KnE Materials Science
ASRTU Conference Proceedings
IV Sino-Russian ASRTU Symposium on Advanced Materials and Processing Technology (2016), Volume 2016

Knowledge E
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Conference Paper

Physical and Mechanical Properties of Sea Ice in Bending

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Abstract

The work presents the study of changes in the physical and mechanical properties of sea ice in bending. Strength limit σ_B and deformation module E_B of ice under bending are conditional mechanical characteristics of sea ice. These characteristics do not reflect the actual stress state of ice destruction at the time. The ratio of the module to the strength limit E_B/σ_B determines the relative radius of curvature of neutral layer in the place of ice destruction. It is shown that this ratio increases with the increase of ice temperature. Dependencies for determining of E_B and σ_B of sea ice that generalize the experimental data are obtained.

Keywords: sea ice, bending, mechanical properties, elasticity, tensile strength

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Received: 9 September 2016
Accepted: 19 September 2016
Published: 12 October 2016

Publishing services provided by Knowledge E

Selection and Peer-review under the responsibility of the ASRTU Conference Committee.

1. Introduction

The Northern Sea Route (NSR) undergoes significant changes in the ice conditions every year. Drifting sea ice is characterized by the following parameters: age; thickness; dimensions; concentration; extent of failure, and other. Ice crystals consist of fresh ice, brine, insoluble salts, and air inclusions. Deformation and fracture of ice are due to its structure, temperature, salinity, and type of deformation. Bending failure of ice is typical for ships and hydraulic structures. The work presents the study of changes in the physical and mechanical properties of sea ice in bending.

2. Ice Physics

The annual change in the temperature of the ice thickness $T(z)$ is shown in Fig. 1a. In summer, the ice temperature is practically constant being close to the average value $\overline{T}$: $T(z) \approx \overline{T}$ = const. Z coordinate reports with the bottom of the ice surface (Fig. 1a) with a thickness H.

Ice is characterized by salinity: $S(z) \approx \overline{S}$ = const.

The average salinity $\overline{S}$ for the seas (NSR) is defined by the following Ryvlin's expression [1]:

$$\overline{S} = 30\left(-0,5H^{0,5}\right) + 4,5, ‰ \quad (1)$$

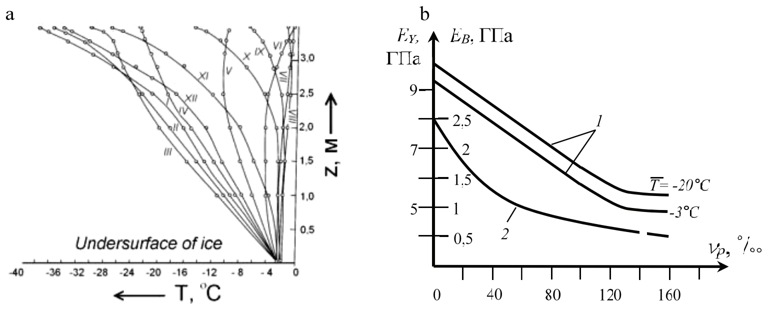

Figure 1: Characteristics of sea ice: (a) temperature variation of sea ice T over the horizon z throughout the year (I…XII – months of the year); (b) changing the Young's modulus E_Y (1) and deformation modulus at a bend E_B (2) of sea ice by the brine content.

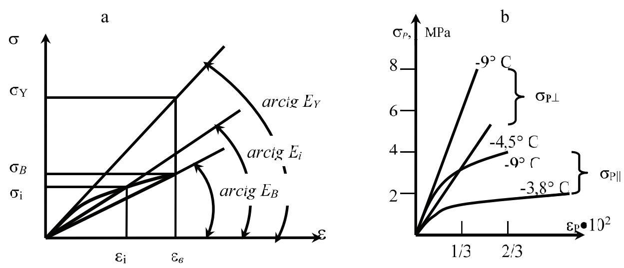

Figure 2: Ice tension diagrams: (a) schematic diagrams σ - ϵ under bending of ice; (b) marine congelation ice in compression (small samples; $\sigma_{B\perp,//}$ - loading direction relative to the horizon, the temperature indicated).

Multi-year ice has a salinity $\overline{S}= 3\ldots 6$ ‰. Salinity is also determined by the relative content of the brine in the volume of ice υ_p described by formula of Frankenstein and Garner [2]:

$$\upsilon_p = \overline{S}\cdot\left(0,532 - 48,19\cdot\overline{T}^{-1}\right), ‰ \tag{2}$$

Ice is separated into two layers: the upper water-snow has a granular structure, while the lower core layer consists of congelation prisms or fibrillation.

3. The Mechanical Properties of Ice Under Load

Deformation and fracture of ice is described in frame of kinetic and mechanical approaches. The kinetic one describes the development of microscopic damage (defects) basing on studies of Griffith, Irwin, and others. For example, this approach is applied for study of bending and compression of ice by Vershinin [2]. A more common approach uses mechanical stress state diagrams $\sigma - \epsilon$ (Fig. 2a).

Ice deforms elastically at low $\overline{T}$ and elastoplastically at increasing $\overline{T}$ (Fig. 2b). In order to take it into account, a simple Hooke's law is replaced by more complex rheological models [3]. At the beginning of the ice deformation, its behavior is described by the elastic modulus (Young's) E_Y. With increasing load, secant modulus E_e is used (Fig. 2a). The extreme value E_i- is deformation module $E_{\mathrm{B}} = E_{i\ min}$ when ice is breaking. The relative value of $E_{\mathrm{B}}/E_Y \equiv \frac{\sigma_{\mathrm{B}}}{\sigma_Y}$ characterizes the degree of ice elasticity. Here, σ_Y is the

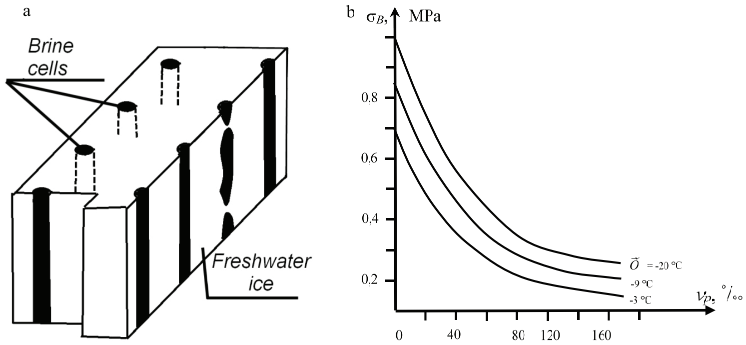

Figure 3: The cellular model of sea ice and the tensile strength of: (a) ice model of the cellular structure (cell brine); (b) limit σ_B bending strength consoles.

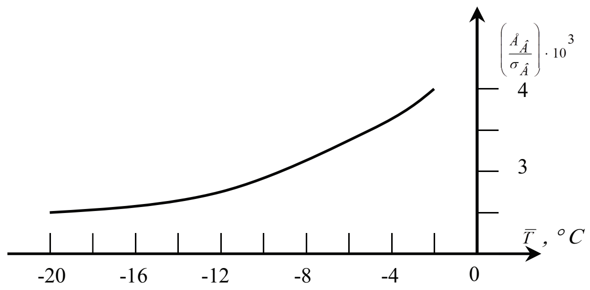

Figure 4: Dependence of the relation of deformation module of sea ice at a bend to the limit strength depending on the temperature. Salinity of the ice is 3 ‰.

ultimate tensile stress of ice, when it is fully elastically deformed (Fig. 2a). Respectively, $1 - E_{\text{B}}/E_Y = \frac{\sigma_Y - \sigma_{\text{B}}}{\sigma_Y}$ is the measure of ice plasticity.

Estimates made by authors show an elastic behavior of the ice at a bend near the neutral sheet and increase of the ice plasticity near the surface (Fig. 4).

4. The Elastic Characteristics of Ice in Bending

The initial deformation of ice is characterized by the elastic modulus E_Y. Reliable way to determine E_Y is a seismic dynamic method. In this case, the speed of bending waves is influenced by all features of ice construction [2]. These field experiments are approximated by the following dependence:

$$E_Y\left(\overline{S}, \overline{T}\right) = E_Y\left(0, \overline{T})(1 - 3,6\, \upsilon_p\right). \tag{3}$$

Here, the Young's modulus for the freshwater ice $E_Y(0, \overline{T}) \approx 9,21(1 - 0,0015\overline{T})$ (GPa).

Simplified example in the study of the bending deformation is the equating of modules (intersecting modules at fracture point) in compression and tension $E_p = E_1 = E_{\text{B}}$. The closest case to the interaction of vessels with ice and sloped waterworks are experiments on the destruction of sawn consoles in ice. Under the destruction on a "top-down" the module E_{B} is defined by the following expression [4]:

$$E_{\text{B}} = 2,3\left(1 - 11,55 \cdot \upsilon_p + 42,6 \cdot \upsilon_p^2\right), \text{GPa} \tag{4}$$

Dependences of the elastic characteristics of the E_Y and E_{B} are shown in Fig. 1b.

5. Results and Discussion

When bending, it is believed that the break-up occurs when the upper limit of tensile strength layer σ_2 is achieved. A direct test of the large ice samples tensile is technologically impossible. Therefore, this test is replaced by the destruction of the console afloat with the definition of conditional flexural strength $\sigma_{\text{B}} = \sigma_2 = \sigma_p$ under the assumption of the equality of the deformation modules $E_{\text{B}} = E_1 = E_2$. Strength limit σ_{B} is determined using the results of the theory of bending beams [5]:

$$\sigma_{\text{B}} = E_{\text{B}} \cdot \rho^{-1} \cdot (0,5H), \tag{5}$$

where ρ - bending radius of neutral console layer.

Presentation of $\sigma_{\text{B}}\left(\overline{S,T}\right)$ data is carried out using a cellular model of ice (Fig. 3a) [1]. Cells with brine of relative volume υ_p pass through the volume of freshwater ice. Therefore, we obtain the following expression [1]:

$$\sigma_{\text{B}} = \sigma_{\text{B}}(0,\overline{T}) \cdot \left[1 - \left(\frac{\upsilon_p}{\upsilon_0}\right)^{\kappa}\right], \tag{6}$$

where $\sigma_{\text{B}}(0,\overline{T})$ – strength of fresh ice, υ_0 - limiting amount of brine, containing which the ice has no strength ($\sigma_{\text{B}} \to 0$); κ - exponent, depending on the shape of the cell section.

Eq. (6) is universal for the entire range of υ_p. For a small amount of brine, strength of the cellular structure is more accurately defined by the formula [6]:

$$\sigma_{\text{B}} = \sigma_{\text{B}}(0,\overline{T})e^{-n \cdot \upsilon_p}, \tag{7}$$

where the exponent n is determined from experimental data.

Tensile strength of fresh ice, determined using results of Butyagin [7], Lavrov [8], and others, is (MPa):

$$\sigma_{\text{B}}(0,\overline{T}) = 0,42\left[1 + 0,34\left(-\overline{T}\right)^{0,5}\right], \tag{8}$$

The authors come to the following final formulas for the flexural strength:

for $\gamma_p < 0,06 \ldots 0,07$

$$\sigma_{\text{B}}(\overline{S},\overline{T}) = \sigma_{\text{B}}\left(0,\overline{T}\right)e^{-15,2\upsilon_p}; \tag{9}$$

for $\gamma_p > 0,07$

$$\sigma_{\text{B}}\left(\overline{S},\overline{T}\right) = 0,46\sigma_{\text{B}}\left(0,\overline{T}\right)\left(1 - 3\upsilon_p\right), \tag{10}$$

	The average temperature of the ice $\overline{T}$,°C				
	-20	-15	-11	-7	-3
v_p at $\bar{s} = 3^{\circ}/_{\circ\circ}$	8,97	11,43	15,01	22,68	50,78
$E_B(0,003;\overline{T}), GPa$	2,07	2	1,9	1,7	1,15
$\sigma_B(0,003;\overline{T}), MPa$	0,88	0,80(5)	0,76	0,57(5)	0,30(5)
$(E_B/\sigma_B) * 10^{-3}$	2,35	2,48	2,5	2,96	3,77

Table 1: Character of changes (E_B/σ_B) in bending.

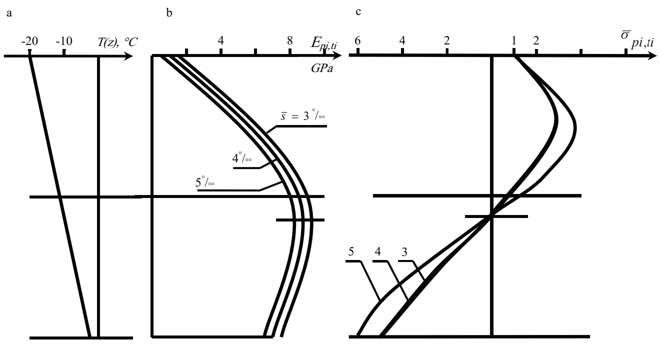

Figure 5: Dependence of the secant modulus (b) and the relative stress (c) sea-ice of congelation at $\bar{\sigma} = -11$°C at a bend. (a) Change in temperature with the thickness. $\bar{s}$- salinity of the ice.

Results of $\sigma_B(\overline{S},\overline{T})$ calculations using (8-10) are shown in Fig. 3b.

Defined values of the physical and mechanical characteristics E_Y, E_B, and σ_B of ice can be directly used in the calculation of the ice propulsion of ships and ice interaction with hydraulic structures. Despite the stability of the concept of modulus flexural E_B, it will allow to determine reliably the value of the rigidity of the cylindrical field of ice as a plate:

$$D = \frac{E_B H^3}{12\left(1-\mu^2\right)}, \tag{11}$$

where $\mu = 0,333 + 6,105 \cdot 10^{-2} exp\left(0,182\overline{T}\right)$ – Poisson coefficient of sea ice [2].

The ratio (E_B/σ_B), in accordance with (5), is related to the radius of curvature of the ice neutral layer in the place of destruction by the following formula:

$$\rho\left(\overline{T}\right)/0,5H = E_B\left(\overline{T}\right)/\sigma_B\left(\overline{T}\right). \tag{12}$$

The nature of the changes of this ratio is shown in Fig. 4.

In the simulation of traffic movements and interactions of hydraulic engineering constructions with ice in the ice model basin, the fulfillment of the condition $(E_B/\sigma_B) = idem$ is one of the criteria of dynamic similarity of the experiment [9]. The calculated value (E_B/σ_B) indicates its growth with decreasing temperature $\overline{T}$ (Fig. 4). This is contrary to the judgment of the opposite tendencies of its measurement [10]. Character of changes of (E_B/σ_B) indicated in Fig. 4 is defined by the calculation in Table 1.

Numerically, it is explained by the fact that the gradient (negative) $\frac{dE_B}{dv_p}$ is much less than the corresponding gradient $\frac{d\sigma_B}{dv_p}$. Studies of stressed state of ice in bending show that fracture occurs in the middle of ice stretching zone, rather than on the surface (Fig. 5). This makes the relation (E_B/σ_B) an artificial characteristic of the physical and mechanical properties of ice. It would be more correct to consider it as the relative value of the curvature radius of the neutral layer in the place of destruction in bending in accordance with (11).

6. Conclusion

Results of research lead to the following conclusions:

1. Strength limit σ_B and deformation module E_B of ice under bending are conditional mechanical characteristics of sea ice. These characteristics do not reflect the actual stress state of ice destruction at the time.

2. At the same time, module E_B allows estimating reliably the cylindrical stiffness of ice field.

3. The ratio of the module to the strength limit E_B/σ_B determines the relative radius of curvature of neutral layer in the place of ice destruction. It is shown that this ratio increases with the increase of ice temperature.

4. Dependencies for determining of E_B and σ_B of sea ice that generalize the experimental data are obtained.

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