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Frederking, R. M. W.; Evgin, E.

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by R.M.W. Frederking and E. Evgin

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Résumé

Les répartitions des contraintes dans un floe de glace idéalisé sous forme de disque circulaire sont calculées pour diverses conditions limites de chargement. Pour effectuer cette analyse, l'auteur utilise un programme polyvalent aux éléments finis, l'ADINA. Il examine également l'effet de la variation de l'épaisseur de la glace sur la répartition des contraintes. Les résultats numériques obtenus dans cette étude, complétés par des données recueillies sur le terrain, ont servi de base pour la formulation de recommandations concernant les endroits où placer les capteurs de contraintes, et pour l'interprétation des mesures des contraintes en rapport avec les forces d'entraînement de la glace de dérive.

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ANALYSIS OF STRESS DISTRIBUTIONS IN AN ICE FLOE

R. M. W. Frederking
National Research Council of Canada
Ottawa, Ontario, Canada

E. Evgin
Department of Civil Engineering
University of Ottawa
Ottawa, Ontario, Canada

ABSTRACT

Stress distributions in an ice floe idealized as a circular disk are calculated for various boundary loading conditions. A general purpose finite element program, ADINA, is used in the analysis. The effect of ice thickness variations on the stress distributions is also examined. The numerical results obtained in this study, complemented with some field data, provided a basis for making recommendations on the locations of stress sensors, and the interpretation of the stress measurements in relation to pack ice driving forces.

1.0 INTRODUCTION

The intensity of pack ice driving forces is one of the important factors influencing the magnitude of the forces acting on arctic offshore platforms (Croasdale, 1984). Considerable uncertainty still exists in quantifying these forces. A substantial reduction in the cost of offshore structures could be achieved if the range of uncertainty was reduced.

In 1984 Croasdale proposed an approach for determining pack ice driving forces. It involved measuring stresses in the centre of an ice floe drifting in the polar pack. The stresses in the floe would integrate all the forces acting on the boundary of the floe as a result of ridge building or interaction with adjacent floes and those internal to the floe such as wind and current drag. Thus the stresses measured in the floe are an indication of pack ice driving forces. In 1986 a pilot project to measure pack ice driving forces was carried out (Croasdale et al, 1986). Two key issues were identified in the project. One was hardware; i.e. sensors capable of accurately measuring in situ stresses in ice. The other was a calculation method to relate measured stresses in a floe to boundary forces.

This paper addresses the development of a calculation method. Stress distributions will be evaluated in an idealized ice floe for various boundary loading conditions. The stress distributions provide a basis for making recommendations on the optimum locations of stress sensors in order to predict the pack ice driving forces.

2.0 FINITE ELEMENT ANALYSIS

The finite element method of analysis was used to calculate the stress distributions in an ice floe for a specified set of boundary forces. The analysis was carried out using ADINA, which is a reliable and efficient general purpose finite element program for static and dynamic analysis. The capabilities of the program are described by Bathe (1982). It has been used successfully in the analysis of many practical engineering problems in structural and geotechnical engineering fields (Evgin and Morgenstern, 1985).

3.0 ANALYSIS OF STRESS DISTRIBUTIONS

The stress distributions in a circular floe were calculated for specified loads applied at the boundaries. The idealized floe is shown in Fig. 1(a). It has the following properties:

Diameter	=	1000 m
Thickness	=	3 m
Elastic Modulus	=	6 GPa
Poisson's Ratio	=	0.3

A plane stress finite element analysis was carried out for each of the boundary forces shown in Fig. 1(b). The ice floe lay in the y-z plane. Load was applied in the y- direction. Compressive stresses are assumed positive in this paper. In all eight different cases of loading, the total load on the perimeter of the floe was constant (100 MN). The width of the loaded area, however, was different in each case, and the magnitude of the distributed load on the boundary varied accordingly to keep the total load constant. Due to the symmetry, only one quarter of the circular ice floe was analyzed.

The mesh shown in Fig. 2 was used in the finite element discretization. The stresses obtained from the finite element analysis were presented for the sections along the z- and y-axes in the circular floe. Normal stresses, σ_y and σ_z, calculated in the finite element analysis for points next to the axes (Sections I-I and II-II) are also the principal stresses. Condensed results of the calculations appear in Figures 3 to 6.

Figure 3 plots the distribution along the z-axis (Section I-I) of stress in the load application direction, σ_y. It can be seen that stress σ_y at the centre (z=0) becomes progressively larger as the loading width becomes narrower (moving progressively from LC1 to LC7). Also stress σ_y is everywhere compressive along Section I-I. At a distance of 250 to 300 m from the center (z = 250 to 300 m), stress σ_y is relatively insensitive to the width of loading.

Figure 4 presents distributions of stress σ_y along the y-axis (Section II-II). Along this axis σ_y is also everywhere compressive. For loading widths down to about 600 m (LC1 to LC4) σ_y distribution along the y-axis is quite uniform. Also near the centre (y < 100 m) stress σ_y is relatively uniform for all loading cases.

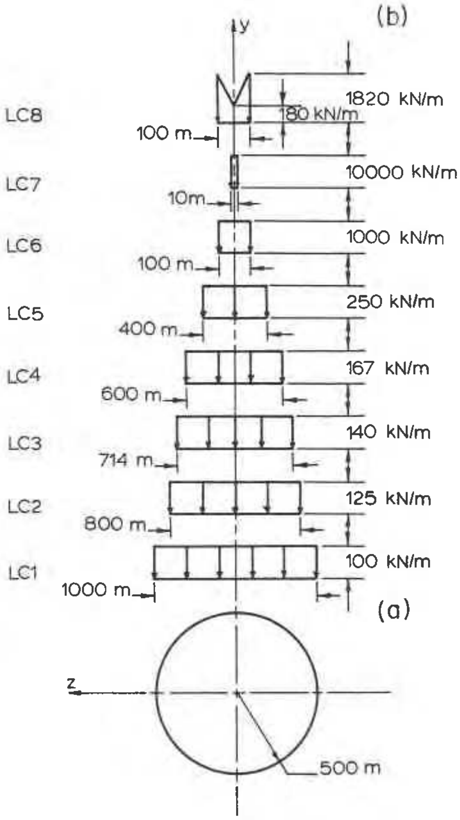

Figure 1 Schematic of ice floe and boundary load cases used in finite element analysis, (a) plan view, (b) boundary load cases

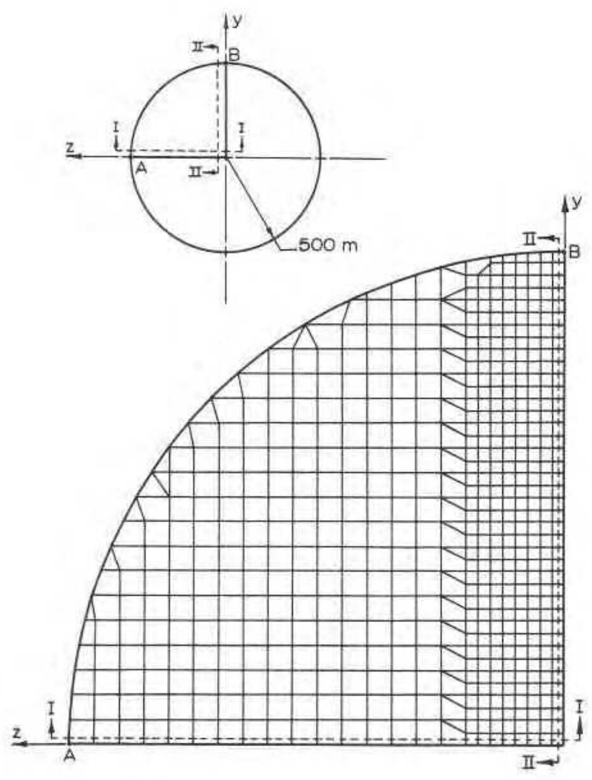

Figure 2 Mesh of floe used for finite element calculations

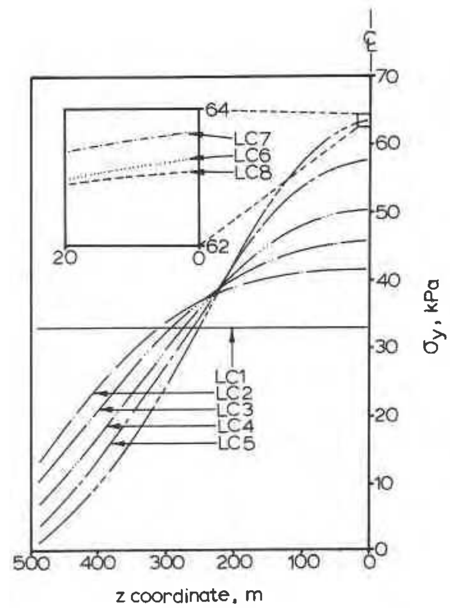

Figure 3 Distribution of stress σ_y along the z-axis (Section I-I)

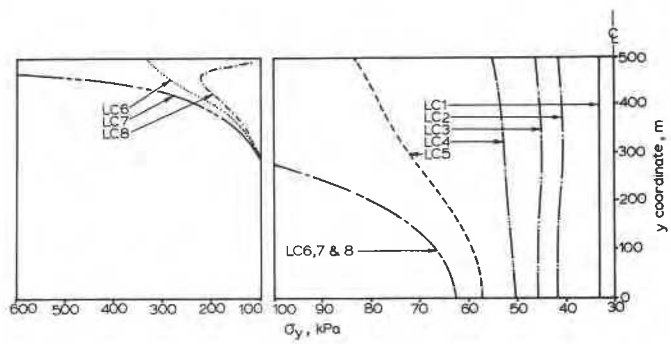

Figure 4 Distribution of stress σ_y along the y-axis (Section II-II)

Stresses in the direction transverse to the loading direction, σ_z, are presented in Figures 5 and 6. Distributions of stress σ_z along the z-axis (Section I-I) are seen to be everywhere tensile (Fig. 5). For loading widths down to about 100 m, stress σ_z has a significant dependence on loading width, provided $z < 100$ m. Once $z > 250$ m, σ_z is relatively insensitive to loading width. The distribution of stress σ_z along the y-axis (Section II-II) is more complex (see Figure 6). Stress σ_z is tensile in the central region $y < 250$ m) but becomes compressive near the perimeter (y approaches 500 m). As along the z-axis, stress σ_z is strongly dependent on loading width near the origin ($y < 100$ m).

The determination of pack ice driving forces from stress measurements requires interpretation of the finite element results. If the boundary forces are applied uniformly in a known direction, the width of the loaded area and the intensity of the load become the two unknowns in this problem.

The following observations can be made from the the results of the finite element analysis to help determine these two unknowns:

1 - If σ_y is constant everywhere in the floe and σ_z is zero, then the boundary pressure is equal to σ_y and is uniformly applied across the full perimeter of the floe.

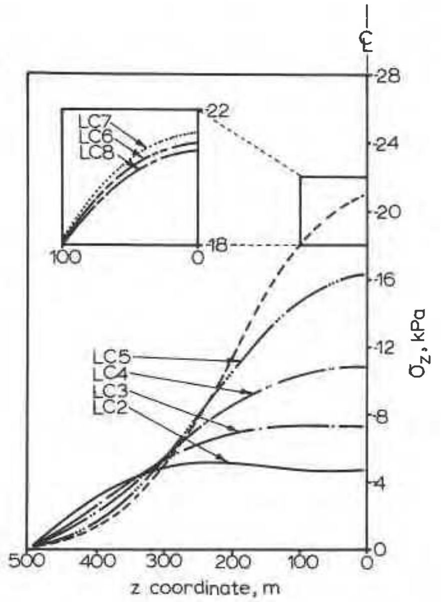

Figure 5 Distribution of stress σ_z along the z-axis (Section I-I)

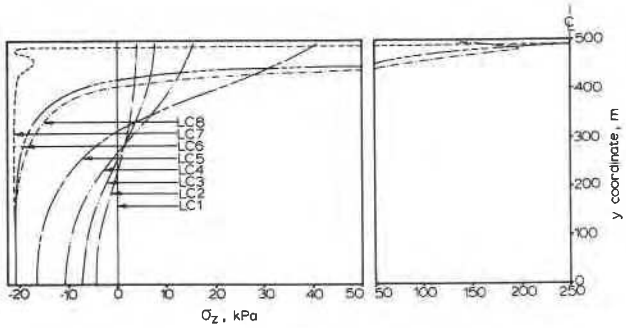

Figure 6 Distribution of stress σ_z along the y-axis (Section II-II)

2 - The rate of reduction in σ_y along the z-axis becomes higher when boundary forces are applied along narrower widths of the boundary.

3 - When the boundary force is applied across less than or equal to a 100 m length of the perimeter, the distribution of σ_y along the z-axis is almost the same for different types of load distributions as long as the total load remains the same. In this case, the magnitude of σ_y at z=0 becomes proportional to the total boundary force.

4 - Normal stress σ_y changes rapidly along Section II-II between y=200 m and 500 m when the total boundary force is applied across a small section of the perimeter (loading cases LC5 to LC8). However, when the total force is distributed on a large portion of the boundary (loading cases LC1 to LC4), the magnitude of σ_y along Section II-II remains almost constant.

5 - In all cases, σ_z along Section II-II is tensile near the centre and compressive at the perimeter. However, the sign of σ_z changes at different distances from the centre depending on the width of the boundary force.

6 - The normal stress σ_z along Section II-II is tensile for all cases of loading.

4.0 NATURE OF STRESS STATE AT CENTRE OF FLOE

When forces act on the perimeter of a floe it is not known in which direction they will be oriented. Also, as the previous analysis shows, stresses near the boundary are very strongly dependent upon local loading conditions. Therefore in the simplest situation stresses in the centre of the floe give the best representation of the boundary forces. In Figure 7 the stress state at the centre of the floe is plotted for various loading widths. Note that the total force on the floe is constant (100 MN) for all cases. It can be seen that the ratio of the stresses varies, depending on the width of loading (see Figure 7(c)). This variation is discernible, provided that the loading width is greater than about 300 m. For narrower loading widths σ_z, σ_y and the ratio σ_z/σ_y are quite independent of the loading width, and loading widths could only be determined by stress measurements nearer to the periphery of the floe. Nevertheless, knowing the ratio of the principal stresses at the center of the floe and their magnitude, the boundary load and its width can be determined. The preceding of course assumes that the applied boundary load is one dimensional. An application of the methodology will be illustrated in a following section where the results of one event in the Croasdale et al (1986) field measurements is analysed further.

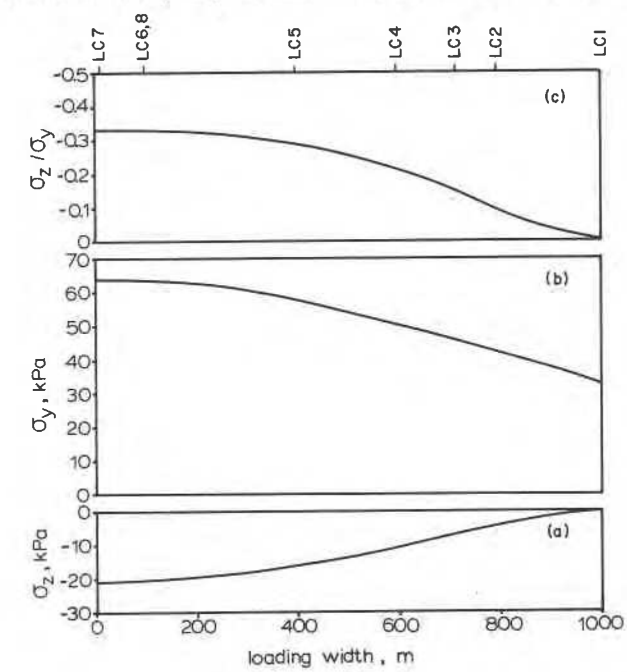

Figure 7 Dependence of σ_z, σ_y and ratio σ_z/σ_y at the center of the circular floe on boundary loading width

5.0 EFFECT OF VARIATIONS IN ICE THICKNESS

The effect of ice thickness variations on the stress distributions was studied for the same circular floe considered in Section 3.0. In order to reduce the computing cost, only the central portion of the ice floe (shown in Fig. 8) was assumed to have variations in thickness (Fig. 9(a)). The load was applied at the boundaries of this central region. Its distribution and magnitude were taken from the finite element analysis used for the loading case LC7.

The normal stresses calculated for elements shown in Fig. 9(a) are given in Figure 9(b) and (c). These results show that the stresses at the same location varied dramatically as a function of depth in the ice cover. Stresses at the mid level in a non-uniform ice cover, however, correspond to those in an ice cover of uniform thickness provided account is taken of local ice thicknesses. Therefore knowledge of the local thicknesses of the ice floe will be an important factor in positioning the ice stress sensors and interpreting the results.

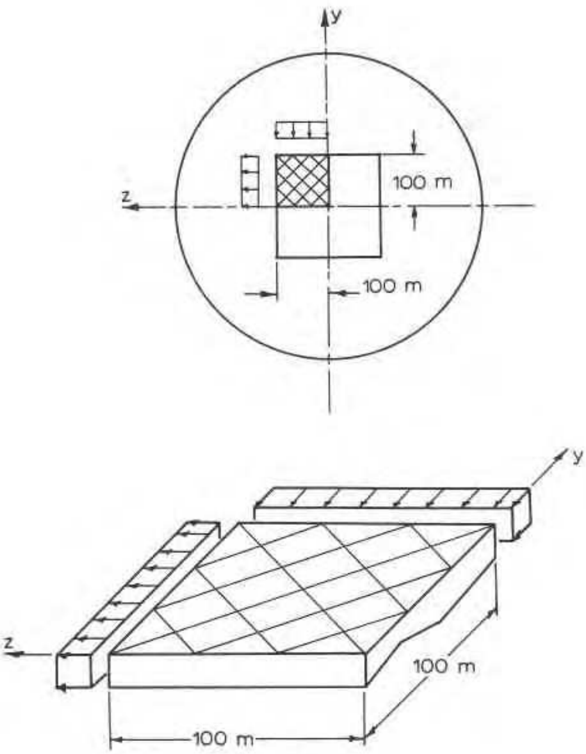

Figure 8 Schematic of central section of the floe used for analysis of effect of thickness variations on stresses

6.0 RE-ANALYSIS OF PILOT PROJECT TEST RESULTS

The original data obtained by Croasdale et al (1986) were re-analysed. This analysis took the form of separating out one of the loading events and examining it in greater detail. The event selected is the same one used by Croasdale et al (1987). The stresses measured by a rosette of three sensors for a 2 hour period in the afternoon of April 22, 1986 were used to calculate principal stresses (see Fig. 10). The recording frequency for these measurements is once per minute.

During the peak loading event (hour 23.5) the major principal stress increased by about 20 kPa while the minor principal stress decreased by about 6 kPa. The actual floe, which had an irregular shape about 6 km long and 3 km wide, was assumed to be represented by the 1000m diameter by 3 m thick idealization used in the finite element analysis. It is recognized that this is a gross simplification, but it is only done here to demonstrate a methodology for using measured stresses to predict boundary stresses and thus pack ice driving forces. The ratio between the two principal stress changes ($\Delta\sigma_1/\Delta\sigma_2$ = -6 kPa/20 kPa = - 0.3) suggests a loading width of about 350 m (see Figure 7(c)). Going down to Figure 7(b) and (c), the corresponding values of σ_y and σ_z are 58 kPa and -19 kPa, respectively. The boundary load for the 350 m loading width (100 MN/350 m = 285 kN/m) has to be scaled down by the ratio 20 kPa/58 kPa to obtain the actual boundary load for this case (285 kN/m . 20 kPa/58 kPa = 100 kN/m). Therefore, the boundary load is 100 kN/m over a width of 350 m.

The floe geometry is very much idealized in this example, but it still serves to provide an indication of the approximate value of pack ice driving forces. The above value falls at the upper range 25 to 100 kN/m suggested by Croasdale et al 1987.

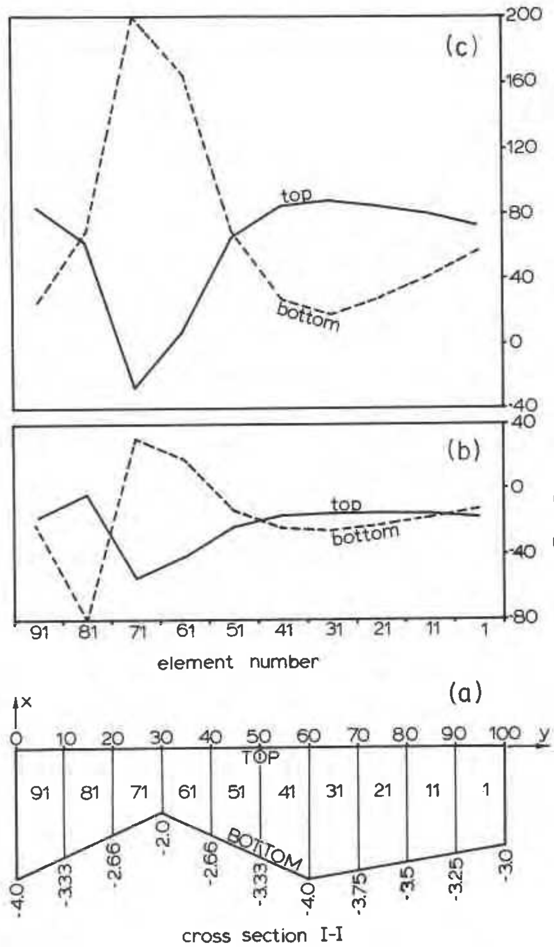

Figure 9 Stress distributions through the floe for non-uniform floe thicknesses

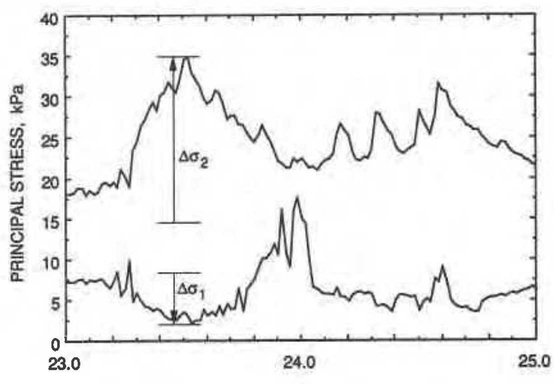

Figure 10 Major and minor principal stresses for loading event on April 22, 1986 (Elapsed time from April 21, 15:50)

7.0 CONCLUSIONS

Based on the results of the finite element analysis presented in this paper, the following conclusions were obtained:

1 - Stress measurements taken with a rosette in the central region of a circular ice floe are sufficient to make a first approximation of the distribution and the magnitude of ridge building forces on the perimeter of the floe and hence pack ice driving forces. More stress sensors should be placed at strategic locations in the floe to obtain a better measure of the state of load acting at the boundary of the floe.

2 - Variations in the ice thickness have a large influence on the measured stresses. It will be necessary to put more than one level of stress sensor at certain locations where bending moments and the reduced cross section affects are expected.

8.0 ACKNOWLEDGEMENTS

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