POAC '99
Espoo, Finland

Proceedings of the 15th
International Conference on
Port and Ocean Engineering
under Arctic Conditions

A MODEL OF MULTIPLE SPLITTING OF AN ICE PLATE END UNDER CONTACT LOADING

R.V. Goldstein, N.M. Osipenko
Institute for Problems in Mechanics,
Russian Academy of Sciences,
Moscow, Russia

ABSTRACT

A model is developed of multiple splitting of an ice plate starting in the zone of its edge section under contact interaction with a wall. The observed splitting phenomenon is considered as a result of brittle crack formation in the edge part of the ice plate contact with a wall through an intermediate layer of crushed ice.

1. INTRODUCTION

One of the characteristic features of thin ice fracture near the wall consists in formation of a narrow zone - "a contact line" of contact interaction along the front of direct ice-wall contact while flaking is the predomenant in ice fracture in this case (Riska et al, 1990). Somewhat another morphological scheme is realized at contact fracture at the scale of natural ice cover (floes) of thickness ~ 1m (see, e.g., Kawamura et al, 1996; Karna et al, 1993). The main difference is associated with the occuring of extended cracks which represent delaminations of the ice plate parallel to its surface and growing from the contact zone (Fig.1).

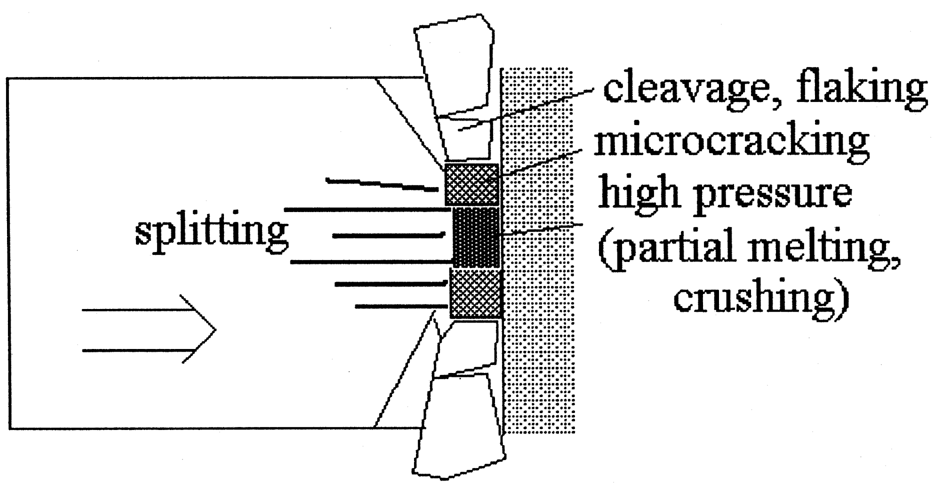

Figure 1. Scheme of the zone of contact interaction of the ice plate and wall

In this case the contact zone becomes more wide, flaking is concentrated near the surface layers of the ice plate and occurs in layers. Horizontal cracks grow up in the loading process (Karna, Jarvinen, 1994). Within the central region of the contact zone ice crushing occurs because of the deformation constraint in the source of contact fracture. A reology of ice in the contact zone depends on realization of the specific softening mechanisms, in particular, the models of an effective viscous fluid or granular medium can be used for modeling of the ice behavior (Melanson et al, 1998).

Different approachs for solving the problems on growth of the cracks of quasibrittle fracture under the conditions of predominant compression are known. A review of crack models used in mechanics of ice contact fracture was given, for instance, in by Zou et al, (1996). We will analyse the effects of delamination formation within the framework of a model which takes into account presence of a thin intermediate layer of crushed ice in the zone of delamination nucleation. The intermediate layer seems to be important for redistribution of local deformations and stresses near the end-section of the ice plate since this layer is more compliant as compared with the ice plate.

2. A MODEL

The suggested approach is based on taking account of the phenomenon of brittle fracture of a plate laying at a fluidlike layer under the wedging action of the fluid. Such a phenomenon was demonstrated by Mukhamediev and Nikitin (1986) for the model of the brittle fracture of the lithosphere pressed to the asthenosphere by gravitational forces.

Let us consider the following model problem (Fig.2).

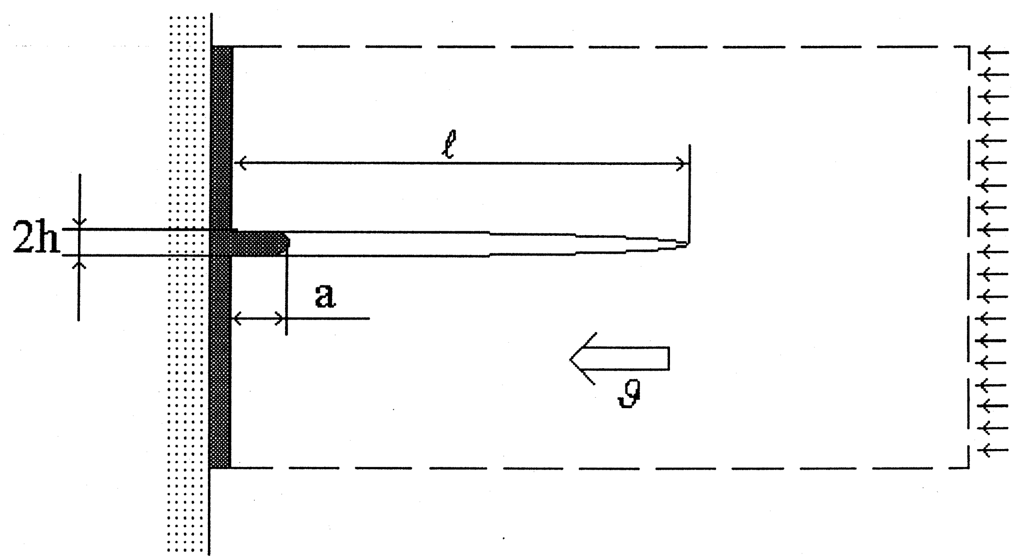

Figure 2. Scheme of a model problem for evaluation of the delamination - crack length

An edge crack of length ℓ emanating on the boundary of a halfplane is in a state of the limit equilibrium under the action of symmetric wedging forces along the part a of its surfaces. These forces are caused by the injection into the crack of a viscous medium under the pressure which is equal to the pressure in the layer of the crushed ice at the wall moving with the same speed, ϑ, as the speed of the crack growth and the front of the injected medium.

To clarify the structure of the basic formulae let us write some simple relations within the assumption that $a \ll \ell$. This inequality is valid for an intermediate layer of high viscosity.

Injection of a viscous medium into the crack we will model as a Poiseile flow in a gap of constant width, 2h. Then the flow speed averaged through the thickness of the gap equals (Moore, 1978)

$$\overline{\vartheta} = \frac{h^2}{3\eta}\frac{dP}{dr} \tag{1}$$

where η is the viscosity and P is the pressure.

Remind, that in our case $\overline{\vartheta} = \vartheta$. The average speed of the flow is equal to the speed of the crushing front in the quasisteady regime.

Denote by P_o the pressure in the viscous layer outside of the crack. Then integrating Eq. (1) with the condition $P=P_o$ at the gap mouth we obtain

$$P(r) = P_o - \frac{3\eta\vartheta}{h^2} r \tag{2}$$

The length of the loaded part of the crack can be evaluated by incorporating the condition $P(a)=0$. Hence,

$$a = \frac{P_o h^2}{3\eta\vartheta} \tag{3}$$

The resulting wedging force equals

$$F = \int_0^a P(r)dr = \frac{P_o a}{2} = \frac{P_o^2 h^2}{6\eta\vartheta} \tag{4}$$

3. DELAMINATION-CRACK LIMIT EQUILIBRIUM

Now consider the limit equilibrium of the crack, ℓ, in case when $a \ll \ell$ under the action of the wedge forces, F, along the boundary of the halfplane. Then the stress intensity factor K_I equals (Murakami et al, 1987)

$$K_I = \frac{nF}{\sqrt{\pi\ell}} \tag{5}$$

where $n \approx 2.59$

On the other hand, the stress intensity factor can be written in another form throught the crack opening, h, at the boundary of the halfplane within the assumption that the value h is known and can be associated with the crack wedging by a rigid wedge of thickness 2h (Cherepanov, 1974)

$$K_I = \frac{2\sqrt{2}\,hE}{\sqrt{\chi\pi\ell}} \tag{6}$$

where χ=3-4ν, E, ν are the Young modulus and Poisson ratio of ice. Equating the values K_I from Eqs. (5), (6) we obtain the relation between h and F in the following form

$$h \approx \frac{nF\sqrt{\chi}}{2\sqrt{2}\,E} \tag{7}$$

Substituting Eq. (7) in Eq. (4) we obtain the wedging force

$$F \approx \frac{48\eta\vartheta E^2}{P_o^2 n^2 \chi} \tag{8}$$

The condition of the crack limit equilibrium can be written as follows

$$K_I = \frac{48\eta\vartheta E^2}{\sqrt{\pi\ell}\cdot P_o^2 n\chi}, \qquad K_I = K_{Ic} \tag{9}$$

Hence, the length of the crack growing in a quasisteady regime equals

$$\ell = \frac{1}{\pi}\left(\frac{48\eta\vartheta E^2}{K_{Ic} P_o^2 n\chi}\right)^2 \tag{10}$$

Note, that the stable crack growth is possible since the stress intensity factor decreases with the increasing of the crack length (see Eq. (9)). The pressure P_o in a moving viscous layer is related to the conditions of local ice fracture, i.e. to the conditions of ice transition from an unbroken state to a broken one at the contact between the ice plate and viscous (quasiliquid) layer. This pressure can be evaluated using the value of an average pressure in the zone of the contact of an ice plate and a vertical wall. According to the experimental data the speed of the ice plate-wall relative motion has a week influence on the value of this average pressure (Karna et al, 1993; Tuhkuri, 1993). Hence, we can assume that the pressure P_o is weakly dependent on the speed of the front motion, ϑ. Then one can conclude on the basis of Eq. (10) that the crack length increases with increasing the speed of interaction of the ice floe and wall.

Note, that another variant of crack loading can occur within the asymptotic under consideration. Indeed, the front of fracture of the ice plate edge-section at the boundary with the intermediate layer is uneven (see, e.g., the sections of the contact zone in model tests given by Tuhkuri (1993)). The size of a characteristic roughness is comparable with the crystal sizes and seems to be a characteristic value for a specific type of ice. An influence of this factor can be interpreted within the given model as a constancy of the crack opening at the section of the ice plate contact with the intermediate layer where the process of wedging medium penetration occurs. Hence, the appearing of the wedging forces can be caused by penetration of crushed ice into the roughness element having the characteristic size of order the crystal size.

Assume that h ≈ const in Eq. (4) them we obtain from Eq. (5)

$$K_I = \frac{n}{\sqrt{\pi \ell}} \frac{P_o^2 h^2}{6\eta\vartheta} \tag{11}$$

If $K_I = K_{Ic}$ then the equilibrium crack size equals

$$\ell = \frac{1}{\pi}\left(\frac{nP_o^2 h^2}{6K_{Ic}\eta\vartheta}\right)^2 \tag{12}$$

Comparing Eqs. (12) and (10) it is easy to see that the regime of the stable crack growth is preserved in the both variants of the crack loading while the form of the crack length dependence on the system parameters ϑ, P_o and η is changed. Note, that this difference of the parametric dependences can serve as a basis for an identification of the fracture mechanisms in the experimental studies. For instance, the increasing of the splitting crack length with the growth of the speed of the ice plate-wall interaction observed by Karna et al (1993) points to the fact that the first of the considered mechanisms was realized during these experiments.

The performed above analysis is directly associated with modeling at the scale of the inner problem. Indeed, in that case the parameters of the physical model and full scale system providing the similarity criteria need to be chosen on the basis of the condition on a constancy of the crack length determined by Eqs. (10) or (12) to the characteristic size of the system (e.g., to the thickness of the ice plate). Then the conditions of nucleation of the delamination-cracks will be fulfilled. Fulfilment of these conditions is necessary for providing the similarity of fracture mechanisms.

We demonstrated a possibility of stable growth of a delamination crack under the action of the wedging effect of the crushed ice. Multiple splitting becomes possible if the loading conditions enable to support a limit equilibrium of a series of parallel growing delamination-cracks. Let us consider this regime for the first of the aforedescribed variants of wedging loading within the assumption that the fluidlike medium filled the almost whole crack, $a \sim \ell$ (e.g., such a case can be realized when the viscosity of the intermediate layer is small or the penetration velocity is high). For simplicity we will average the loads and displacements along the crack surfaces. Then the stress intensity factor for the system of parallel cracks equals (Cherepanov, 1974)

$$K_I \approx \sigma\sqrt{\frac{w}{2}} \tag{13}$$

where w is the crack spacing and σ is the uniform stress at the crack surfaces.

Assuming that $\sigma \sim \frac{F}{\ell}$ in Eq. (13) and taking into account an interrelation of the load, F, and average crack opening we obtain similarly to Eq. (8) the following relation

$$F \sim \frac{24\eta\vartheta E^2 \ell^2}{P_o^2 n^2 \chi w^2} \tag{14}$$

The condition of the crack limit equilibrium for the crack system has the following form according to Eqs. (13) and (14)

$$K_{Ic} \sim \frac{24}{\sqrt{2}} \frac{\eta\vartheta E^2 \ell}{P_o^2 \chi w^{3/2}} \tag{15}$$

Then the resulting formula which represents the dependence between the crack spacing and their length can be written as follows

$$w \sim \left(\frac{24}{\sqrt{2}\, n} \cdot \frac{\ell E^2 \eta\vartheta}{P_o^2 \chi K_{Ic}} \right)^{2/3} \tag{16}$$

4. CONCLUSION

The phenomenon of multiple splitting of the ice plate near the edge section under its contact interaction with a wall was considered. A model which describes formation of the delaminations and enables to evaluate their sizes was developed.

The approach based on an analysis of a brittle instability of an ice block loaded through an intermediate moving layer was used. Key point for this approach is the property of the fluid or fluidlike medium to align the local pressure in different directions. In the conditions of constraints the property determines the fracture process far from the upper and lower boundaries of the ice plate (through which the fluid could flow out) such that the unique possibility of the fluid motion consists in its penetration into cracks or cracklike defects and their wedging. The proposed in our paper scheme of multiple cracking at the edge of an ice plate demonstrates a possible mechanical nature of the observed effect. Note, that the fluid presure and wedging represent the main source of mechanical loading which leads to multiple splitting in the central (through the thickness) zone of the ice plate edge. The described scheme of ice fracture seems to be inherent to contact fracture of thick ice plates since for these plates the constraint effects in the contact zone are essential.

We did not specified the properties of a fluidlike layer since for the proposed scheme of fracture it was only essential an ability of this layer to transform a longitudinal load into all-round pressure. Generally, a wide spectrum of fluidlike layer properties (in particular, its effective viscosity) is possible in dependence on the system parameters. For instance, the contact zone can be wet (containing water as a result of the phase transition) or dry (consisting of pulverized powder of crushed ice) in dependence on the initial ice temperature and local pressure. Note, that a small grain fraction of the pulverised ice will be most mobile within the central part of the contact zone where the local pressure attains its maximum. This small-scale fraction and/or water can form a wedging quasiliquid layer.

The proposed approach can also be useful for modeling the dynamic problems on ice interaction with the indentors of different nature.

This work is supported by grant 99-01-00925 of the Russian Foundation for the Basic Research.

REFERENCES

Cherepanov, G.P. 1974. Mechanics of brittle fracture. Nauka Publ. Moscow, 640p.

Karna, T., Nyman, T., Vuorio, J., Jarvinen, E. 1993. Results from indentation tests in sea ice. Proc. 12th Int. Conf. Offshore Mech. and Arctic Eng. (OMAE-93), Glasgow, IV: 177-185.

Karna, T., Jarvinen, E. 1994. Dynamic unloading across the face of a wide structure. Proc. 12th IAHR Ice Symp. (IAHR-94), Trondheim, 3: 1018-1039.

Kawamura, M. at all. 1996. Ice-structure interactions in medium scale field indentation test. Proc. 13th IAHR Ice Symp. (IAHR-96), Beijng, 1: 228-236.

Melanson, P.M., Jordan, I.J., Megalis, I.L. 1998. Modelling of damage in ice. Proc. 14th IAHR Ice Symp.. Ice in Surface Water. Balkema. Rotterdam, 2: Moore, D.F. 1978. Principles and applications of tribology. Pergamon Press. Oxford.

Mukhamediev, Sh.A., Nikitin, L.V. 1986. About one type of gravitational instability in reologicaly delaminated tectonosphere of the Earth. Reports of USSR Ac. of Sci., 289: No.2, pp.327-331.

Riska, K., Rantala, H., Joensuu, A. 1990. Full scale observations of ship-ice contact. Helsinki University of Technology, Rep M-97. Otaniemi. 68p.

Stress intensity factors handbook. Ed. Murakami Y. 1987. V.1. Pergamon Press. Oxford.

Tuhkuri, J. 1993. Laboratory tests of ship structures under ice loading, v.I. Rep. M-166. Helsinki University of Technology. Otaniemi, 178p.

Zou, B., Xiao, J., Jordaan, I.J. 1996. Ice fracture and spalling in ice-structure interaction. Cold Region Sci. and Technology, 22: 213-220.