 5 and 6). With an eye on applications in arctic offshore drilling or production platforms, Finnish industry decided to measure ice forces against a conical structure in order to validate design ice force predictions. This is achieved by running both scale model tests in the ice tank and full-scale

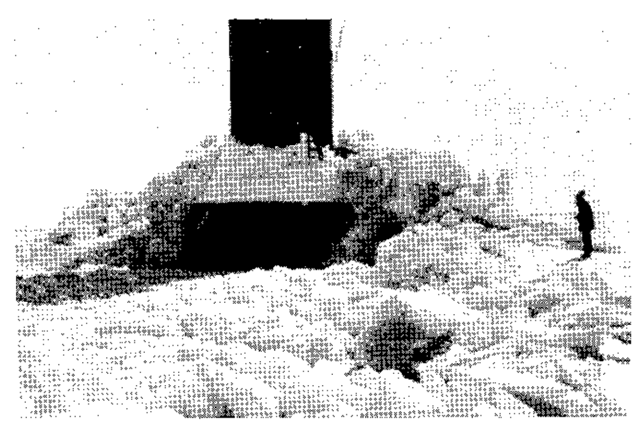

FIG. 6. A medium size pressure ridge passing the cone.

FIG. 7. Kemi I test cone scale model tests.

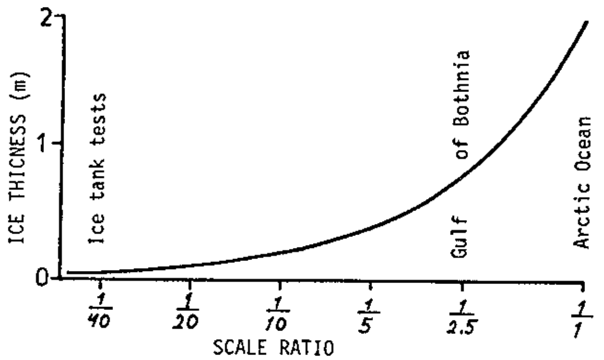

FIG. 8. Scale ratios from the ice tank via the Gulf of Bothnia to the Arctic.

tests in the Gulf of Bothnia which give a reliable base to extrapolate to real arctic ice conditions (Fig. 7). The scale ratio from the Gulf of Bothnia to the Arctic Ocean is an order of magnitude less than from scale model tests to the Gulf of Bothnia (Fig. 8).

The test cone project, started in 1983, has yielded good data in variable first-year ice conditions including sheet ice, rafted ice, pressure ridges, and broken ice fields (Fig. 9). Also tests with a simulated multi-year ice are planned. The results have indicated that adjustments are needed for present theoretical models which calculate ice forces against conical structures.

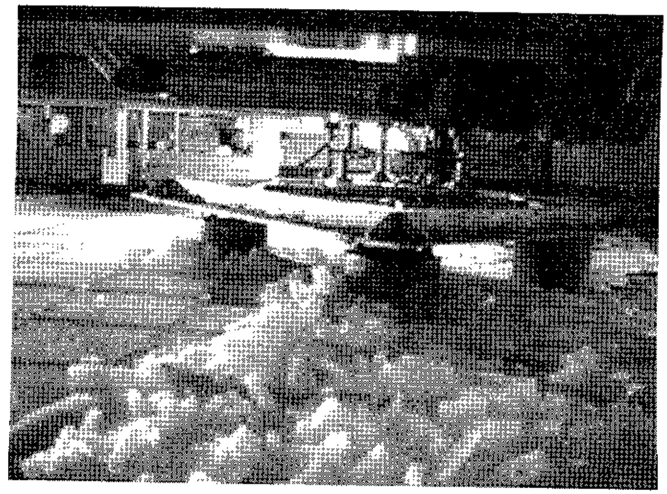

FIG. 10. Scale model test for a multilegged offshore platform. (Courtesy E. Eranti/Finnstroi.)

Scale model testing

The objective of scale model tests are to repeat in-field full-scale phenomena in a controllable environment. Then experimental models can be developed, and the effect of a single parameter can be distinguished for refining theoretical models, or results can be used directly in design. In the latter case the overall optimum design is often more important.

The large number of completed scale model research projects limits us in this paper from referring to even all the major ones. Most of the full-scale projects from the previous chapter have their counterparts in model testing [2, 13, 15, 18, 27, 29, 47]. Arctic offshore structure scale model testing has proven valuable, because in many cases no theoretical models validated with full-scale data exist (Fig. 10). In the case where the model research has been funded by industry the data is kept proprietary for a certain period.

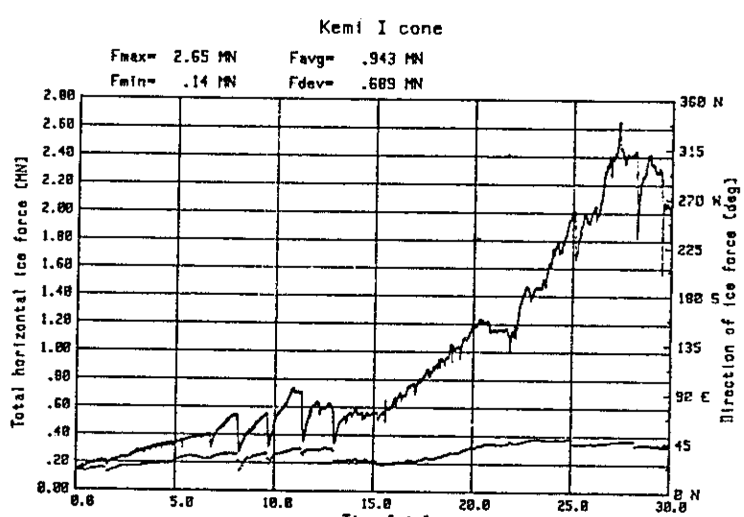

FIG. 9. Horizontal ice load build-up during a pressure ridge action against the Kemi I test cone.

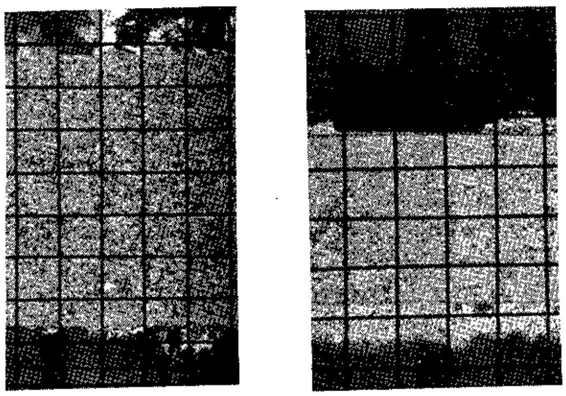

FIG. 11. Fine grain model ice thin sections, grid 10 mm: (a) horizontal, (b) vertical.

In Finland, techniques for the scale model testing were started in 1969 by using sea water, seeding, and tempering in order to reduce ice strength and stiffness with scale ratio. In 1983 a new fine grained (FG) ice was developed in WARC [3]. FG ice is made by spray-icing most of the ice sheet thickness. This results in homogeneous randomly oriented fine grained ice crystallography with a high modulus of elasticity/strength ratio and more natural cracking behavior than with conventional model sea ice or urea ice. Also, the required tempering time after freezing is short, which increases the productivity of the test basin by allowing the scheduling of one ice sheet per day. The latest refinement in FG ice is strength and elasticity control through the ice thickness. In 1986 hardware was added to control the salt content during the spraying. Hence the salinity profile through the ice sheet thickness can be controlled, thus further enhancing the properties of FG ice (Fig. 11). For example, a stronger low salinity layer can be formed at the bottom, top, or middle of the ice sheet depending on whether ice failure is downward or upward bending, or crushing. This allows problem-specific ice stiffness, strength, and cracking properties adjustments for natural ice failure simulations. With this new model ice, now known as FGX, the modulus of elasticity/flexural strength ratio can be varied up to 15 000 (Fig. 12).

Friction modelling is another new development in scale modelling techniques at WARC. The amount of friction can be varied by mixing different particles in the paint for scale models. For actual friction measurements both in full scale and scale model tests, an advanced panel with force measuring instrumentation along six axes was developed to be mounted as a section of ship hull or offshore structure wall.

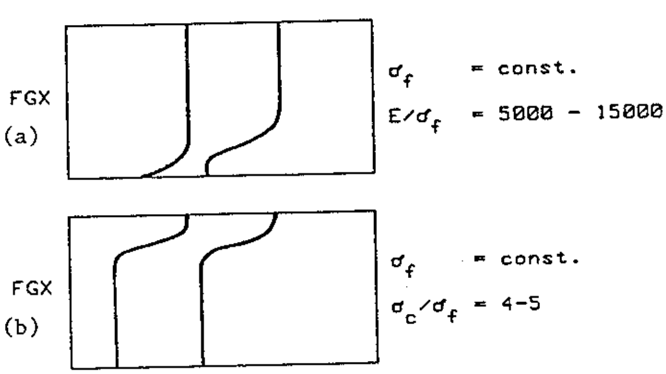

FIG. 12. Fine grain model ice with salinity profile control, salinity right curve, strength left curve (increasing to left): (a) hard bottom, high modulus of elasticity/flexural strength; (b) soft surface, high crushing strength/flexural strength.

Theoretical and numerical simulation

With steadily decreasing computing costs, computational mechanics is becoming a more important approach in simulating ice mechanics or ice structure interaction phenomena. Due to nonlinear ice behavior, supercomputer capacity is needed in many applications. The first step is always to develop a theoretical model, but to validate the models both scale model and full-scale tests are desirable. The following examples have greatly utilized the results of measurements that were described in the previous sections.

The earliest applications were simulating dynamic ice–structure interaction by solving the equations of motion of the structure with a coupled nonlinear ice strength dependence on loading rate [4, 26]. The aspect ratio effect in ice crushing was numerically solved by developing a nonlinear large-displacement finite-element model with viscoelasto-plastic ice behavior [35, 36, 37]. Ice sheet buckling against offshore structures has also been analyzed by taking ice viscosity into account [43, 44]. For offshore structures, finite element modelling of a caisson island was used to simulate ice–structure–soil interactions.

A theoretical model to explain the fundamentals of ice friction with low velocities was developed taking the energy balance at the contact zone as a starting point [33, 34].

A new area in numerical modelling, as well as in theory, is to observe the effect of cracking in the ice material model, (continuous damage models). There are two doctoral candidates at the University of Oulu working with this topic, and results are expected in 1987. Preliminary results have indicated excellent agreement in all strain rates including transitions from the ductile range to brittle range in tension or compression.

The development of theoretical models of ship resistance in ice in Finland has motivated research in the different disciplines of ice mechanics, which include the mechanical properties of ice, local ice crushing against hulls, global dynamic ice sheet failure, friction, etc. Subsequently, the results of these projects have been used to update the Baltic Ice Class Regulations [48].

Numerical models are also being developed to simulate ship powertrain dynamics and control while the propeller is hitting ice floes [5] (Fig. 13). Another problem, ship kinetics while maneuvering in ice, is also being studied [15].

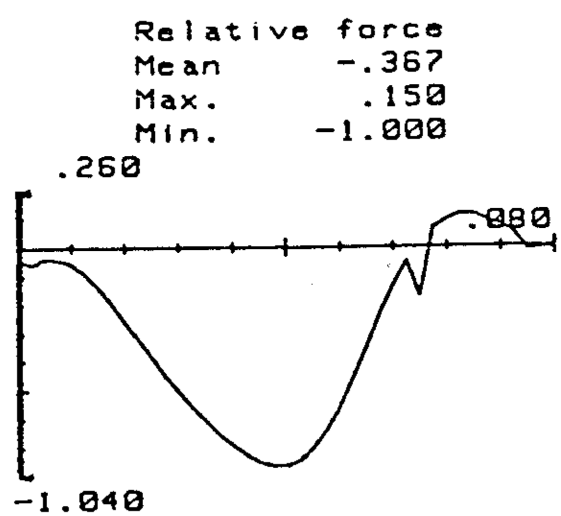

FIG. 13. Ice flow hitting a propeller blade, load versus time [8].

EDUCATION

Most of the ice mechanics researchers in Finland are self-taught. Even though ice and a cold climate are familiar to everyone, there is no specialization in the ice mechanics field either in the secondary or university levels of education. Only the University of Oulu has devoted lecture courses to the subject of ice mechanics, and these have been running since 1981. In conjunction with courses on shipbuilding at the Helsinki University of Technology there exists a long tradition of teaching basic knowledge about ice.

INTERNATIONAL COOPERATION

As a small country, Finland is bound to cooperate with foreign countries. There are more scientific and technological contacts to the west than to the east.

There is a long tradition of scientific–technological cooperation between Finland and the Soviet Union even though the Arctic Technology Subcommittee was founded as late as 1981. The objective of this subcommittee is to promote and coordinate the cooperation between Finnish and Soviet organizations and enterprises concerning the exploitation of hydrocarbon resources on the continental shelf of the Soviet Arctic seas.

The working procedure of the Arctic Technology Subcommittee is the following. Mutually interesting and important research topics are chosen and assigned to executive organizations. The research itself is usually conducted separately and results are presented together with reports in joint meetings. Researcher interchange is officially encouraged but in practice it has been realized only in limited cases. More than 10 proprietary reports have been produced thus far. From the Finnish point of view the most interesting results have been the Soviet methods of designing offshore structures against ice forces.

With western world partners, Finnish industry has cooperated in an *ad hoc* manner on several occasions in the field of arctic activities, including involvement in projects in the area of ice mechanics. Perhaps the best known has been the Manhattan project in the 1960s with Exxon. Lately there has been a trend to establish permanent cooperation agreements or to become an active partner. In addition to benefitting research, this is also a straight channel to an otherwise protected market or a way to acquire specialized knowhow.

In the public sector Finland has cooperated with the Swedes in winter navigation since 1924. Research is coordinated and sponsored by the Finnish–Swedish Winter Navigation Research Board. By June 1986 this cooperation produced 43 research reports. Other major results are the Baltic Ice Class Regulations and the Baltic sea ice model [48, 20]. The Technical Research Centre of Finland has a research cooperation agreement with the US Army Cold Regions Research and Engineering Laboratory (CRREL) and the University of Alaska. With the latter, first research projects have already yielded results on ice strain measurements and on adhesion and spray ice accretion research [42, 23]. In addition to the above-mentioned organizations there has also been an exchange of researchers with CRREL [27, 28] and the National Research Council of Canada [40]. Further ice mechanics cooperation is expected with German and Japanese research organizations.

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Advances in ice mechanics in West Germany

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Ice research in West Germany (Federal Republic of Germany) started after World War II with the first small ice tank built at HSVA in Hamburg in 1958. The discovery of hydrocarbons in the Arctic and the membership in the Scientific Committee for Antarctic Research led to the need for model tests and the advancing ice modelling techniques. In 1984 a new, large ice model basin was built at HSVA. Substantial progress has been made in the experimental research of basic ice mechanics and ice forces for the past 20 years. Computational methods and quantum statistical approach have recently been introduced for the study of ice properties. Predicting methods of ice forces with model and full scale experiments have been investigated. This paper highlights West German contributions for the last 20 years.

INTRODUCTION

Although the first icebreaker was built by Steinhaus in 1878 with a spoon bow type forebody, ice research in West Germany started only after World War II. A first small ice tank was constructed at the Hamburgische Schiffbau-Versuchsanstalt (HSVA) in 1958, in which the so-called "Stampfanlage"—a rotating eccentric mass—was developed as an icebreaking aid. Some years later, Schwarz [13] carried out uniaxial strength tests on various types of ice and measured ice forces on a vertical pile at the Eider River [14]. The discovery of hydrocarbons in the Arctic also stimulated the Germans to intensify their ice research. This led to the construction of an ice model basin in 1971 and the development of ice modelling techniques and of new icebreaking ships.

Another boost came from West Germany's desire to become a full member in the SCAR (Scientific Committee for Antarctic Research). This membership required Antarctic research, in the course of which a new polar research vessel (POLARSTERN) was built in 1982, a polar research institute [Alfred-Wegener-Institut für Polarforschung (AWI)] was founded in Bremerhaven and a permanent station was established on the Antarctic continent (Georg von Neumeyer Station) both in 1981.

The demand for model tests in ice and the advancing ice modelling techniques motivated HSVA in 1982 to build a new, large ice model basin which was inaugurated in 1984 in conjunction with the International Association for Hydraulic Research's (IAHR) Symposium on Ice.

BASIC ICE MECHANICS

Brockamp and Querfurth [2] established the *E*-modulus of freshwater ice by seismic methods; their results and those of their scholars (eg, Kohnen and Reuter) are used even today in handbooks [1]. Strength tests on river, lake, and sea ice were carried out by Schwarz [13]. In these tests the uniaxial compressive strength was established as a function of strain rate (nominal), temperature, and air content. It was found that the strength increases with strain rate, and that it reaches a maximum at approximately $\dot{\epsilon} = 3 \times 10^{-3} s^{-1}$ and drops off at higher strain rates. Cubes were used as test specimen and the strain rate was only nominal because the strain rate was not picked up from the ice sample nor was the deformation velocity constant throughout the test.

The testing techniques for establishing mechanical properties of ice have been significantly improved by Häusler [5], who used the closed loop technique to control the strain rate throughout the test and applied the brush-platen-technique to provide a uniaxial state of stress throughout the specimen. In addition, he expanded the testing capability of the machine to allow measuring of true triaxial strengths (Fig. 1). Based on this modified equipment Häusler established the triaxial failure criterion for saline ice [5].

In a further study, Häusler [7] carried out a series of 128 strength tests in uniaxial compression and tension and in biaxial compression on columnar grained ice grown from 1% urea doped water in an ice model basin (urea content within the ice, ca. 0.25%).

The strengths have been used to determine the five coefficients of planar isotropic Pariseau yield functions for the six combinations of strain rate and temperature investigated.

Figure 2 shows the intersections of the yield surfaces defined by the above coefficients with the σ_1–σ_2 and σ_1–σ_3 planes of the principal stress space.

The results of this study are summarized as follows:

- The complete even multiaxial niveau of strength raised with increasing strain rate in the ductile regime, and leveled out when reaching the brittle regime.
- Ductile tension yield strength was equal to the compression yield strength at the same strain rate, while in the brittle regime the compressive strength was two (perpendicular to growth direction) to three times (parallel) the tension strength.
- The biaxial strength in plane with the ice cover was from fourfold (high strain rate) up to sevenfold (low strain rate) the uniaxial compressive strength in the same plane, while the

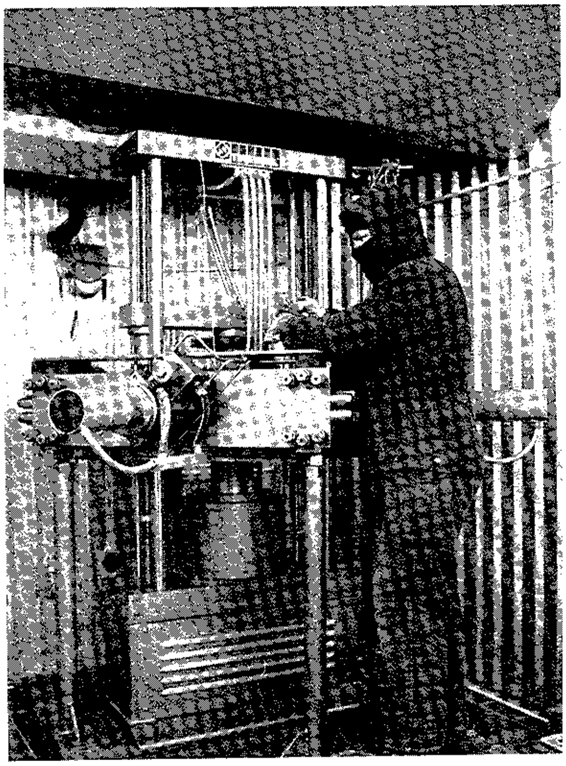

FIG. 1. Triaxial strength test apparatus.

biaxial strength in a plane parallel to the growth direction exceeded this strength only by a factor of 1.1 to 1.3.

- In uniaxial compression the ratio between the strengths parallel and perpendicular to the growth direction was 2 to 5, while in uniaxial tension it was 1.5 up to 3; in both cases the factor became smaller with decreasing strain rate.
- In plane with the ice cover the shear strength was in all cases about 40% of the uniaxial compressive strength.
- The σ_{31} shear strength in a plane parallel to the growth direction decreased from about 75% at 10^{-5} s^{-1} strain rate to about 22% of the uniaxial compressive strength in plane with the ice cover at 10^{-3} s^{-1}.
- In plane with the ice cover the ratio between the G_{12} shear modulus and the E_{11} elastic modulus as well as the ν_{12} Poisson number equaled the values of an isotropic material.
- The G_{31} shear modulus in a plane parallel to growth was found to be a quarter of the G_{12} shear modulus in plane with the ice cover.

In order to find out how well the deformation behavior of ice covers can be predicted by means of the finite element method (FEM), the above failure criteria have been implemented in a nonlinear finite element program [10] in conjunction with an anisotropic elastic-plastic material model. Using this simplified material model, calculations were carried out on an FEM model of point loaded model ice covers, which were geometrically almost equal to ice covers loaded physically in the ice model basin. The comparison of computed and measured forces and deformations showed that the deformation behavior of columnar grained ice covers can be predicted—even though not fully sufficiently—by means of nonlinear FEM analyses applying an elastic-plastic anisotropic material model [8].

In a joint research project between the HSVA and MAN-Technologie GmbH crystallographic and mechanical properties of saline (NaCl) ice have been determined by a quantum statistical approach which is based on molecular and atomic input data. Quantum statistics and self-consistent field method were used on a microscopic level, while fluid dynamic theories have been applied to describe the phonon turbulence in the macroscopic range. The feasibility and accuracy of this theoretical approach has been confirmed by experiments which have been carried out on the tensile and compressive strengths (Fig. 3) as well as on the E- and G-moduli at various strain rates [16]. Of special interest are the theoretically calculated strength data at high strain rates, where experimental results are difficult to obtain: Classical ice mechanics has assumed that the strength, after reaching a maximum at a certain strain rate ($\dot{\epsilon} = 10^{-3}$ s^{-1}), decreases and remains constant with further increasing strain rate. The theoretical calculation by the use of quantum statistical theory, however, predicts both for tensile and for compressive strength a significant increase at strain rates

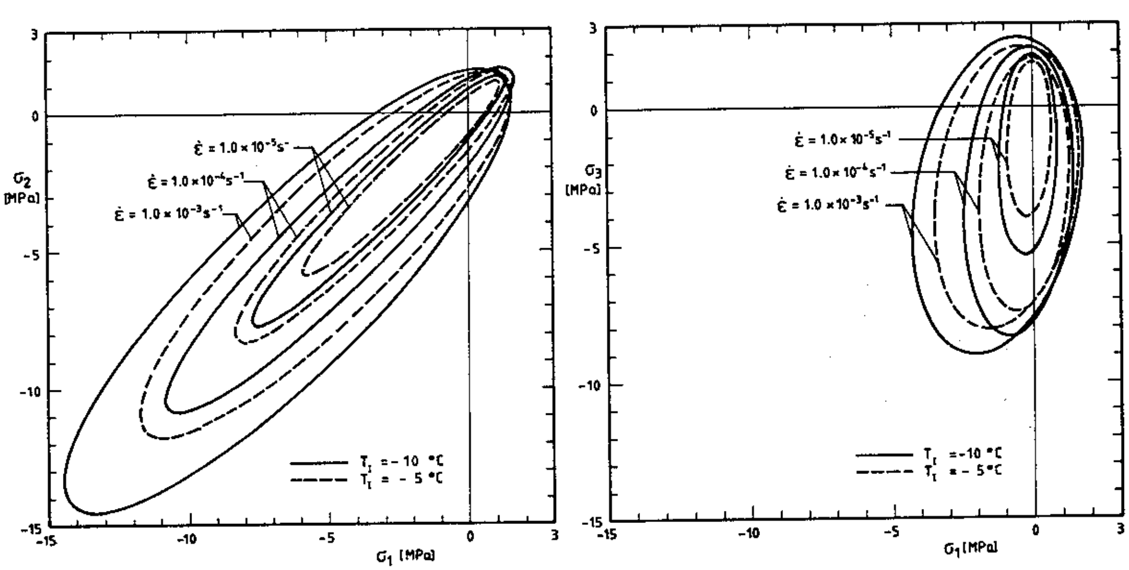

FIG. 2. Failure surface σ_1–σ_2 and σ_1–σ_3 of carbamide model ice [7].

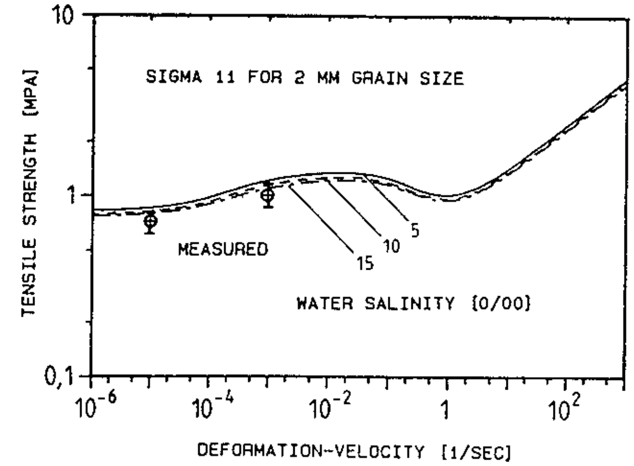

FIG. 3. Tensile strength as a function of strain rate as obtained by quantum mechanics and experiment [15].

$\geq 10^0\ s^{-1}$. Results of Lange and Ahrens [9] seem to confirm this increase in strength at higher strain rates.

Another area of research at HSVA is the investigation of the mechanical properties of mush ice. For this purpose a shear box and a viscosimeter were developed. Figure 4 shows the general layout of the transparent shear box, which has a shear surface of 0.5 m^2 on each side of the main chamber. The velocity can be varied between 1 and 300 mm s^{-1}. The normal pressure from both side chambers can be varied up to 20 kPa.

Results of shear strength tests for mush ice of different piece size distributions show that τ, the internal shear strength, decreases with increasing shear velocity and increases linearly with normal pressure; the internal shear angle can reach values of approximately 60° if the shear velocity is small.

In addition to the shear tests, the resistance of simple bodies (cones, plates) has been measured when they were pushed at different velocities through mush ice. The results of these tests indicate a shape and velocity dependency of the resistance. Furthermore it was found that not the projected area of the body but the shear plane is the relevant parameter in describing the resistance (shear failure).

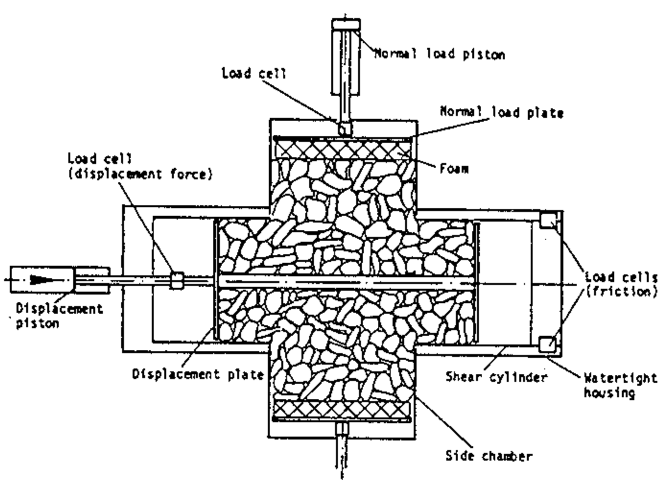

FIG. 4. Graphical illustration of shear box.

MODEL TEST FACILITIES

For more than 10 years, HSVA has operated an ice model basin of 30 m length, 6 m width and 1.2 m depth. With the advancing ice modelling technique this tank became too small. Therefore a new larger ice model basin was built and inaugurated in 1984 [15]. This large ice tank is 78 m long (test length: 60 m), 10 m wide and 2.5 m deep (see Fig. 5). One section of 12×10 m has a depth of 5 m. The motor driven towing carriage provides a speed range of 1 mm/s to 3000 mm/s. The carriage weighs approximately 50 tons. Due to its friction drive, the towing force capacity is approximately 50 kN. The air cooling system provides temperatures as low as −25°C. The model ice presently used for testing is made from a carbamide solution.

An underwater carriage runs on a track at the bottom of the tank; it provides a foundation for offshore structure models. The same track is used for a television camera carriage. Direct observations of the model tests from below are possible through windows in the bottom of the tank. In order to simulate deep water conditions in connection with fixed articulated or moored offshore structures, the large ice tank has a well at its end.

The following ice conditions can be simulated:

level ice,

rafted ice,

broken ice,

pressure ridges,

rubble ice, and

mush ice.

Possible modes of model tests are:

resistance tests,

self-propulsion tests,

ramming tests,

maneuvering tests,

propeller tests in ice-water mixtures,

measurement of forces on fixed offshore structures,

measurement of mooring forces and movements of floating offshore structures,

special tests under shallow water conditions, and

ice management tests.

ICE FORCES ON STRUCTURES

The determination of ice forces on structures started in West Germany in the late 1960s with full scale measurements on a bridge pier at the Eider River [14]. These full scale data were used to prove small scale test results of ice forces on vertical piles obtained by Schwarz, Hirayama, and Wu [17] at the Iowa Institute of Hydraulic Research (USA). For circular piles the effective pressure of level ice was found to be

$$\sigma_{eff} = 3.56\sigma_0 d^{-0.5} h^{0.1}, \qquad (1)$$

where σ_0 = uniaxial compressive strength; d = pile diameter (cm); and h = ice thickness, (cm).

Even though full scale measurements of level ice forces on piles up to 2 m diameter were in good agreement with forces as established by formula (1) it was always a question up to which structure width this formula could be applied.

Only recently, Sanderson [12] published a paper in which he showed (Fig. 6) that all available model and full scale data of

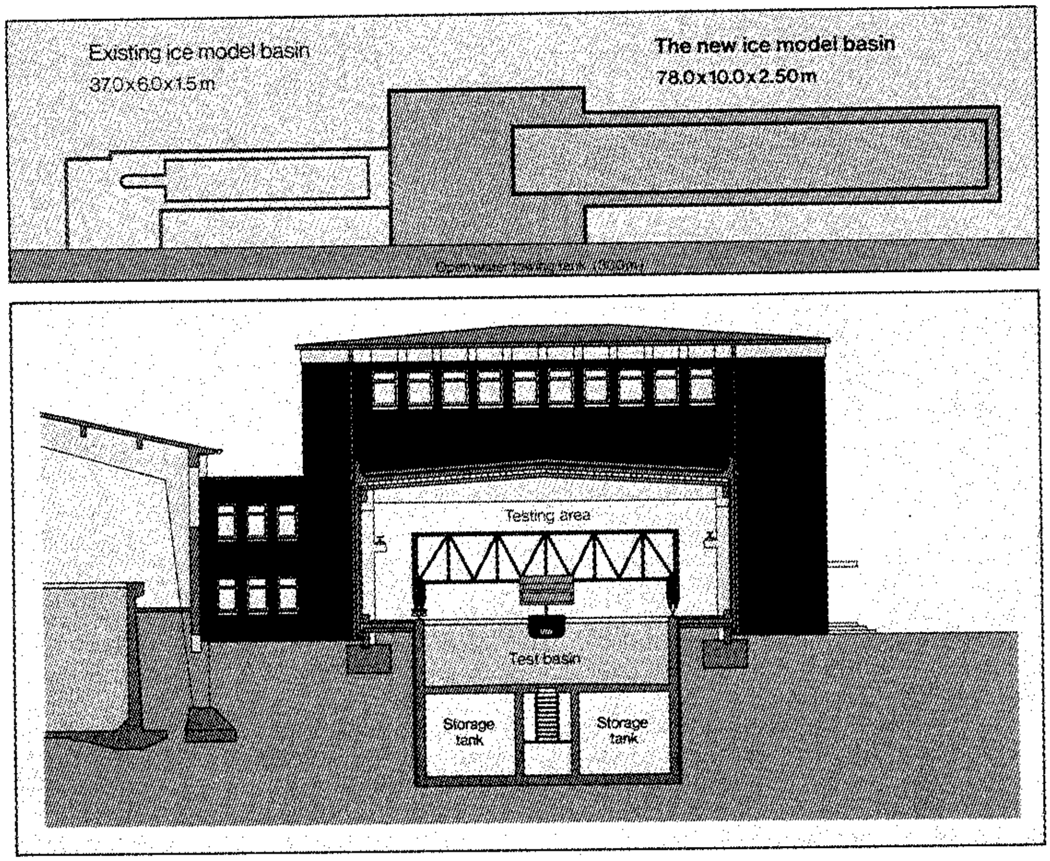

FIG. 5. Graphical illustration of HSVA's new ice model basin.

effective ice pressure on structures followed the relationship

$$\sigma_{\text{eff}} \propto A^{-0.5}, \tag{2}$$

$$\sigma_{\text{eff}} \propto d^{-0.5}. \tag{3}$$

From Sanderson's paper it can be concluded that $d^{-0.5}$ in formula (1) is valid for slender piles as well as for structures of more than 100 m width. Sanderson explains the significant decrease of effective pressure with structure width by the non-simultaneous ice failure over the structure surface. This explanation is supported by the force records which were obtained by Schwarz [14] at five load cells located side-by-side half way around a 60 cm diameter pile (Fig. 7).

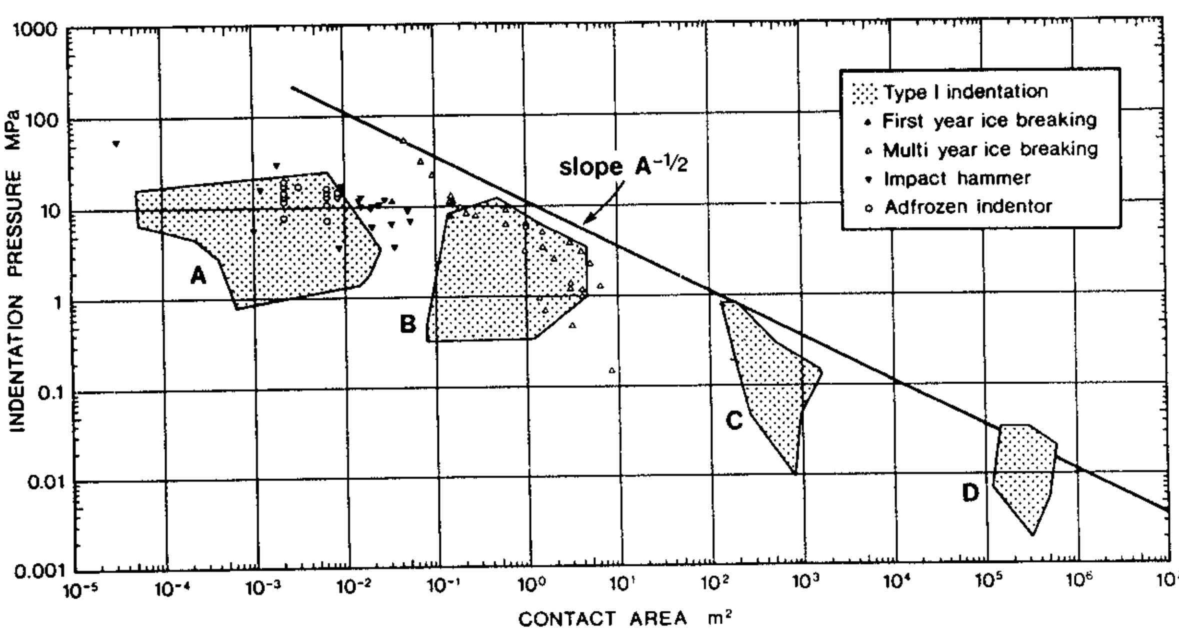

FIG. 6. Indentation pressure versus contact area; after Ref. 12. A = Laboratory tests; B = lighthouses, bridge piers; C = arctic islands and structures; D = Meso scale models.

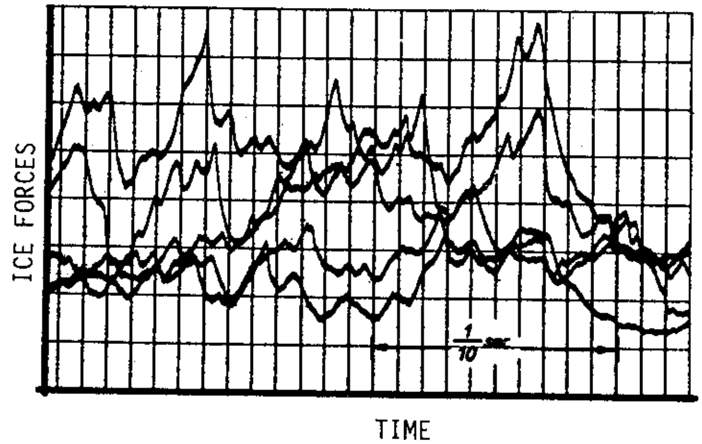

FIG. 7. Record of ice forces on five side-by-side load cells versus time [14].

Ice forces on structures have been determined at HSVA by model tests as well as by full scale measurements. Besides the parameter study on ice forces on vertical piles, conical structures [18] and multilegged structures [3] have been tested within the joint industry project COSMAR.

The most challenging model test program HSVA has performed so far were the tests for Gulf Canada's Conical Drilling Unit (CDU), which is being operated successfully in the Beaufort Sea for exploration under the name "Kulluk." The CDU is a floating circular polygon consisting of 24 sides. It was designed to break ice by way of its downward breaking conical shape. It is moored by 12 mooring cables. In the model tests these cables were simulated by wire ropes and springs which were selected so as to reproduce the required spring constants. In order to simulate the entire dynamic behavior of the CDU, not only the mooring system but also the full scale dynamic trim conditions were simulated. A certain preload was applied to all 12 mooring cables. Measured items were the 12 mooring cable forces, the motions in x, y and z directions, pitch, roll, and yaw.

In the course of the model tests, the underwater shape of the CDU was modified to prevent ice ingestion into the mooring lines under normal operating conditions. The tests were carried out in level ice and in level ice with ridges having different degrees of consolidation. In addition, special ice managing tests were performed to establish the towing forces through various ice conditions in order to develop procedures for towing the CDU most efficiently. Full scale measurements of ice forces against Kulluk were carried out by Gulf Canada [11]. They show the reliability of HSVA's predictions by model tests (Fig. 8).

Biaxial stress transducers (IRAD–GAGE vibrating wire ice stress sensor) were used by HSVA in order to determine ice forces on large structures. The transducers were frozen in the ice cover around a natural island in the Lancaster Sound (Adams Island) as well as around the artificial caisson retained island, "TARSIUT," in the Beaufort Sea.

These full-scale measurements in fast ice conditions of relatively slow ice movement rates showed that almost all of the stress was transmitted in the top 1 m of a typically 1.7 m thick level ice cover. The maximum stress averaged over the full depth of the ice cover was only 250 kPa, which despite the low stress level caused huge ice buckling features. By integrating the ice stresses, which were measured at discrete locations, the global ice load on the natural island and on the exploration structure could be determined [4].

In 1985 HSVA joined the international research project on ice force measurements at Swedish lighthouses in the northern Gulf of Bothnia. The dynamic ice failure at these cylindrical

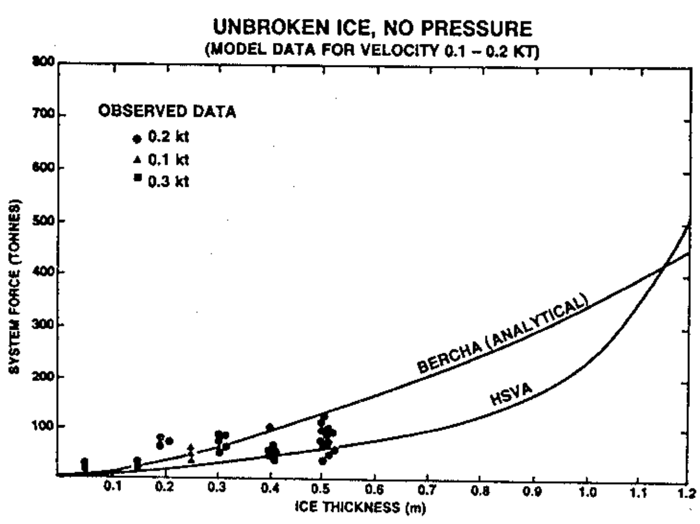

FIG. 8. Ice forces (system) versus ice thickness; comparison between model test prediction, analytical prediction and full scale measurements (after Ref. 11).

offshore structures is characterized by complex load distributions and peak loads of short duration. For these conditions HSVA has developed a two-dimensional ice force panel (TIP), which measures the total load applied over the panel front plate, regardless of how that load is distributed. The panel has a large stiff collector front plate and all load paths towards the support base plate are instrumented by strain gauged load cells. Thus, any local ice pressure distribution will be averaged over the panel area. A unique feature of the TIP-panel is the capability of measuring the shear or tangential ice force component (parallel to the waterline) additionally to the normal ice force component. To date, HSVA has constructed and successfully tested three TIP ice force panels, which will be installed for long term measurements at the Swedish lighthouse Norströmsgrund in summer 1987.

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Recent advances in ice mechanics in Canada

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Work on the mechanics of ice, which has been carried forward on a broad front in Canada, has resulted in a number of significant advances in the last 10 years. The factors influencing the growth of various types of sea ice have been quantified fundamentally and methods for examining the resulting material structure have been developed. Extensive work has been done on strength and deformation characteristics of ice. A significant effort has been the development of analytical expressions to describe the rheological behavior of ice. Elastic modulus, Poisson's ratio, and creep were also treated. A great deal has been done on measuring the compressive strength of various types of naturally occurring ice and subsequently these data were combined into a suitable description of a failure envelope. Work has also been done on measuring the flexural strength, shear strength, adhesion and fracture toughness. Methods for laboratory testing and *in situ* measurements of mechanical properties have been developed. The problem of defining ice forces on structures has been the primary motivation for research on ice. Analytical modelling, physical modelling, laboratory studies and very extensive field studies have been used. Work done in this area has included development of methods and their application to actual problems and has benefitted greatly from the integration of all four approaches. Very significant progress has been made. Ice and ice covers have been successfully used to support various offshore activities: drilling off floating ice platforms, stabilizing grounded rubble fields to protect structures and transporting large loads over ice.

1. INTRODUCTION

Because of Canada's cold climate and offshore gas and oil resources in the Beaufort Sea, Sverdrup Basin, and Hibernia locations, a considerable amount of effort has been spent on research in ice mechanics. Research and funding for research is provided by government, industry, and universities. A large number of relatively small groups of researchers scattered across the country have contributed in the development of ice mechanics in this country. A great deal of work was performed by or under the auspices of the petroleum industry. To coordinate this effort and to help share the high costs associated with carrying out the necessary field projects, the Arctic Petroleum Operators Association (APOA) was established. Also, a strong and active community of consulting firms came into being and expanded to participate in many of these projects. Universities too became active in this area, some on a long standing basis of experience in ice engineering and others developing new expertise. Finally a number of government agencies became active, both in terms of their own laboratory and field programs, and in providing funding.

Canada has been involved in almost all areas related to offshore engineering in cold climates. Advances have been made in increasing the bank of experimental information on ice properties as well as in providing insight and understanding in several key areas. In this paper, the authors have attempted to report on a large number of significant advances made in many areas of ice engineering in Canada during the past ten years. In particular, there is a strong emphasis in the work *offshore* (in both the Arctic and Hibernia locations). These include the physical properties of ice-structure, strength and rheology (Section 2), ice forces on structures (Section 3), and ice as a construction material (Section 4). Due to space restrictions, several areas of ice research (such as river ice engineering, ice navigation, glaciers, etc) have been omitted. It should be kept in mind that this paper represents recent advances in ice mechanics in Canada and it is not intended to be a state-of-the-art review.

1.1. Ice: The material

Although the working temperatures in ice are low in terms of human comfort, they are very high in terms of materials. The temperature of ice in nature rarely goes below $-40°C$ or an equivalent temperature of 0.85 T_m, where T_m is the melting point in Kelvin. Its working temperatures are therefore greater than the homologous temperature of 0.85 T_m. In metals and alloys, working temperatures higher than about 0.4 T_m are considered to be elevated temperatures. At these levels polycrystalline materials, including ice, exhibit pronounced creep and grain-boundary embrittlement. A direct consequence of high-temperature deformation and failure modes is that the strength of ice is rate sensitive and loading history becomes important in ice mechanics. Recent Canadian advancement in ice mechanics is centered around this theme.

The detailed structure of ice, from the microscale to the mesoscale, has a significant influence on the properties, behavior, and interaction processes in ice.

1.1.1. Macrostructure

Ice in nature has a particular grain structure and texture which depends on the growth processes, and thermal and mechanical histories. A classification system for freshwater river and lake ice on the basis of its genesis, structure, and texture was established by Michel and Ramseier (1971). The detailed analysis that led to this classification is given in Ramseier (1976).

1.1.2. Microstructure

Traditional methods for examining the grain structure have been refined, leading ultimately to the double-microtome technique (Sinha, 1977a) that eliminates completely the use of any hot plate. This technique does not disturb the thermal state nor destroy the microscopic structure. A new method of combined cross-polarized light and scattered light technique was also developed. Used with etching and replicating methods and the scanning electron microscope (Sinha, 1977b, 1978a, 1986a) this technique permits insight into the structure and behavior of ice at the microscopic and sub-microscopic level (see Fig. 1). This procedure in conjunction with macroscopic observations and acoustic emission (Sinha, 1982c) showed that the low homologous temperature dislocation pile-up mechanism might not be the prime mechanism of crack nucleation in most engineering situations (Sinha, 1984a). An alternate crack nucleation mechanism, amenable to high temperature, was proposed by Sinha (1982b) which was expanded later to take account of the effect of temperature (Sinha, 1984a) and to model the damage accumulation in creep (Sinha, 1984b). The etching-replicating technique was also used to study the microcracks in ice, revealing the absence of any crack-tip plasticity (Sinha, 1984a).

1.1.3. Microscale

Both the thickness and quality of ice covers are influenced by the past as well as the prevailing climatological conditions. Based on a substantial volume of data on the weather and snow and ice characteristics collected by the Arctic Research Establishment in Eclipse Sound, Baffin Island, and for the winter seasons of 1977–78 and 1978–79 Sinha and Nakawo (1981) proposed a simple numerical integration method for predicting growth of ice in the sea. The method is capable of incorporating variations in snow conditions and physical properties of ice and snow during the growth period. It was shown that rapid desalination occurs within about a week after freezing. Although it decreases very slowly during the rest of the growth season, the salinity could be considered to have attained a quasi-stable value within a few weeks after ice formation. The vertical salinity profile in the ice toward the end of the season provides a record of previous climatological conditions. A relation has been shown between the predicted growth rate and the measured salinity (Nakawo and Sinha, 1981). It was shown further that the growth rate and hence the growth history determined the vertical variation of porosity and microstructure. (Nakawo, 1983; Nakawo and Sinha, 1984). The average brine layer spacing, a measure of the sub-grain structure, was shown to be inversely proportional to the growth rate as a first approximation. The existence of highly oriented sea ice was also confirmed at several locations in the Arctic (Sinha, 1983a, 1984c; Nakawo and Sinha, 1984).

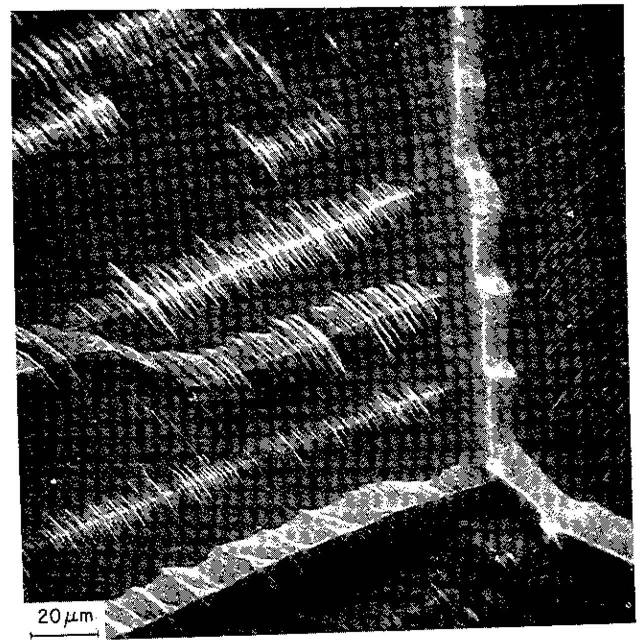
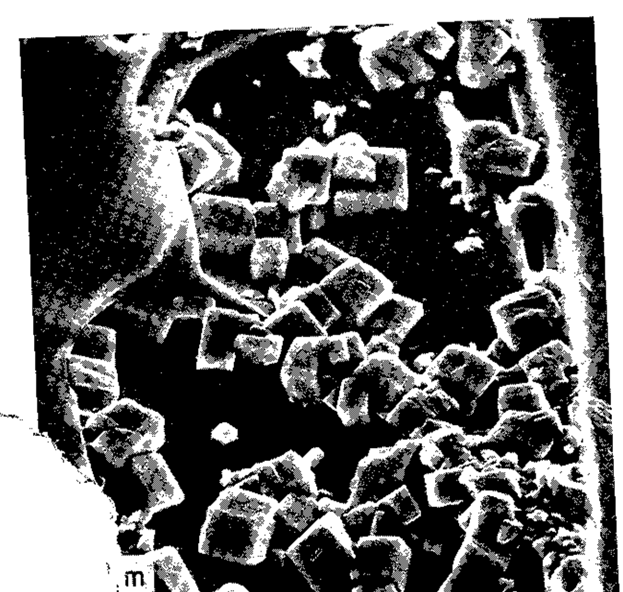


FIG. 1b. Dislocations pile ups against a grain boundary in ice (after Sinha, 1978a).



,alt crystals in brine pocket in sea ice (after Sinha, 1977a).

The aging of a sea ice cover was studied at Mould Bay, Prince Patrick Island during the 1981–82 and 1982–83 seasons. Measurements of the physical, chemical, microwave, and mechanical properties were carried out in October 1981, June–July 1982, and April 1983 on the same ice cover whose entire growth history was recorded continuously by the staff of the Weather Station run by the Atmospheric Environment Services of Canada. The changes which took place in the physical, chemical and microstructural properties during the aging process have been presented by Sinha (1983b, 1984c, 1985a, 1986a), Bjerkelund et al (1985), Holt and Digby (1985), and Digby (1984).

1.1.4. Mesoscale

For a safe structural design of a structure which is to be used in ice-covered waters, it is necessary to know the maximum credible size, thickness, and concentration of any ice features in the region. This, along with a knowledge of the mechanical and rheological properties of the ice, can then be used in appropriate predictive equations for estimating both global and local loads on the structure. For several years there has been considerable effort spent on observing, recording, and predicting the large (or meso) scale ice conditions in Canadian waters. Several Canadian government agencies such as the Atmospheric Environment Service (AES) and Canada Centre for Remote Sensing (CCRS) have been instrumental in providing information on ice conditions in the Arctic, Gulf of St. Lawrence, and Great Lakes, and east Newfoundland and Southern Labrador. In addition, several private companies such as Canarctic Shipping, Nordco, INTERA, Canmar, Bercha Alberta, etc have provided ice reconnaissance information. Several sophisticated remote sensing devices are actively employed including laser profilometer, infrared line scanner, airborne radiation thermometer, synthetic aperature radar (SAR) and side-looking airborn radar (SLAR). These are used along with satellite imagery (TIROS/NOAA and LANDSAT) to develop composite charts of current ice conditions. Due to space limitations a review of this topic is not possible here. For recent work, see eg Rossiter and Bazeley, 1980; or information can be obtained from the Directors of AES in Downsview, Ontario and CCRS in Ottawa.

In addition to significant improvements in the area of remote sensing of ice, a considerable effort has been devoted to ground truthing or directly measuring the ice features in the Arctic and offshore Newfoundland. Several industry sponsored programs have documented the characteristics and statistics of extreme ice features in these areas. For the Beaufort Sea, studies on ridging include those of Wright et al (1981), Hudson (1982, 1983), Spedding (1982), and Metge et al (1982). For the east coast, a knowledge of the number, size, distribution, shape, movement, etc of icebergs are of particular importance, and several studies have documented these including Lowrey and Miller (1983) and Diemand (1983). The staff from Memorial University, C-CORE and Bedford Institute are particularly active in this area. Several models have been developed to predict the behavior of the ice on the mesoscale including models to estimate the forces involved in the ridge-building process (Sayed and Frederking, 1984, 1986), and to predict the drift trajectories of icebergs (Sodhi and El-Tahan, 1980; El-Tahan, 1980; El-Tahan et al, 1986; Smith and Banke, 1983; Lever and Sen, 1986; Chandler, 1986; Gaskill and Harris, 1986). In 1980 a workshop on ridging and pile-up summarized Canadian work in the area (ACGR, 1982). A three-day workshop on extreme ice features was held recently in Banff, Alberta under the sponsorship of the NRC Snow and Ice Subcommittee. The Proceedings of this workshop provide a good overview of the knowledge of the size, extent, and physical properties of extreme ice features (Pilkington, 1987) in Canada.

2. MECHANICAL PROPERTIES

2.1. Strength

2.1.1. Introduction

The strength of ice is the maximum stress which an ice specimen can support. It is the mechanical property which is of great importance when dealing with problems such as the determination of ice forces on a structure, load bearing capacities of ice covers, etc. To date, numerous investigators have measured the strength of ice. A comprehensive review of earlier investigations on mechanical properties of fresh water ice have been made by Gold (1977) and Michel (1978b). A compilation of test results on sea ice has been made by Lainey and Tinawi (1984). Many factors influence the response of ice including temperature, salinity, density, ice type, grain size, specimen size, loading rate, and failure mode. In spite of its complexity and the number of factors influencing it, an understanding of strength as a material property is emerging. In this section, the strength studies and subsequent understanding of ice strength by Canadians is documented for compressive strength (Section 2.1.2), shear strength (Section 2.1.3), flexural strength (Section 2.1.4), failure envelope (Section 2.1.5) and fracture toughness (Section 2.1.6).

2.1.2. Compressive strength

The strength of ice in compression is of fundamental importance in almost all aspects of ice mechanics. Studies in Canada can be categorized into three different types: *uniaxial* compression in which a uniform uniaxial stress is applied to a specimen; *multiaxial* compression in which a more complex stress state is applied to a specimen; and *in situ* where the ice is tested in its natural state in the ice cover. These tests have been performed in both freshwater ice and sea ice. Three commonly applied loading conditions for determining strengths are (a) constant displacement rate, (b) controlled constant strain rate, and (c) controlled load or stress rate. Most of the experiments have been conducted under category (a) because of the availability of universal test machines, capable of delivering precise cross-head displacement rates over a wide range. Strength values obtained under this condition at the same cross-head rate have been shown by Sinha (1981a) to vary from one machine to another. Efforts have been made in the last four years to carry out tests under categories (b) and (c) using a closed-loop test system.

Uniaxial compression: Many tests have been performed to measure the uniaxial compressive strength of freshwater ice, both laboratory grown and field ice. These studies include those of Parameswaran and Jones (1975), Ramseier (1976), Frederking (1977), Michel (1978a,c), Sinha (1981b, 1982a, 1982b, 1982c), and Jones and Chew (1983) on laboratory grown ice; Vittoratos and Kry (1979) on lake ice; Gammon et al (1983a), El-Tahan et al (1984), Nadreau (1986), and Sinha and Frederking (1987) on iceberg ice; and Frederking and Timco (1981, 1983a, 1984a), and Timco and Frederking (1980, 1984, 1986a), and Sinha (1983a, 1983b, 1984c, 1985a, 1986a, 1986b) on first-year, second-year, and multi-year ice; and Sinha et al (1986) on offshore built-up platform ice.

Strength values, ranging from 0.5 to 10 MPa, are a strong function of loading rate. Gold (1978) and Nadreau and Michel (1984a) reviewed some of the earlier published literature on the basis of nominal strain rate, $\dot{\varepsilon}_n$ and noted that the strength increases with strain rate to $\dot{\varepsilon}_n \simeq 10^{-3}\ s^{-1}$ whereupon strength values generally decrease with increasing strain rate. In most uniaxial tests described in literature, the strength of the ice is obtained by loading with a constant displacement rate for which the nominal strain rate of the ice is given by $\dot{\varepsilon}_n = \dot{x}/l$, where $\dot{x}$ is the cross-head rate and l is the specimen length. These types of tests are usually referred as "constant strain rate tests" and created confusion in the literature, not only in the field of ice but also in material science as a whole. Sinha (1981b) has shown that interpretation in terms of *nominal* strain rate can be significantly in error, as the actual specimen strain rate is not constant during a test of this type. Strain rate in the specimen increases monotonically with time and approaches the nominal strain rate only after reaching maxi[m] stress for upper yield type failure. The stiffness of t[h] system affects both the pre-yield behavior and fai[l] such that the measured "strength" value depend[s] stiffness of the test machine if conventional analysis nominal strain rate is used for the category (a) tests Frederking, 1979). It is shown that a lower capaci yields lower strength (Sinha, 1981a). Moreover, th ductile-to-brittle transition depends upon this syste The analysis by Sinha (1981b) has been instrumental the methods by which uniaxial (a) type tests are analyzed. Further, it emphasizes the need to perform these types of tests using test machines in which the strain-rate or stress-rate can be controlled accurately. Whether the tests are conducted under category (a) or under (b) there is a strong relation between upper yield failure stress, σ_f, and the corresponding failure time, t_f. Sinha [1981b, category (a); 1982b, category (b)] noted this dependence as

$$t_f/t_0 = C(\sigma_f/\sigma_0)^{-\theta}, \tag{1}$$

where C and θ are constants, t_0 is the unit of time (= 1 s), and σ_0 is the unit stress (= 1 MN m^{-2}). There is a remarkable similarity between this equation and the dependence of creep rupture time on stress for metals and alloys at high temperatures. Numerical values of θ at $-10°$C have been found to be in the range of 2.3 to 2.8 for columnar-grained freshwater ice [Sinha, 1981b, category (a) and 1982a, category (b)] as well as sea ice [Sinha, 1983a, 1984a, 1986b—category (a)] with load applied normal to the columns and frazil sea ice [Sinha, 1984c—category (a); Sinha 1986a—category (b)] and built-up platform ice [Sinha et al, 1986—category (a)]. Tests involved four different test machines ranging in capacity from 9 kN to 1 MN indicating large differences in stiffness. Equation (1) applies also to *in situ* borehole jack tests (Sinha, 1986b) where θ was found to be 2.1. It is also applicable to confined tests in first-year sea ice (Sinha, 1986b) and second year sea ice (Sinha, 1985a).

The simplest evaluation of the rate sensitivity of strength, as suggested by Sinha (1981b) is to be obtained by using the average stress rate to failure $\dot{\sigma}_f = \sigma_f/t_f$. It can be shown using eq. (1) that

$$\sigma_f/\sigma = M(\dot{\sigma}/\dot{\sigma}_0)^m, \tag{2}$$

where $\dot{\sigma}_0$ is the unit stress rate (= 1 MN m^{-2} s^{-1}), $M = C^m$, and $m = 1/(1+\theta)$. Equation (2) has been successfully applied by Sinha in all his work mentioned above. Although θ and hence m does not show much sensitivity to ice types, loading direction or temperature, C and hence M does vary significantly with variations in these factors. Similar observations were also made by Frederking and Timco (1981) who measured the compressive strength of vertically-loaded land fast ice in the Beaufort Sea and the strengths of both vertically and horizontally loaded ice around Tarsiut Island (Frederking and Timco, 1983a, 1984a).

Most recently, Timco and Frederking (1986a) analyzed many of these data for category (a) tests and found that the uniaxial strength of columnar ice could be related to the average stress rate by

$$\sigma = 8.4(\dot{\sigma}_a)^{0.22}\left(1 - \sqrt{v_T/320}\right) \tag{3}$$

for horizontally-loaded samples, and

$$\sigma = 32.6(\dot{\sigma}_a)^{0.22}\left(1 - \sqrt{v_T/280}\right) \tag{4}$$

for vertically-loaded samples, where σ is in MPa, $\dot{\sigma}$ is in MPa s^{-1} ($10^{-3} \le \dot{\sigma}_a \le 10°$) and v_T is the total porosity (brine + air) in parts per thousand. Similar expressions have been determined in terms of nominal strain rate. These equations relate the uniaxial compressive strength of columnar sea ice explicitly in terms of loading direction, loading strain rate, loading stress rate, and total porosity of the ice, and implicitly in terms of ice salinity, temperature, and density.

Justification for the above approach of using stress rate comes from the fact that load and time can both be measured readily and accurately without much difficulty. Moreover, the response of a test system is reflected in the measured loading rate and consistent results, useful for the purpose of comparison, are obtained using stress rate. These results should not, however, be considered the material property under truly constant stress rate. This is primarily because stress rate is not constant in these tests but approaches zero at upper yield and then reverses. Category (c) tests conducted by Sinha (1982a), using a closed-loop controlled system, indicated that the stress-rate dependence of upper yield stress, as derived from category (a) tests and eq. (2), underestimates strength under truly constant stress-rate. Stress-rate analyses could, under certain circumstances depending on the load capacity of test system, lead to erroneous results and hence erroneous conclusions (Sinha, 1983a).

There is no substitute for measuring both the load and specimen deformation. With known stress and strain histories, analyses can be made simpler, more straightforward and devoid of misinterpretation (Sinha, 1981b, 1982a, 1983a, b, 1984c, 1986a; Timco and Frederking, 1983a). For category (b) tests under controlled constant strain rate, $\dot{\varepsilon}_c$, the dependence of upper yield σ_f on $\dot{\varepsilon}_c$ can be presented as

$$\sigma_f/\sigma_0 = P(\dot{\varepsilon}_c/\dot{\varepsilon}_0)^p, \tag{5}$$

where P is the failure stress at unit strain rate, $\dot{\varepsilon}_0$ (= 1 s^{-1}) and p gives the strain rate sensitivity. Equations (5) and (1) give all the interdependence between σ_f, t_f and failure strain ε_f.

To date, only two sets of data from Canada for category (b) tests are available in the open literature. From true constant strain-rate ($\dot{\varepsilon}_c$) tests, the uniaxial upper yield strength (σ_f) at $-10°$C of horizontally loaded columnar grained freshwater ice is given by $\sigma_f = 212(\dot{\varepsilon}_c)^{0.34}$, where σ_f is in MPa and $\dot{\varepsilon}_c$ is in s^{-1} such that $1 \times 10^{-7} \le \dot{\varepsilon} \le 1 \times 10^{-4}$ s^{-1} (Sinha, 1982a). The corresponding relation for congealed frazil sea ice (salinity: 5‰) at $-10°$C is found to be $\sigma_f = 70(\dot{\varepsilon}_c)^{0.34}$ for $\dot{\varepsilon}_c \le 2 \times 10^{-3}$ s^{-1} (Sinha, 1986a). The strains at failure are less than 1×10^{-3} for freshwater ice and less than 2×10^{-3} for sea ice.

Equation (5) applies well to category (a) tests also, giving comparable values for P and p, if $\dot{\varepsilon}_c$ is replaced by the average strain rate to failure, $\dot{\varepsilon}_{af}$. However, the customary use of $\dot{\varepsilon}_n$ gives only a good estimation of p. In this case P value depends on stiffness of the machine and usually a higher value is obtained with stiffer machines (Sinha, 1981a). Detailed comparison between the two common types of tests can be seen in Sinha (1981b, 1982a) for freshwater ice and in Sinha (1984c, 1986a) for sea ice. The latter papers also compare field tests with laboratory tests and examine the suitable methods of transportation and storage of sea ice. These tests also assisted in drawing a conclusion that the strain rate sensitivity, as given by the value of p in the previous paragraph, is the same for freshwater as well as sea ice.

One to one numerical correspondence between the rate effect on strength in controlled constant strain rate, category (b) test, and the rate effect on viscous flow in a constant load or stress creep test, to be discussed in Section 2.2.2, were established for pure freshwater S-2 ice by Sinha (1982a), who showed that the two sets of results are related numerically by

$$\dot{\varepsilon}_{v_0} = P^{-1/p} \text{ and } n = 1/p, \tag{6}$$

in which $\dot{\varepsilon}_{v_0}$ is the viscous flow rate for unit stress and n is the stress exponent. The applicability of eq. (6) for sea ice is still an open question, primarily because of lack of constant stress creep data on sea ice.

Michel (1978a) has proposed a phenomenological model to describe the crushing strength of freshwater ice in both the brittle and ductile range of ice behavior. In the brittle regime, Michel proposed that the crushing strength σ_f(Pa) is

$$\sigma_f = 9.4 \times 10^4 (d^{-1/2} + |\theta|^{0.78}), \tag{7}$$

where d is the grain size (in m), and θ is the ice temperature (in °C). In the range of ductile behavior, Michel proposed an equation of the form

$$\dot{\varepsilon}_n = A\sigma_f^n \exp(-Q/R\theta^*), \quad (8)$$

where $\dot{\varepsilon}_n$ is the nominal strain rate, A and n are constants, Q is the activation energy, R is the universal gas constant, and θ^* is the absolute temperature. These equations yield a relatively good fit to the strength data reported by Michel.

Both eqs. (7) and (8) should be used with caution. Equation (7) bears similarity to Hall–Petch relation developed for yield strengths in metals and alloys at low temperatures. Jones and Chew (1983) did not find any grain size effect on compressive strength for granular ice. While trying to find an explanation for the observed differences, Sinha (1983c) noted that in all of these studies on ice, including those carried out elsewhere, the dependence of strength on grain size was examined by conducting tests in which other parameters, as well as the grain size, varied. Moreover, in Michel's tests various grain sizes actually represent different types of ice with different textures and fabric such as frazil, granular and columnar-grained. It should also be pointed out that eq. (8) suffers from the fact that the strain rate is nominal strain rate and that Q, in this case, depends on σ_f (Sinha, 1984d) which, on the other hand, depends on the stiffness of the test system. Whether the strength of ice depend on grain size and how Q depends on σ_f are still open questions.

Multiaxial compression: The strength of ice under a multiaxial stress state is of interest for the development of failure criteria appropriate to the complex stress states associated with field problems. Confining sub-presses have been used to do biaxial tests and conventional triaxial cells for triaxial tests. All the tests available now in the literature are of category (a). Recently a test system has been developed for doing proportionate loading triaxial tests (Smith et al, 1986). For freshwater ice Frederking (1977) and Croasdale et al (1977) have performed strength measurements on columnar-grained S-2 ice for the case of confined (biaxial) compression. In this case, for both confinement and loading in the plane of the ice cover, the biaxial strength is from 2–4 times higher than the uniaxial strength measured under similar conditions, with the difference being smaller at higher strain rates. Jones (1978), in tests carried out in a triaxial cell on granular T1 ice at −11°C found that at a confining pressure of 30 MPa and a nominal strain rate of 5.4×10^{-4} s^{-1}, the yield strength increased to 12 MPa from about 6 MPa for the unconfined loading case. More recently, Nadreau and Michel (1986a) report on triaxial tests on laboratory made freshwater ice and iceberg ice and on low-salinity granular ice.

For sea ice, there have only been a few multiaxial tests. Timco and Frederking (1983a, 1984, 1986a) report on confined compression tests on granular, discontinuous columnar and columnar ice over a range of loading rates, confinement conditions, and temperatures. Blanchet and Hamza (1983) measured the confined compressive strength with horizontal loading at one temperature and a very limited range of strain rates. Nawwar et al (1983) performed triaxial tests on laboratory-grown saline ice as a function of loading rate, confining pressure, temperature, and loading direction. Sinha (1986b and 1985a) reports respectively on the biaxial confined strength of oriented first-year and second-year columnar-grained sea ice in Mould Bay. He found that for oriented ice, the confined strength could be 10 times greater than the uniaxial strength. He found also that the strength and its rate sensitivity of second-year sea ice was comparable to the strength of laboratory-made freshwater ice tested under ideal conditions. Strength values up to 15 MPa were measured in these field tests.

In situ *field tests*: Measuring the strength of ice *in situ* offers a number of advantages including testing the ice in a relatively undisturbed condition, maintaining ambient temperatures, avoiding transportation problems and having a large scale sample. In addition, in situ testing usually requires a minimum of sample preparation. Several types of *in situ* measuring devices have been developed and tested in Canada. The Fenco borehole jack (Kivisild, 1975; Masterson, 1983) consists of two circular cylindrical surfaces which are jacked horizontally outward into the surrounding ice while the plate pressure is recorded against relative displacement. The device has been used extensively in many field evaluations of ice quality for assessing bearing capacity of ice covers, ice loads on structures, etc. Usually pressure increases monotonically with displacement in a borehole jack test. Assessing a strength index is, therefore, problematic if consideration is given only to the pressure–displacement curve. This explains, probably, why no data on borehole jack tests on different types of ice are available in the open literature. Recent tests by Sinha (1986b) on first-year and multi-year sea ice and Sinha et al (1986) on offshore built-up platform ice have verified that this device, with some modifications in the method of analysis, is very useful in characterizing ice strengths. It was pointed out that analyses must include the loading histories. Sinha has modified the basic borehole jack and a test program with this new version is in progress. Another borehole device is the pressuremeter (Ladanyi and Saint Pierre, 1978; Murat et al, 1986; Ladanyi and Huneault, 1987) which uniformly expands a cylindrical cavity, generating cylindrical stress and deformation fields which are amenable to analysis. More recently, Michel and Hodgson (1986) developed a relatively high-pressure borehole pressure meter to measure the crushing strength of ice. Preliminary results are encouraging. Flat jacks are another type of device used to carry out *in situ* loading in an ice cover (Vittoratos and Kry, 1979).

A test series was performed by Imperial Oil Ltd. (Esso) using the "nutcracker" technique to measure the crushing strength of Arctic ice. In these tests flat and cylindrical indentors up to 1.5 m across were pushed through the ice. Crushing strengths from 4 to 6 MPa were measured (Croasdale, 1974).

2.1.3. Shear strength

Shear is characterized by lateral movement within a material, ie, angular distortion or change in shape. It is considered a separate type of material response to load, although it is really only a special case of multiaxial loading. In many engineering problems there is a need to know the shear strength of ice and, because the complete multiaxial failure behavior is not yet known, shear tests are performed to obtain strength values.

Roggensack (1975) carried out direct shear tests on columnar grained S-2 ice with loading direction perpendicular to and shear plane surfaces parallel to growth direction. The loading rate was 0.1 mm/s and the test temperature −2.5°C. This set of experiments investigated the effect of normal stress, σ_n, on shear strength, τ_f, and found an expression of the form

$$\tau_f = 0.7 + 0.47\sigma_n, \quad (9)$$

where stresses are in MPa and the maximum normal stress in the range 0.5 to 1.4 MPa. Extrapolating eq. (9) to the case of zero normal stress, a shear strength of 0.7 MPa is obtained.

The asymmetric four-point bending method which has been developed for determining the shear strength of fiber reinforced polymers and ceramics has been applied to ice. The technique produces more consistent results than the single or double direct shear methods traditionally used. In tests on granular/discontinuous columnar sea ice of salinity 4‰ (parts per thousand) and at a temperature of −13 ± 2°C, the average shear strength obtained was 550 kPa with a standard deviation of 120 kPa (Frederking and Timco, 1984b). No effect of loading direction or shear plane orientation with respect to ice sheet growth direction was observed. A further test program was carried out on columnar grained sea ice at temperatures of -2 and $-12°C$ (Frederking and Timco, 1986). It yielded an average shear strength of 600 kPa at $-2°C$ independent of loading direction or shear plane orientation. At $-12°C$ shear strength was 700 kPa irrespective of whether the shear plane was parallel to or perpendicular to the ice growth direction and 900 kPa when the shear plane was orientated 45° to the growth direction.

2.1.4. Flexural strength

Information on the flexural strength of ice has application to such problems as measurements of icebreaker performance, determination of ice forces on inclined structures, ridge building and rubble building processes, and establishing safe bearing capacity of ice covers. Flexural testing has the disadvantage of creating a nonuniform complex stress field. It is also an indirect test since the interpretation of the results requires some knowledge of material behavior. On the other hand it has the advantage of simulating, at least in an analogous fashion, a representative loading condition in the ice cover. There are several basic types of flexural tests; ie, cantilever, three-point loading (also called simple beam), four-point loading, and plate loading.

The cantilever beam test has been examined as a method for determining *in situ* flexural properties of floating ice covers. Field tests and finite element analysis of cantilever beams in a 0.4 m thick columnar-grained freshwater ice cover indicated that the application of simple beam theory could result in significant errors in interpreting flexural strength and elastic modulus (Svec and Frederking, 1981) because of stress concentrations and rotations at the root of the beam. This lead to a photo-elastic and three-dimensional finite element analysis of stress concentrations at the root of a cantilever beam (Svec, Thompson, and Frederking, 1985). It was shown that circular holes at the root of the beam effectively reduced stress concentrations. A follow-up field program was carried out to evaluate these techniques for reducing stresses in a 0.35 m thick freshwater ice cover (Frederking and Svec, 1985). The conclusion of all this work was that for the usual cantilever beam tests with a saw-cut root and length 7–10 times thickness and width 1–2 times thickness flexural strength determined from simple beam theory can be corrected by applying a factor of 1.35 to eliminate stress concentration effects. This factor applies to freshwater ice. The elastic modulus determined from simple beam theory can be corrected by applying a factor of 1.2 to account for rotation at the root of the beam. Corrected values of flexural strength and elastic modulus obtained in a 0.3 thick freshwater ice cover were 700 and 6 GPa, respectively.

Frederking and Timco (1983b) determined the flexural strength and elastic modulus of cantilever beams. The tests were performed in a model basin on 40 to 70 mm thick fine grained, columnar freshwater ice covers. If simple beam theory was used, the effect of beam width and length in relation to ice thickness had a significant effect on flexural properties. An analytical model developed for beam deflections taking into account effects of buoyancy, shear, rotation and deflection at the root satisfactorily explained the observed behavior. The corrected elastic modulus determined was 6 GPa. The average flexural strength obtained was 800 kPa. In a concurrent test series on the same ice, simple beams removed from the ice cover and tested at $-10°C$ had a flexural strength of 2200 kPa (Timco and Frederking, 1982). Sinha (1982c) investigated acoustic emission and microcracking in the same ice under compressive loading and proposed a method of estimating the tensile strength by giving consideration to the observed time of formation of cracks and their sizes. He estimated the tensile strength of this ice at $-10°C$ to increase from about 900 to 2000 kPa for an increase in the strain rate from about 1×10^{-7} to 2×10^{-5} s^{-1} or a stress rate of 3×10^{-3} to 1×10^{-1} MPa s^{-1}. The effective modulus at the highest rate was found to be about 5 GPa.

Michel (1978b) developed an analytical method to take into account the effects of temperature gradients and development of a plastic moment in a beam. This approach showed the apparent flexural strength (resisting moment at failure) to be a function of strain rate, but actually controlled by the tensile strength of the extreme fiber of the beam which is relatively strain rate and temperature independent.

Studies on the loading rate and temperature dependence of the flexural strength of small beams of laboratory grown columnar sea ice were carried out by Lainey and Tinawi (1981) using four-point loading. Flexural strength increased from about 500 kPa at $-5°C$ to about 2000 kPa at $-40°C$. Stress rates covered the range 10^{-1} to 600 kPa s^{-1}. For temperature higher than $-20°C$, strength decreased monotonically by 20% with increasing stress rate in the range studied, but for lower temperature there was an intermediate peak strength between 50 and 100 kPa s^{-1}.

Timco and Frederking (1983b) carried out flexural tests of small beams of sea ice sampled from the Beaufort Sea using four-point loading. Salinity of the ice was 5‰. At $-20°C$ the flexural strength was 1160 kPa for granular (1 mm diam) ice and 860 kPa for columnar (3 mm diam) ice. Flexural strength of the columnar sea ice tested varied from 900 kPa at $-20°C$ to 500 kPa at $-40°C$, comparable to results obtained by Lainey and Tinawi (1981).

Acoustic emission studies carried out in a field station at $-10°C$ on multi-year columnar grained sea ice with salinities in the range of 0.5 to 1.5‰ led Sinha (1985b) to estimate the tensile strength. He noted the values to increase from about 500 to 1200 kPa for an increase in the stress rate from 3×10^{-4} to 1×10^{-1} MPa s^{-1}. These numbers agree well with those obtained from direct flexural tests discussed above.

2.1.5. Failure envelope

The failure envelope is a description of the stress levels at which a material yields for any combination of compressive and tensile stress states. For ice, the failure envelope has been determined by using the combined results of uniaxial compression tests, confined compression tests and shear strength tests both for mostly granular sea ice (Timco and Frederking, 1983a, 1984), and columnar sea ice (Nadreau and Michel, 1984; Timco and Frederking, 1986a) over a range of loading rates and temperatures. Due to the hexagonal structure of the ice lattice and the horizontal alignment of the *c*-axis in the columnar ice, there is a marked difference in the failure envelope between the two ice structures (see Fig. 2). This figure compares the failure envelope for sea ice with that of freshwater ice for both granular and columnar sea ice for plane stress conditions. It is evident that the void volume (brine and air) in sea ice significantly reduces the size of the failure envelope compared to that for freshwater ice at the same loading rate and temperature. For columnar ice, the failure envelope extends much further into the compression–compression quadrant than that for granular ice. This implies that columnar structured ice in a confined state (such as that in an ice cover) will sustain much higher stresses before failure than granular structured ice. This has clear implications when viewed in terms of the forces which an ice sheet can exert on a structure. A mathematical description of the three-dimensional failure envelope based on a modified *n*-type yield function has been given for both granular and columnar

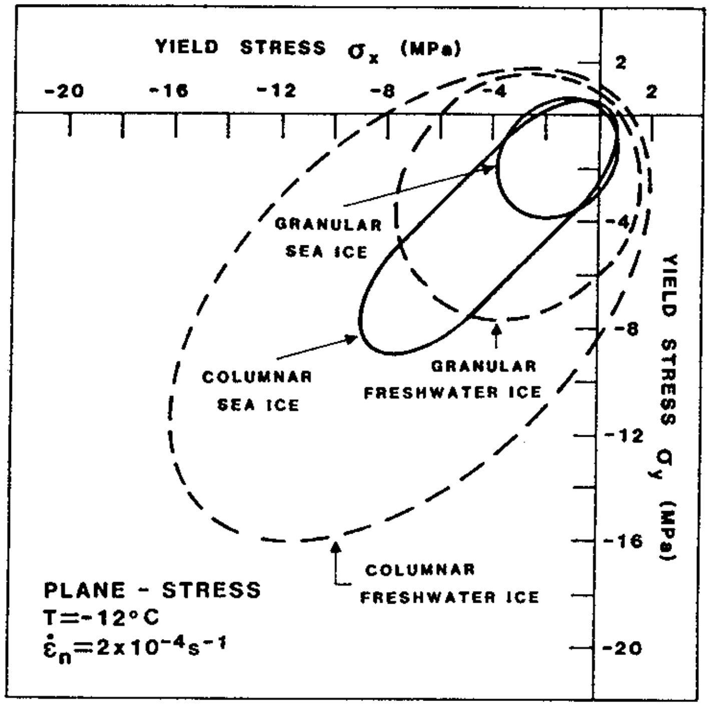


FIG. 2. Comparison of the failure envelopes for both granular and columnar sea ice and freshwater ice in the horizontal plane (after Timco and Frederking, 1984).

structured ice (Timco and Frederking, 1984, 1986a), allowing its use in analytical models. The importance of using the correct yield function in these types of analyses has been demonstrated by McKenna et al (1983).

Using triaxial test results of Jones (1982) and Nadreau and Michel (1985) on granular freshwater ice, Nadreau and Michel (1986b) proposed a new formulation for describing the failure envelope. The proposed yield surface models the pressure melting, sensitivity of the ice at high confining pressures. It is a cubic function of the invariants of the stress tensors. The three-dimensional surface defined by this criterion is teardrop-shaped and symmetrical around the hydrostatic line. The volume of this teardrop envelope is rate sensitive and increases with the increase in strain-rate.

2.1.6. Fracture toughness

The fracture toughness (or critical stress intensity factor (K_{1c})) has been measured by a few investigators for both freshwater ice and sea ice. The understanding of this property as a material property of ice is, however, still in its infancy.

For freshwater ice, measurements of K_{1c} have been performed by Timco and Frederking (1982) in a test series comparing several mechanical properties measured under comparable conditions. Hamza and Muggeridge (1983) measured the nonlinear fracture toughness of small ice beams while investigating the effects of loading rate, temperature, and specimen size. A field test series measuring the fracture toughness of large beam specimens was performed by Parsons and Snellen (1985). They measured the highest K_{1c} values reported to date with mean values of K_{1c} approximately 200–250 kPa m$^{1/2}$ depending upon the loading direction. Finally, Timco and Frederking (1986b) investigated the effects of both anisotropy and microcracks on the fracture toughness of fine-grained columnar ice. They found that the presence of microcracks causes a decrease in the apparent fracture toughness of the ice. Based on these tests, Cormeau et al (1986) performed a finite element (FE) analysis of this process. They found that depending upon the position of a microcrack relative to the main crack, there can be an amplifying or shielding effect on the stress intensity factor. Overall, the FE analysis showed excellent agreement with the test results, and provided valuable insight into the mechanics of fracturing in ice.

The fracture toughness of sea ice has been measured by Timco and Frederking (1983b) on small beam samples and by Parsons et al (1986) on large beams. The latter study investigated the effects of anisotropy and temperature and showed that K_{1c} increases with decreasing temperature with mean values of the order of 500 kPa m$^{1/2}$ at -25°C and 150 kPa m$^{1/2}$ at -10°C.

2.2. Rheology: Introduction

Rheology in ice is part of a broad subject that involves the stress–time–temperature dependent deformation and fracture of polycrystalline materials at elevated temperatures. Polycrystalline ice in nature is generally an anisotropic, nonlinear viscoelastic solid and its mechanical behavior is described by the generalized Hooke's Law relating strains ε_i to stress σ_j:

$$\varepsilon_i = S_{ij}\sigma_j;\ i, j = 1,2,3,4,5,6, \tag{10}$$

where S_{ij} are the compliances. Granular snow ice, for all practical purposes, may be considered as an isotropic material and its deformation properties may be described by $S_{11} = S_{22} = S_{ii}$ and $S_{12} = S_{21} = S_{ij}$ $(i \neq j)$. For commonly observed transversely isotropic (or orthotropic) columnar grained lake, river or sea ice, classified as S-2 ice, we are concerned usually with the compliances $S_{11} = S_{22} \neq S_{33}$, in which the Cartesian axes are chosen in order to have the 3-axis along the axis of the columnar grains, ie, the vertical (growth) direction, and the 1-axis and 2-axis in the plane of the ice cover perpendicular to the growth direction, hence in the horizontal plane. For stresses applied along 1-direction, which is the case in many engineering situations, the important lateral compliances are S_{21} and S_{31}.

A minimum of three macroscopically observed strain components describe the deformation of any material irrespective of operational conditions. Regardless of loading conditions, the deformation, ε_i, of any polycrystalline material (including ice), at high homologous temperatures can be described phenomenologically as (Sinha, 1978b)

$$\varepsilon_i = S_{ij}\sigma_j = \varepsilon_{ie} + \varepsilon_{id} + \varepsilon_{iv}, \tag{11}$$

where ε_{ie} is pure elastic and immediately reversible, ε_{id} is delayed elastic and recovers with time, and ε_{iv} is the viscous or permanent strain. Delayed elasticity is particularly noticeable in ice because it is always, in nature, at high temperatures.

The simplest method for bringing out the macroscopic behavior is the uniaxial tensile or compressive test. Two commonly applied experiments to determine material properties for engineering applications are the uniaxial "constant stress" creep and the "constant strain rate" deformation tests. Ideally a certain stress is suddenly imposed and held constant in the creep tests; in the other tests, a certain strain rate is suddenly imposed and held constant.

2.2.1. *Elasticity*

Unless low amplitude and very high frequency loading, in the order of MHz, is involved, it is almost impossible to have only elastic deformation with no contributions due to grain-boundary sliding or delayed elastic and viscous deformation. This observation is applicable to deformation parallel as well as normal to the axis of loading. Consequently, the compliances S_{ij} given by the observed ratio, ε_i/σ_j or the corresponding moduli and the ratio between lateral strain and longitudinal strain reflects the contribution due to nonpure elastic deformation. It is preferable, therefore, to use the term "effective modulus" for the reciprocal of compliance or σ_j/ε_i except where Young's modulus and other elastic moduli, in the formal sense, are intended.

The dependence of the effective moduli, for freshwater ice, on the rate of loading and temperature and grain size, for loads less than 0.5 MN m^{-2} in uniaxial loading, has been studied experimentally by Gold and Traetteberg (1975) and Traettenberg et al (1975). These along with many previous results, were compiled by Gold (1977). Figure 3, taken from Sinha (1979a), shows that the effective modulus increases with increase in rate of loading and grain size. Similar rate sensitivity was noted in saline water ice by Murat (1980) and Murat and Lainey (1982). The illustration also shows that the experimental observations, however complex, are reasonably predicted by a simple micromechanically based rheological model to be discussed later. The applicability of this model in the case of saline ice can be seen in Sinha (1981d), which also explains why sea ice appears to be more ductile than freshwater ice.

Shear modulus has also received some attention. While examining the bearing capacity of saline ice covers, Lainey (1982), and Lainey and Tinawi (1983) realized and emphasized the importance of shear deformation. Selvadurai (1981) modelled an ice cover, containing a primary snow ice layer and secondary columnar zone, as a composite structure assuming the secondary ice as a Pasternak–Vlazov-type elastic layer which possesses only shear interaction. Murat and Degrange (1986) examined the relative influence of shear and flexural deformation on the deflection of laboratory made transversely isotropic, saline ice beams. They concluded that the shear deflections could be 2 to 3 times greater than those expected for an isotropic material.

2.2.2. *Creep*

The term "creep" is defined as "the slow deformation of a material" according to BS 5168 or British Standard Glossary of Rheological terms (1975). This definition is broad enough to be universally acceptable. One might object to the term "slow"—however, slow or fast are only relative terms. It has been pointed out by Sinha (1979b) that a very short creep time of 10 s at a homologous temperature of 0.96 T_m is equivalent to a creep time of 12 days at 0.7 T_m, 36 years at 0.6 T_m and about half a million years at 0.5 T_m. It should be pointed out here, to give a feeling of the actual thermal state, a homologous temperature of 0.96 T_m in ice is a temperature of −10°C and a temperature of 0.5 T_m in austenitic stainless steel could be as high as 700°C.

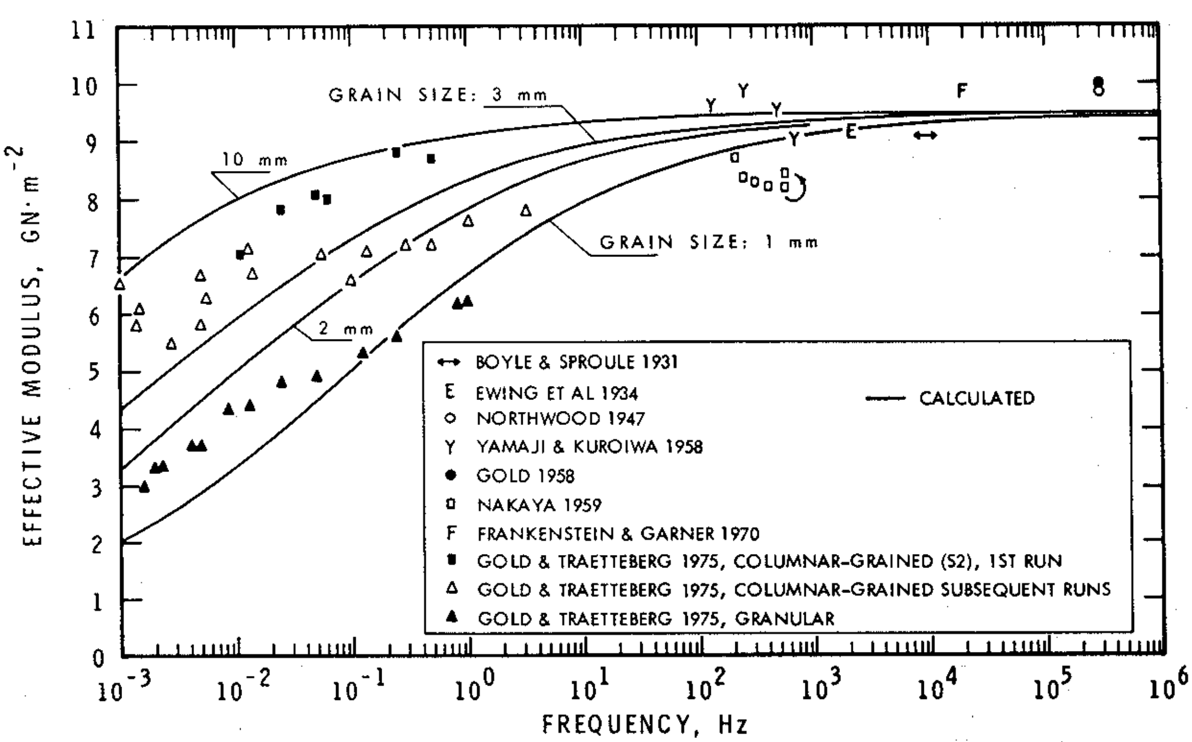


FIG. 3. Frequency dependence of effective modulus for polycrystalline ice at −10°C. Experimental data are from Gold (1977). Calculated results are shown by the solid lines for stress amplitude of 0.3 MN m^{-2} (after Sinha, 1979a).

Creep is usually measured under constant stress or rather constant load. Three distinct types of constant load tests have been conducted in Canada in the last decade reviewed here. Among these, two belong to the laboratories and the third belongs to the field. Laboratory tests usually involve uniaxial deformation of prismatic or cylindrical specimens (Sinha, 1978b; Nadreau and Michel, 1985; Gold, 1983) or bending of beams or plates (Murat, 1978; Tinawi and Murat, 1979; Lainey, 1982; Lainey and Tinawi, 1981; Nadreau and Michel, 1981, 1986a). Field tests involve deflections of ice covers under slowly moving or static loads (Eyre and Hesterman, 1976; Eyre, 1977; Frederking and Gold, 1976; Beltaos, 1978, 1981).

Bending of beams or plates is relatively simple to perform in the laboratory and in the field. However simple these experiments may be, results are difficult to analyze (Williams, 1976; Murat, 1978; Liu and Hsu, 1982; Vinogradov, 1984) because stress levels vary with depth and the viscoelastic response of ice is not only nonlinearly stress dependent but also depends on temperature and the history of loading. Consequently, the significance of beam or plate bending tests lies in the fact that they give strength indices or bearing capacity indices for applications to real life engineering problems.

Efforts have also been made to estimate *in situ* creep properties using borehole pressuremeters or jacks (Ladanyi et al, 1978; Sinha, 1986b; Sinha et al, 1986; Michel and Hodgson, 1986; Murat et al, 1986). Again the tests are simple but results are difficult to use to develop constitutive equations for creep.

Phenomenological observations, expressed in a general sense in eq. (11), describe ice as a viscoelastic material. Experimental observations discussed in Section 2.2.1 show that ice does not behave as an ideal elastic material even at relatively high loading rates. Its behavior, on the other hand, cannot be described by the classical elastic-plastic model, because Gold and Traetteberg (1975) noted that for a significant time following the initiation of loading the strain imposed on ice is essentially recoverable and grain size dependent. Many problems involve only this initial creep—a range referred by Sinha (1979a) as "elasto-delayed elastic." A very significant number of applied mechanics problems for ice involve elastic and primary deformation or the transient creep behavior. They include most ice-structure interaction problems, all bearing capacity problems for moving loads and static bearing capacity problems for which the maximum deflection is limited to the free board (Gold, 1977). The level of strains involved in these problems is indeed very small (Gold and Sinha, 1980). Measurements carried out by Allan (1979) and Masterson et al (1979) show that maximum surface strain actually measured in a floating platform toward the end of a drilling season of more than 3 months was only about 1.5×10^{-3}. This is due to a combined effect of creep and consolidation, and the average strain rate of about 10^{-10} s^{-1} indicates little cracking activity. Failure strains involving severe cracking activity, for uniaxial upper-yield type compressive failures have also been measured to be small—about 2×10^{-3} for both freshwater ice (Sinha, 1981b, 1982a) and sea ice (Sinha, 1983b; 1984c, 1986a; Frederking and Timco, 1984). In case of problems involving tensile fracture, such as in bending, the fracture strains are less than 5×10^{-4} and 95% of these are recoverable (Sinha, 1984d). Compressive brittle type failures at high rates also involve strains of these magnitudes (Sinha, 1981b). Upper yield failure strains under confined compression loading conditions are relatively large but still only in the range of about 1×10^{-2} (Sinha, 1985a). To be applicable to most ice engineering problems, a constitutive model must describe the rheological behavior at small strain. Constitutive equations developed in Canada in the last decade seem to focus strongly in this direction (Sinha, 1978b, c, 1979b; Michel, 1978a, b, 1981; Gopal et al, 1984; Szyszkowski et al, 1985; Vinogradov and Bakalchuk, 1986).

Uniaxial, constant-load creep and recovery on unloading, of polycrystalline ice was used by Sinha (1978b) to show that ice can be treated as a nonlinear thermorheologically simple material. He also demonstrated a method of examining experimentally the three strain components in eq. (11) and in developing a phenomenological equation capable of explaining inconsistencies in the results of earlier creep investigations of ice (Sinha, 1978c). It was shown that pure elastic deformation was related to lattice deformation and the viscous component could be attributed to intragranular deformation processes, particularly to the movement of dislocations for the level of stresses and rates of loading encountered in engineering situations. Delayed elasticity was hypothesized to be associated with intergranular sliding phenomena. These physical processes were considered in modifying the phenomenological creep model of Sinha (1978b) to what might be called a micromechanically based model, allowing the incorporation of the effect of grain size (Sinha, 1979b). Key assumptions in developing this model are (a) the primary creep depends on grain size and (b) the viscous creep rate is independent of grain size for conditions where grain boundary diffusional creep does not play the dominating role and where the microstructure has not deteriorated by internal cracks or voids. Data published in the literature since then from France and Australia (Duval and LeGac, 1980; Jacka, 1984) support these assumptions. The axial strain, ε_1, at time t, in pure randomly oriented polycrystalline material of grain size, d, subjected to a uniaxial stress, σ_1, at a temperature, T, was given by

$$\varepsilon_1 = (\sigma_1/E) + c_1(d_1/d)(\sigma_1/E)^s\left[1 - \exp\{-(a_T t)^b\}\right] + \dot{\varepsilon}_{v_0} t(\sigma_1/\sigma_0)^n, \quad (12)$$

where E is Young's modulus; $\dot{\varepsilon}_{v_0}$ is the viscous strain rate for unit or reference stress σ_0; c_1 is a constant, corresponding to the unit or reference grain size, d_1, that depends on grain boundary structure and texture; b, n and s are constants; a_T is the inverse relaxation time. Both $\dot{\varepsilon}_{v_0}$ and a_T vary with temperature T in Kelvin and were shown to have the same value for the activation energy as follows,

$$\dot{\varepsilon}_{v_0}(T_2) = \dot{\varepsilon}_{v_0}(T_1)F_{1,2}$$

and

$$a_T(T_2) = a_T(T_1)F_{1,2}, \quad (13)$$

where T_1 and T_2 are two temperatures and $F_{1,2}$ is a shift function given by $F_{1,2} = \exp\{(Q/R)[(1/T_1) - (1 - T_2)]\}$ in which Q and R are the activation energy and gas constants, respectively. Note that both delayed elasticity and viscous flow have the same activation energy. Recovery, on unloading, is described as the mirror image of the delayed elastic term.

Equation (12) was developed not just for ice but for also metals, alloys and ceramics. Experiments on ice indicated that $s = 1$ and $b = 1/n$ (Sinha, 1978b). Consequently, the creep equation in ice is relatively simple and is described in terms of only five material constants, E, c_1, a_T, $\dot{\varepsilon}_{v_0}$, and n. Since E can be estimated fairly well from available single crystal elastic moduli (Parameswaran, 1982, 1987), the unknown material constants reduce to only four. With the assumption of $n = 3$, because of intragranular dislocation mechanisms, the unknown material constants reduce to only three. For the system in which grain size, d, is expressed in meters (ie, $d_1 = 1$ m), stress, σ_1, in MPa (ie, $\sigma_0 = 1$ MPa), and time, t, in seconds, experimental observations in pure ice (Sinha, 1979b) provided the following values: $E = 9.5$ GN m^{-2}, $c_1 = 9 \times 10^{-3}$, a_T ($T = 263$ K) $= 2.5 \times 10^{-4}$ s^{-1}, $\dot{\varepsilon}_{v_0}$ ($T = 263$ K) $= 1.8 \times 10^{-7}$ s^{-1}, and $n = 3$. The activation energy, Q, was found to be 67 kJ mol^{-1} (16 kcal mol^{-1}) taking $R = 8.32$ J mol^{-1} K^{-1}. It should be pointed out that the E value chosen above agrees well with the calculated by Parameswaran (1987) from single crystal elastic constants determined by Gammon et al (1980, 1983a, b) using the method of Brillouin spectroscopy. Direct application of eq. (12) with the above values of material constants, to predict effective modulus (Fig. 3) and to a wide range of independent experimental observations including conditions for superplasticity, creep rupture, cracking activities, and damage accumulation in constant stress creep can be seen in Sinha (1978c, 1979a, b, 1982b, 1984a, b). A simple method for prediction of strain, and hence a stress–strain diagram, corresponding to a monotonically increasing stress history, such as encountered in constant cross-head rate tests and constant stress rate loading, were then developed and applied successfully to both compressive and tensile experimental data (Sinha, 1981c, 1983d, 1984d) on the basis of eq. (12) and the material constants given above. This model has now been used also to predict the rate sensitivity of Poisson's ratio (Sinha, 1987), tertiary creep, and anisotropic deformation of common ice types.

Basal slip is comparatively easier than slip on other planes in a single crystal of ice with hexagonal structure. This is the essence of the model proposed by Michel (1978a). He assumes that grains best oriented for basal slip deform first, on application of a load, and grain boundary sliding occurs to accommodate the total deformation. An equation for this model which, for uniaxial constant stress, σ, and temperature, T, is given by

$$\dot{\varepsilon} = A\left[1 + \alpha(\varepsilon/\varepsilon_t)^m\right]\left\{1 + \beta(1 - \varepsilon/\varepsilon_r)^n\right\} \times (\sigma/\sigma_0)^n \exp(-Q/RT), \tag{14}$$

in which n, A, α, m, β, ε_r, and ε_t are material constants; σ_0 is the unit stress, and Q and R are activation energy and gas constant, respectively. Note that the above equation combines both delayed elastic and viscous flow. Consequently calculating the recovery curve, on unloading, is to be performed by another equation.

It has been demonstrated by Michel (1978a, 1981) that the model can be used accurately fit experimentally observed creep and recovery curves. The model has also been shown to be capable of fitting the stress–strain relation obtained under constant cross-head rate loading. Fitting of experimental curves is done by empirically adjusting the numerical values of the constants. This is a complex procedure which may require different values of the constants from one test to another for similar ice.

An empirical nonlinear spring/dashpot model that requires six parameters was proposed by Szyszkowski et al (1985) to describe the primary and secondary stage of creep behavior. An improved phenomenological model capable of describing tertiary creep was then proposed by Szyszkowski and Glockner (1985). This later model, which requires eight parameters, is promising but rather lengthy, cumbersome, and difficult to use. Numerical techniques, in conjunction with trial and error, are required to solve even the simplest case of a constant stress unconfined creep test. Although excellent experimental data from Canadian laboratories was available to these authors, no effort has been made so far to examine the predictive capabilities of their model.

2.2.3. *Poisson's ratio*

The ratio of the lateral strain to the longitudinal strain in a homogeneous material for a uniaxial elastic loading condition is defined as Poisson's ratio and is often denoted by μ. It is a manifestation of the factors that play a central role in three-dimensional constitutive formulations. Poisson's ratio is an important property which has received surprisingly little attention.

The complexities in the interdependence between the axial and the lateral strain can be seen in the experimental work of Murat and Lainey (1982) on laboratory made saline ice beams for loading conditions involving no cracking activity. While examining the rate sensitivity of compressive strength of congealed frazil sea ice, Sinha (1986a) observed that the ratio depends not only on the rate of loading or loading history but also on stress and strain level and the damage state of the material. He coined the term "strain ratio" and suggested that the use of Poisson's ratio should, in a formal sense, be restricted to loading conditions in which only elastic responses related to lattice deformations are involved.

The contribution of the grain-boundary or interplatelet sliding strain to the total strain, in addition to pure elastic and viscous flow, influences both effective modulus and strain ratio. These mechanisms were proposed briefly by Sinha (1981e) in explaining the experimental work on strain ratio in sea ice by Wang (1981). This model has now been formalized for estimating lateral strain and simple equations have been developed to predict the complex response of strain ratio in ice. Application of the theory to granular ice is presented in Sinha (1987). Experimental and theoretical work carried out at NRCC in anisotropic ice indicates that the strain ratio could be significantly higher than 0.5 even for conditions with no cracking activities.

2.3. Interface properties

This class of property which relates to the behavior at the interface between ice and a substrate material involves mechanical and thermal processes. The properties are commonly known as adhesion, friction, icing, etc. Friction is not included because there has been no recent work on the topic in Canada.

2.3.1. *Adhesive strength*

A floating ice cover can develop substantial vertical loads on a structure to which it is frozen as a result of water level changes. Because of this, a knowledge of the adhesive strength of ice to various materials is important. A number of tests have been performed in the laboratory to measure adhesive strength. Frederking (1979) determined the effects of deflection rate, ice thickness, and pile diameter on vertically acting ice loads on wooden piles. Parameswaran (1981) measured the adfreeze bond strengths of wood, concrete and steel H-section piles embedded in freshwater ice under constant displacement rates for rates between 10^{-4} and 10^{-1} mm/min. He measured adhesive strengths of 0.6–1.8 MPa for wood, 0.8 MPa for concrete and 0.2–0.6 MPa for steel. Frederking and Karri (1981, 1983) carried out laboratory tests on piles of six different materials: polyethylene, polyvinylchloride, steel, wood, concrete, and steel coated with Inerta 160 marine coating. Typical adhesive strengths were ≈ 0.05–0.07 MPa for the PE and PVC piles, 0.25 MPa for the Inerta coated piles, and 0.4–0.5 MPa for the others. Most recently, Cammaert and others (1986) have reviewed the published information on adhesive strength and have developed an analytical approach for calculating adfreeze loads on conical structures.

2.3.2. *Icing*

Spray icing can cause considerable loads and inconvenience to helicopters, icebreakers and offshore platforms. For many years, Canada has been involved in investigating the growth, properties, detection and methods of alleviation of spray ice. Three groups in particular have been active: the Low Temperature Laboratory of the National Research Council of Canada, the Université du Québec à Chicoutimi, and the University of

Alberta in Edmonton. These groups have produced numerous contributions and the reader is referred to the *Proceedings of the international workshop on atmospheric icing on structures* (CRREL Report 83-17, 1983) for representative examples. More recently, Lozowski and Gates (1985), and Lozowski and others (1986) present overviews of marine icing research, especially as applied to mobile offshore drilling units.

3. ICE FORCES ON STRUCTURES

A considerable amount of work has been done in Canada to measure and predict the forces which ice features can exert on a structure. There have been several approaches to this problem including analytical predictions (Section 3.1), physical modelling (Section 3.2), laboratory studies (Section 3.3), and field studies (Section 3.4). A great deal of exchange of information, insights, and ideas amongst these approaches has gone on within the ice community.

3.1. Analytical predictions

Work in Canada on analytical predictions of ice forces on structures has benefited from and been guided by access to extensive field experience (Gold, 1978). This has provided the opportunity of calibrating prediction methods with actual field data and observations. Both deterministic and probabilistic approaches have been used and they have been integrated together in certain cases. The subject of analytical predictions has addressed both narrow and wide structures and rigid and flexible structures. A general review of mathematical modelling was made by Kivisild and Iyer (1978), examining the suitability of various methods (finite element or finite difference) for various ice–structure interaction problems. A detailed study on the physics of ship/ice interaction processes and energies, based primarily on recent measurements from ramming by icebreakers (Ghoneim and Keinonen, 1983; Ghoneim et al, 1983; Daley, 1984; Daley et al, 1984) has been presented by Kivisild et al (1987).

Ice loading on conical structures was examined analytically by Danys and Bercha (1976). The ice was treated as an elastic brittle material and loads were determined as a function of ice properties, structure geometry and ice–structure friction. The work showed the importance of ice–structure friction in determining ice forces and failure mode.

Kry (1980) effectively summarized the state of the art of predicting global ice forces on wide structures. Four failure modes (flexure, rubble formation, buckling, and crushing) were identified and the likelihood of occurrence related to ice thickness—going progressively from flexure for thin ice to crushing for thick ice. Analytical prediction equations were developed for each failure mode. Of particular interest was the proposal of multiple zones of failure in the case of the crushing mode, which provided a means of introducing the statistical influence of nonsimultaneous failures across a wide structure. This approach leads to the so-called "limit-stress" global ice forces. Closed-form solutions for ice loads on several categories of rigid structures (narrow, wide, vertical, and sloped) were also compiled by Croasdale (1980). Sodhi and Hamza (1977) developed expressions for loads associated with ice sheets failing in buckling against a structure. For wide structures, aspect ratio and size effect are important factors. Iyer (1983) has examined these factors, distinguished between them and presented expressions for each. Blanchet (1986) has developed a method for relating local failure pressures to ice property variations with depth.

In examining the approaches to calculating global ice forces, Croasdale (1984) has identified three limits to global ice forces: "limit-stress," "limit-momentum," and "limit-force." The identification of these conditions has helped provide a rational framework within which various loading scenarios could be examined. The maximum force is given by the limit-stress case; ie, the ice cover or feature fails against the full width of the structure. It is possible, however, that the environment cannot generate sufficient load to reach the limit-stress condition. In this case either the limit-momentum or limit-force would apply. In the limit-momentum approach the kinetic energy of the ice feature is absorbed as the ice fails against the structure until such time it is brought to rest. Depending on the size or velocity of the floe the final contact area could be significantly less than the area assumed in the limit-stress case. In the limit-force approach the environmental forces which can be generated on a large ice feature lodged against a structure are examined. These include wind and current drag and ridge building forces. Work is still required on establishing the level of ridge building forces.

Various scenarios of ice loading have been incorporated into computer models for predicting ice loads. These have been developed for use in the design process where structure characteristics can be changed (Bruce and Allyn, 1983) and for making probabilistic predictions of ice loads (Marcellus and Croasdale, 1984).

The problem with many prediction methods is either the absence of data on ice mechanical properties to insert in the model and/or ice force data to calibrate the method. One case where some of these shortcomings have been addressed is an analysis of failure modes and damage processes for indentation tests in freshwater ice (Tomin et al, 1986). The three modes of global fracture (radial, spalling and flexural cracking) were analyzed using the finite element and the *J*-integral methods to determine the crack extension force for each mode. Local fracture, which leads to pulverization of the ice, was examined with Sinha's criterion for internal crack initiation and a continuous damage model for the following progressive microcracking. The combined approaches provide insight into the mechanics of ice failure in the indentation process.

The finite element method potentially provides a more precise method for calculating ice loads given the complex boundary conditions which apply for various ice loading scenarios. Cormeau et al (1984) have used the method in an energy-based approach to study ice–structure interaction. Energy sinks such as fracture, creep, and fragment rotations were identified as being significant in ice load determination. Recently, Jordaan (1986) has reviewed the use of FE techniques for predicting ice loads on structures.

Probabilistic methods have also been used in predicting ice loads. These include statistical characterization of ice kinematic and mechanical data, probabilistic analysis of ice–structure interaction, and simulations of interaction scenarios. Bercha (1984) prepared a review of the above statistical methods and their application to ice loading. Blanchet and Metge (1984) used a probabilistic approach with classical statistical data on ice strength, thickness, and floe size to arrive at global load predictions for the case of multi-year ice floe impacts ("limit momentum") in summer.

The case of iceberg impact on a gravity structure has been treated by Cammaert et al (1983). The analysis pointed up the importance of structure shape and mechanical properties in predicting ice loads. Bergybit impacts on semi-submersible structures were modeled numerically using conventional structural dynamics and showed local denting of columns to be likely (Swamidas et al, 1983).

In the dynamic interaction between structures and ice the flexibility of the structure has a significant effect on the ice load generated on the structure. This has been examined in the case of offshore structures (Reddy et al, 1979) and bridge piers (Montgomery et al, 1980).

3.2. Ice forces on structures: Physical modelling

Physical modelling is a technique which has been used to a large extent to study the problem of ice interacting with structures. In these model tests, the forces involved in the interaction process are reduced but maintained in the same ratio as those in the full scale. Special techniques and facilities are required for accurate results.

In Canada, there are five laboratories which have the necessary equipment for performing model tests. These include the Esso test basin in Calgary (Robbins et al, 1975), the Arctec test basins in Calgary and Kanata, the NRC tank in Ottawa (Pratte and Timco, 1981), and the new NRC facility in St. John's (Jones, 1986). The latter facility, which opened in late 1985, is the largest in the world comprising a refrigerated ice tank $80 \times 12 \times 3$ m. Great strides have been made in the development and understanding of the "model ice" which is an integral part of the modelling process. The model ice must be an accurate representation of the full scale sea ice in all of its mechanical properties. Michel (1969) developed a synthetic model ice which is proprietary in nature and used by a private consulting company in both Canada and the United States. Timco (1979) developed a refrigerated model ice grown from an aqueous solution containing carbamide (or urea) as a chemical dopant. This type of model ice is now used in the majority of ice modelling facilities in the world. More recently, Timco (1986a) developed a new type of model ice—termed EG/AD/S ice—which is grown from an aqueous solution containing ethylene glycol, aliphatic detergent, and sugar. Analysis of the structure of this ice indicates that it is single-layered, fine-grained, and strictly columnar. This ice has excellent scaling of the mechanical properties of sea ice, including the flexural strength, uniaxial and confined compressive strength, strain modulus, and critical stress intensity factor.

To date, there have been a large number of model test studies measuring the ice forces on several Arctic structures (Hnatiuk and Felzein, 1986; Pilkington et al, 1986). At this time, however, the results of many of these are proprietary. Studies have elucidated the forces on more basic shaped structures and these have been used to verify analytical models of the interaction process. These include studies on conical and sloping structures (Abdelnour, 1981; Frederking and Schwarz, 1982; Timco, 1984a; Frederking and Timco, 1985), on vertical-sided piles (Frederking et al, 1982), arrays of piles (Timco and Pratte, 1985), and on ice-breakers (Nawwar et al, 1984). A recent review article has been written by Timco (1984b).

3.3. Ice forces on structures: Laboratory studies

A number of tests have been performed in the laboratory to study ice–structure interactions at a small scale (as compared to the field situation). In these tests, freshwater ice is used. Because the properties of this type of ice have been studied to a large extent, this allows an analysis of a tractable experimental situation, which can provide good insight into the physics of the interaction process.

To date, most studies of this type have looked at the horizontal loads which an ice sheet can exert on a structure. Tests of this type have been performed over a wide range of loading rates covering the range from ductile indentation (Frederking and Gold, 1975; Croasdale et al, 1977; Michel and Toussaint, 1977) to the transition (Michel and Jolicoeur, 1986) and brittle regions (Michel and Blanchet, 1983; Timco, 1986b). These studies have been concerned with many aspects of the interaction problems including loading rate effects, aspect ratio effects, peak and average pressures, failure modes in the ice, etc. Most of the test results have been interpreted in terms of the Korzhavin equation $p = C_i mk\sigma$ which gives the pressure (p) on the structure in terms of the strength of the ice (σ), and empirical coefficients for indentation (C_i), structure shape (m), and degree of contact (k). A compilation of the test results which gives the variation of the indentation coefficient for various aspect ratios (structure width to ice thickness) for various loading rate regimes can be found in Michel and Jolicoeur (1986).

3.4. Field studies

Canada has benefited from having many structures placed in an offshore environment exposed to ice and the opportunity of monitoring ice behavior and forces around these structures. This has been a key element in the rapid advances in ice mechanics and in improving confidence in the design of offshore structures for ice covered areas. The results of field measurements are used to verify design loads and also as an integral part of operational alert procedures. There are two basic approaches to estimating the total ice force on a structure; either from *in situ* pressure measurements in the ice cover around the structure or else measuring pressures on or response of the structure. An extensive review of techniques was made by Croasdale and Frederking (1986).

For determination of forces on the artificial islands constructed in the land fast ice region of the Beaufort Sea, the approach taken was to place transducers in the level ice cover around the island to measure *in situ* ice pressures. Large thin panel type transducers were initially developed (Metge et al, 1975) and successfully used at a number of locations (Metge, 1976; Strilchuk, 1977; Semeniuk, 1977). They were relatively temperature sensitive and so were subsequently replaced by MEDOF panels which were used around the Tarsiut Island location (Pilkington et al, 1983). More recently Arctec Canada has built a wide thin metal sensor called the Hexpac (Graham et al, 1983) and Weir–Jones a similar transducer called the Ideal panel (Witney et al, 1986). Also a hydraulic flat-jack type transducer (Masterson, personal communication) and a stiff biaxial transducer (CMEL 1984) have been developed.

In a recent experiment ten different sensors used for determining ice pressures were tested in a large outdoor ice basin under controlled load conditions (Croasdale et al, 1986b). The results of the experiment showed that all the sensors predicted stresses within ±30% of the applied ones. A good level of confidence has been established in the ability to accurately measure *in situ* ice stresses.

A number of projects have been carried out to measure ice pressures around caisson structures, and natural islands. The results tabulated in Croasdale and Frederking (1986) show that global loads can be satisfactorily estimated from measurements made *in situ* in the ice cover.

Another approach to measuring ice forces during ice–structure interaction is to deduce the ice forces from floe motions during an impact. Such an approach was used at Hans Island in 1980, 1981, and 1983. At Hans Island the decelerations of multi-year floes impacting the island were measured. By also estimating the mass of the floes, the ice forces acting between floe and island were deduced. These experiments have been described by Metge et al (1981) and Danielewicz et al (1983).

There are three means of measuring ice loads from structure response: (i) measure strains, deformations or movements of the structure itself, (ii) addition of load sensing panels to the structure, and (iii) in cases of dynamic loads, measure accelerations of the structure, which, when combined with a knowledge of the dynamic response of the structure, allows loads to be determined. All three approaches, but particularly the first two, generate information relevant to both local and global ice loads.

Canadian measurements of direct structure response to ice loads are summarized in Croasdale and Frederking (1986). Over the years, there has been considerable refinement in the instrumentation. Measurements started with work on bridge piers in the 1960s and lightpiers in the 1970s (Danys, 1975). Extensive instrumentation to measure ice forces was built into the caisson structures deployed into the Beaufort Sea into the 1980s; eg, Tarsiut, Dome's SSDC, Esso's CRI, and Gulf's Molikpaq. The transducers used ranged from large panels 4 × 4 m down to 50 mm diam pressure sensors. Panel type transducers with sensing areas of the order of 1 m^2 have proved most successful. The information obtained from these transducers has been used to develop a better understanding of the nature of ice loads and as a primary real-time indicator of ice load levels. This knowledge of loads when combined with interpretation methods is used to establish alert levels which govern the drilling operation (Wright and Weaver, 1983).

4. ICE AS A CONSTRUCTION MATERIAL

4.1. Ice roads and airstrips

Many areas in Canada depend heavily on winter roads and ice crossings across rivers, lakes, and marshy areas. Experimental and theoretical studies on the bearing capacity of freshwater ice covers have been covered well by Eyre and Hesterman (1976), Eyre (1977), Frederking and Gold (1976), Beltaos (1978, 1981). A workshop was held in 1980 in Ottawa to bring together a small group of people with a common interest and involvement in these areas and to exchange ideas and information. The proceedings of this meeting (ACGR-1980) provides valuable information on the practical aspects of constructing and maintaining these important communication links. The papers by Betteridge and Clift (1980) and Haspel and Masterson (1980) provide important data on the construction of floating ice roads in support of offshore drilling activities. Betteridge and Clift presented a detailed study on the successful completion of a 200 km river ice road from Tuktoyaktuk to the middle delta of the Mackenzie River. This road was used to haul the heavy equipment required for Esso Resources Canada Limited's Beaufort exploration drilling program for the winter of 1978–1979.

4.2. Floating ice platform

Sea ice remains relatively stationary during the winter months within the high Arctic islands in Canada. Exploratory offshore drilling has been successfully performed in this area for over 12 years by Panarctic Oils Ltd., from artificially thickened floating ice platforms in water depths up to 450 m (Baudais et al, 1974; Kivisild, 1975; Masterson and Kivisild, 1980). The drilling pads usually cover a 150 × 300 m area and are from 4.5 to 7.5 m thick. The pads are made by successive flooding around the clock, an existing ice cover thick enough to support men and machines. Submersible pumps lowered to sea water through holes drilled through the ice covered are used to draw the water. An average of five layers every 24 h are frozen during very cold weather giving almost 8 cm of new ice being added each day. Construction of a platform usually begins in November when the ice is thick enough to allow to the location. It takes about 2 months to build a platform.

Heat exchanges at a flooded ice surface during construction of a platform were studied by Nakawo (1980) primarily to determine the dependence on meteoroligical variables of the freeze time taken to flooded layer and hence to establish a basis for determining the optimum build-up rate for an ice platform. He concluded that sensible heat loss accounts for most of the latent heat released during freezing. Combined evaporation and sensible heat losses were noted to be about four times larger for this flooding situation than expected in neutral conditions.

Both vertical and horizontal migration of brine occurs in a platform during construction. Detailed observations on salinity of flooded water and built-up ice were carried out by Nakawo and Frederking (1981). The bulk salinity of built-up ice has been observed to be about half that of sea water which is about 30‰ in the area. The technique of freeflooding also allows considerable entrapment of air in the ice. The ice exhibits layered structure with fine grained regions at the top and bottom of each layer. Finer grains developed as a result of rapid freezing when the sea water, just above freezing point, comes in contact with the cold ice surface and air. *In situ* strength and deformation of this layered ice at various depths and temperatures have been studed by Sinha et al (1986) using a borehole jack developed earlier (Kivisild, 1975). Uniaxial tests were also conducted on this ice in the field. Both confined and uniaxial strengths show similar rate of loading and temperature sensitivity. The rate sensitivity of this ice has been noted to be also similar to other types of ice including freshwater ice.

Ice platforms have been used to support drilling rigs up to the size of 1 or 2 million kg for periods up to about 3 months. Finite element as well as probabilistic techniques have been used to analyze the long-term response (Masterson and Strandberg, 1979; Hamza and Muggeridge, 1983). Long term deformation processes were also studied directly by installing gauges in the ice (Masterson et al, 1979; Allan, 1979). Embedded wire strain gauges were used by the former group whereas the latter investigator used wire strain meters consisting of displacement gauges. Surface strains in the range of 1.5×10^{-3} at about the end of the loading period were reported by both the groups.

4.3. Grounded ice pads

Grounded ice pads have been used to support construction activities in winter for many decades. The technique used has been to pump water from under the ice cover up onto the surface where it freezes. This is done in successive layers or lifts until the ice cover grounds on the bottom. This technique was used in the construction of the Eagle River Bridge (McCutcheon, 1979).

In exploratory drilling in the Canadian Beaufort Sea grounded ice pads have been constructed to provide a site for relief well drilling. This was generally done by spray flooding over existing rubble adjacent to the caisson. With spray flooding heat is extracted from the water droplets while they are being projected through the air with the result that higher build up rates can be achieved than with simple surface flooding. The objective was to produce a level area with sufficient freeboard and surcharge load to resist horizontal ice forces. The grounded ice pad produced at Tarsiut had a freeboard of 8 m. Its design, construction, and stability analysis were described by Neth et al (1983). Since the prime objective was to produce a large mass of ice quickly, it soon became apparent that this could be achieved best by the "spray ice" technique. Water is sprayed into the air where the droplets cool and freeze, falling to the surface as ice crystals. The ice formed is more porous than sea ice and thus has lower density and strength. In a trial conducted over the winter 1983/84 production rates from 20 cm/day up to 2 m/day were achieved depending on the capacity (power) of the spraying system (Goff and Masterson, 1986). Esso Resources Canada has also carried out work on the production and properties of spray ice for grounded ice pads (Kemp, 1984) and will be constructing a pad as a primary drilling site for the winter 1986/87.

5. CONCLUDING REMARKS

The contributions made by Canadian researchers in the field of ice mechanics are certainly impressive and significant. In this review paper the authors have covered a wide range of topics in this area and have presented highlights of these achievements. In summary, some of the salient advances are:

1. The development of microstructural observation techniques including: (a) double microtoming technique for making thin sections, (b) combined cross polarized-scattered light technique, (c) etching-replicating technique, and (d) scanning electron micrography of ice. These methods have made the metallographical studies in ice comparable to those in metals and other materials.

2. The study of growth and aging processes, in conjunction with observations on texture and structure, in natural sea ice in the Arctic are considered to be the best in the world. These assisted in bringing out the major factors influencing the mechanical properties of sea ice.

3. The detailing of the extreme ice features in the Beaufort Sea and Hibernia locations giving valuable information on the geometry, size and strength of pressure ridges, ice islands, icebergs, etc.

4. The understanding of the mechanical behavior of ice. Refined laboratory and field techniques have provided more accurate and detailed information and insight into the strength of ice. The effects of loading rate, temperature, confinement, texture, structure, etc are now much better understood, especially for all types of sea ice.

5. Study of deformation properties in the transient range—the range important to most engineering situations. Great progress has been made in the understanding of crack nucleation and damage accumulation in ice. In fact, these studies helped to understand the mechanical properties of polycrystalline materials, in general, at elevated temperatures.

6. Measurement of the forces which an ice sheet can exert on different types of structures in both the laboratory and the field. Comparisons have shown that there is a definite "size effect" and a pronounced discrepancy between the global pressures. Both types of measurements have proved invaluable in understanding how ice interacts with a structure.

7. Analytical and numerical methods for calculating ice forces on offshore structure. The importance of providing good input information has been highlighted.

8. The construction and use of floating ice covers in the High Arctic as offshore drilling platform.

9. The development of physical model testing. Significant progress has been made particularly in developing "model ice" especially refrigerated urea ice, which is used worldwide, and more recently EG/AD/S model ice. The world's largest ice tank has recently been constructed in St. John's, Newfoundland.

10. In the area of remote sensing of ice, particularly in the application of SAR, impulse radar, and thermal scanning. This research has helped greatly in advancing many areas including navigation through ice infested waters and in the safe use of ice covers.

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Advances in sea ice mechanics in the USA

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A brief review of significant advances in the field of sea ice mechanics in the United States is presented in this paper. Emphasis is on ice forces on structures, as the subject relates to development of oil and gas resources in the southern Beaufort Sea. The main topics discussed here are mechanical properties, ice–structure interaction, modeling of sea ice drift, and oil industry research activities. Significant advances in the determination of ice properties are the development of testing procedures to obtain consistent results. Using stiff testing machines, researchers have been able to identify the dependence of tensile and compressive strengths on different parameters, eg, strain rate, temperature, grain size, *c*-axis orientation, porosity, and state of stress (uniaxial or multiaxial). Now reliable data exist on the tensile and compressive strengths of first-year and multi-year sea ice. Compressive strengths obtained from field testing of large specimens ($6 \times 3 \times 2$ m thick) were found to be within 30% of the strengths obtained from small samples tested in laboratory at the same temperature and strain rate as found in the field. Recent advances in the development of constitutive relations and yield criteria have incorporated the concept of damage mechanics to include the effect of microfracturing during the ice failure process. Ice forces generated during an ice–structure interaction are related to ice thickness and properties by conducting analytical or small-scale experimental studies, or both. Field measurements of ice forces have been made to assess the validity of theoretical and small-scale experimental results. There is good agreement between theoretical and small-scale experimental results for ice forces on conical structures. Theoretical elastic buckling loads also agree with the results of small-scale experiments. Though considerable insight has been achieved for ice crushing failure, estimation of ice forces for this mode is based on empirical relations developed from small-scale experiments. A good understanding of the ice failure process has been achieved when ice fails in a single failure mode, but our understanding of multi-modal ice failure still remains poor. Field measurements of effective pressure indicate that it decreases with increasing contact area. Research in fracture mechanics and nonsimultaneous failure is underway to explain this observed trend. Ice ridge formation and pile-up have been modeled, and the forces associated with these processes are estimated to be low. The modeling of sea ice drift has progressed to a point where it is able to determine the extent, thickness distribution, and drift velocity field of sea ice over the entire arctic basin. Components of this model relate to momentum balance, thermodynamic processes, ice thickness distribution, ice strength, and ice rheology.

INTRODUCTION

The development of hydrocarbon resources in the southern Beaufort Sea requires safe operation of drilling structures and systems. Structures placed in an ice environment must be stable and strong enough to resist ice forces that are generated as a result of relative motion between the ice and the structure. Ice forces depend to a large extent on ice properties and conditions as well as on the type of ice–structure interaction. The main objective of ice mechanics research is to understand the processes by which ice fails against a structure and to identify the parameters that are important for the determination of ice properties. To assess ice conditions and velocity fields, large-scale ice drift models have been developed combining thermodynamic and mechanical processes that govern the state of ice at a given location and time.

In this review, discussion is limited to sea ice mechanics, and only the US contributions are covered. Emphasis is placed on ice forces because this is an important factor in the design of arctic structures. Not all contributions are included here, and we apologize in advance for any inadvertent omissions. In keeping with the theme of this paper, we will discuss the following major topics: mechanical properties, ice–structure interaction, sea ice drift modeling, and oil industry research activities. Other important areas that have not been discussed are properties of freshwater ice, navigation in ice, river ice jams, frazil ice, freezing and melting of ice, etc. It is beyond the scope of this paper to discuss the arctic environmental conditions in detail, and the reader is referred to papers on sea ice morphology [38, 39, 82, 99].

MECHANICAL PROPERTIES

A knowledge of the mechanical properties of sea is required to develop constitutive laws and failure criteria for analytical and numerical ice–structure interaction models. While numerous mechanical property tests have been conducted on sea ice [44, 68, 95, 96], only recently have "high-quality" multiaxial tests been performed on closed-loop testing machines where adequate attention has been given to sample characterization and preparation. Unfortunately, most testing of sea ice samples in the 60s and 70s was conducted on relatively soft, constant displacement rate testing machines, which resulted in lower than actual strengths and moduli [68]. Many of the earlier tests also gave insufficient attention to appropriate sample diameter, length-to-diameter ratio, sample end flatness, and end plane parallelism [45] to achieve reproducible results indicative of the bulk material properties of the ice. The structure and air content of the ice were also not documented or studied. Work by Weeks and Gow [97, 98] and Kovacs and Morey [35, 36] have since shown that, generally, sea ice sheets have a preferred *c*-axis orientation, ie, the *c*-axes are not randomly oriented in the plane of the ice sheet as in laboratory grown saline ice. The equations derived by Cox and Weeks [13] to calculate the brine and air volumes of sea ice samples also showed that the air volume can make up a significant portion of the ice porosity, particularly in deteriorated first-year ice, multiyear ice, and laboratory grown saline ice.

There are several institutions in the United States that are involved in determining the mechanical properties of ice. However, only three of these are actively working on field sea ice samples or laboratory grown saline ice. These are Exxon Production Research Company (EPR), the US Army Cold Regions Research and Engineering Laboratory (CRREL), and Dartmouth College. In the 60s and 70s, valuable contributions were also made by the University of Alaska's Geophysical Institute [51, 83] and the Naval Civil Engineering Laboratory (NCEL) [17, 83], but work at these facilities has stopped. It should also be noted that frequently the results from mechanical property tests on freshwater ice are used in sea ice mechanics problems, when data on sea ice are lacking. However, it is beyond the scope of this paper to review US progress on determining the mechanical properties of freshwater ice.

Uniaxial tests

One of the most widely quoted studies on the unconfined compressive strength of sea ice using state of the art testing techniques was performed by Wang [88, 89] at EPR. Wang systematically investigated the effects of ice structure and strain rate on the compressive strength of horizontal samples of sea ice. The samples were obtained at several locations in the Prudhoe Bay area off the north Alaskan coast, packed in dry ice, and shipped to Houston for testing. He found that, in the plane of an oriented columnar ice sheet, the ice strength varied with *c*-axis orientation, confirming the earlier work of Peyton [51]. In addition the ice strength was found to increase with increasing strain rate and decreasing grain size in both columnar and granular sea ice samples. In a subsequent paper, Wang [90] also reported that Poisson's ratio can vary appreciably in columnar sea ice. In uniaxial tests on horizontal samples, deformation was significantly greater in the direction normal to the columns.

For some time there has been considerable speculation regarding the effect of sample size on the strength of ice. It was generally believed that ice strength should decrease with increasing sample size, as the likelihood of encountering a significant flaw would be greater in a larger sample. During the winters of 1979–80 and 1980–81, EPR carried out a unique series of large-scale sea ice strength tests near Prudhoe Bay [6, 41]. Test blocks that were as thick as the full ice sheet, $6 \times 3 \times 2$ m thick, were loaded in uniaxial compression at controlled strain rates varying from 10^{-7} to 10^{-3} s^{-1}. At the same time, small, similarly oriented ice samples were obtained at different depths adjacent to the large-scale ice blocks. These samples were shipped to EPR's testing facility in Houston and later tested at *in-situ* temperatures and strain rates corresponding to those measured in the field on the large blocks [50, 93]. When the small-scale test results were averaged over the full thickness of the ice sheet, the computed strengths from the small samples were within 30% of the *in-situ*, full-thickness ice strengths. It was concluded that full-thickness uniaxial strengths at strain rates less than 10^{-3} s^{-1} can be reasonably predicted on the basis of laboratory unconfined compression tests. The small-sample data also provided considerable information on the horizontal uniaxial compressive strength of sea ice over a wide range of temperatures, strain rates, and c-axis orientations.

Uniaxial compression and tension tests (Fig. 1) on first-year sea ice and laboratory grown saline ice are also being performed at CRREL and Dartmouth College at various temperatures, strain rates, and sample orientations [61, 64, 66]. In addition, MIT is in the process of setting up an ice testing facility. CRREL investigators are also studying the effect of temperature (−10 to −0.5°C) and porosity on the creep properties of saline ice.

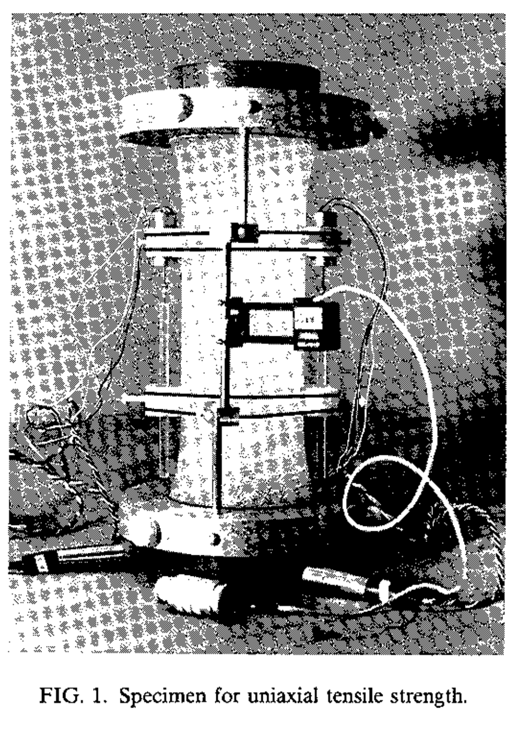


FIG. 1. Specimen for uniaxial tensile strength.

Multiaxial tests

Needless to say, the combined efforts of EPR, CRREL, and Dartmouth have significantly contributed to our understanding of the uniaxial strength of sea ice. However, closer examination of ice–structure interactions, and ice stress and load measurements around structures, indicate that in most cases, the ice fails in a complex state of stress. It is now apparent that ice force prediction formulas based on uniaxial data may give unrealistic ice load estimates. Consequently, the emphasis in test programs of sea ice strength has shifted from uniaxial compression and tension to confined compression and combined tension and compression. A concerted effort is now being made to define a three-dimensional sea ice yield criterion.

In the United States, conventional triaxial tests are now being conducted on sea ice at CRREL, and in the near future Dartmouth College will have a multiaxial closed-loop system, similar to that used at HSVA in West Germany [20]. To date CRREL has conducted conventional triaxial tests on aligned sea ice samples from Prudhoe Bay [61] and on laboratory-grown, transversely isotropic saline ice [64]. These tests were conducted in a specially designed triaxial cell (Fig. 2) where the radial confining pressure, σ_r, was ramped in constant proportion to the axial stress, σ_a [10]. Various σ_r/σ_a ratios were used: 0.25, 0.50, and 0.75. The tests on aligned first-year sea ice were performed at $-10°C$ and at three strain rates (10^{-5}, 10^{-3}, and 10^{-2} s^{-1}) on horizontal samples oriented at 0°, 45°, and 90° to the mean *c*-axis direction. The confined tests on the transversely isotropic, laboratory-grown saline ice were carried out on both vertical and horizontal samples at a strain rate of 10^{-3} s^{-1} and temperatures of -3, -5, and $-10°C$. As anticipated, ice strengths increased as the strain rate or confinement was increased, and decreased with increasing porosity. The confined test strengths also varied with sample orientation in the same manner as already observed in unconfined tests. Unlike previous tests on both freshwater and saline ice, a strength decrease was not observed from 10^{-3} to 10^{-2} s^{-1}, indicating that additional "high-quality" tests are needed to characterize the properties of sea ice in the ductile-to-brittle-transition region.

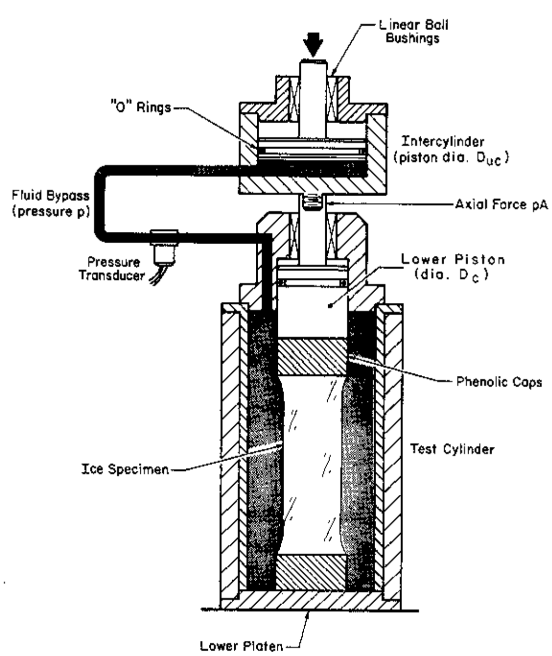


FIG. 2. Schematic sketch of multiaxial compressive strength test apparatus.

Such work is now in progress at Lawrence Livermore National Laboratory [102] where unconfined and confined compression tests are being performed on saline ice samples at 10^{-2} s^{-1} and 0.5 s^{-1}.

Now that we are beginning to gain an appreciation for the nature of the sea ice yield surface in the compression-compression quadrant, CRREL, in 1987, will begin testing cylindrical sea ice samples under combined radial confinement and axial tension. It is hoped that, in addition to defining the yield surface in the compression-tension quadrants, we will be able to extrapolate the yield surface into the tension-tension quadrant. Tension tests are difficult enough to perform, let alone biaxial and triaxial tension tests.

Multi-year sea ice

For a considerable time, little was known about the mechanical properties of multi-year sea ice. This was rather surprising, as multi-year ridges and floes are considered to be "design" ice features for drilling structures in exposed areas of the Beaufort and Chukchi Seas. Five years ago, with combined support from the petroleum industry and the Minerals Management Service (US Department of the Interior), a major effort was initiated at CRREL to determine the mechanical properties and structure of ice samples from multi-year pressure ridges in the Alaskan Beaufort Sea.

Uniaxial compression tests were first carried out on both vertical and horizontal ridge samples [14, 62]. A statistical analysis of the strength of vertical ice samples from 10 of the ridges, between cores located side by side on the same ridge, and between samples from the same core, indicated that the main factor contributing to the variance in ice strength was the variation in ice strength within each core. In effect, the strength of ice samples from different ridges was not statistically different [94]. This was not surprising as the internal structure in each ridge was highly variable [62]. However, in most of the sampled ridges, many of the individual ice blocks were oriented in a near horizontal position [63]. Consequently, vertical ice samples from the ridge were generally stronger than horizontal ice samples taken from near the same location [62].

In the second part of the program, the emphasis shifted to uniaxial tension tests and confined compression tests. The tensile strength of vertical ridge samples showed little variation with either temperature or strain rate [11]. The confined compressive strength data indicated that it may be reasonable to model multi-year ridge ice under compression as a Tresca material [8]. For a given strain rate and temperature, the deviatoric yield stress showed little variation with confining pressure [12].

Constitutive laws and yield criteria

During the past several years a number of uniaxial constitutive laws have been proposed by US investigators to describe the rheological behavior of sea ice under a variety of loading conditions: a four-element, nonlinear, viscoelastic model [4]; an elastic-plastic model [59]; a four-parameter mathematical model [91]; a continuous damage model composed of brittle and viscous elements [30]; a nonlinear, viscoelastic model with damage [19]; a continuous damage model composed of a rate-sensitive elastic spring and a nonlinear viscous dashpot [77, 80]; and a single-integral, viscoelastic model [5].

The constitutive equations proposed by Karr, Ting, and Sunder at MIT are novel in that they are the first to apply the concept of damage mechanics to microfracturing in ice. The damage models describe reasonably well the microfracturing associated with tertiary creep in constant-stress tests and strain softening in constant-strain-rate test. Karr [30] formulated his damage model on the results from acoustic emission tests on ice. Of the above-mentioned models, the model developed by Ting and Sunder [80] appears to be the most comprehensive; however, even with eight parameters it is difficult to describe all the aspects of ice behavior under different conditions well. There is also an obvious need for a standard test data-set for model verification and tuning.

Efforts are underway at MIT to extend their uniaxial model to multiaxial loading. However, until there is better cooperation between those conducting the mechanical property tests and the modelers, progress will be slow.

Various yield criteria have been used to describe the failure envelope of sea ice under a complex state of stress. For simplicity and lack of test data, it is generally assumed that the ice is transversely isotropic, that is, there is no preferred *c*-axis orientation in the horizontal plane. As more data become available on the confined compressive strength of natural sea ice, orthotropic yield criteria will be formulated.

One of the most widely used yield criteria in sea ice load calculations was proposed by Ralston [57]. He suggested that the failure envelope can be reasonably well described by a Pariseau parabolic yield criterion. In addition to providing differences in vertical and horizontal ice strengths, the criterion also allows for differing tensile and compressive strengths and describes a parabolic increase in strength with confining pressure. More recently, Karr et al [31] have proposed an anisotropic yield criterion, based on a generalization of the distortion energy, which is exponentially dependent on the hydrostatic pressure. Unlike many anisotropic yield criteria, yield due to the application of purely hydrostatic compression can be described. Significant contributions to sea ice constitutive laws and yield criteria are also being made in Canada and West Germany.

ICE–STRUCTURE INTERACTION

When an ice cover moves against a structure, it induces forces as a result of interaction with the structure. These forces may be limited by the amount of environmental force acting on the ice cover, the total momentum of the ice floes, or the force required to fail ice. To obtain an upper limit, the design ice forces are usually taken to be those that result in ice failure.

Ice forces resulting from an ice–structure interaction depend on the geometry (ie, width, slope and height) of the structure, the morphology and properties of the ice and the mode of ice failure (ie, crushing, bending, buckling, or multimodal). Brief reviews of the work on each of these failure modes are presented in the following sections.

…rushing failure

One of the most severe ice actions on structures is that of an …e sheet crushing against narrow, vertical structures. Even thick …1 m) ice sheets have been reported to fail in crushing against …le (≈ 80 m) structures [101]. Usually, the effective pressure … for crushing failure of ice is defined as the total force …ded by the product of the structure width (b) and the ice …ness (h). The effective pressure is often assumed to be …tly proportional to the uniaxial unconfined compressive …gth (σ) of ice at the applicable strain rate ($\dot{\epsilon}$), temperature …ther parameters. Further, the ratio of effective pressure to …ompressive strength depends upon many factors: aspect …defined as b/h), the shape of the structure, the degree of actual contact between the ice and the structure, and the ice velocity (v). As mentioned earlier, considerable effort has been devoted to finding the dependence of compressive strength on strain rate, temperature, grain size, confinement and other parameters. We would now like to outline briefly the US contributions to determine the effects of aspect ratio and ice velocity on the normalized effective pressure (p/σ).

Ralston [59] presented a plastic limit analysis to relate the compressive strength to indentation pressures for the columnar-grained ice sheets. In that study, an anisotropic yield function was used to describe the ice strength to account for the observed difference in compressive strengths when columnar ice is tested with different degrees of lateral confinement and in different directions relative to its growth direction. Recently, Karr [32] presented a three-dimensional plastic limit analysis to determine the normalized effective pressure of a flat, rigid punch on a columnar ice sheet. An anisotropic yield criterion was also used to reflect the properties of columnar ice. Karr gave only the lower bound solutions by optimizing assumed three-dimensional stress fields. The effects of varying the aspect ratio was also investigated. The above analyses showed that the normalized effective pressure is high for small aspect ratios (plane strain condition) and that it decreases to a constant value at high aspect ratios (plane stress condition).

During the past 10 years, a number of sensors have been developed to measure ice stresses around offshore arctic structures. Development has been slow and costly because the modulus of ice can vary by over an order of magnitude and because ice also exhibits variable rheological properties. One cannot simply measure the ice strain and then calculate reliable ice stresses from the ice modulus.

One of the first attempts to measure stresses in ice was by investigators at the University of Alaska [46]. Subsequently, ice stress sensors in the US have been developed by Exxon [78], ARCO [43], and CRREL [9]. In general, measured global ice loads on arctic offshore structures have been lower than anticipated. This has forced us to reexamine the dominant ice failure modes around structures, the large-scale mechanical properties of the ice cover, and the magnitude of pack ice driving forces.

A series of measurements has demonstrated that effective ice pressure decreases with increasing contact area. A test program [1] was conducted inside a tunnel dug into a grounded iceberg at Pond Inlet, Canada. In these tests, spherical impactors of various sizes (0.1 to 3.0 m^2) were indented into the ice walls of the tunnel. The objective of these tests was to find a trend of effective pressure with increasing of contact area. In another field study, three trenches ($50 \times 2.5 \times 3.5$ m) were dug in thick, multi-year ice off Melville Island, and a ram loading mechanism was installed in the trenches. Three different sized, indentors—2.5 and 1.0 m^2 curved, and 1 m^2 flat—were mounted on the rams and the rams were punched into the trench sides at several different velocities. Pressure transducers were mounted in the indentor face. The results were used to obtain an effective-pressure-versus-area curve and to investigate the effects of indentor velocity and shape.

Field measurements of effective pressure against wide structures (on the order of 10^2 m) have shown that the effective pressure continues to decrease with the increase of structure width or contact area. The average effective pressures over very large areas are low (≈ 0.1 MPa). In mesoscale modeling of the ice pack in the Arctic Ocean [24, 103], the assumptions made for the gross "compressive strength" of polar pack ice are in the range of 5×10^3 to 5×10^5 N/m. The effect of aspect ratio on normalized effective pressure, as deduced from plastic limit analysis, is not able to account for the decrease in effective pressure as measured in the field. Two mechanisms have been proposed to account for this decrease in effective pressure: scale effects and nonsimultaneous failure. On the basis of large-scale testing by EPR [6,41,50,93], we can say that there is likely no significant reduction of sea ice strength as a result of increasing the size of the specimen. Thus, the mechanism of nonsimultaneous failure is a plausible explanation for the reduction of effective pressure as structure width or contact area increases [65].

Work is in progress at MIT, Dartmouth College, Clarkson University, and CRREL to assess the role of fracture mechanics in explaining the reduction of effective pressure with increasing contact area. The process of nonsimultaneous failure of an ice sheet against wide structures involves localized crushing and fracturing of ice.

Ice action on flexible structures causes considerable vibrations in them. Theoretical, laboratory and field studies have been conducted to understand these vibrations. Peyton [51,52,53] and Blenkarn [2] measured the ice forces by instrumenting the vertical, cylindrical legs of a number of drilling platforms in the Cook Inlet, Alaska. These structures were subjected to moving sea ice sheets, including ridges. Besides presenting extensive data on ice forces and compressive strength, both Blenkarn and Peyton gave considerable attention to the cyclic force variations. Peyton concluded that the frequency of ice force variations, although corresponding closely to the natural frequency of the platform, originated basically from the ice failure mechanism and that there was a great possibility of forced resonant oscillations of structures. Blenkarn dissented from Peyton's postulation of a "characteristic failure frequency" by stating that the filtered response to random forces most likely contributed a major part of the observed dynamic response to Cook Inlet structures. Further, Blenkarn presented a concept of negative damping for the origin of ice-induced vibrations. The negative damping was derived from the decrease of ice crushing strength with increase of stress rate or strain rate.

To study the characteristic frequency of force variations in continuous crushing of sheet ice against cylindrical structures, Sodhi and Morris [73,74] performed small-scale experiments by pushing cylindrical structures of different diameters at different velocities through columnar ice sheets of varying thickness. The dominant frequency of ice force variations, defined as the characteristic frequency, was determined from the frequency spectra of the force records. They found that the characteristic frequency (f) varied linearly with the velocity-to-thickness ratio (v/h), which implies that the average length of the damage zone is proportional to the ice thickness. On the basis of their data, they found that the average length of the damage zone to be about one-third of the ice thickness; it varied between one-fifth to one-half of ice thickness.

Recently, Daoud and Lee [16] have presented a theoretical, nonlinear model to explain the ice-induced dynamic loads on offshore structures. Their approach is based on generalized modeling of ice loads, which takes into account the inherent periodic nature of the ice crushing phenomenon as well as its dependence on the loading rate. The proposed ice force model incorporates a time-dependent, saw-toothed function, similar to that proposed by Matlock et al [42]. The ice force dependence on loading rate is represented by a Heaviside step function, which vanishes for deflection rates that are greater than the ice velocity. The results from this model indicated that the response of the structure depends substantially on the ice crushing period, and the predicted dynamic magnification factor shows a good agreement with the experimental results of Tsuchiya et al [81].

The effect of velocity on effective pressure is taken in the form of compressive strength dependence on strain rate. An empirical relationship is used to define strain rate ($\dot{\epsilon}$) as the ratio of ice velocity to a multiple of the structure width (ie, $\dot{\epsilon} \approx v/4b$). Bohon and Weingarten [3] conducted indentation and compressive strength tests to establish a relationship between effective pressure and crushing strength of ice. Their results indicate that the empirical definition of strain rate ($v/4b$) is valid only at low strain rates. At high strain rates or relative velocity, the velocity-to-thickness ratio can be used for approximate definition of strain rate. Sodhi and Morris [73] also found in their experiments with urea model ice at high strain rates that the normalized effective pressure was dependent not only on aspect ratio but also on velocity-to-thickness ratio. In addition they found that there was no dependence of normalized effective pressure on velocity-to-diameter ratio and that the normalized effective pressure decreased with increasing velocity.

The interaction of a large structure with a multiyear ridge will result in large ice forces, if crushing of the ridge is assumed at the structure interface. Prodanovic [56] presented upper bound estimates of ridge pressures on a structure using plastic limit analysis. Croasdale [15] proposed a scenario in which the force on a structure is limited by the failure of the ice sheet behind a large ice feature.

Bending failure

When an ice sheet moves against a sloping structure, such as an inclined pier or a conical structure, it is pushed up or down and fails in bending. The resulting ice forces are lower in comparison to those caused by crushing.

Ralston [58] employed a plastic limit analysis to calculate the ice forces that are generated when an ice sheet interacts with a conical structure. The model was based on observations made during small-scale experiments. His theoretical formulation includes the effect of cone angle, waterline line diameter, exposed conical surface, ice–structure friction, ice flexural strength and ice thickness. The results of this model compare favorably with model test data from small-scaled experiments (Fig. 3) [18,76]. Because of the good agreement, his model has been extensively used in industry. However, a different approach has to be taken if a rubble field exists in front of a conical structure.

For the interaction between multi-year ridges and conical structures, Ralston [58] pointed out that a ridge of finite length may induce a higher ice force than that induced by an infinitely

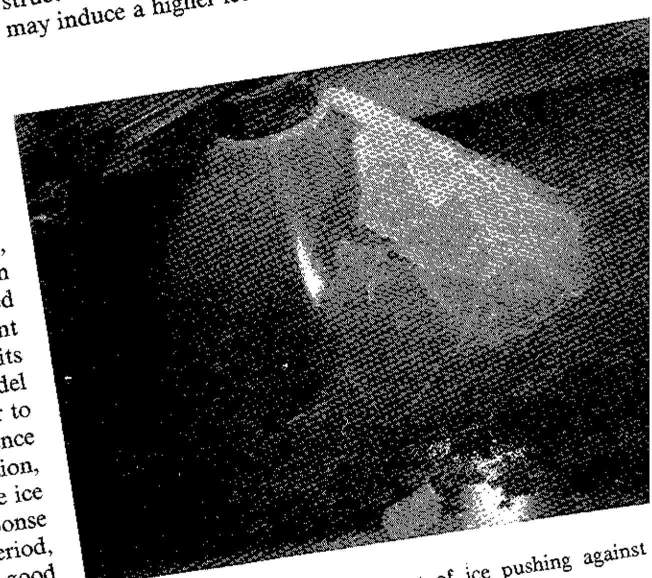


FIG. 3. Small-scale experiment of ice pushing against structure.

...elastic analysis was used for the above deriva-... Wang [92] presented a formulation for the above problem using plastic limit analysis. He assumed different velocity fields for different lengths of ridges, in which both bending and twisting of the ridge were possible. When he compared the theoretical results from the elasticity and plasticity methods with those from tests with wax model ice and with natural saline ice, Wang found that the elasticity method underestimated the experimental results, whereas the plasticity method overestimated them. He attributed this to the difference in failure criteria used in the two methods. Recently, Winkler and Nordgren [100] developed a model for estimating of the forces on a conical structure during ride-up of an ice ridge.

Haynes et al [21] conducted small-scale experiments by pushing model ice sheets against narrow, sloping structures with different slope angles. A relationship between the nondimensional force and the slope angle was found, and it agrees with the theoretical results for an approximate two-dimensional bending failure of an ice sheet against sloping structures.

Buckling failure

In buckling analyses the floating ice sheets are assumed to be beams or plates resting on an elastic foundation; an assumption that is valid for a floating ice sheet as long as it does not completely submerge under the water or completely emerge out of the water. This assumption is also adequate for linear buckling analyses where the deflections of the ice sheet are assumed to be small and the buckling load corresponds to the incipience of instability. The foundation modulus in the case of floating ...eets is the specific weight of water. ...ckling analyses of uniform beams on elastic foundations ...een formulated by Hetenyi [22], and analyses of tapered ...ave been formulated by Kerr [34] and Nevel [47]. Sodhi ...nza [72] and Wang [87] presented buckling analyses of ...ite floating ice sheets using finite element and finite ... methods, respectively. Sodhi [69] determined the ...ads of wedge-shaped floating ice sheets of different ...gles using a finite element method. An experimental ...lso undertaken by Sodhi et al [75] to verify the ...se analyses. For a wide range of structure-width-...ic-length ratios, most of the experimental data ...ween the theoretical values of the normalized ...or frictionless and hinged boundary conditions, ...d the extreme situations for the ice–structure ... experiments. Since there was no control over ...itions during the experiments, the agreement ...mental and theoretical buckling loads was ...od. However, there was considerable scatter ...e ice velocity was increased from 0 to 10 ... Sodhi [70] conducted an analytical and ...o show that the dynamic buckling load of ...creases with an increase in ice velocity. ...presented the results of experimental and ...hich they determined the buckling loads ...ith vertical cracks emanating in different ...ge of a structure.

... United States will involve determining ...d as a function of relative velocity be-... This will enable us to assess the range ... elastic analyses are valid.

... pile-up

...formed when two ice floes are pushed ...d an understanding of their formation is important in estimating the forces required for ridge formation. Parmerter and Coon [49] presented a kinematic model of pressure ridge formation, in which the lateral and vertical displacement of ice blocks is combined with a force balance and breaking stress calculation. In a computer simulation of the ridge building process, the ice sheet is advanced incrementally through the rubble, which loads the ice sheet from the top and the bottom. The advancement of the ice sheet proceeds until it breaks and forms rubble, and the penetration of the ice sheet starts again from the computer-generated and the measured profiles of ridges is found to be good. When the ridge model proceeds through many steps, a limit cycle is achieved that provides a limiting height for ridges, which depends on the thickness and strength of the ice in this model.

Nevel [48] presented a ridge building model based on a two-dimensional analysis of force interaction between ice blocks and a floating ice beam. This analysis considers both in-plane and transverse forces acting on the beam.

On a geophysical scale, estimates of the ice forces in the arctic pack ice are in the range of 10^4 to 10^5 N/m [24, 54]. These force levels are in the range of values estimated for ice ride-up and pile-up [37] and for pressure ridge building processes [49]. In discussing the implication of the forces associated with ice ridging, Croasdale [15] proposed that the ridge building force itself limits the ability of the pack ice to transfer forces from a large area to a structure. Vivatrat and Kreider [85] also discussed the concept of a limited driving force in the formation of pressure ridges, rubble fields and shore ice pile-ups. The validity of these concepts can only be assessed by experience and through the measurement of ice forces on wide structures.

SEA ICE DRIFT MODEL

In the last 15 to 25 years, scientists have been able to gain a reasonable picture of pack ice as being a collection of irregularly shaped, interlocked pieces of ice driven by air and water currents, influenced by internal stresses, deflected by the Earth's rotation, and subject to melting and freezing as dictated by the regional climate. In the 1970's the large-scale Arctic Ice Dynamics Joint Experiment (AIDJEX) program was launched to acquire a set of synoptic data to gain a better understanding of the interaction of the atmosphere and the Arctic Ocan. With the help of these and later studies, the modeling of sea ice drift has progressed to a point where it is able to determine the extent, thickness distribution, and drift velocity field of the sea ice over the entire arctic basin.

There are several components of a sea ice drift model [23, 24, 25] as shown in Figure 4. These components relate to momentum balance, thermodynamic code, ice thickness distribution, ice strength, and ice rheology. A brief description of these components is given below.

The modeling of sea ice dynamics is based on the balance of all forces acting on a representative area of an ice cover. This representative area depends upon the scale of the numerical model, which may be on the order of 10 to 100 km for the case of a sea ice cover. The forces exerted by winds and currents on the top and bottom surfaces of the ice cover are the two most important forces that influence its drift. On a geophysical scale one must also include inertial forces, the Coriolis force and the forces due to variations in internal ice stress. The forces associated with tilt of the sea surface and the Coriolis effect are the results of the coupling between the Earth's rotation and the movement of water and ice. The ice can drift from one region to another under the influence of lateral forces caused by variations in internal ice stress. The evidence of an internal ice force is derived from observations that, at times, high d...

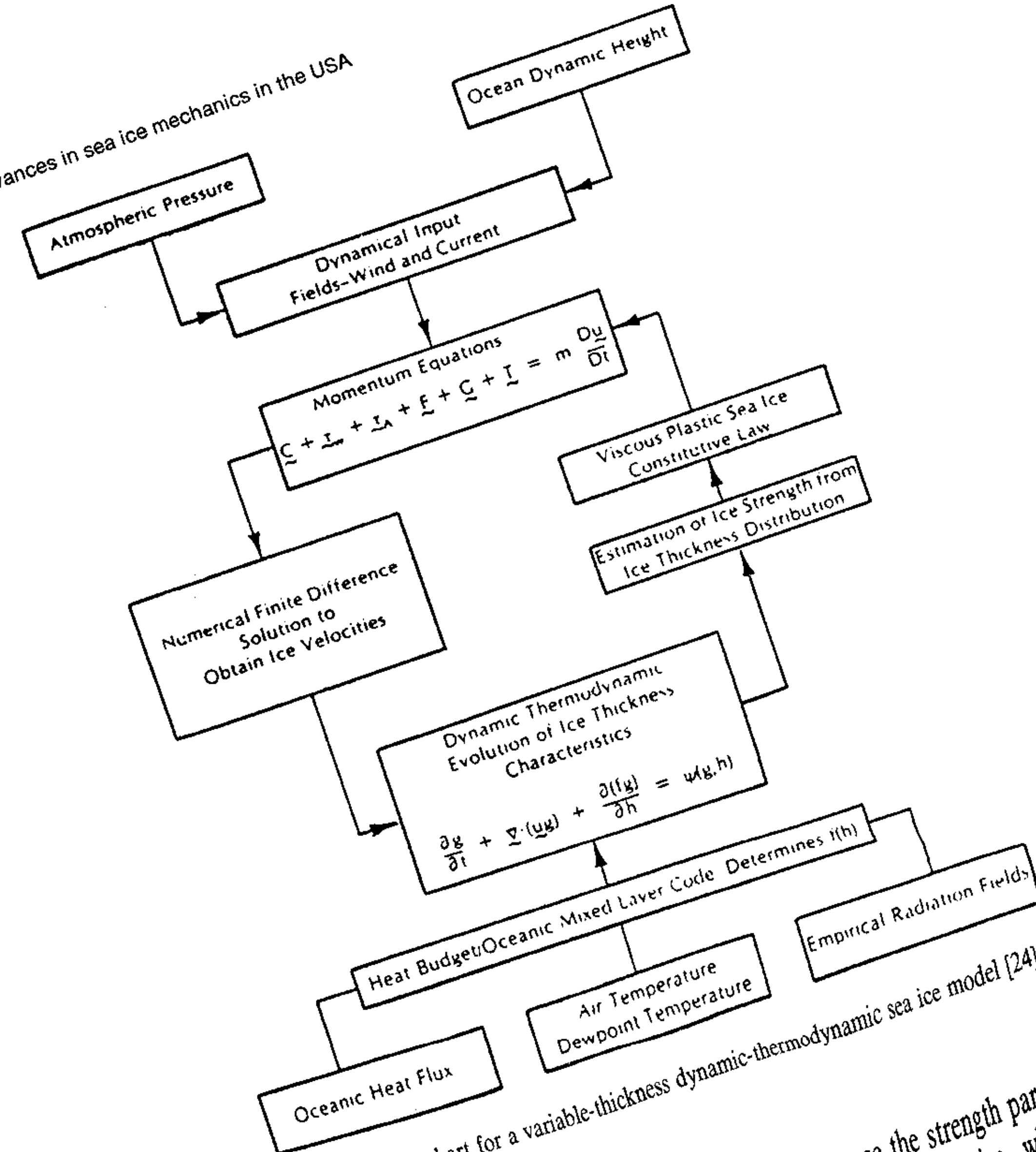


FIG. 4. Flow chart for a variable-thickness dynamic-thermodynamic sea ice model [24].

and severe ridging occur during periods when the local wind and currents are small, and conversely there are instances when no motion may occur under substantial wind conditions.

The results of a thermodynamic code [24] are used to specify the ice growth and decay rates for various ice thicknesses. This is accomplished by determining the surface temperature for ice of any specified thickness and by taking into account the heat conduction through the ice, the air temperature, the surface albedo, the ice thickness, the amount of heat transferred from the ocean to the ice, the geostrophic wind, the specific humidity, and short- and long-wave radiation terms. Furthermore, the code can handle the effect of a snow cover, lateral melting of ice floes during the summer, and ablation of the uppe surfaces of ridges.

The ice thickness distribution in a given area describes the percentage of area occupied by ice in a given rate of thicknesses. The thickness distribution can change as the result of three principal processes: advection (the movement of ice of different thicknesses from one region to another), thermodynamic growth, and mechanical processes such as ridging, rafting and the formation of leads [79].

The ice strength parameter of an ice cover is a measure of the large-scale strength of the two-dimensional granular-media pack ice. Rothrock [103] derived the strength equation by assuming that the rate of deformation work equals the work done through ridge building. Hibler [24] related the strength to the ice thickness distribution and compactness of the ice cover. In the latter case the strength parameter is str[...] on the amount of thin ice, which is char[...] compactness of the ice cover.

The final component of the numerical m[...] tion of ice rheology that relates the ice stre[...] and strength. In recent modeling efforts, t[...] tive laws have commonly been used: the e[...] in AIDJEX model [7,54,55] and a visc[...] oped by Hibler [23]. Both of these mo[...] describe the behavior of sea ice that is n[...] levels but allows large deformations [...] limiting value. In limited comparative s[...] predicted similar ice behavior. The vis[...] putationally simpler and faster, and i[...] wide variety of both linear and nonlin[...]

The information generated from d[...] sea ice drift model can be combine[...] conditional (winds or atmospheric pr[...] fields, air temperature) and the mo[...] pute the ice drift velocities (Fig. 5) a[...] thickness characteristics (Fig. 6) [23,[...]

Tucker [104] employed a two-le[...] the viscous-plastic model to simula[...] velocities for a region east of Green[...] difficulties in attempting to model ic[...] sea with an open ice edge. He conclu[...] was necessary to use a coupled dynam[...]

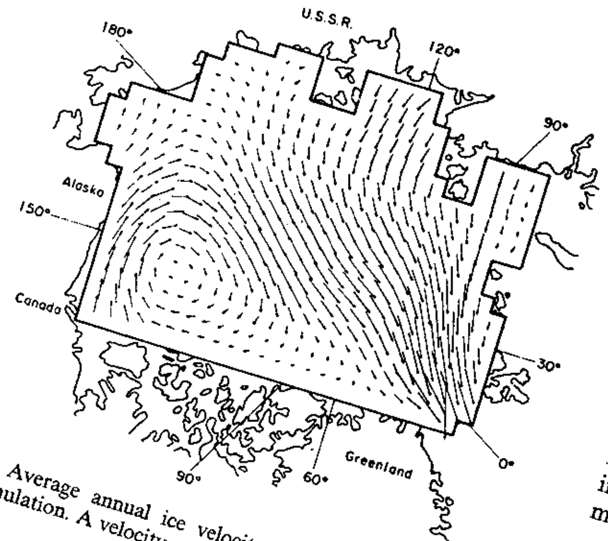
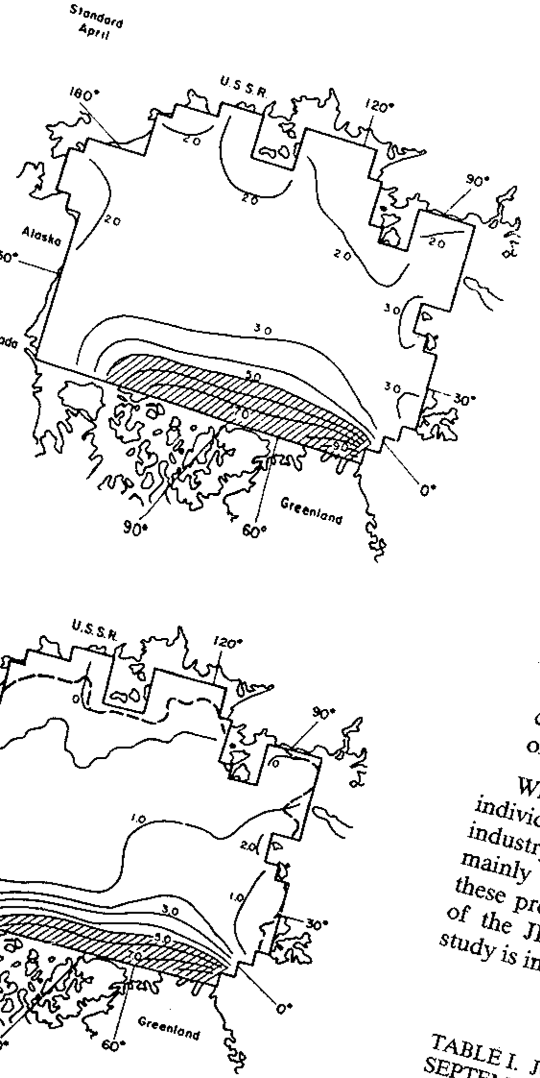


FIG. 5. Average annual ice velocity field for the 5 years of a standard simulation. A velocity vector one grid space long represents 2 cm/s [24].



...ugust thickness contours (*m*) for the ...ation. The dashed line represents the ...tour at the end of August for the time ... the British Meteorological Office,

to provide adequate simulations for such regions. Variations of the sea ice drift model have been applied to mesoscale regions such as Lake Erie by Rumer et al [105] and Bay of Bothnia by Hibler et al [28].

Work is underway to develop a coupled ice-ocean model that incorporates a complete treatment of sea ice dynamics and mechanics to examine the role of nonlinear ice interaction on ocean circulation near an ice margin, to analyze the kinematics of ice floes, and to ascertain the role of the polar regions in climatic change through coupled atmosphere–ice–ocean numerical modeling experiments. The above-mentioned work has recently been funded by the US Navy through a multimillion dollar grant to Dartmouth College. The research will involve mostly numerical simulation with some field experiments.

INDUSTRY RESEARCH ACTIVITIES

In addition to the work on sea ice mechanics described in the open literature, the oil industry in the United States has made significant contributions that are, at this time, confidential. We hope that over the next several years the results from industry programs will be published and thereby benefit the entire sea ice mechanics community. We will attempt in this section to describe some of the work on sea ice mechanics by the oil industry.

Oil industry related research for the last 2–3 years can be divided into the following categories:

1. Projects that obtain data to better describe the environment of areas to be offered for lease by the federal or state governments.
2. Projects that investigate the feasibility of using several different offshore platforms in a lease area and provide estimates on the economic benefits of each.
3. Projects that investigate basic ice properties, such as compressive strength of multi-year ice. These results can be used in any lease area in which this type of ice and failure mode is expected.
4. Projects that investigate ice–structure interaction, either in an analytical or numerical manner. These results can be used in any lease area in which the structural type and ice failure mode is expected.
5. Projects that obtain site specific data that are applicable to only one or several lease blocks owned either by one oil company or a consortium of oil companies.

While all of the above projects can be undertaken by either individual companies or a groups of companies in a joint industry project (JIP), projects in the latter two categories are mainly accomplished by one company. Thus, the results of these projects are confidential and are rarely released. Results of the JIP studies are typically released 5–7 years after the study is initiated. All JIP studies are compiled by the Alaska Oil

TABLE I. JOINT INDUSTRY PROJECTS INITIATED SINCE SEPTEMBER 1984 AND LISTED IN *AOGA PROJECT BOOK*.

Projected related to use of concrete for structures	5
Projected evaluating feasibility of structures	7
Projects evaluating ice loads on structures	13
Projects related to ice environment description	23
Whale or bird research	6
Oceanographic research	5
Geotechnical investigations	11
General technology development	5

and Gas Association (AOGA) in a book entitled the *AOGA Project Book*.

Since September 1984, over 75 projects have been initiated and carried out in JIP efforts as listed in Table I. Summaries of all of the above projects can be found in the *AOGA Project Book* available from the AOGA office in Anchorage, Alaska.

SUMMARY

To explore for and to develop hydrocarbon resources in the arctic, it is essential to operate arctic structures safely in the presence of ice. The research on ice mechanics in the United States has led to significant progress towards understanding of ice behavior and estimation of ice forces on structures. Major topics included in this brief overview are the mechanical properties of ice, forces induced as a result of ice–structure interaction, modeling of large-scale sea ice drift, and oil industry research activities.

With improved testing procedures, reliable data exist on the tensile and compressive strengths of first-year and multi-year sea ice. Dependence of these strengths on different parameters have been identified. Strengths obtained from field testing of large samples were found to be within 30% of those obtained from small samples tested in the laboratory at the same temperature and strain rate.

There is generally good agreement between results of theoretical and small-scale experimental studies when an ice sheet fails in bending or buckling modes. Though considerable insight has been achieved for ice crushing failure, estimation of ice forces for this mode is based on empirical relations developed from small-scale experiments. Models for ice ridge formation and pile-up are based on energy considerations, and forces associated with these processes are estimated to be low. Large-scale testing and field measurement of ice forces indicate a trend of decreasing effective pressure with increasing contact area between ice and structures.

During the last decade, there has been significant progress made in modeling sea ice drift. Combining mechanical and thermodynamic processes, it is now possible to determine the extent, thickness distribution, and velocity field of sea ice over the entire arctic basin.

ACKNOWLEDGEMENTS

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REFERENCES

The abbreviations used in this list of references have the following explanations:

AOGA Arctic Oil and Gas Association

APOA Arctic Petroleum Operators' Association, Calgary AB, Canada

CRREL US Army Cold Regions Research and Engineering Laboratory, 72 Lyme Rd, Hanover NH 03755

IAHR '70 Proceedings of the International Association for Hydraulic Research Symposium on Ice, Reykjavik, Iceland, 7–10 Sep 1970

IAHR '72 Proceedings of the International Association for Hydraulic Research Symposium on Ice, Leningrad, USSR

IAHR '75 Proceedings of the International Association for Hy Research Symposium on Ice, Hanover NH, USA, 18–21 Aug 1975

IAHR '78 Proceedings of the International Association for Hydraulic Research Symposium on Ice, Lulea, Sweden, 27–31 Jul 1978

IAHR '81 Proceedings of the International Association for Hydraulic Research Symposium on Ice, Quebec PQ, Canada, 27–31 Jul 1981

IAHR '84 Proceedings of the International Association for Hydraulic Research Symposium on Ice, Hamburg, FRG, 27–31 Aug 1984

IAHR '86 Proceedings of the International Association for Hydraulic Research Symposium on Ice, Iowa City IA, 18–22 Aug 1986.

OMAE '82 Proceedings, 1st International Symposium on Offshore Mechanics and Arctic Engineering, 1982

OMAE '83 Proceedings, 2nd International Symposium on Offshore Mechanics and Arctic Engineering, Houston TX, 1983

OMAE '84 Proceedings, 3rd International Symposium on Offshore Mechanics and Arctic Engineering, New Orleans LA, 1984

OMAE '85 Proceedings, 4th International Symposium on Offshore Mechanics and Arctic Engineering, Dallas TX, 1985

OMAE '86 Proceedings, 5th International Symposium on Offshore Mechanics and Arctic Engineering, Tokyo, Japan, 1986

OTC '70 2nd Annual Offshore Technology Conference, Houston TX, USA 22–24 Apr 1970

POAC '71 Proceedings of the 1st International Conference on Port and Ocean Engineering under Arctic Conditions, Trondheim, Norway, 1971

POAC '73 Proceedings of the 2nd International Conference on Port and Ocean Engineering under Arctic Conditions, Reykjavik, Iceland, 1973

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POAC '81 Proceedings of the 6th International Conference o Ocean Engineering under Arctic Conditions, Qu Canada, 27–31 Jul 1981

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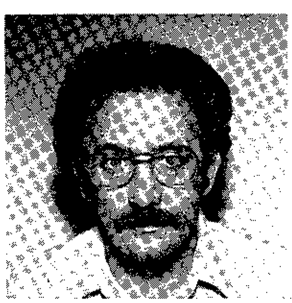


Gordon F N Cox *is a Research Geophysicist in the Snow and Ice Branch at the US Army Cold Regions Research and Engineering Laboratory in Hanover NH. Since 1980 he has worked on a variety of sea ice problems including: design, fabrication and verification of an ice stress sensor; ice force measurements on offshore arctic structures; mechanical properties of sea ice; and theoretical models to predict the salinity, temperature, and mechanical properties of first-year sea ice. Dr. Cox has served on the Sea Ice Mechanics Panel for the Marine Board of the National Academy of Engineering and the Glaciology Panel for the Polar Research Board of the National Academy of Sciences. He received his PhD in Geology from Dartmouth College in 1974 and after worked for Amoco Production Company as a Senior Research Engineer on problems relating to the design and operation of offshore arctic drilling structures. From 1978 to 1980, he was Arctic Manager at Oceanographic Services where he was responsible for planning and directing environmental data acquisition programs in the Arctic. He is a member of ASME, the International Glaciological Society, American Geophysical Union, and the Arctic Institute of North America.*

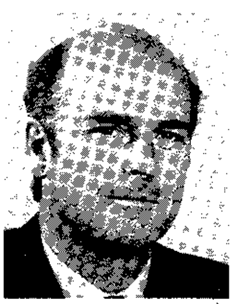
R Frederking *is a Senior Research Officer with the National Research Council of Canada. He has worked in the ice engineering field for over 15 years. This work has focused on field studies of forces which ice exerts on structures and investigations of the mechanical properties of ice. He has served on a number of technical committees for the preparation of guides and codes, as well as provided evaluations to Canadian regulatory agencies on ice engineering aspects of offshore projects.*

Sheila D Hallam *received her first degree in Engineering Science from Cambridge University in England. A brief research study on the strength of ice led to an interest in the strength of brittle materials in compression. This was followed by a three year research study leading to a PhD on the growth and interaction of crack populations under compressive loading and the development of multiaxial failure maps which can illustrate changes in failure mechanisms. From 1984 until the current day she has worked for the British Petroleum Company on problems related to offshore structures in Arctic Areas. This work has involved active research on ice mechanics related to the understanding of ice failure processes and forces on offshore structures. She has participated in several full-scale ice load measurement field programs in the Alaskan and Canadian Arctic.*

Mauri P Määttänen *received his MS in aeronautical engineering in 1968 and completed the Doctor of Engineering in 1978 both at the Helsinki University of Technology where he was also employed as assistant of Strength of Materials and as a research engineer. Since 1970 he has been at the University of Oulu, Finland, first as an Associate*

Professor of Strength of Materials, and from 1978 a full Professor of Engineering Mechanics. His research activities include ice mechanics, especially dynamic ice-structure interaction and ice forces. During a sabbatical in 1978–79 he conducted ice–structure interaction research in the US Army Cold Regions Research and Engineering Laboratory. Based on his research and design, ten ice-induced vibration isolated steel lighthouses have been constructed in the Northern Baltic. Dr. Määttänen is a member of the International Association of Shell and Spatial Structures and the International Association for Hydraulic Research.

Timothy Sanderson *studied Physics and Philosophy at Oxford University and graduated in 1975. He shortly afterwards sailed south to Antarctica as a glaciologist with the British Antarctic Survey, with whom he spent three years studying the flow regime of ice shelves and ice caps. In 1978 he turned his attention to research on active volcanoes and received a PhD in Geophysics from Imperial College, London, for work on gravimetric detection of magma movements within Mount Etna, Sicily. Since 1982 he has been with the British Petroleum Company, and has been closely involved with research into design load specifications for offshore structures in Arctic regions. He has taken part in a wide variety of full-scale Arctic field measurement programs, and has recently completed a book on ice hazards and offshore operations. At present he is working as a commercial analyst with BP Exploration Company Ltd.*



Joachim Schwarz *started to work on ice engineering problems in 1963 (mechanical properties of ice). He received his Dr Ing degree at the Technical University of Hannover (FRG) in 1970. His thesis topic was "Ice forces on piles." In 1971 he accepted an invitation from the Iowa Institute for Hydraulic Research where he spent 3 years, the last year as Adjunct Assistant Professor. In 1974 he returned to W Germany (Hamburg) where he became and still is the head of the Ice Engineering Department at the Hamburgische Schiffbau-Versuchsanstalt. He has been the leader of various expeditions to the Arctic and is a member—in some cases chairman—in several international organizations dealing with polar research.*

Nirmal K Sinha *is a Senior Research Officer with the National Research Council of Canada. After joining NRC in 1975, he has been studying micro-scale to meso-scale ice mechanics, including remote sensing, and has travelled extensively in the High Arctic on various projects. These projects ranged from detection of hazardous ice for safe navigation of ships to the growth processes in ice. Earlier he worked on glass and ceramics in an industrial R&D laboratory in Canada (1964–71) followed by work on microwave communication antennae (1972–75). He has a B Sc (Physics) degree from the University of Delhi (1961), India and a PhD (Rheo-optics of glass) degree from the University of Waterloo, Canada (1971).*

Devinder S Sodhi *received his undergraduate education in Mechanical Engineering at the Indian Institute of Technology, Kharagpur, India. After five years of industrial experience in India, W Germany, and Canada, he studied at the University of Toronto, completing his PhD in 1972. He was an Associate Professor at Memorial University of Newfoundland, where he became interested in problems related to floating ice sheets. Since 1978, he has been at the US Army Cold Regions Research and Engineering Laboratory, Hanover NH, as a Research Engineer. Dr Sodhi has worked on diverse problems related to drift of sea ice and icebergs, buckling of floating ice sheets, and ice forces generated during bending and crushing failure of ice sheets moving against structures. He is a member of ASME, International Glaciological Society, International Association for Hydraulic Research and Lions International. He was an Associate Editor of the* Journal of Energy Resources Technology *(1984–86) and is currently an Associate Editor of the* Journal of Offshore Mechanics and Arctic Engineering *(1986–).*

Garry W Timco *is an Associate Research Officer in the Division of Mechanical Engineering at the National Research Council of Canada. During the past ten years he has made several important contributions to problems related to the forces which an ice sheet can exert on a structure, with a special emphasis on physically modelling the interaction process. Dr. Timco has served on several international committees in this area, and he is currently the Chairman of the IAHR Working Group on Ice Forces on Structures.*