The MIT Marine Industry Collegium
Opportunity Brief #39

Wave and Ice Impact Loading and Reponse of Ocean Structures

A Project of
The Sea Grant College Program
Massachusetts Institute of Technology
MITSG 85-20

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WAVE AND ICE IMPACT LOADING AND RESPONSE OF OCEAN STRUCTURES

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Revised Edition
August 1, 1985

Marine Industry Advisory Services
MIT Sea Grant Program

Cambridge, Massachusetts 02139

Report No. MITSG 85-20
Grant No. NA84AA-D-00046
Project No. A/M-2

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1.0 INTRODUCTION AND BUSINESS PERSPECTIVE

According to a survey by the U.S. Salvage Association, 105 out of 1079 cases of reported damages to ships in 1978 were directly related to severe weather, and a large portion of these vessel casualties can probably be attributed to hydrodynamic impact forces encountered in stormy seas. Environmental damage to ships and offshore structures has economic and safety implications for builders, owners and operators. This Opportunity Brief covers some of the important work at MIT in areas of critical interest to offshore operations.

Improved methods for predicting the strength of marine structures under impact loading conditions are clearly needed to prevent catastrophic structure failures and reduce repair costs. Criteria for defining acceptable levels of permanent deformation of offshore structures are also extremely important. Yet our current ability to predict extreme wave loads is hampered by insufficient data and theoretical and experimental difficulties.

Researchers at MIT are developing methods to forecast wave impact loads on ocean structures coupled with predictions of the structural response. At the Marine Industry Collegium Meeting on December 13, 1984, Professor Kendall Melville presented work to measure and predict wave-breaking impact forces on surface-piercing structures. Professors C.C. Mei and Tomasz Wierzbicki talked about the response of the structures to waves, with Professor Mei addressing slow drift motion of the structure and Professor Wierzbicki discussing the local response of structures to such hydrodynamic impact loads. Professor Wierzbicki also reviewed his work on how to determine ice loading on structures, while Professor Paul Xirouchakis proposed how a ship or structure might be strengthened to withstand extreme ice loading.

2.0 DEEPWATER WAVE BREAKING FORCES ON OCEAN STRUCTURES

Predicting wave forces on ships and offshore platforms is an economically important but scientifically difficult problem. A recent survey found that "blows by waves...are the most common source of heavy-weather damage to ships and that...catastrophic casualties to merchant vessels occurred in seaways which were...steep and/or confused."

As one step toward improving predictions of breaking wave forces, Professor Kendall Melville and graduate student Eng-Soon Chan of the MIT Department of Civil Engineering are conducting laboratory experiments using a programmable wave generator to produce repeatable breaking waves and measure the forces imposed on prototype structures. The repeatability of the experiments permits the forces to be measured in a controlled manner for waves just before, at, and after breaking.

Six major parts of the experimental program are to:

1. Generate and carefully measure breaking waves in modulated wave trains.

2. Measure total forces on a series of prototype structures.

3. Measure pressure distribution, and hence moments, on the same structures under the action of breaking waves.

4. Measure the modification of the wave field due to the presence of the structure.

5. Correlate the measured forces and pressures with measurements of the breaking waves.

6. Evaluate available field data on wave breaking and wave-breaking forces in the light of laboratory measurements proposed in these six parts.

Professor Melville would like the project to produce "the reference set of laboratory measurements for breaking-wave forces on structures, which would provide a reliable foundation for further theoretical and numerical modeling." He believes that they will have that set of measurements in the next year.

According to Professor Melville, the work so far has shown that the wave pressure on a structure can rise from zero to its maximum value in milliseconds or less. In controlled laboratory experiments, the sampling system can be triggered to start a few milliseconds prior to the impact, thereby catching the full pressure field. But in actual ocean tests the randomness of the waves prevents a prediction of when a wave will break against a structure, suggesting that most measurements of force in the field are probably not done on the necessarily short timescales.

In the past, variability in generating the waves has led to variability in the measurements. By exactly reproducing the generating process, Professor Melville and Chan reduce the ambiguity so that any lack of reproducibility in the wave pressure measurements is due to variability in the fine scale structure of the breaking process itself. In order to quantify these fine scales, the usual pressure and surface displacement (wave shape) measurements are being complemented by high speed photography and fluid velocity measurements using laser anemometry (measuring movement at an exact spot).

Professor Melville believes that one reason why the details of the pressure field may not be reproducible is because the velocity field varies unpredictably on a very fine scale, particularly just before the breaking wave hits the structure. Wave breaking is a transition process between predictable laminar flow and unpredictable turbulent flow. Before doing theoretical and numerical modelling, the source of the variability must be isolated. One approach is to correlate the velocity and pressure measurements from test to test. If the pressures vary significantly while maintaining a significant correlation with the velocity field, then the researchers will have a good idea of the source of the variability.

Waves generated in the experiments are several meters long, 10 to 20 cm high and have a typical period of about 1 second. Scaling up to likely ocean dimensions of perhaps 100 times larger is not easy. However, in a related project, Profesor Melville and graduate student Ronald Rapp have found that by using a limited number of dimensionless parameters to describe the waves, they have been able to correlate breaking events in the laboratory. "We believe that we now know how to scale the breaking waves, which was really quite important for doing these experiments in an orderly manner," says Professor Melville. "I am confident that we will produce scaling laws which will permit us to reliably extrapolate our measurements to full scale."

The velocities in breaking waves may be an order of magnitude larger than those in unbroken waves of the same height. Therefore, structures in the immediate neighborhood of the surface may be subjected to higher loads more frequently than anticipated from simple breaking-criteria estimates. "That fact is not appreciated very much by wave statisticians but comes out clearly in related measurements we've been making. The conventional surface displacement measurements are really a very poor predictor of the velocity field if the waves are breaking, and waves are breaking even in the more benign sea states. There is clearly a need for an improved statistical description of the velocity field associated with the wave field," states Professor Melville.

The simplest structure used in the laboratory is a flat plate which may represent the side of a supertanker. "We intend to devise an impact algorithm to predict the pressure on the structure given the details of the waves prior to impact," says Professor Melville. The other prototype structures are cylinders mounted with axes either vertically or horizontally.

Much more is known about the effect of waves on vessels moving through the water than about the effect of waves on structures. Extreme wave conditions usually result from wind forcing during storms, but also may arise from wave-wave or wave-current interactions. Wave breaking limits the wave height but may also impose large loads on ships or offshore structures hit by the breaking waves.

The extent of actual damage to ships or structures from extreme or breaking waves must often be inferred from hindcasting or circumstantial evidence. Some hard evidence, though, is available from the International Ship Structures Congress (1982). The Report of Committee II.3 on Transient Dynamic Loadings and Response quoted a survey of structural failures in U.S. merchant and naval ships by Buckley and Stavovy, who found that:

- "Wave impingment on superstructures, appendages, deck-mounted equipment and structures topside is, collectively, the most common source of heavy-weather damage (35% of all cases)";

- "All catastrophic casualties to merchant ships studied in the survey occurred in seaways which were not fully developed for the winds at hand....In general, hull slamming or pounding was reported by the supervisor prior to the casualty."

Two types of waves are most likely to cause structural damage: 1) waves of very unusual or unexpected proportions for the existing seaway, such as the "giant waves" in the Agulhas Current, and 2) elevated waves with unusually steep forward faces. The committee report emphasized the necessity of time-domain rather than frequency domain (spectral) analysis of data relating to these extreme events. Structural heavy-weather damage is probably reduced by speed and course changes ordered by the captain when he senses his ship to be in danger, although such operational adjustments may be impossible for fixed or moored offshore structures.

One of the most extensive and detailed accounts of losses caused by extreme or breaking waves is summarized by Kjeldsen et al. Between 1970 and 1979 in Norwegian waters, 26 large Norwegian vessels (up to 500 GRT with total lengths up to 76 m) were lost with 72 people drowned. In half these cases survivors confirmed that the vessels capsized in large breaking waves, while the other 13 vessels were lost with no survivors. In addition, numerous small fishing vessels were also lost. This situation led to the initiation of an ongoing project, called "Ships in Rough Seas," which was designed to improve the safety of smaller vessels by providing a better understanding of ship response to extreme conditions.

Breaking waves also threaten fixed or moored structures, where the multi-dimensional nature of the problem is more apparent. First comes the need to predict the localized force on the basic structural elements (cylinders, plates, etc.), which Professor Melville is working on. Second, one must predict the response of the whole structure to this forcing. One current design difficulty associated with some large offshore structures is predicting the forcing and response at long resonance periods, such as 100 seconds. Wave-group statistics and second-order forcing are important in this case, since the period of the wave groups may be in the resonance band of the structure.

Wave breaking appears to be associated with modulations of the wave field (Thorpe and Humphries, Longuet-Higgins, Melville) and it must be measured to adequately describe wave breaking and thereby predict impact loads. Until the continuing development of remote electromagnetic and acoustic sensing techniques makes this possible, laboratory experiments can play an important role.

Extensive literature is devoted to laboratory measurement of the forces from shoaling waves, while relatively little work appears to have been done on deep-water breaking forces. However, Kjeldsen and Myrhaug conducted experiments to measure the shock pressures on flat plates due to waves breaking in a converging channel. They measured wave pressures simultaneously at six vertical locations, for different horizontal locations of the plate relative to the break point, and for three inclinations to the vertical. Preliminary results show that even under heavily controlled conditions, the pressure field exhibits considerable variabilty from run to run, while the integral of the pressure field is repeatable.

3.0 LOCAL RESPONSE OF MARINE STRUCTURES TO HYDRODYNAMIC IMPACT LOADS

Professor Tomasz Wierzbicki of the MIT Department of Ocean Engineering is interested in understanding the response of ocean structures to extreme wave and ice loading. With support from the Sea Grant Program, Professor Wierzbicki began in July 1983 to develop design procedures capable of predicting the amount of local damage to ships and marine structures subjected to hydrodynamic impact loading.

The interaction of three different levels of response -- local dishing of plates, interframe deformation of stiffened plates, and global collapse of web frames -- has been addressed to determine the maximum deflection of the affected part of the hull girder and/or superstructure. The overall whipping response of the hull girder will also be taken into account. Several new factors are being considered in the dynamic analysis, including lateral instability of stiffeners, bending, local buckling and crushing of the support structure and elastic restraints at the boundaries.

Professor Wierzbicki is collaborating with the Research Division of Det norske Veritas (DNV) of Norway, which supplies valuable field data. The methodology presented at the Collegium workshop was developed for ship hulls, but most of the results can be directly applied to damage assessments of the decks of offshore platforms operating in severe seas.

The extent of damage to ships or structures caused by stormy weather may vary from minor denting of side or bottom hull to gross plastic deformation and fracture of the hull girder. Detailed accounts of severe damage suffered by ships crop up in various trade journals. In a typical incident, a 60,000 DWT crude oil tanker bound from the Persian Gulf to Europe encountered extreme sea conditions and hurricane winds. With wave heights of 20 to 30 feet above deck, the storm was so intense that at least one vessel sank and many others in the area were imperiled. The most serious damage occurred in the tanker's midship permanent water ballast tank, where the web plates and the face plates at the gunwall corner, the strut, and the bottom transverse near the bilge corner were deformed and fractured.

Although such extensive damage from hydrodynamic impact forces rarely occurs, ships and structures must be designed to withstand extreme environmental forces as well as milder loads. Less severe damage to the hull girder such as dishing or local denting of the bottom or side shell may lead indirectly to a more catastrophic structural failure, because local out-of-plane deflections of plating may induce a significant loss of stiffness and strength under in-plane loading.

"From the point of view of construction and operational costs, it is inconceivable to think of a completely damage-proof vessel or offshore platform," states Professor Wierzbicki. Subjected to once-in-a-lifetime loading, hull and superstructure plating should be permitted to experience substantial permanent deformation as long as watertight integrity remains.

"However, failure of the members which could result in substantial loss of watertight integrity or which could lead to gross structural failure should not be permitted." In an example of the latter case, a tanker foundering in a storm southeast of South Africa sprung a leak in the side shell. This damage triggered a sequence of events leading to an internal explosion and almost total loss of the vessel.

To prevent such disasters and to reduce repair bills, improved strength prediction methods are needed for marine structures under dynamic loading conditions. Criteria are also needed to define acceptable structural behavior and acceptable levels of permanent deformation of ships and offshore structures operating in heavy weather.

Regarding ultimate failure, the plating usually has a much higher ultimate load capacity than the stiffeners. As increased load is applied to a stiffened panel and plate deflection becomes very large, restraints against edge pull-in develop and increase. Gradually the plate becomes a fully plastic membrane with an enormous rupture load. Usually the plastic collapse of stiffeners or the supporting structure is observed well before the panel becomes unserviceable or the ultimate strength of the plate is exhausted. Exceptions would be a fatigue-induced fracture or a puncturing type of load such as a collision, grounding, or projectile impact.

Professor Wierzbicki's goal is to reduce costs of repairing minor damage on ships caused by hydrodynamic wave loading, and to diminish the possibility of serious casualties and possible loss of vessels. This aim can be achieved by implementing the structural design procedure for selecting scantlings on the basis of their fracture properties of plastic energy absorption characteristics. The procedure will consist of predicting the extent of local damage and the magnitude of loads that cause fractures of the side shell. At the same time a thorough understanding of the mechanisms of structural collapse in severe casualties will help modify future designs, so that watertightness will be preserved despite any major local damage. Most of the results established for ships would also apply for damage prediction of the decks and equipment of offshore platforms, and can be applied by designer and operational crews to insure the integrity and safety of structures in heavy weather.

4.0 SLOW DRIFT MOTION OF OCEAN STRUCTURES

Professor Chiang C. Mei of the MIT Department of Civil Engineering is studying the slow drift motion of ocean structures caused by waves. At the Collegium meeting he described his approach to understanding drift forces on a two-dimensional body moored in seas coming from the beam.

In an irregular sea with a narrow banded spectrum, second-order effects contribute an exciting force with low frequencies [Hsu and Blenkarn, Remery and Hermans, Newman]. As the natural frequency of the moored vessel may also be low, slow-drift oscillation can be excited to cause significant strain in the mooring lines or to affect the dynamic positioning of a floating platform.

Ships and offshore platforms are often subject to seas with these narrow banded spectra. Usually the natural frequencies of the mooring system are at the order of 0.01 Hz, which is much below the peak frequency of the incident sea. However, at these low frequencies, long-period resonance can be induced by a second-order force associated with the difference frequencies of short period waves. The low frequency force can also be sufficiently large to affect the design or operation of dynamic positioning devices. During the past 15 years there has been increasing interest in the low frequency effects of irregular waves interacting with floating bodies

Several authors have focused their attention on the long-period exciting force on a fixed body in a narrow-banded stationary sea. Newman has shown that the slowly varying force corresponding to the small frequency difference $\omega_m - \omega_n$ when $_m$ and $_n$ are two neighboring frequencies in the spectrum, can be approximately related to the constant drift force for $\omega_m = \omega_n$. Alternatively, Pinkster and Faltinsen and Loken have attacked the full second-order problem which involves high (sum) and low (difference) frequencies. This is necessary if all parts of the second-order theory are desired, or when the sea spectrum is broad. However, the numerical task for practical problems is large.

Since among the second-order effects one is often interested primarily in the slow drift oscillation, the contrasting frequencies suggest the use of the perturbation method of multiple scales. Steps have been taken in this direction by Molin and Bureau, and by Triantafyllou. In their analysis the concept of multiple scales was applied only to time but not to space. It is well known for free waves that slow modulation in time is accompanied by slow modulation in space in the plane of propagation. This feature was not utilized in their treatment of the water-wave dynamics, and the advantages of the multiple-scale analysis were, therefore, not fully exploited.

Professor Mei has applied multiple-scale expansions to both space and time to a two-dimensional body moored in beam seas. After specifying the slowness of modulation, not only is the need for analyzing the short-scale problem alleviated, but extending the long-scale problem to include its transient evolution is also unnecessary. Thus the incident wave envelope can be finite or semi-infinite in duration. The initial growth, the approach to quasi-steady state, or the final decay are studied through several examples. There are also two kinds of long waves radiated to infinity: one propagating at the group velocity and one at $\sqrt{gh}$. The concept of radiation stress which is well known in coastal oceanography and engineering is also brought into the present problem of wave-body interaction.

In order to illustrate the analytical procedure and to examine the physics clearly, Professor Mei and colleagues have chosen very simple geometries and assumed the drift displacement to be small. Specifically, a floating rectangular block on a sea of finite constant depth has been examined. The clearance between the keel and the seabed is very small (including zero), and the block is allowed to sway only. Analytical expressions are derived for the transient slow drift motion for three kinds of incident waves: (1) a wave packet, (2) periodically modulated groups started from rest, (3) a uniform wave train started from rest.

Most authors have approached the slow drift problem by a straightforward second-order theory. In the special case of a regular (monochromatic) wavetrain, the steady drift force, which is second order in wave slope, can be found from the solution of the first order (linearized) problem. Newman suggested that the drift force can be written in terms of quadratic transfer functions of the wave components. The terms contributing to the slow drift force are functions of the frequency difference. If the spectrum is narrow-banded, these terms can be approximated by their values at zero difference. Thus the slowly varying drift force is formally the same as the steady drift force, except that the incident wave amplitude now varies slowly in time. Newman's result has been widely used in recent studies, but its range of applicability appears not to have been fully examined.

Since oscillations of long periods should imply the presence of long waves, the complete hydrodynamic problem must involve both long and short length scales. Thus the methods of multiple scales should be useful. While Newman's result is quite adequate for horizontal drift forces in most cases, an additional contribution to the vertical drift force should be accounted for. This new force is associated with a long wave field.

5.0 DETERMINATION OF ICE LOADING ON STRUCTURES

For thick ice from one to three meters, "existing methods of making predictions for eccentric loading aren't good enough," says Professor Tomasz Wierzbicki of the MIT Department of Ocean Engineering. Most of the literature analyzing ice forces on vertical structures assumes that a perfect contact exists at the ice-structure interface throughout the whole deformation process, even though the pressure distribution across the plate thickness is often far from uniform. (See Figure 1.)

These previous assumptions of perfect contact have led to predictions of critical or failure loads which considerably overestimate the measured forces, especially for large ice features. According to Professor Wierzbicki, the redistribution of contact pressures and the presence of eccentric compressive loading of large ice sheets should be considered as a rule rather than an exception.

Existing predictions of ice forces on vertical structures are much too high, claims Professor Wierzbicki. "Our intention is to show the significance of eccentric loading in bringing the force predictions closer to reality for large ice features. By taking the eccentricities into account, the predicted forces become almost consistent with experiments, and ten times lower than previously proposed. Even though researchers in the oil industry know the actual force levels are much lower, they are reluctant to base a design on experimental evidence without understanding the processes theoretically."

Global failure results in the formation of large ice fragments with diameters several times thicker than the ice sheet. Professor Wierzbicki wants to determine global failure modes and associated failure forces in semi-infinite ice plates pressing against vertical structures. (See Figure 2.) The global failure is assumed to be induced by load eccentricity arising at the plate-structure interface as a result of local phenomena such as crushing, melting or flaking.

Determining local failure modes and the near-field distribution of stresses is a formidable task. The process of local deformation is controlled by the mechanical properties of ice, strain rate sensitivity, temperature, inhomogeneity, and anisotrophy and as a result must be formulated as a two- or three-dimensional problem. On the other hand, determining the global, or far-field, failure modes is more of a structural problem and appears to be controlled simply by the elastic and fracturing properties of ice. Professor Wierzbicki hypothesizes that the analysis of global failure modes can be decoupled from the analysis of local failure modes.

If the free edge of large ice features is rough or inclined at a certain angle to the structure, the contact force is transmitted over a smaller area or is shifted with respect to the plate middle surface. For vertical and smooth edges, a perfect initial contact established at the ice-structure interface gives way to highly non-uniform stress distribution caused by a ductile plastic flow, local crushing or flaking. Even when the edge of a large ice plate is smooth and vertical, it may interfere with a field of ice rubble surrounding the structure. The non-uniform contact loads may be further enhanced by the inhomogeneity of ice plates, variable thicknesses, small internal flaws or surface cracks, temperature gradients, or wave motion induced by submerging ice fragments in the vicinity of impact.

Professor Wierzbicki investigated the possibility of ice fracture from eccentric loading and derived expresssions for the loads associated with a given mode of failure. Indentation spalling and flexural cracking, two failure modes which had not been previously attributed to the eccentric loading, were identified and analyzed in some depth. Simple closed-form solutions were derived for the magnitudes of the critical forces under which ice plates fail by cracking. These loads are shown to be at least one order of magnitude lower than similar predictions based on buckling or plastic failure mechanisms.

Professor Wierzbicki is working on an idealized, one-dimensional model of ice behavior. To study the effect of the vertical variation of contact pressures on the failure load, the ice plate was assumed to be the same width as the structure. This oversimplification leads to force levels which are a few times smaller than those for structures of finite widths. However, since the analysis of all failure modes will carry the same assumption, the relative values of critical forces associated with various failure modes are expected to be realistic. "Moreover, our intention is to show the significance of the eccentric loading in bringing the force predictions closer to reality for large ice features rather than calculating the actual value of the breaking force," says Professor Wierzbicki.

In laboratory experiments the point of application of the load can be controlled so that the theoretical buckling load is attained. In field experiments some load eccentricity is always present so that ice plates will undergo flexural failure well before reaching the critical load. If this conclusion holds also for ice plates loaded by finite width punches, which is believed to be true, then the present analysis offers a completely new interpretation of the buckling induced failure under in-plane compression.

In developing simple one-dimensional models of ice responses, closed-formed solutions were derived for the magnitudes of average stresses and total failure forces. A map of failure modes was then constructed as a function of the plate thickness, in which the intersections of the respective curves define transition points from one mode to the other. The envelope of the lowest failure stresses clearly shows that the failure load never exceeds 5% of the load corresponding to uniform crushing of the plate.

Professor Wierzbicki also demonstrated a good correlation between the maximum failure stress approach and the fracture mechanics approach in predicting flexural cracking of ice sheets. The proposed analysis is significant because it identifies the importance of edge moments, which arise from the redistribution of stresses at the ice-structure interface, for ice failure.

Figure 1. Rc[illegible]e in the Arctic.

As a natural extension of the present method, a semi-infinite ice plate acted upon flat or circular indentors will be considered taking into account eccentrically applied line loads and buoyancy effects. Such solutions, in conjunction with a thorough analysis of local crushing phenomena, will hopefully close the gap between existing theoretical predictions and the results of large-scale field measurements in the Arctic.

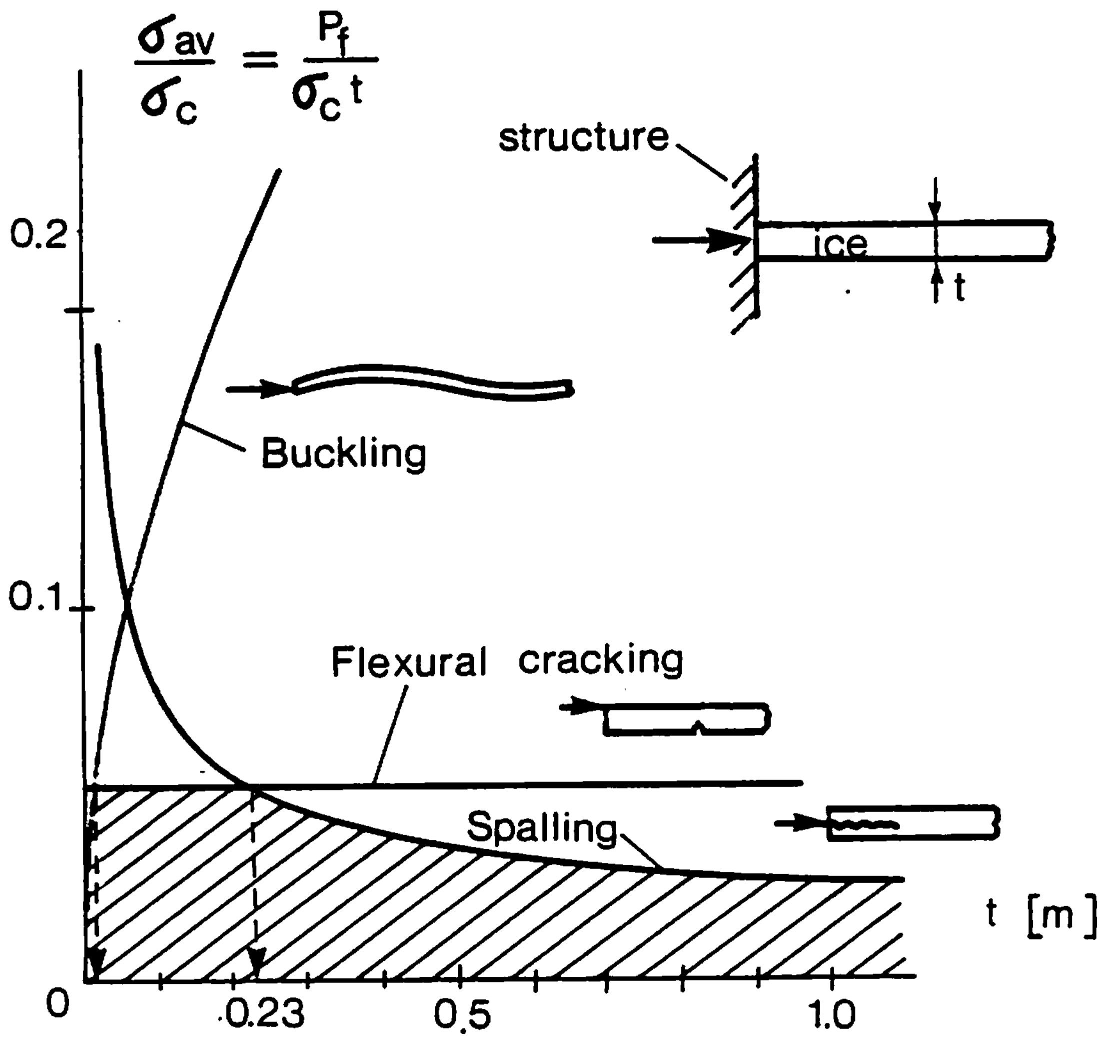

Figure 2. Envelope of lowest failure stresses of ice sheets pressing against a vertical structure.

6.0 SELECTION OF STRENGTHENING CRITERIA FOR NAVIGATION IN ICE

Guidelines for reinforcing ice transiting vessels vary with different regulatory bodies around the world. Recently two ships which followed the strictest rules, the Canadian Arctic Shipping Pollution Prevention Regulations, nevertheless suffered severe damage from ice.

While ships need substantial protection in ice-choked waters, costs from overdesigning can be formidable. For example, thickening the shell plating of a Coast Guard ice breaker by 0.125 in. (3.175 mm) might add around 90 tons and cost about $250,000.

Professor Paul Xirouchakis of the MIT Department of Ocean Engineering worked with Sea Grant funds to define strengthening criteria for navigation in ice. Definition of these criteria requires a structural design methodology to determine the scantlings (reinforced plate thicknesses) and spacings of various structural members. He also examined the influence of ice properties and hull structural parameters on the response.

Strengthening requirements can be classified into first-yield, ultimate plastic, gross tearing and fatigue criteria. These categories must be prescribed for the primary, secondary and tertiary response structural levels. Referring to the deformation of the hull girder, the primary level includes the longitudinal and transverse strength. The secondary level considers the stiffened plating deformation with criteria for transverse frames and longitudinal stringers. The tertiary level involves the plating deformations.

The structural design method must also consider the prevailing sailing conditions: continuous motion in level ice, impacts from broken ice floes hitting the hull, hull striking against an unbroken ice edge (ramming), and compression of the hull in ice. The method must also give guidelines depending on the time of year, the geographic location, the design ice conditions, and the type of ship (ice breakers, cargo ships, tugboats).

Sea ice properties vary enormously depending on the size and orientation of ice grains, ice temperature, salinity, brine volume, strain rate and degree of confinement. Newly frozen smooth sheets create different problems than ragged multi-year deposits with ridges, rubble fields or fragmented ice covers. The ice failure models - bending, buckling, crushing - also influence the maximum ice loading.

Many of the current regulations are based on work done in Finnish shipyards by B.M. Johansson, who selected the maximum displacement of the ship and the amount of installed horsepower as basic variables to describe the design ice local load on the structure. According to Xirouchakis "The bigger and more powerful the ship is, the more you expect it to go into thicker ice where it would encounter higher loads." Separating the pressures where damage occurred from those which left ships unscathed, Johansson created guidelines for designing the vessels to withstand certain pressures.

Whether the ship escapes damage from ice depends on many more parameters besides the size of the vessel and the horsepower, including the angle attack of the ice, the type of ice and the vessel speed. The model being developed in the MIT Department of Ocean Engineering takes into account the type of ice feature, the expected failure mode and the prevailing sailing conditions.

Professor Xirouchakis describes ice failure as a very difficult problem because of the poorly understood behavior of ice, particulary at the higher strain rates. "In some cases we're interested in impact conditions, or moderately high strain rates. Also, we don't know much about the various failure mechanisms. Most probably there will be a mixture of buckling, bending and crushing."

Engineers commonly choose one of two approaches to determine the design pressure. They could study the force of the current or wind which drives the ice to make a model and find the pressure. Professor Xirouchakis feels the easier way is to take the maximum expected pressure, which involves asking what the maximum load is that a given ice field can sustain, or the maximum load that can possibly be applied to the structure. However, the number of parameters which affect ice properties complicates the second approach. (See Figure 3.)

Besides trying to describe the ice load, understanding the ice strength and how it is affected by parameters such as the rate of pressure application, Professor Xirouchakis and colleagues wanted to incorporate all of the above in a meaningful and simple way for people to use. The work is done theoretically because of the difficulty of modeling real or synthetic ice, especially describing local ice load. However, theoretical predictions are compared with reported ice damage records.

Usually ships are fortified against ice by adding thicker plates and more stiffening directly above and below the water line. Professor Xirouchakis feels a more integrated design results by redesigning the whole vessel from the beginning as an ice transiting ship. For example, an ice transiting vessel might be designed up to a certain deck level with transverse framing to combat local ice loading. But the motion of an ice breaker which rides up on ice, slides back and rams up on the ice sheet again requires stiffening elements in the longitudinal and horizontal direction.

Recently Professor Xirouchakis and the American Bureau of Shipping (ABS) examined how his work could be used in determining new standards for ice transiting vessels. For example, the ABS has a rule to design the bow frames, one of the most important structural elements, but nobody knows if a factor on the reduction in the framing strength is optimistic or conservative. "We showed that existing criteria are acceptable only in a certain range of parameters. However, for a whole other range we find a lower collapse strength in some cases, so existing numbers are not always conservative," cautions Professor Xirouchakis.

In the past, ships were built in a transverse frame mode with closely spaced, strong frames. But now ships are constructed in a longitudinal mode with stringers and web frames at a greater distance apart. "Ice transiting vessels previously had transverse frames, while today's ice transiting vessels are generally built with mixed longitudinal and transverse frames, depending on the specific class," explains Professor Xirouchakis. "Whereas existing criteria assume infinite stiffness of the transverse frames, we derived structural criteria for any finite stiffness of the transverse frames. We also pointed out that when the stiffness of the frames is not infinite, we can get lower collapse loads."

Robert Stortstrom, Geoffrey Abbott, and Esther Chi-Fran Chen have participated in the project, which is financed by MIT Sea Grant and the American Bureau of Shipping. Stortstrom and Professor Xirouchakis showed how the scantlings, stiffening and spacing influence the strengthening mode when level ice compresses against the side of the vessel. Eventually the work should be compared to experimental evidence. The computer program to do plastic analysis, developed by Abbott, could be used as a design approach for the grillage ultimate strength of the side shell structure. Since classification societies and regulatory bodies need formulas in addition to computer models, Chen is working on analytical models which will produce results to compare with Abbott's program predictions.

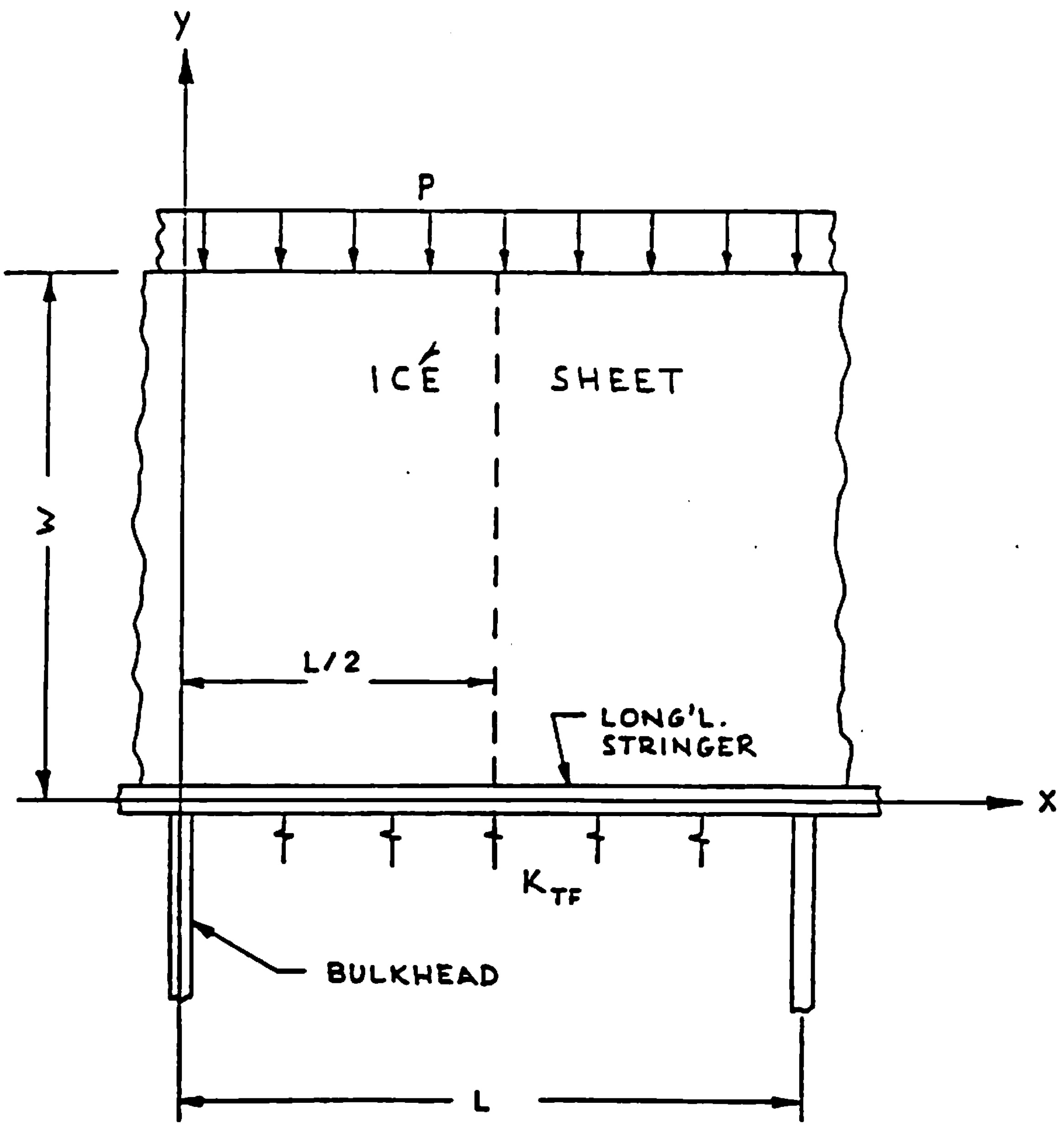

Figure 3. To determine the stress distribution, the ice sheet is analyzed as a flat plate under a uniform in-plane load P, acting a distance W from the side wall ship structure.

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