CHAPTER 342

EXPERIMENTAL STUDY ON DEFORMATION AND FRACTURE OF ICE SHEET BY PROPAGATING WATER WAVE

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ABSTRACT

A criteria of ice sheet fracture by propagating waves is proposed based on an elastic bending theory. Experiments with a model ice are carried out to examine the validity of the criteria. Comparisons with experimental results show that the proposed criteria is available for a wide range of ice properties. The crack span induced by waves is between 1/4 and 1/2 of wave length in ice.

INTRODUCTION

In the sub-Arctic sea, wave-induced motion of ice is a dominant factor causing many coastal problems; e.g. damages to structures by ice impact forces, or beach erosion by ice drift. To estimate the wave energy inside the ice zone, it is necessary to understand how waves transform under the ice cover. Previous studies show that the presence of ice causes wave energy attenuation, and the attenuation rate depends on the ice floe size and concentration. If some floes are fractured by waves, the distribution of floe sizes will be changed, and then the effects of the ice zone on waves will also vary. Therefore, for estimation of wave energy inside an ice zone, it is important to consider the ice deformation and fracture caused by waves.

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Ice-wave interaction has been mainly investigated by field observations, however it is very difficult to observe the deformation and fracture of ice since these occur in stormy sea conditions. A few experiments have been carried out, while in most of them plastic sheets were used as a model ice, and the effects of the difference in material properties between ice and plastic have not been examined. Furthermore, ice fracture cannot be simulated in the experiment with plastic sheets. In the present study, experiments with a model ice were carried out to examine wave-induced deformation of ice sheet and to verify the availability of the ice fracture criterion described hereafter.

EXPERIMENTS

Experimental Equipment and Procedure

Experiments were carried out in an ice tank which is 35m long, 6m wide and 1.8m deep, as illustrated in Figure 1. Water in the tank was doped with a solution of propylene glycol to weaken the ice which would be formed on the water surface. It took 10 hours or more to form an ice sheet of 25mm thickness and another 10 hours to set up experimental equipments, to test material properties and to observe the ice sheet deformation and fracture. Totally, 2 days were needed to perform one experiment, and one more day was necessary for the experiment with the ice sheet of 50mm thickness. The bending strength and the elastic modulus of ice were measured by a cantilever beam failure test and Plate Deflection Method, respectively.

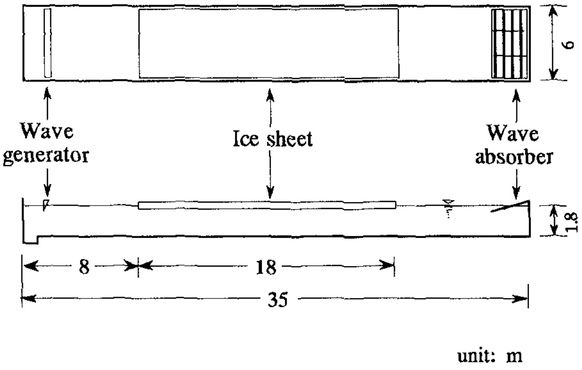

Figure 1 Experimental equipment

The wave was generated by a plunger type wave generator. At the far end of tank, a wave absorber was set up to decrease wave reflection. The vertical displacement of the ice sheet was measured at several points along the center of the tank, by using laser sensors and ultra-sonic sensors. Each experiments started with a very small incident wave height. If the ice sheet fracture was not observed in this condition, another experiment with a little larger wave height was carried out. This procedure was repeated till the ice sheet fracture occurred. After the occurrence of the first fracture, the above procedure was also continued to observe proceeding fracture of ice sheet. The conditions of the incident wave and the material properties of ice are listed in Table 1.

Table 1 Experimental condition

Case No.	Wave Period T(s)	Wave Height in Open Water H_0 (mm)	Ice Thickness h_i (mm)	Bending Strength of Ice σ_t (kPa)	Elastic Modulus of Ice E (MPa)
1	1.19	20.5~30.2	49.2	35.1	21.8
2	0.80	20.6~26.1	25.2	22.6	5.3
3	0.79	12.3~32.0	28.4	36.0	31.4
4	0.80	18.9~32.2	53.3	39.7	29.3
5	0.99	29.7	53.3	39.7	29.3
6	1.40	20.6~27.7	53.3	39.7	29.3
7	1.20	27.7~29.7	54.2	38.1	34.3
8	1.40	14.3~26.7	23.2	119.3	125.4
9	1.20	17.9~23.8	24.3	137.4	202.5
10	1.00	18.4~26.0	23.2	87.9	201.5

Experimental Results

As the incident wave penetrates into the ice-covered water, the wave height changes significantly near the ice edge and attenuates gradually under the ice. Figure 2 shows the effects of incident wave height on the change of

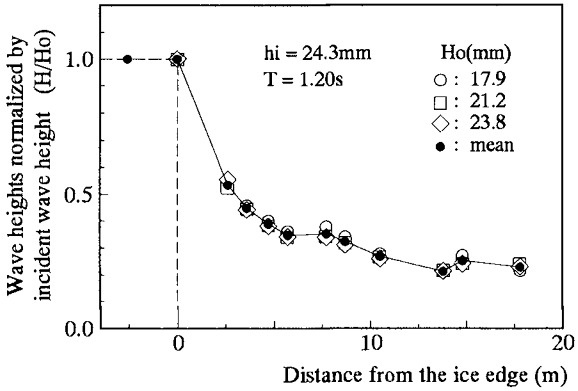

Figure 2 Wave height under ice sheet

wave height under the ice. The wave heights in this figure were normalized by the wave height in the open water. This ratio does not contain the effects of reflected wave from the ice edge since the wave height in the open water were estimated by subtracting reflected wave energy from incident wave energy. Generally, non-linear effects appear clearly with increasing of wave steepness, however there cannot exist steep waves under ice sheet since such waves cause ice sheet fracture. Figure 2 indicates that there is no effect of wave steepness on the wave height change under ice sheet in the condition where the ice sheet fracture does not occur. So, it can be concluded that the non-linearity of waves under ice sheet is to be negligible. Figure 3 gives an example of wave profile under ice sheet. The measured profile is described by a trigonometric function.

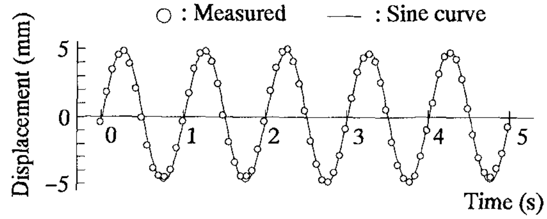

Figure 3 Example of wave profile under ice sheet

The wave celerity under ice sheet differs from that in open water and is almost constant over ice sheet, as shown in Figure 4. The non-linear effects of wave steepness on wave celerity is negligible, as well as on wave height change. A linear theory for waves under elastic plate gives a good explanation to experimental results of wave celerity under ice sheet(see Figure 5).

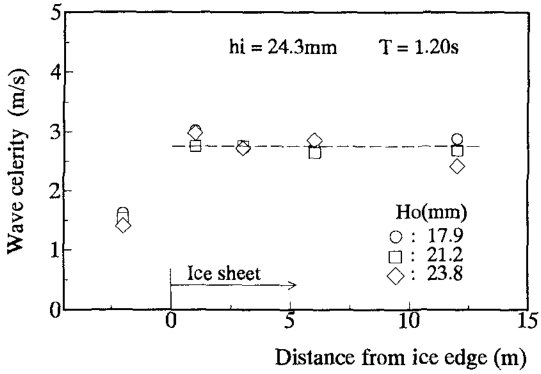

Figure 4 Wave celerity under ice sheet

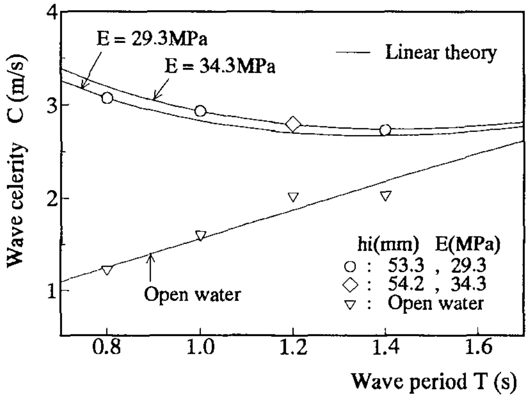

Figure 5 Comparison between measured and calculated wave celerity

THEORY

Ice sheet fracture is to be analyzed based on an elasto-plasticity fracture mechanics. However, it will be helpful for simple theoretical analysis on ice sheet fracture to consider how the elasticity or the plasticity of ice influences on ice-wave interactions. Liu and Sakai(1996) compared the numerical calculation of wave under elastic plate with experimental results of waves under elasto-plastic plate. Their comparisons showed that the calculated wave height near the edge agrees with experimental data fairly well and that the calculated values become somewhat larger than measured one as waves penetrate deeper in the plate. This discrepancy might be brought by a lack of plasticity effects in the numerical calculation. Wadhams(1973) explained the attenuation of wave height under ice sheet by energy loss due to a time dependent plastic strain (creep), and showed that this theory gives a good explanation for field observations of wave height attenuation in sea ice. These studies indicate that the deformation of ice sheet by waves is essentially elastic and the plasticity of ice cannot be negligible with increasing of penetration. Generally, ice sheet fracture by waves occurs near the ice edge. Therefore, it is reasonable to regard ice sheet fracture as a results of elastic deformation induced by waves.

An elastic bending theory gives a stress on the ice sheet surface as;

$$\sigma = \frac{Eh_i}{2(1-\nu^2)} \frac{\partial^2 \zeta}{\partial^2 x} \tag{1}$$

where E is elastic modulus of ice, h_i is ice thickness,ν is Poisson's ratio(=0.3), ζ is wave profile of ice sheet and x is direction of wave propagation.

As shown in Figure 3, a wave profile is expressed by a trigonometric function as follows;

$$\zeta = \frac{H}{2}\sin(kx - \omega t) \qquad (2)$$

where H is wave height in ice, k is wave number($= 2\pi/L_i$, L_i is wave length in ice) , ω is angular frequency($= 2\pi/T$, T is wave period) and t is time.

When the bending stress on the surface reaches the bending strength σ_f, ice sheet fracture occurs. Therefore, a fracture criterion is expressed as follows;

$$\frac{Hh_i}{L_i^2} = \frac{1-\nu^2}{\pi^2}\frac{1}{E/\sigma_f} \qquad (3)$$

VALIDITY OF ICE FRACTURE CRITERIA

The measured wave height is not accurate since the ice separated from the main part of ice sheet moves as an ice floe, not as a continuous ice sheet, and this floe dissipates wave energy penetrating into the ice sheet. The wave height can be estimated from the wave height in open water and the distance of fracture point from the ice edge, since the ratio of wave height in ice to that in open water does not depend on the incident wave height for a given wave period, as illustrated in Figure 2. Another quantities in Equation (3) were directly measured in the experiment. The wave length in ice can be also calculated from a linear theory for wave under elastic plate, which gives a good estimation for wave celerity, as shown in Figure 5.

Figure 6 shows that the ice fracture criteria proposed herein is available over a wide range of the ratio of elastic modulus to bending strength of ice. This agreement of the criteria based on an elastic bending theory with experimental results also ensures the applicability of the elastic bending theory for analysis on ice fracture by waves.

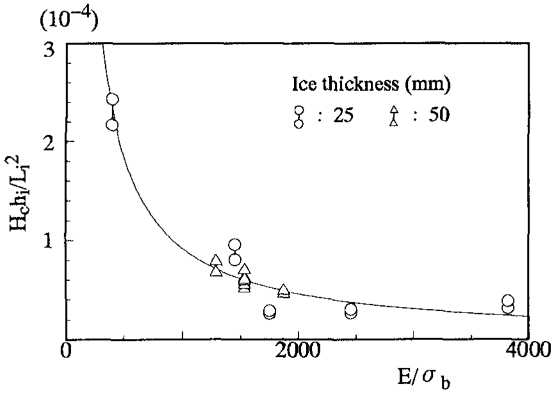

Figure 6 Ice fracture criteria compared with experimental results

CRACK SPAN IN ICE

The cracks in ice are almost perpendicular to the direction of the wave propagation, and the crack span is within 1/4 and 1/2 of the wave length under the ice sheet, as shown in Figure 7. The splits of ice were fractured laterally, resulting in rectangular pieces of almost same size. This regular pattern of ice fracture is also observed in the actual sea ice.

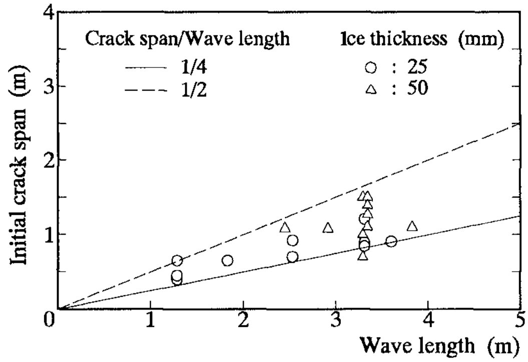

Figure 7 Relation between crack span and wave length in ice

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