NUMERICAL MODELING OF ICE-STRUCTURE INTERACTION

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1. INTRODUCTION

OBJECTIVE OF PROPOSED WORK:

The objective of this project is to investigate using numerical models the mechanics of deformation and progressive failure in ice for the purpose of predicting global and local ice pressures on offshore structures proposed for deployment in the Arctic. The focus is on ice sheets interacting with rigid cylindrical indenters. The project involves the following three major areas of study:

1. Development of constitutive models to characterize the thermo-mechanical behavior of sea ice.
2. Development of finite element methods of analysis to allow for the complexity of sea ice behavior; simulate time-varying contact between ice and structure; and simulate the generation of new contact zones and their time variation due to macrocracking in ice.
3. Numerical solution of boundary-value problems for selected ice features and structural configurations.

BACKGROUND:

Over sixty percent of the U.S. hydrocarbon reserves, comparable in magnitude to those of the Persian Gulf, are estimated to lie in the Arctic. The extraction of these resources in an economical and safe manner poses many technical challenges to offshore engineering. At the root of these problems is the severe environment created by perennial ice features that impart global and local pressures on structures which are several times greater than those from waves in non-Arctic environments. Typically, two levels of ice loading are considered for design purposes. Global ice loads govern the overall structural geometry and dimensions as well as the foundation design, while local ice pressures are likely to dictate wall thicknesses and local framing, and may well govern structural cost.

Most of the emphasis in ice force research has been on predicting global forces. Only during recent years, as the focus changed from overall feasibility to preliminary and detailed design, has the importance of local pressures emerged. It is widely recognized that significant uncertainties exist in the ice load models in use today and that some design loads may be overestimated by an order of magnitude. Research is necessary to assess the uncertainties in ice loads and to develop improved load prediction models in order to design safe and economical structures.

Uncertainties in existing ice load models arise primarily from four sources: (i) incomplete modeling of the thermomechanical behavior of ice, (ii) use of semi-empirical formulations, calibrated without adequate regard for similitude modeling and scale effects, (iii) failure to realistically model the contact forces at the ice-structure interface and the presence of macrocracks, and (iv) not accounting for the finiteness of the environmental forces driving the ice features.

The complexity of sea ice behavior is due mainly to: (a) strong dependence on strain-rate, which is spatially and temporally variable, (b) simultaneous occurrence of ductile, strain-softening, and brittle modes of deformation, (c) pressure sensitivity leading to different strengths in compression and tension (at moderate to high strain rates) and to melting point depression, (d) anisotropic variation in strength by a factor of three, and (e) strong dependence on temperature, varying in first year ice from melting point at the water interface to perhaps -50°F at the air interface.

STAFFING:

Dr. S. Shyam Sunder, Assistant Professor of Civil Engineering, is Principal Investigator for this project while Dr. Jerome J. Connor, Professor of Civil Engineering, is Co-Principal Investigator. In addition, two full-time graduate Research Assistants are participating in this research: Mr. S-K. Ting, a doctoral student with considerable experience in concrete testing and dynamic behavior of offshore structures; and Mr. F.S. Chehayeb, a doctoral student whose background is in numerical analysis and finite element methods.

2. SUMMARY OF RESEARCH ACTIVITIES

The principal technical developments during this reporting period have been: 1. The study of sea ice indentation in the creeping mode of deformation, characteristic of "breakout" conditions in the winter, and 2. Initiation of research to develop failure criteria for sea ice accounting for tensile cracking and compressive crushing. Specific accomplishments and current research directions are discussed below:

Sea Ice Indentation in the Creeping Mode: Global and local pressures generated during sea ice indentation in the creeping mode are being studied, accounting for the spatial variation of strain-rates. Two methods of analysis are being considered: (a) approximate methods, i.e., upper-bound method and strain path method, and (b) "exact" method based on the finite element method. In both cases, a two-dimensional idealization of the indentation process is considered. In order to provide continuity with previous work, the isotropic, incompressible three-dimensional extension of the uniaxial power-law creep model is studied. Pressures predicted with this model are being compared with those from previously published formulas, e.g., API Bul. 2N, Ponter et al., and Bruen & Vivatrat. Ice pressures are also being obtained for a new uniaxial model that accounts for the stress-strain-strainrate behavior of sea ice, including its strain-softening behavior.

The key difference in the two approximate methods of analysis is that point stresses within the continuum can be obtained with the strain path method. As a result, local stresses at the ice-structure interface can be estimated, unlike the upper bound method which only yields the global pressure. However, both methods rely on an adequate specification of the velocity field in the ice sheet. This is obtained through a combination of theoretical modeling based on fluid mechanics and field ice movement survey data from an artificial island in the Beaufort Sea. In particular, two theoretical kinematic models are considered: one resulting from the superposition of a point source and a uniform flow (Kinematic Model A) that has been proposed by Bruen & Vivatrat; and the other resulting from the superposition of a doublet and a uniform flow (Kinematic Model B). Since, in both cases a two-dimensional velocity field is postulated, the numerical solutions apply to plane strain conditions. However, for typical artificial islands the plane stress case is of greater interest. Only if one assumes sea ice to be transversely isotropic, i.e., it is much stronger in the vertical direction, do the two solutions tend to become similar. This assumption has been made in the past in the case of columnar sea ice in the Arctic nearshore zone.

The results of the approximate methods indicate that:

(a) Kinematic Model B better models the ice movement survey data used here than Kinematic Model A.

(b) In the creeping mode of ice deformation, local ice pressures are of the same order of magnitude as the global pressures.

(c) Under the same conditions, Kinematic Model B, the API model, and the Ponter et al. model predict similar global pressures.

(d) The variation in global pressures for different power-law model parameters (Wang, Sanderson, Ting & Shyam Sunder) is on the order of 30%.

A key finding of the work is that for rate-dependent material models describing sea ice behavior, interface adfreeze and friction stresses can significantly influence both local and global ice pressures. The only realistic way to study these effects is through numerical models based on the finite element method of analysis. This research has been summarized in a paper entitled "Sea Ice Indentation Accounting for Strain-Rate Variation" to be published in the proceedings of the ASCE Specialty Conference: ARCTIC '85 - Civil Engineering in the Arctic Offshore to be held at San Francisco, CA, March 25-27, 1985. A copy of the paper is attached in Appendix A.

The finite element formulation is based on the NIKE2D computer program developed at the Lawrence Livermore Laboratory. A major effort has been expended in implementing a new solution algorithm and allowing the program (originally developed for plane strain and axisymmetric problems) to accept plane stress problems. The program originally had an explicit solution algorithm which is known to lead to stability problems in nonlinear analysis. A generalized implicit integration scheme (the α-method) has been incorporated now. In addition, a graphics pre- and post-processor for the program called ORION has been made operational. This processor is capable of producing contours of stresses, strains, strain-rates, and velocities in the ice sheet as well as the distribution of stresses at the ice-structure interface. A series of verification studies have been performed to assess the accuracy of numerical solutions generated by the program for two types of materials: linear elastic and elastic-plus-creep (power-law). These studies lead us to believe that the program is working correctly and in consonance with theory. Studies have also been carried out to select an appropriate mesh for the "breakout" problem. We are currently in the process of making a number of simulations incorporating different boundary conditions at the ice-structure interface (fixed, roller, free), different diameters (to assess

the possible effect of the rubble pile), different velocities (0.1, 0.64, and 1 ft/hr), and different material parameters (Wang with N=4, and Sanderson with N=3). The results from these simulations and from the approximate methods of analysis will be compared and described in a paper entitled "Sea Ice Indentation in the Creeping Mode of Deformation" to be published in the proceedings of the 17th Annual Offshore Technology Conference to be held in Houston, TX, May 6-9, 1985.

Failure Criteria for Sea Ice: Preliminary results from our indentation studies indicate that the ice sheet consists of three regimes of principal stresses; i.e., compression-compression, compression-tension, and tension-tension. The latter two regimes occupy a major fraction of the area of the continuum. Thus, tensile stresses are very important in explaining indentation phenomena. From a material modeling point of view, the tensile behavior of ice deviates from the compressive behavior at strain-rates exceeding about $5 \times 10^{-8} s^{-1}$. At higher strain-rates, ice behaves in a brittle manner in tension (tensile cracking) but remains ductile in compression up to strain-rates of about 5×10^{-4}. When the strain-rate exceeds this value, ice fractures in compression. At very high strain-rates failure in both compression and tension is by fracture. It is therefore necessary, even in the case of "breakout" during relatively slow ice movements to account for the differing behavior of ice in tension. Since ice is weaker in tension than in compression once tensile cracks occur, ice pressures should decrease.

The uniaxial stress-strain-strainrate model developed for ductile and strain-softening modes of deformation has been extended to account for compression fracture and tensile cracking. A cracking criterion based on limiting tensile strain is currently being studied to explain first cracking in ice. Initial results look encouraging and seem to follow the experimental data of Gold (1972) well. This seems to provide an alternative and more appealing criterion for cracking in ice than the delayed elastic strain criterion of Sinha (1982). A definitive statement about the adequacy of the limiting tensile strain criterion should be possible in the next month. If the results are positive, as we expect them to be, the next step would be to generalize the model to account for unloading and reloading as well as to make it applicable to a multi-axial stress state (at least biaxial for plane stress problems of interest).

As a point of interest it is important to recognize that two approaches can be used to explain material cracking: a tensile strain or strength criterion, and fracture mechanics criterion based on pre-existing distribution of cracks in the continuum. In the case of load bearing systems such as structures, a fracture mechanics criterion for cracking is conservative. However, in the case of load

transmitting systems such as ice sheets, a fracture mechanics approach may lead to unconservative results, e.g., if the ice sheet does not contain the assumed distribution of cracks. We feel that in order to account for tensile cracking and compressive fracture in ice and still be conservative in our force and pressure predictions, a limiting strain or strength criterion is preferable to the fracture mechanics approach. It is the former approach that we will be pursuing in this project.

Several approaches are available to account for cracking in a finite element framework. Two of the more common approaches are the discrete cracking models which follow individual discrete cracks between elements and the smeared cracking models which treat the gross (smeared) effect of cracks in an element. The latter approach has been preferred in finite element enalyses of concrete since it is computationally far more convenient. One of our future tasks is to extend the finite element program to incorporate cracking in ice.

A paper entitled "Ductile to Brittle Transition in Sea Ice Under Uniaxial Loading" will summarize the limiting tensile strain criterion for cracking in ice. This paper will be presented at the 8th International Conference on Port and Ocean Engineering Under Arctic Conditions to be held at Narssarssuaq, Greenland, September 6-13, 1985.

3. NOTABLE NON-TECHNICAL ACTIVITIES

PUBLISHED OR SUBMITTED PAPERS:

1. Ting, S-K., and Shyam Sunder, S., "Sea Ice Indentation Accounting for Strain-Rate Variation," Proceedings of the ASCE Specialty Conference: ARCTIC '85 - Civil Engineering in the Arctic Offshore, San Francisco, CA, March 25-27, 1985. In Publication.
2. Chehayeb, F.S., Ting, S-K., Shyam Sunder, S., and Connor, J.J., "Sea Ice Indentation in the Creeping Mode of Deformation," Proceedings of the 17th Annual Offshore Technology Conference, Houston, TX, May 6-9, 1985. Abstract Accepted, Paper in Preparation. Paper to be simultaneously reviewed for publication in the Journal of Engineering Mechanics, ASCE.
3. Shyam Sunder, S., and Ting, S-K., "Ductile to Brittle Transition in Sea Ice Under Uniaxial Loading," Proceedings of the 8th International Conference on Port and Ocean Engineering Under Arctic Conditions, Narssarssuaq, Greenland, September 6-13, 1985. Abstract Accepted, Paper in Preparation. Expanded version of paper to be submitted for publication in Cold Regions Science and Technology.

SEMINARS AND TALKS:

1. Both Professors S. Shyam Sunder and Jerome J. Connor participated in the Workshop on Breaking Process of Ice Plates[1] held at MIT on November 1-2, 1984. The title of their presentations are listed below:
   a. Professor S. Shyam Sunder: Sea Ice Indentation Accounting for Strain-Rate Variation.
   b. Professor Jerome J. Connor: Numerical Simulation of the Creep Mode in Ice-Structure Interaction.

   Professor S. Shyam Sunder was invited to talk on the same topic at the weekly seminar of the Constructed Facilities Division of the Department of Civil Engineering at MIT on December 5, 1984.
2. Professor S. Shyam Sunder has been invited to talk on Sea Ice and Its Mechanical Behavior at a series of seminars on Engineering in the Arctic to be organized during MIT's Independent Activities Period, January 1985.

PROFESSIONAL ACTIVITIES:

1. Professor S. Shyam Sunder is a member of the Conference Committee for ARCTIC '85 - Civil Engineering in the Arctic Offshore Specialty Conference[2] of the ASCE to be held in San Francisco, March 25-27, 1985. He is also moderating a session on Probabilistic Methods in Arctic Offshore Engineering.

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1. A copy of the workshop program is attached in Appendix B.
2. A copy of the conference program is attached in Appendic C.

2. Professor S. Shyam Sunder has been appointed Chairman of ASCE's Subcommittee on Arctic and Frontier Regions. This subcommittee operates under the ASCE Structural Division's Committee on Reliability of Offshore Structures.
3. Professor S. Shyam Sunder is a member of the ASCE Task Committee on Reliabilty-Based Techniques for Designing Offshore Arctic Structures which is entrusted with the responsibility of producing a monograph bearing the same name.
4. Professor S. Shyam Sunder attended the Arctic Energy Technologies Workshop organized by the U.S. Department of Energy as part of a recently initiated Arctic and Offshore Research Program. The workshop was held at Morgantown, West Virginia, on November 14-15, 1984. He also participated in the discussion group on Arctic Offshore Structures which had the task of defining the state-of-the-art, identifying technical issues, listing research and development needs, and recommending topics for research support by the U.S. DOE.
5. Professor Jerome J. Connor is leading the organization of an International Conference on Ice Technology (ITC '86) to be held at MIT, June 10-12, 1986. An international Scientific Advisory Committee has been set up with Professor Connor and Dr. C.A. Brebbia of Southampton University, England, as Co-Chairmen. This conference will be sponsored by the Center for Scientific Excellence in Offshore Engineering at MIT, the Centre for Adavnced Engineering Studies at the University of Southampton, and the MIT Sea Grant Program. Announcement and Preliminary Invitation to the conference is expected to be mailed shortly.

EXPERIMENTAL DATA FROM U.S. ARMY CRREL:

An informal agreement has been reached with the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, Group under the leadership of Dr. Gordon Cox concerning our use of experimental data obtained by them. Under this agreement we have immediate access to all their experimental data, although any publication by us of their data would in general be dated after they have had an opportunity to publish the results themselves.

4. BUDGET

The total expenditure as of November 30, 1984 is $7463.64. This reflects expenditures for the three month period September 1, 1984 (the requested project starting date) through the end of November.

Professor S. Shyam Sunder is charging 10% of his salary to the project and 20% to the Sohio account. From January 1, 1985 he is expected to charge 20% of his salary to the MMS account, and an equal amount to the Sohio account. Professor Jerome J. Connor is charging 10% of his salary to the MMS account and 10% to the Sohio account. This is expected to remain unchanged through May 31, 1985, i.e., the academic year.

Mr. S-K. Ting and Mr. F.S. Chehayeb are full-time Research Assistants on the project. During the Fall Term their salary and tuition came from the Sohio account. During the Spring Term their salary will be charged to the MMS account.