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EEP19/83

AN ICE-STRUCTURE INTERACTION MODEL BASED ON OBSERVATIONS IN THE GULF OF BOTHNIA

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Report to the 10th Conference on
Port and Ocean Engineering under Arctic Conditions - POAC 89,
Luleå, Sweden, June 12-16, 1989

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ABSTRACT

On the basis of experiences from studies of ice-structure interaction in the Gulf of Bothnia a model has been outlined for the characterization of periodic ice forces associated with resonant structural vibrations. A generalized ice force time-history is proposed to be used for engineering purposes, and the model is discussed in terms of ice mechanics. It appears that the basic features of the model are of a generic character and that the suggested ice force equations are relevant, in principle, to cases of static as well as of dynamic structural response.

1. LONG-TERM STUDIES OF ICE-STRUCTURE INTERACTION

For about 30 years ice action on offshore lighthouse structures in the Gulf of Bothnia has been increasingly studied. Largely, each decade represents a specific stage of development.

During the 1960's the studies were quite unsophisticated: simply a follow-up of the performance of the structures when affected by drifting ice, ice-piling, icing etc. On the basis of the rather poor knowledge of ice action at that stage and, apparently, a portion of good intuition, ice forces were predicted rather closely to the optimum risk level. A few cases of damage gave fairly clear indications as regards particular ice conditions, requiring adjustments of the design loads.

During the 70's the problem of ice-induced vibrations was realized and the most strongly affected structure was instrumented. Vibration records sampled during that decade, together with the continued follow-up and analysis of a few cases of static and dynamic overloading of Finnish and Swedish lighthouses, improved the understanding of ice-structure interaction considerably.

During the 80's the studies have been expanded appreciably, quantitatively as well as qualitatively. Taking advantage of the Gulf of Bothnia as a convenient facility for Arctic research, several independent ice study projects with international participation have been conducted and some are in progress. The product is a continuous inflow of parametrically well-defined data and subsequent improvements of the bases for ice-force predictions for Arctic areas, whereever the fundamental ice parameters can be quantified and where ice conditions are not essentially different from those prevailing in the Gulf of Bothnia.

2. RECENT STUDIES

In 1985 the studies of ice-structure interaction were intensified in that a joint study project was agreed between Arco, Exxon and Mobil (USA), Norwegian Contractors, Canadian Coast Guard, Mitsubishi, the Swedish National Industrial Board, Hamburgische Schiffbau-Versuchsanstalt and VBB. The latter two companies, cooperating with the Swedish Administration of Shipping and Navigation and with the University of Luleå obtained financial and advisory support for a comprehensively extended field study of ice-structure interaction, by employing some large lighthouses in the Bothnian Bay as objects for data sampling and other observations.

The instrumentation of the lighthouses was improved and during a three years' period the database was greatly enlarged, and suitable analysis methods were developed for transformation of measured structural response to ice forces. Since the instrumented lighthouse structures serve, in principle, as full-scale elastic obstacles and measurement devices with calibrated constitutive properties, static as well as dynamic relations between the structural response and the ice forces can be determined within uncertainty ranges that are judged to be quite acceptable from an engineering viewpoint.

Two years of development, including trial operations and refinements, resulted in an elaborate system for data acquisition and processing, based on the following elements:

* Accelerometer and inclinometer systems including computers, filters, tape recorders, etc, for sampling of response data in the form of records of acceleration and inclination (in principle two types of accelerograms).

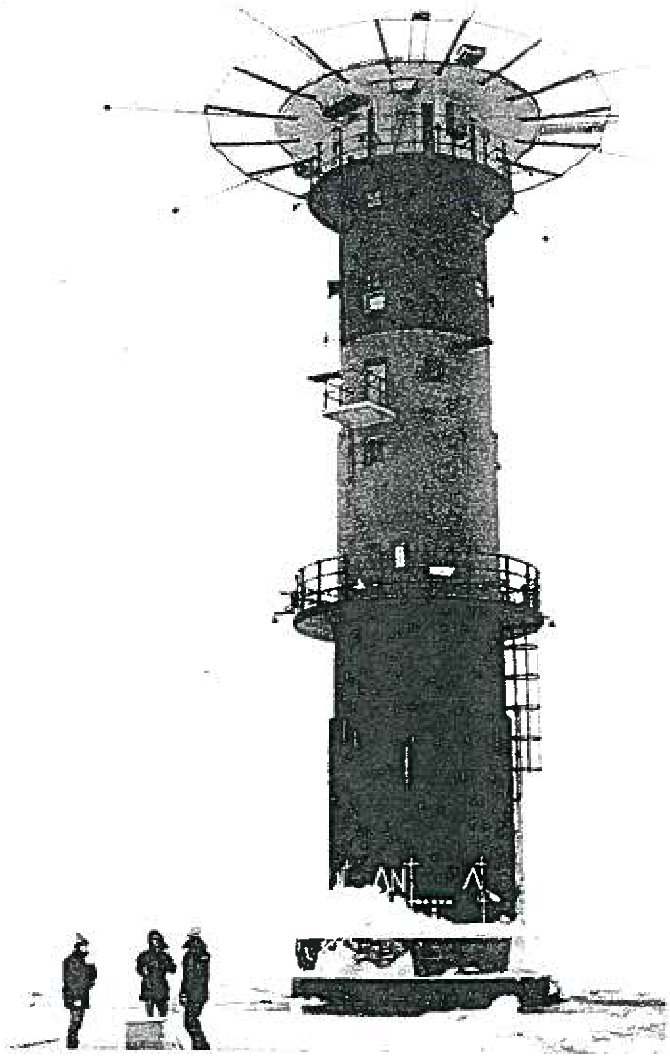

Figure 1. Sampling of ice data in connection with an event of indentation

* Video camera systems, coordinated with the above systems, for observation of ice movements etc.

* Signal processing procedures especially developed for the analysis of the rather complex data records, involving separation of signals in respect of frequencies as well as directions. (The lack of reference points on the open sea and the strongly vibrational character of the structural response necessitate that very small gravity related signals must be distinguished in the inclinometer records, containing predominantly signals caused by horizontal inertia due to the strong vibrations.)

* Constitutive models of the lighthouses, calibrated by pull tests etc, for transformation of response data to ice force time-histories.

* Field sampling and laboratory investigation of ice data (Figure 1).

3. ICE FORCE TIME-HISTORIES DERIVED FROM RECORDS OF OBSERVED STRUCTURAL RESPONSE

The records of structural response data and the corresponding ice force time-histories studied so far present a fairly clear picture of the mechanism of ice-structure interaction from the mechanical point of view. On the basis of these data the mechanism can be modelled mathematically in terms of ice force and response time-histories. By selecting simple characteristics, such as the maximum and minimum ice forces as key parameters, the relationships can be normalized, resulting in a set of ice force expressions for engineering applications.

Obviously, the type of ice-structure interaction that involves dynamic structural response and, particularly, resonant vibrations is a more complex manifestation of ice action than stationary ice pressure or steady-state indentation. This presentation will still originate from the dynamic type of ice structure interaction and it will be demonstrated, that the various types of ice action are closely related. By way of introduction some ice force records from a large offshore lighthouse in the Bothnian Bay are shown. The diameter of the cylindrical structure is 7.2 m (Figure 1).

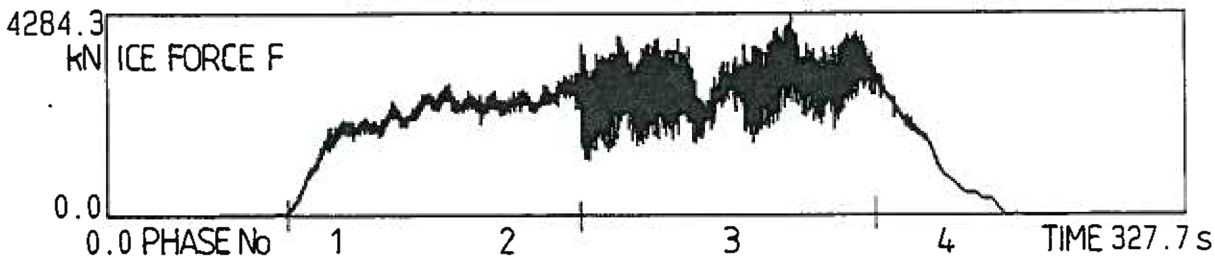

Figure 2. Condensed ice force time-history from an event of indentation through an ice floe drifting with a speed of 0.04-0.06 m/s. Four different phases are observed: Initial indentation with increasing interface width, steady-state indentation without major structural dynamics, indentation associated with a greatly fluctuating ice force and, finally, a phase of load decay.

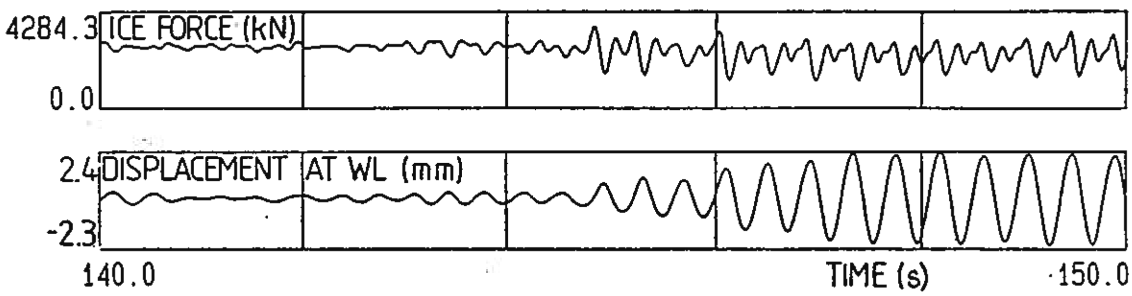

Figure 3. The sequence 140-150 s from the above record displayed in an extended time scale together with the corresponding time-history of structural displacement at the ice force level. (Positive for displacement in the ice force direction.)

During this short sequence the ice-structure interaction changes from an almost "static" mode to a mode associated with periodic fluctuation of the ice force as well as the structural displacement. The latter phase is initiated by a sudden load peak followed by a load drop. The corresponding amplitude of the structural response motion is sufficient for starting the periodic phase of the ice-structure interaction, associated with increasing amplitudes of structural deflection until energy equilibrium is reached. The frequency of vibration is very close to the fundamental natural frequency of the structure and the vibrations are of a typically resonant character.

The study of numerous records of strong vibrations and associated periodic ice forces has provided unambiguous evidence on the following points:

* When an ice cover is being indented by a flexible structure and fails mainly in a crushing mode, so-called self-induced vibrations occur frequently. The resonant vibrations are coupled to a periodic fluctuation of the resultant ice force.

* If the drift speed is not much lower than the maximum velocity of the structural vibrations, the frequency of the predominant structural oscillations determines the frequency of the load fluctuations. Obviously, the structural vibration induces the periodicity of the ice force, that in turn amplifies the vibration and so on, until the energy consumption due to damping becomes equal to the energy input from the resonant load.

* When the vibration amplitudes are below the threshold, where the periodic interaction becomes significant, the resultant ice load also fluctuates, but the amplitudes are comparatively small and the fluctuations are more irregular. The character of the load is almost the same for a rigid structure as for a flexible one and the deflection of the latter is essentially static. Whereas a distinction is made betwen static and dynamic structural response during indentation, it should be kept in mind that the ice force during indentation is always more or less dynamic.

* The most important feature of the ice force time-history during periodic indentation associated with resonant vibrations is the sudden drop of the resultant force after reaching the peak of each load cycle. Another important observation is that the time-averaged resultant ice force appears to be essentially equal to the ice force during non-periodic indentation of the same ice-floe. The maximum, mean and minimum ice forces (F_{max}, F_0, F_{min}) are therefore suitable key parameters for characterization of a sequence of periodic as well as non-periodic ice-structure interaction.

* The periodic ice force can be characterized in a spectral form, by means of Fourier analysis, i.e. by breaking down the force time-history into component sine waves, the amplitudes and phases of which can be represented in a spectral form. In Figure 4 the power density spectrum of the sequence previously displayed in Figure 2 is shown as an example. The spectrum clear-

ly demonstrates the strong coupling between the structural oscillations and the ice force fluctuations. The component waves of the ice force time-history have their frequencies predominantly concentrated at the fundamental structural frequency 2.34 Hz and its multiples, an observation that will be further referred to, when generalizing the ice force time-history for design purposes.

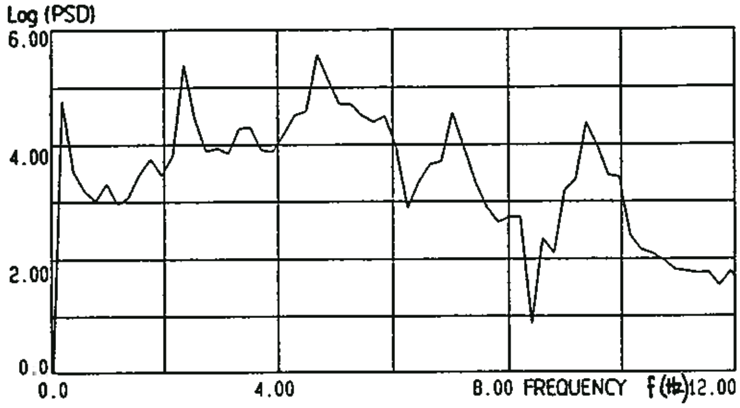

Figure 4. Typical power density spectrum of ice forces associated with resonant structural vibrations.

2. OBSERVED BEHAVIOUR OF DRIFTING ICE DURING INDENTATION

The following observations are based mainly on studies of video records from events of strong ice action associated with continuous as well as periodic indentation of ice-sheets with thicknesses of 0.5-1.0 m. Occasional direct visual observations are also referred to.

* The load limiting mode of ice failure is <u>crushing</u>. Occasionally, the load limit is set by splitting, associated with more or less radial cracks (seen from the centre of the structure). However, splitting does not occur continuously and can therefore not be relied upon for design purposes. Consequently, crushing across the whole width of the structure can be regarded as the ultimate load limiting mechanism, at least when dealing with conditions similar to those prevailing in the Bothnian Bay. In waters where there are multiyear ice ridges the utlimate loads exerted by such ridges are sometimes limited by other failure modes than crushing, but in other respects the Bothnian Bay conditions are broadly representative for Arctic areas.

* The crack propagation and crushing take place within a short distance from the ice-structure interface. Normally, it has the character of pulverisation of the ice. From laboratory experiments we have learned that such a pulverisation is the final phase in a course of initial fracture growth, progressive cracking and final collapse of the ice structure.

* Obviously the cracking and pulverisation are more or less outspread in space and time, which is associated with a corresponding limitation and variation of the interface contact. At a certain instant the contact is concentrated at limited spots or zones. At each zone the ice is stressed to a condition between ductile strain and cracking, and the phases are more or less different from one zone to another. This phase difference or non-simultaneous failure is a key feature in our following considerations.

* Basically, the large scale mode of ice failure appears to be that of crushing in case of static structural response as well as in case of strong vibrations. The non-uniform distribution of failure zones has sometimes been discerned in the video records, but the resolution is, of course, not sufficient for allowing details such as the periodicity of the crushing and the local phase difference to be distinguished.

5. A GENERIC MODEL OF ICE-STRUCTURE INTERACTION

It is particularly in the light of recent experiences from the field studies in the Bothnian Bay that all the findings seem to converge towards basically one single mode of ice-structure interaction during indentation. Based on a few variants of that mode, simple explanations can be found for various forms of interaction such as steady-state indentation, periodic indentation associated with strong structural vibrations and even interaction with unbroken ice to some extent.

A generic model of ice-structure interaction is therefore proposed, with reference to the following categories of supporting material.

* The above-mentioned observations of the mode of ice failure and the observations of structural response and ice force time-histories, enabling a mathematical characterization of "static and dynamic" ice forces against structures in the Bothnian Bay.

* Current knowledge regarding relations between ice strength, strain and strain-rate as well as reported observations concerning apparent relations between ice forces and the size of the interface area, the aspect ratio etc.

* Observations and qualitative explanations, admittedly hypothetical to some extent, regarding the details of the transient ice stress and failure conditions close to the interface.

The model has the following basic features:

* During the course of indentation the contact between the ice and the structure is predominantly concentrated at local zones, the location of which vary with time.

* At each temporary contact zone the ice undergoes at least one cycle of transient conditions, from increasing stress associated with ductile behaviour to cracking and pulverisation. The load cycles at different contact zones are more or less out of phase.

One extreme is a random phase distribution (although there is, most likely, a certain coupling between adjacent contact zones due to interactive stress conditions). The opposite extreme is synchronized load cycles at the various contact zones.

* During a course of steady-state indentation (when the indentor does not oscillate) the local zones are consecutively undergoing their individual stress cycles, the rate being determined by the ice drift velocity. This parameter also determines the strain-rate and, therefore, it probably influences the ice strength and the amplitude of the contact forces. Since the time distribution of the load impulses, represented by the local contact forces, has a random feature, the global load on a large interface area will be rather uniform and correspond to the average contact force. In case of a smaller interface and only a few contact zones, the majority of the contact forces may be in phase occasionally and the global force is likely to be fluctuating irregularly. The maximum effective contact pressure will exceed the pressure associated with a large area. For otherwise homogeneous ice conditions the maximum value will be determined by

the ice drift velocity and the random phasing, thus by the duration of the indentation.

The widely observed size effect on the effective pressure may thus be explained by the phase distribution of local contact forces. However, for narrow indentors the effect of confinement due to unstressed ice adjacent to the interface should not be neglected. There are strong indications pointing at confinement effects in some cases of over-loading when narrow structures have been damaged. The aspect ratios have, however, not exceeded the order of 4 in those cases.

* During a course of periodic rate of indentation the vibrating indentor influences the local load pulses largely. The structural movements affect the strain-rate and coordinate the local pulses, as illustrated in Figures 5 and 6.

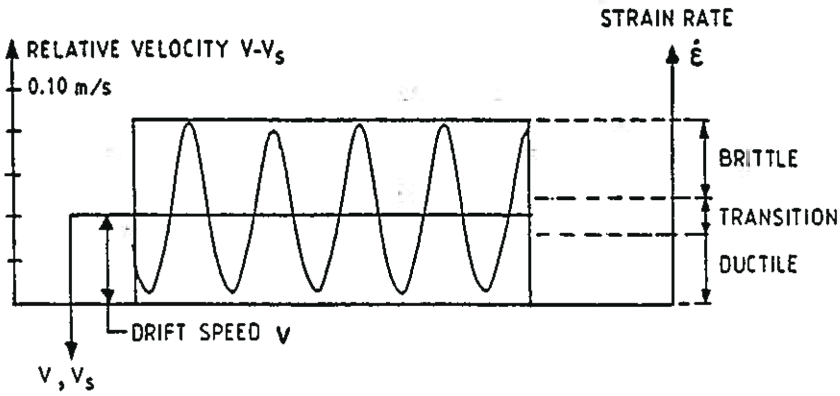

Figure 5. During each cycle of structural oscillation the relative velocity and the strain-rate (as well as the strain) passes to and fro over the ranges corresponding to ductile deformation, fracture growth and brittle failure.

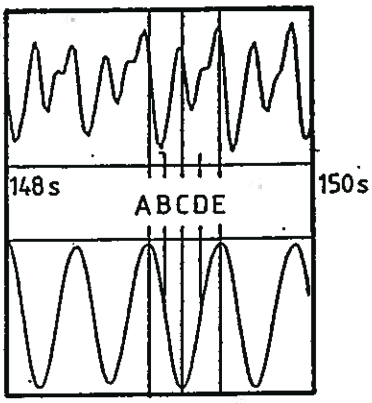

Figure 6. Various phases of ice-structure interaction during a cycle of oscillation:

A-B: The structure moves backwards after the preceding coordinated ice failure. The strain-rate is high, the contact reduced and the ice force passes its minimum.

B-D: The structure slows down and then turns, the strain-rate decreases and the contact pressure increases to a peak before the forward velocity increases and the structure tends to move ahead from the ice.

D-E: The structure decelerates, the contact pressure increases once more in a ductile manner until a sudden coordinated failure occurs, when the ice strength is being exceeded.

The global peak load is therefore composed of relatively <u>well-coordinated local pulses</u>. The peaks of the individual load cycles may reach the limit corresponding to the maximum strength of the ice almost simultaneously. During the phase when the structure moves in the ice drift direction the onloading is soft and the strain-rate is initially rather low. Therefore, the ice strength may come close to its optimum before the coordinated failure, and the peak load may reach the same order as in case of any initial failure over a smooth interface. Actually, no cases have yet been observed, where such an initial peak has exceeded the peaks during subsequent resonant vibrations.

Beside the build-up of the peak load the <u>sudden stress drop</u> following the peak is the most important feature as regards the periodic ice-structure interaction. This stress drop occurs almost simultaneously at various contact zones and is the strongest coordinating factor. The mechanism of coordination is quite understandable, considering the brittleness of the ice after the fracture nucleation, leading to progressive cracking not only within the induvidual fractured zones but also leading to progressive collapses when the load at one collapsed zone is overtaken by adjacent zones.

The obvious lower limit of the minimum force, locally and globally, is zero. However, our observations indicate, that the global load drop is normally of the order of 50 per cent of the peak load in case of strong resonant vibrations, and that 75 per cent of the peak load is an extreme value.

6. GENERALIZED CHARACTERIZATION OF ICE FORCE TIME-HISTORIES FOR ENGINEERING PURPOSES

In respect of the choice of key parameters the development of ice force formulae for engineering purposes can be approached in two steps:

* Characterization of a generalized load time-history normalized to the key ice force parameters F_{max}, F_0, F_{min} or the corresponding "effective pressure" parameters p_{max}, p_0, p_{min}.

* Formulation of relationships between the above load parameters and fundamental parameters for characterization of ice conditions.

It is recognized that a more or less probabilistic approach must be considered, for the latter step in particular. However, generalized relationships may very well be formulated deterministically, assessing approximate uncertainty ranges for the parameters until sufficient data have been acquired for enabling a refined probabilistic approach.

With reference to the Fourier analyses of ice force time-histories and the example of an ice force spectrum given in Figure 4, the following simple expression has been chosen for characterization of a generalized time-history of the effective ice pressure:

$$p(t) = p_0 + \sum p_n \cdot \cos(n\,\omega_1 t + \theta_n) \qquad (1)$$

The loading function can thus be represented by a constant and a number of sine waves with n = 1, 2, 3, 4 etc., the angular frequencies $n\,\omega_1$ of which are multiples of the fundamental structural frequency ω_1.

For most engineering purposes four sine waves are sufficient for obtaining a realistic generalization of the loading function, as demonstrated in Figure 7.

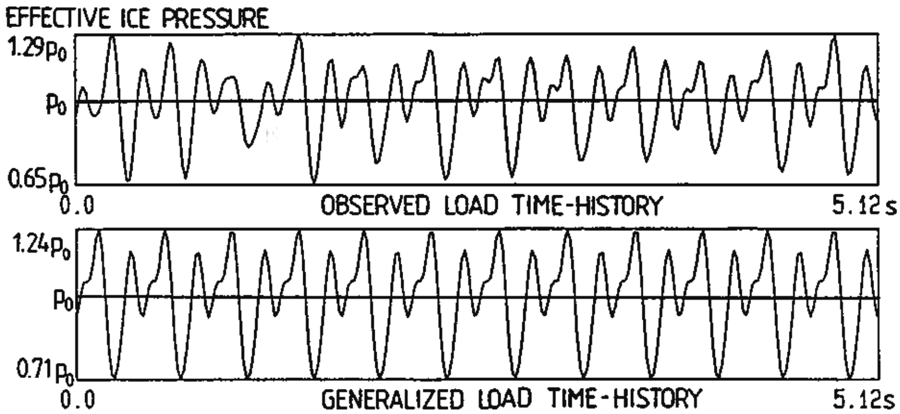

Figure 7. Comparison of an ice pressure sequence from the record shown in Figure 3 and the corresponding generalized function (below), composed of a constant pressure and four sine waves. The normalized constants are $p_0/p_{max} = 0.78$,
$p_1/p_{max} = 0.110$, $p_2/p_{max} = 0.165$, $p_3/p_{max} = 0.050$, $p_4/p_{max} = 0.040$ and the phase angles are 5.38, 2.24, 4.62 and 3.66 radians respectively, for $n = 1-4$.

Equation (1) can be applied to ice-structure interaction associated with dynamic as well as static structural response. Steady-state indentation is represented by the first term and in case of resonant vibrations the sine terms are to be included. The use of the maximum effective pressure as a normalizing parameter is motivated by its close relation to the maximum ice strength before fracturing.

The next problem is to establish a reliable relationship between the effective pressure and a well-defined ice strength parameter. We may refer to the classical Korzhavins formula and set

$$p = k_S \cdot k_I \cdot k_C \cdot f_{um} \qquad (2)$$

where f_{um} is the uniaxial compressive ice strength averaged over the thickness.

For relatively large cylindrical structures as those referred to above the effects of shape (k_S) and of lateral confinement (k_I) need not be assessed explicitly and the relationship can simply be expressed by one factor $k = p/f_{um}$. In case of invariable interface area and ice strength the time function of k is obtained from Eq. 1:

$$k(t) = k_0 + \Sigma k_n \cdot \cos(n\omega_1 t + \theta_n) \qquad (3)$$

It follows from the above that the factor k varies strongly with the mode of ice-structure interaction. Typical maximum and mean values during sequences of saturated resonant vibrations are 0.6 and 0.4, respectively.

7. CONCLUSIONS AND OUTLOOKS

Previous experiences and future objectives of the ongoing ice force studies in the Gulf of Bothnia may be briefly summed-up as follows:

* The model outlined in Sections 5 and 6 for the characterization of static and dynamic ice structure interaction, including the proposed generalized ice force equations, is intended to provide engineers with an improved basis for the design of offshore structures including installed equipment. A simplified spectral presentation of the ice force function has been chosen. This is for practical reasons and for allowing transperancy, but a more complete spectral presentation, including higher-frequency components if needed, might be incorporated in the future work.

* In addition to the observation that a generalized ice force function can be expressed in terms of a few key parameters, such as the maximum, mean and minimum ice forces during a sequence of periodic interaction, it is important to note that the basic features of the function can be explained in terms of ice mechanics. Key elements are the interactive cycling of the interface pressure, the variation of the constitutive properties of the ice during each load cycle, the synchronism of ice failures at local zones, the strain-rate dependence etc. Further investigations of these relations will be performed by means of a system of ice force sensing panels, enabling separation of local pressures in time and space.

* In the first approach the ice force relationships have been expressed mainly in a deterministic manner, the probabilistic aspects covered only by indicating fairly broad ranges of uncertainty and expected spread. These ranges are based on the long-term experiences from the Gulf of Bothnia. The experiences are, however, sufficient only for very rough probabilistic quantifications. Acquisition of more data, for improved probabilistic considerations is therefore programmed to become an important part of future activities.

BIBLIOGRAPHY

The present report contains selected highlights from a series of reports, produced within the scope of the joint industry research project "ICE FORCES AGAINST OFFSHORE STRUCTURES". Detailed descriptions of methods and means for data sampling and analyses, as well as reviews of data records and analysis results, are compiled in those project reports.

For general "state-of-the-art" information concerning static and dynamic ice-structure interaction, reference is made to publications such as Bernard Michel's: Ice Mechanics (1978) and T.J.O. Sandersons's: Ice Mechanics-Risk to Offshore Structures (1988).

The problem of ice-induced structural vibrations has been addressed at several conferences on cold regions research during the last years, not least at the POAC conferences since 1977, when ice-induced resonant vibrations were tentatively analysed in papers by M. Määttänen and A. Engelbrektson.