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A Study on the Stem Angle and Icebreaking Capability of Icebreaking Vessels

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ABSTRACT

Among various design factors affecting icebreaking capability of an icebreaker, the stem angle (i.e., angle between bow stem and ice sheet) is the most important one under continuous icebreaking operation. This study focuses on the relationship between the bow stem angle of an icebreaker and its icebreaking capability. Considering relatively high loading-rate conditions with typical advancing speed of 3 to 4 knots, the material properties and deformation characteristics of sea ice are regarded as entirely elastic and brittle. In this paper the dynamic interaction process of icebreaker with level ice is simplified as a beam of finite length supported by Winkler-type elastic foundation simulating water buoyancy. The wedge type ice beam is loaded by the vertical impact forces due to the inclined bow stem of icebreaking vessels. The numerical model provides locations of maximum dynamic bending moment where extreme tensile stress arises and also possible fracture occurs. The model can predict a characteristic length of broken ice sheet given environmental and design parameters.

KEY WORDS: Icebreaking vessel, Wedge beam, Elastic foundation, Characteristic length

INTRODUCTION

Arctic region is known as the last frontier on earth for natural resources and many Arctic interest nations are trying to utilize those oil and gas reserves. Recently with a natural gas development project in eastern Siberia and Sakhalin Island, sea transportation routes from Far East region of Russia to LNG consumer countries in Asia, such as Korea and Japan, became important. Those sea routes in the Sea of Okhotsk are normally covered by sea ice of less than 1 m thickness from December to April and the sea-going vessels should be equipped with sufficient icebreaking capability or at least ice-worthiness (Sanderson, 1988; Cammaert and Muggeridge, 1988).

Comparing with conventional ships, icebreaking vessels require the most advanced technologies in the fields of hull structures, propulsion systems and outfittings. Icebreaking capability of an icebreaker is often determined by the maximum thickness of sea ice sheet which the icebreaker can break. For example, Canadian ASPPR classifies a ship's icebreaking capability level by the thickness of ice sheet in feet through which the vessel continues to break and advances at speed of about 3 knots. The higher levels of icebreaking capability require more expensive construction and operation costs and hence smaller cargo spaces are arranged due to heavy machineries and strengthened hull structures. Therefore the design regulation on icebreaking capability of an icebreaker plays an important role in deciding methods and schedule for Arctic development plans (Glen, 1984; Jones, 1989; Dick and Laframboise, 1989).

It is known that among various design parameters an inclined bow hull form is the most important one affecting icebreaking capability of an icebreaker. Icebreaking in flexural mode requires less amount of energy than icebreaking in compression mode. Due to its bending failure mechanism, the stem angle contributes a significant icebreaking force in vertical direction on ice sheet.

Ice sheet interaction with a sloping structures was often idealized as a beam on an elastic foundation by many previous researchers. To estimate the bearing capacity of a radially cracked ice sheets, Nevel (1961) studied a narrow wedge beam on an elastic foundation. He used power series to calculate maximum bending moment in an infinite wedge due to vertical load at the tip of the beam. Later he published several papers on this topic. To consider ice sheet breaking process upon a sloping structure, Nevel (1979) studied bending and buckling of a wedge beam under vertical and horizontal forces simultaneously. In his study only static deflections and bending moments were presented. In consideration of a wedge beam on elastic foundation, some researchers (Barnerjee, 1985; Wierzbicki et al., 1986) regarded ice as a plastic material to find positions of plastic hinges, but these studies deals static or quasi-static responses of ice sheet.

In this paper the relationship between the stem angle of an icebreaker and its icebreaking capability on level ice is studied. As the same idea in previous research, the interaction process of icebreaker with level ice is simplified as a beam supported by Winkler-type elastic foundation simulating water buoyancy. The wedge type ice beam of finite length is loaded by the vertical impact forces due to the inclined bow stem of icebreaking vessels. Unlike the interaction process between a fixed offshore structure and incoming ice sheet, the icebreaking situation by icebreaking vessels is a relatively fast process and it should be modelled with dynamic formulation. Considering elastic and brittle behaviors of ice at high loading-rate conditions, this study focuses on the estimation of maximum breakable thickness of ice sheet by an icebreaker. Also the numerical simulation provides locations of maximum dynamic bending moment where extreme tensile stress arises and also possible fracture occurs.

ESTIMATION OF ICEBREAKING CAPABILITY

Ice is an extraordinary material comparing other structural materials and various factors affect the material behavior of ice. Tensile or compression tests show that the material strength of sea ice differs from one to the other depending on its loading-rates, grain sizes, c-axis orientations, temperatures and the amount of impurity contents such as air bubble, brine etc. Generally ice is considered as a brittle material, however, in case of slow deformation and high temperature it shows creep or plastic deformation behavior.

For ice deformation with strain-rates below 10^{-5}/sec, it can be regarded as perfectly plastic material. This strain-rate values in strength tests are equivalent to the movement of several cm/sec in indentation tests. Since the continuous icebreaking operation on level ice has average speed of 3-4 knots, the dynamic loading-rate upon ice sheet can be regarded. as sufficiently fast and for this case the material behavior of ice may be considered as purely elastic and brittle.

In order to understand continuous icebreaking operation on level ice a typical icebreaking process by the icebreaker is shown in Fig.1. As the ship advances, it exerts sufficient amount of vertical force to break the ice sheet. The vertical component of the icebreaking force is transmitted to ice sheet through the forebody hull structure. If the vertical force exceeds a certain value, radial cracks propagating from the loading point form first. As the failure process continues further, secondly circumferential cracks form in the wedge shape ice beams due to excessive bending moment and then ice fails. This iterative icebreaking procedure is characterized by ice thickness, speed of ship, amount of vertical force etc.

Icebreaking capability is often considered as icebreaking resistance of a ship's hull, however, in this study it is only regarded as the maximum thickness of ice to be broken. The relationship between vertical forces on ice and bow hull shape is usually expressed by an empirical or analytical formulas by many researchers. For example, White (1970) suggested a mathematical model to connect propeller thrust force T and bow hull shape to vertical force F_v on ice sheet.

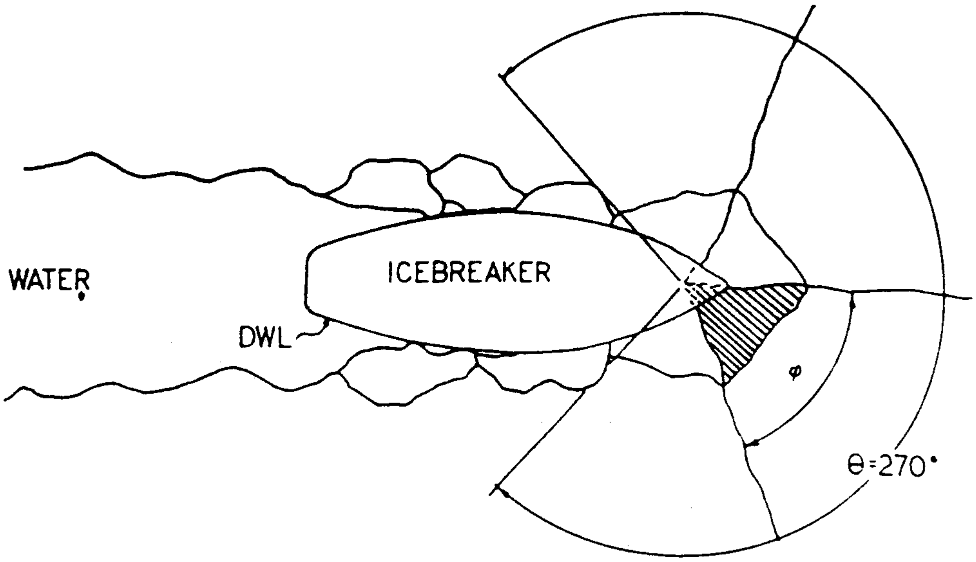

Fig.1 Radial Cracks and Circumferential Cracks in Icebreaking Process

$$F_v = \frac{\cos\alpha\ (\cos\beta + \mu\ \sin\beta) - \mu\ \sin\alpha}{\sin\alpha\ (\cos\beta + \mu\ \sin\beta) + \mu\ \cos\alpha} T \qquad (1)$$

where μ = dynamic friction coefficient,
α = stem angle,
β = spread angle complement.

From Eq.1 for the same displacement and propeller thrust, we find that the vertical force F_v increases with smaller stem angle α and spread angle complement β. In fact smaller values of α and β mean a bow hull shape of nearly flat plate, therefore many problems such as in water resistance, and manoeuvrability in conventional sea operation may arise and the merit of increased vertical force, i.e. icebreaking capability, is reduced. Relatively large values of stem angle in the old type icebreakers tends to reduce to about 20° recently. White also used an empirical formula for the relationship between vertical force F_v and maximum thickness of ice sheet h.

$$F_v = c\,\sigma_t\,h^2 \tag{2}$$

where c is a constant for the tensile strength of sea ice σ_t and ice thickness h. From Eq.2 we notice that the maximum thickness of broken ice is proportional to square root of vertical force.

NUMERICAL SIMULATION

In this study the dynamic interaction process of icebreaker with level ice is simplified as a beam of finite length supported by Winkler-type elastic foundation simulating water buoyancy. The wedge type ice beam is loaded by the vertical impact force due to the inclined bow stem of icebreaking vessels. The numerical model provides locations of maximum bending moment where extreme tensile stress arises and also possible fracture occurs. Here it is assumed that once the calculated tensile stress exceeds the flexural strength of ice, then the ice beam fails.

Coordinate system used in this numerical analysis is shown in Fig.2. We limit the validity of analysis in elastic responses, but shear deformation and rotational inertia effects are included. Governing equations for the flexural vibration of a beam are as follows:

Dynamic Force Equilibrium:

$$m \ddot{y} + k y - \frac{\partial V}{\partial x} = P(x,t) \tag{3}$$

Dynamic Moment Equilibrium:

$$I_z \ddot{\phi} - V + \frac{\partial M}{\partial x} = 0 \tag{4}$$

Moment-Curvature Relation:

$$M = - EI \frac{\partial \phi}{\partial x} \tag{5}$$

Shear-Slope Relation:

$$V = \kappa A G \gamma \tag{6}$$

$$\frac{\partial y}{\partial x} = \gamma + \phi \tag{7}$$

where m(x): effective mass per unit length
k(x): stiffness coefficient of the elastic foundation (= ρ_w g)
I_z(x): rotational moment of inertia
EI(x): bending rigidity
κAG(x): shear rigidity
P(x,t): external force per unit length
y(x,t): deflection
ϕ(x,t): bending slope

$\gamma(x,t)$: shear slope
$M(x,t)$: bending moment
$V(x,t)$: shear force

Since section properties of a beam change along its length and loading history along time, Eqs.3-7 do not have exact solutions in analytical form except some special cases. In this study the finite difference numerical technique is used. Eqs.3-7 are simultaneous partial differential equations with two independent variables x and t, hence difference equations should apply to length of a beam and time simultaneously. Especially the difference equation applied to time domain means time-integration and in this study the 4th-order Runge-Kutta method is used to calculate dynamic responses of a beam.

RESULTS AND DISCUSSION

Numerical anaysis is carried out for a wedge shape beam as shown in Fig.3 and following material properties are used for sea ice:

Mass density of sea ice: ρ = 918 Kg/m^3
Flexural strength of sea ice: σ_f = 0.5 MPa
Modulus of elasticity: E = 2.0 GPa
Poisson's ratio : ν = 0.33
Equivalent shear area coefficient : κ = 0.851
Dynamic friction coefficient: μ = 0.2
Density of sea water: ρ_w = 1025 Kg/m^3

In order to understand the icebreaking capability, a parametric study is carried out using parameters representing dimensions of a wedge beam and vertical impact forces. For typical conditions assuming radial cracks propagating from the loading point in infinite ice plate, 50 m

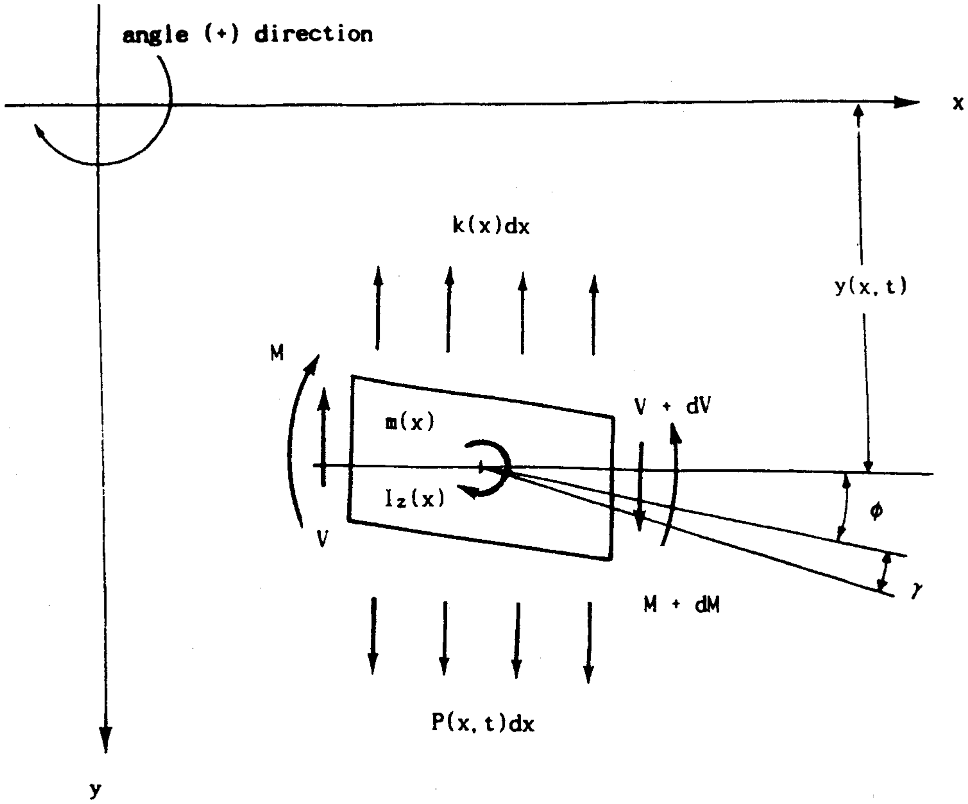

Fig.2 Coordinate System and Sign Convention

and 100 m are chosen for the finite length L of a wedge shape beam. It is assumed that the boundary conditions are free at the tip of a wedge beam and fixed at the root of beam. The actual conditions at the root of a cantilever ice beam on water buoyancy may be regarded as between free end and fixed end.

For the wedge angle φ between two sides of the wedge beam, 30°, 45° and 60° are chosen arbitrarily. From field investigations Kashteljan et al. (1968) reported 67.5° for the angle φ. With above parameters, the location of maximum bending moment and fracturing positions are determined by changing ice thickness. Also the breakable maximum ice thickness is calculated by varying vertical impact forces

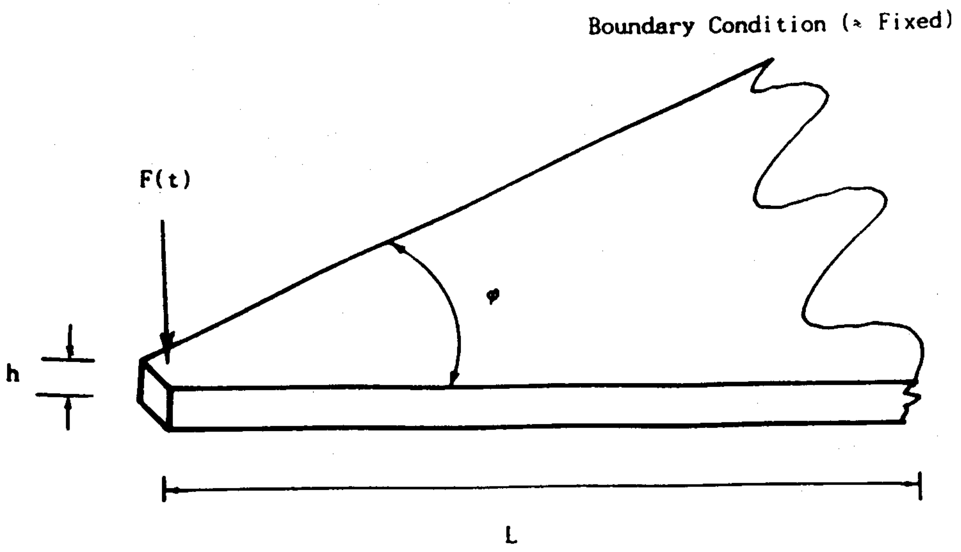

Fig.3 Wedge Type Model Beam for Sample Calculation

which indirectly represent the stem angle changes. Results are given in Fig.4 - Fig.9.

In Fig.4 and Fig.5 shows the positions of dynamic bending failure (i.e., characteristic length of the broken ice piece) with variation of the ice thickness for wedge angle φ of 60° and length L of 50 m and 100 m respectively. The figures show that the characteristic length increases with the increase of ice thickness and for the same thickness the characteristic length decreases as the vertical load increases. This resulst from the fact that for larger impact forces the stress wave travels to reach a critical bending moment position in shorter time and distance. With the increase of vertical forces ice begins to fail and the general trend shows that in the beginning the position of bending failure occurs between the tip and mid body of the beam from the tip. The time to failure is around one half of natural frequency of the beam. As the load increases the failure position

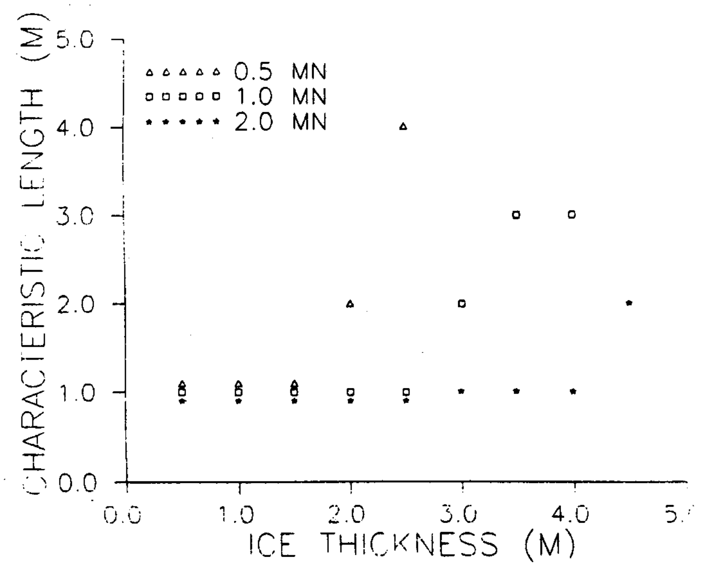

Fig.4 Characteristic Length vs. Ice Thickness (φ = 60° L = 50 m)

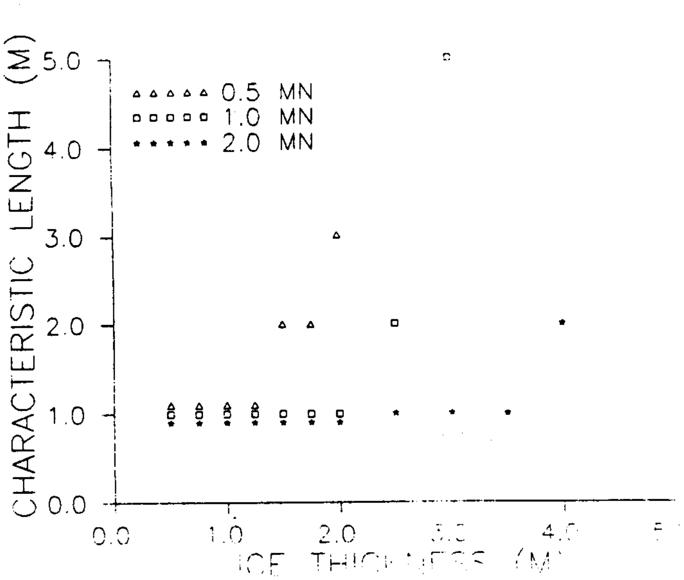

Fig.5 Characteristic Length vs. Ice Thickness (φ = 60° L = 100 m)

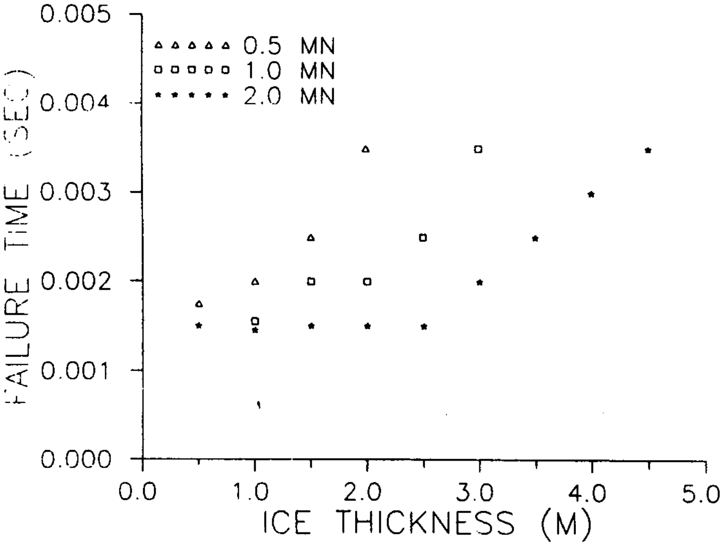

Fig.6 Failure Time versus Ice Thickness (φ = 60° L = 50 m)

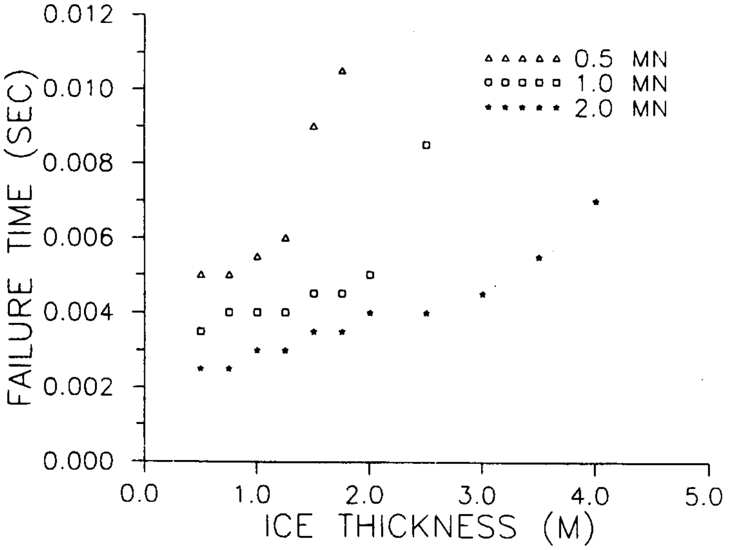

Fig.7 Failure Time versus Ice Thickness (φ = 60° L = 100 m)

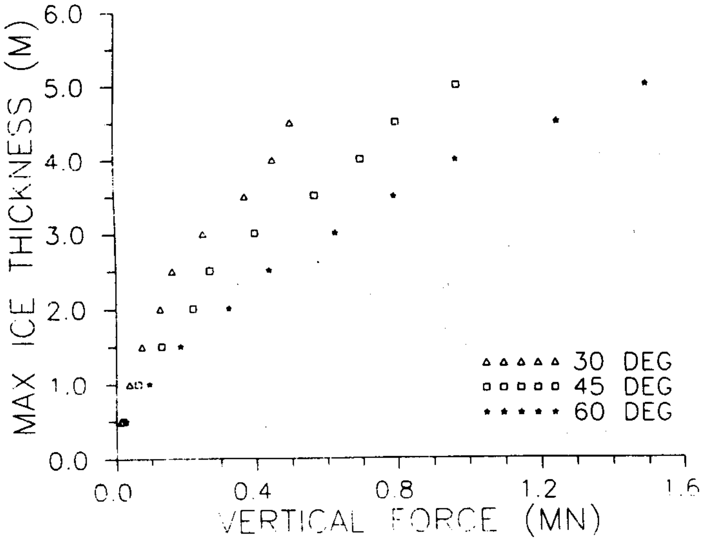

Fig.8 Maximum Ice Thickness Broken vs. Vertical Force (L = 50 m)

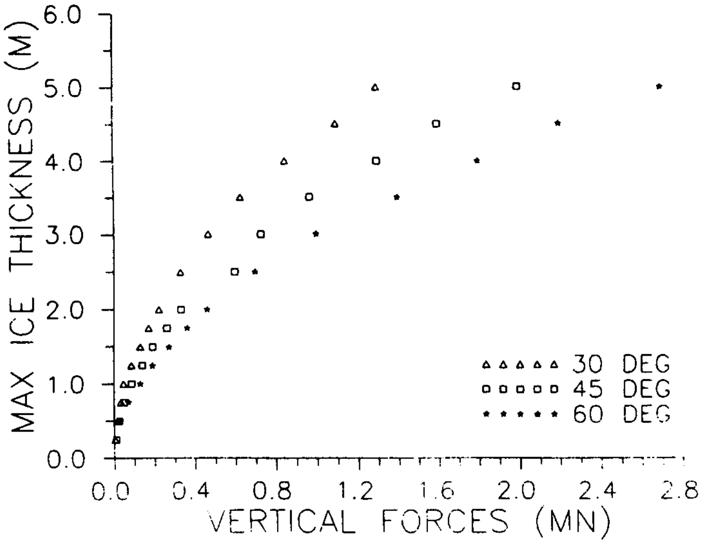

Fig.9 Maximum Ice Thickness Broken vs. Vertical Force (L = 100 m)

moves to the tip and the failure time of beam becomes short as shown in Fig.6 and Fig.7.

In Fig.8 and Fig.9 the maximum ice thickness to be broken is shown versus vertical impact forces which are calculated from bow stem angle as in Eq.1. Hence the figures imply the icebreaking capability along with the change of bow hull form indirectly. According to the figures the maximum thickness of ice increases nonlinearly as vertical force increases. Curve fitting reveals the nonlinear relation in the figures proportional to nearly 1/2 power.

Characteristic length l_c for an infinite ice plate sometimes means an action radius of the floating plate by the vertical load defined as:

$$l_c = \left[\frac{E\,h^3}{12(1-\nu^2)k}\right]^{1/4} \tag{8}$$

where E is Young's modulus, ν Poisson's ratio and k stiffness of elastic foundation. According to Eq.8 the characteristic length l_c is proportional to $h^{3/4}$ where h is thickness of ice plate. In this study, however, characteristic length implies only the actual length of the ice pieces broken by the vertical impact forces. In fact the circumferential cracks is offen observed at the distance of 3 to 6 times ice thichkness from the loading point and the maximum ice thickness is proportional to the square root of vertical load (Michel, 1978). Therefore the calculated results agree well with the observed maximum ice thickness and characteristic length of ice pieces.

CONCLUSIONS

In this paper the dynamic interaction process of icebreaker with level ice is simplified as a beam of finite length supported by Winkler-type elastic foundation simulating water buoyancy. The wedge type ice beam is loaded by the vertical impact forces due to the inclined bow stem of icebreaking vessels. The numerical model provides locations of maximum dynamic bending moment where extreme tensile stress arises and also possible fracture occurs. The model can predict a characteristic length of broken ice sheet given environmental and design parameters assuming the material properties of ice under continuous icebreaking operation as elastic and brittle. The calaculated results agree well with the observed maximum ice thickness and characteristic length of broken ice pieces. The characteristic length increases with the increase of ice thickness and for the same thickness the characteristic length decreases as the vertical load increases. The maximum breakable thickness of ice is nearly proportional to square root of the vertical impact forces.

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