POAC'23
Glasgow, United Kingdom

Proceedings of the 27th International Conference on
Port and Ocean Engineering under Arctic Conditions
12-16 June 2023, Glasgow, United Kingdom

Experimental investigation on fracture toughness of model ice with pre-notched beams

TIAN Yu-kui, GANG Xu-hao, YU Chao-ge, KONG Shuai, KOU Ying

State Key Laboratory of Hydrodynamics, China Ship Science Research Center, Wuxi, 214082, China

ABSTRACT: The fracture toughness of ice is one of the important mechanical properties which affects the ice dynamic behaviors, such as ice breaking, rafting and ridging, so the researches on it are of remarkable engineering significance. Taking the model ice in the small ice model basin in China Ship Scientific Research Center (SIMB, CSSRC) as research object and using three-point bending method, a series of pre-notched model ice beams in same geometric size were tested to investigate the fracture properties of the model ice. In the tests, the depth of the notch was controlled to be constant, the load-time history and displacement-time history curves under different notch deep and loading rates in the fracture progress of the ice samples were documented. With the experimental data, the correlation between fracture toughness and loading rate and notched deep were studied, and the fracture toughness of the model ice was calculated with American Society for Testing Materials (ASTM). The results can provide a reference to the study of fracture process of ice cover and can be also applied to analyze ice loading on structures.

KEY WORDS: model ice, pre-notched beam, three-point bending tests, loading rate, fracture toughness

INTRODUCTION

There are many different modes of large-scale sea ice floes, ice ridges, and overlapping ice under the external drive of atmospheric and oceanic conditions, as well as the interaction with engineering structures, among which sea ice fracture is a typical and widespread failure form. The fracture toughness of sea ice is a measure of the ability of the material to resist crack instability propagation in the plane strain state, and is the property of the material itself. It is the main mechanical characteristics that affect the dynamic behavior of sea ice such as fracture, overlap and accumulation. Early as 1921, Griffith assumed that when the strain energy release rate reached or exceeded the critical energy needed to form a new crack, then cracks began to be generated and transmitted. In 1961, Kaplan et al. introduced the theory of fracture mechanics into concrete structures. Gold began the study of ice fracture mechanics in 1963 by forming ice cracks in ice plates by thermal shock. Liu and Loops obtained the result that the K_{IC} of freshwater ice increases as the test temperature and loading rate decrease. Dempsey et al. used ice samples of different sizes to conduct fracture tests, and obtained that the K_{IC} value of fracture toughness of thicker ice samples was about 250 kPa· $m^{1/2}$, which was significantly higher than the K_{IC} of sea ice fracture toughness obtained by other researchers using smaller ice samples. Through the experimental study on fracture toughness of sea ice samples in Lai Zhou Bay during the winter of 2011-2012, Ji et al. focused on the analysis of the effects of sea ice brine volume (temperature and salinity) and loading rate on fracture toughness, and determined the basic characteristics of K_{IC}. Gharamti investigated the influence of loading type, loading rate, and test size on the fracture energy of columnar freshwater S2 ice, used Rice J-integral and VFCM to compute the apparent fracture en ergy at crack growth initiation. The K_{IC} of sea ice is affected by the structure of ice crystals, and the K_{IC} of vertical crack direction is significantly lower than that of horizontal crack direction in sea ice. It is also closely related to the sharpness of the crack tip, and the fracture toughness decreases with the increase of the sharpness.

At present, the research methods of ice characteristics and the interaction between ice and structures mainly include model test, numerical calculation and empirical formula. Among them, the model test to simulates the real sea ice environment and the ship ice-breaking sailing situation through the accurate control of various test parameters, and profoundly reveals the internal relationship between various physical phenomena. The quality of the model ice is mainly determined by the physical and mechanical properties, fracture mode and motion mode of the ice. By testing the fracture toughness of the pre-notched ice specimen, the mechanical properties, fracture mode and brittleness coefficient of the model ice can be obtained, and the similarity between the model ice and the sea ice can be effectively determined. Therefore, the research on the fracture characteristics of the model ice has important engineering significance. In this paper, using the model ice in the small ice model basin in China Ship Scientific Research Center (CSSRC SIMB), and the ASTM (American Society for Testing Materials) recommended formula was used to analyze the change of fracture toughness of model ice at different loading rates and notch depths, then the fracture toughness of model ice was calculated.

FRACTURE TOUGHNESS MEASUREMENTS

ASTM recommended formula

ASTM was used to calculate the ice fracture toughness of the model ice, and the calculation results were compared and analyzed. The ASTM fracture test standard is calculated as follows:

$$K_{IC} = \frac{P_Q S}{w h^{3/2}} f(\frac{a}{h}) \tag{1}$$

$$f(\frac{a}{h}) = \frac{3(\frac{a}{h})^{1/2}\left[1.99-(\frac{a}{h})(1-\frac{a}{h})(2.15-3.93\frac{a}{h}+2.7\frac{a^2}{h^2})\right]}{2(1+\frac{2a}{h})(1-\frac{a}{h})^{3/2}} \tag{2}$$

Where K_{IC} is fracture toughness; P_Q is critical load; S is the nominal span; h is the sample thickness; w is the sample width; a is the precast crack length. Because the material of model ice is brittle, there is no obvious subcritical expansion before fracture, the maximum load Pmax is the critical load P_Q of crack instability expansion at this time

In ASTM recommended formula has some assumptions need to be notation:

1. Using the maximum load force as the critical load;
2. Letting the effective crack length equal to the initial fabricated crack length;
3. Assuming that the specimen thickness is adequate;
4. Assuming that the crack is mathematically sharp;
5. Assuming that the material is homogeneous, isotropic, and linearly elastic.

Equivalent crack model

The equivalent fracture model is based on the load-deflection curve to calculate the fracture toughness. According to the model, the decrease of the stiffness of the three-point curved beam with notches in the nonlinear stage of the rising stage (also known as the "subcritical development" stage of the fracture) is completely caused by the development of the fracture process zone. This model introduces a virtual crack in the calculation, and the critical crack length of the virtual beam is a, while the real initial crack length of the actual beam is a_0.

Take a point (P_i, Q_i) from the linear elastic section of the load-deflection curve of the fracture test, and use this point to calculate the initial elastic modulus E:

$$Q_i = \frac{P_i}{4wQ_i}(\frac{S}{b})^3\left[1+\frac{5qS}{8P_i}+(\frac{h}{S})^2(2.70+1.35\frac{qS}{P_i})-0.84(\frac{h}{S})^3\right]+\frac{9P_i}{2tQ_i}(1+\frac{qS}{2P_i})(\frac{S}{b})^2 F_1(\alpha_0) \quad (3)$$

E is the initial elastic modulus, S, w and h are the span, height and thickness of the beam, respectively, and q is the deadweight per unit length of the beam. The function $F_1(\alpha_0)$ is as follows.

$$F_1(\alpha_0) = \int_0^{\alpha_0} xY(x)^2 dx \quad (4)$$

Where, $\alpha_0 = a_0 / b$, Y(x) is the geometric factor of the three-point bending beam, which is determined by the following equation:

$$Y(x=\alpha=\tfrac{a}{b}) = 1.93-3.07\alpha+14.53\alpha^2-25.11\alpha^3+25.8\alpha^4 \quad (5)$$

$$Y(x=\alpha=\tfrac{a}{b}) = \frac{1.99-\alpha(1-\alpha)(2.15-3.93\alpha+2.7\alpha^2)}{(1+2\alpha)(1-\alpha)^{3/2}} \quad (6)$$

In order to find the fracture toughness K_{IC}, the critical fracture length a_e needs to be found first. The ultimate load P_i and the corresponding deflection Q_i can be expressed by a_e as follows.

$$Q_i = \frac{P_i}{4wE}(\frac{S}{b})^3\left[1+\frac{5qS}{8P_i}+(\frac{h}{S})^2(2.70+1.35\frac{qS}{P_i})-0.84(\frac{h}{S})^3\right]+\frac{9P_i}{2tE}(1+\frac{qS}{2P_i})(\frac{S}{b})^2 F_1(\alpha_e) \quad (7)$$

Replacing α_0 with α_e in equation (2), the function $F_1(\alpha_e)$ becomes:

$$F_1(\alpha_e)=\int_0^{\alpha_e} xY(x)^2 dx \tag{8}$$

$F_1(\alpha_e)$ can be found by substituting the peak point (P_i, Q_i) of the load-displacement curve into equation (7). Combined with Equation (8) to find the upper limit of integration $\alpha_e = a_e / b$, the critical crack length α_e can be obtained. After the critical fracture length a_e is obtained, the fracture toughness K_{IC}^e is calculated as follows.

$$K_{IC}^e = 6YM_{MAX}\sqrt{a_e}/(tb^2) \tag{9}$$

Two parameter model

The two-parameter model uses the a_e calculated in Equivalent crack model to calculate the opening displacement of the crack:

$$CMOD_C = \frac{24P_i a_e}{whE}F_2(\frac{a_e}{b}) \tag{10}$$

$$F_2(\frac{a_e}{b}) = 0.76 - 2.28\frac{a_e}{b} + 3.87(\frac{a_e}{b})^2 - 2.04(\frac{a_e}{b})^3 + \frac{0.66}{(1-a_e/b)^2} \tag{11}$$

Opening displacement of crack tip:

$$CTOD_C = CMOD_C \cdot U(\frac{a_e}{b},\frac{a_0}{a_e}) \tag{12}$$

$$U(\frac{a_e}{b},\frac{a_0}{a_e}) = \left\{(1-\frac{a_0}{a_e})^2 + (-1.149\frac{a_e}{b}+1.081)[\frac{a_0}{a_c}-(\frac{a_0}{a_c})^2]\right\}^{1/2} \tag{13}$$

The critical instability fracture toughness determined by the two-parameter model can be calculated by the following equation:

$$K_{IC}^s = 3(P_c + 0.5W_b)\frac{S\sqrt{\pi a_e}F_3(\alpha_e)}{2wh^2} \tag{14}$$

Where, $W_b = W_s S / L$, W_s is the deadweight of the beam and L is the length of the beam. Is another geometric factor of a three-point curved beam and is equal to:

$$F_3(\alpha_e = \frac{a_e}{b}) = \frac{1.99 - \frac{a_e}{b}(1-\frac{a_e}{b})[2.15 - 3.93\frac{a_e}{b} + 2.7(\frac{a_e}{b})^2]}{\sqrt{\pi}(1+2\frac{a_e}{b})(1-\frac{a_e}{b})^{3/2}} \tag{15}$$

Different treatment methods were suitable for different test scenarios, and the ASTM recommended formula was chosen to calculate the fracture toughness of the model ice in this paper.

TEST SCHEME AND ICE SAMPLE TREATMEN

The experiments were performed in the Small Ice Model Basin at China Ship Scientific Research Center (CSSRC). The basin is 8 m long, 2 m wide and has a depth of 1 m (Fig.1). The model ice used in the tests was natural grown columnar grained model ice frozen from a sodium chloride solution. Seeding method was used, to create the initial ice layer. The freezing temperature was kept to -20°C. After reaching the target thickness, the strength was adjusted by rising the air temperature and warming the ice sheet. When the target strength was reached, the air temperature was kept constant and the test was started (Tian et al, 2021).

Figure1 Interior view of SIMB

The test utilized columnar grained model ice specimens and typical three-point bending experimental setup. A 30 kN hydraulic testing machine was employed for the loading process with internal displacement control. The apparent engineering strain rate ranges from 1 $\times 10^{-5}$ to 1 ×100 1/s at testing temperatures of -12°C. The loading mode and structure size of the three-point bending ice sample are shown in Fig. 2, where *S*, *h* and *w* are the ice sample span, ice thickness and width respectively, *a* is the initial crack length and *F* is the applied load.

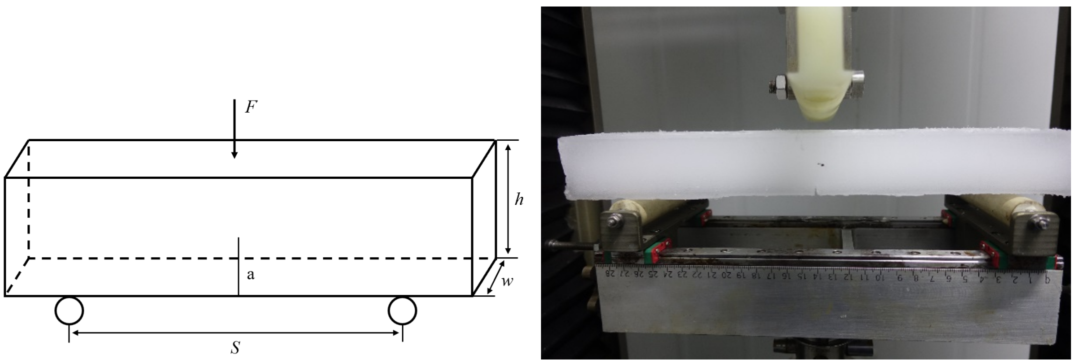


Figure 2. The loading mode and structure size of the three-point bending

In order to study the influence of loading rate and notch depth, the displacement loading rate was set as 114mm/min. 8.76mm/min; 2.79mm/min, and the notch depth was set to 0.2*h* and 0.4*h*. The test conditions are shown in Table 1.

Table 1. Test conditions and parameters

No.	Sample size	Notched	Loading rate	Times
1	S=240mm，w=80mm，h=40mm	0.2*h*	114mm/min	2
2		0.2*h*	8.76mm/min	2
3		0.2*h*	2.79mm/min	2
4		0.4*h*	114mm/min	2
5		0.4*h*	8.76mm/min	2
6		0.4*h*	2.79mm/min	2

Specific experimental steps are as follows:

(1) Before put the ice sample on hydraulic testing machine, its length, thickness and height should be measured first.

(2) When placing ice samples, it was necessary to check carefully, so that the central axis of the uniaxial compression ice sample and the axis of the hydraulic testing machine were in the same straight line, so as to ensure that the loading of the sample was uniform, to prevent the occurrence of eccentric loading, affecting the accuracy of the data.

(3) Then manually adjust the hydraulic testing machine beam down, so that the position of the head down was just in contact with the upper surface of the sample, begin the test.

(4) When the sample was completely destroyed, the hydraulic testing machine will save the obtained experimental data, repeat the above steps to start the next experiment.

The experimental process of the three-point bending fractured ice sample was the same as the above steps, but it should be noted that the prefabricated crack and the pressure head should be in a straight line, so that the force directly acts on the crack when loading. During the test, different loading rates were applied downward until bending failure of the ice sample occurred, and the force exerted on the ice sample at different times was recorded. During the test, every 2 samples were taken as a group to ensure the accuracy of the results. When the ice sample was damaged by bending, the bending test force reached the maximum value $P\text{max}$, and the data were recorded. The force curve and load-deflection curve at time were shown in Fig. 3.

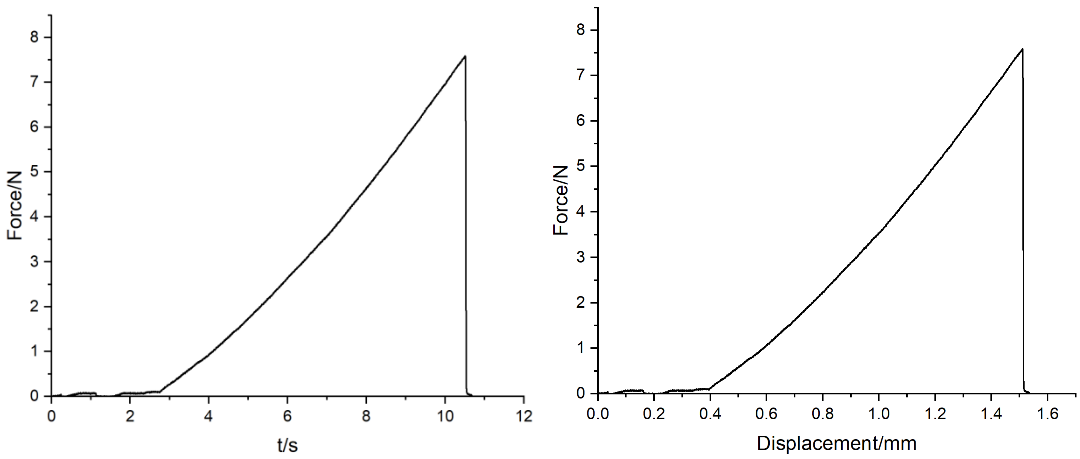


Figure 3. The force curve and load-deflection curve

TEST RESULTS AND ANALYSIS

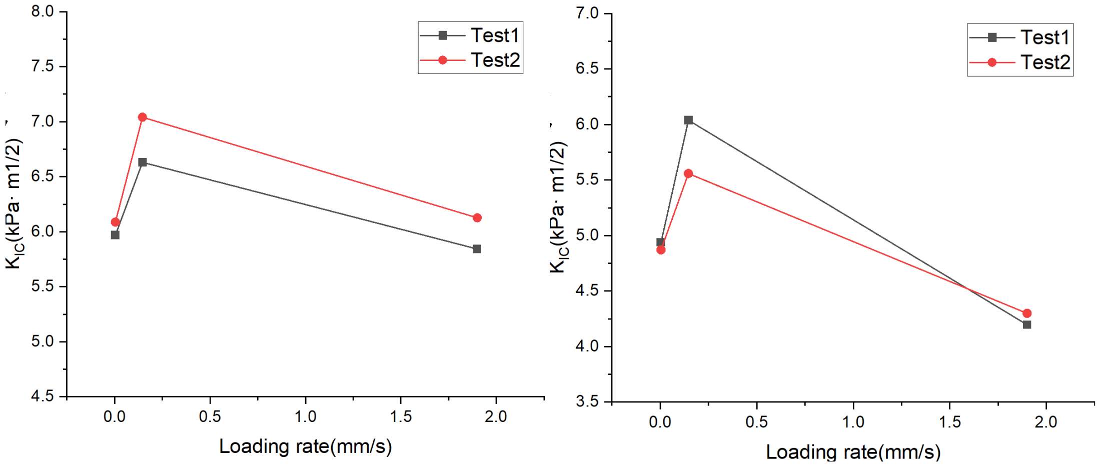
The ASTM recommended formula was used to calculate the ice fracture toughness of the model, and the calculation results are shown in the Table 2.

Table. 2 Fracture toughness calculation results

No.	Tempture (°C)	Sample size (mm)	Loading rate (mm/s)	Fracture toughness（kPa·m$^{1/2}$）	
				a/h=0.2	*a/h*=0.4
Test1	-1.5	*S*=240 *w*=80 *h*=40	1.9	4.20	5.84
Test2			1.9	4.30	6.12
Test3			0.146	6.04	6.63
Test4			0.146	5.56	7.04
Test5			0.045	4.93	5.96
Test6			0.045	4.87	6.09

EFFECT OF LOADING RATE

The relationship between ice fracture toughness and loading rate have always been the focus of domestic and foreign scholars. According to the research data, it can be obtained that the ice fracture toughness will change with the change of the loading rate, and generally K_{IC} will increase with the decrease of loading rate, because of the relaxation of stress at the tip crack and the influence of material creep. However, Nixon and Schulson research showed that this loading rate was not satisfied with the whole range of loading rates, but when the rate was higher than a critical value, the change of fracture toughness was not obvious, and when the loading rate was small to a certain extent, the state of plane stress would change to plane strain. In this paper, an experimental investigate on the effect of loading rate on fracture toughness was carried out for the CSSRC ice pool model ice (Fig.4). The experimental data shown that the fracture toughness of the model ice decreases gradually with the change of loading rate when the loading rate was greater than 0.146mm/s. However, when the loading rate was 0.045mm/s, the fracture toughness value was less than that when the loading rate is 0.146mm/s. It was inferred that the stress state of the ice sample changes in this range, from the plane stress state to the plane strain state, resulting in the change of fracture toughness value.



a/h=0.2 *a/h*=0.4

Figure 4 Change of fracture toughness at different loading rates

EFFECT OF *a/h*

In this paper, the average value of fracture toughness at different loading when *a/h* is 0.2 and 0.4 were counted, as shown in the table 3 and figure 5. The test data shown that the fracture toughness value at a/h is 0.2 and 0.4 had little deviation, and it can be considered that the fracture toughness was the same when *a/h* was different, which has no effect on the test results.

Table 3 Mean fracture toughness at different *a/h*

Loading rate (mm/s)	*a/h*=0.2	*a/h*=0.4	Deviation
1.900	4.24	5.98	1.74
0.146	5.79	6.83	1.04
0.045	4.91	6.03	1.12

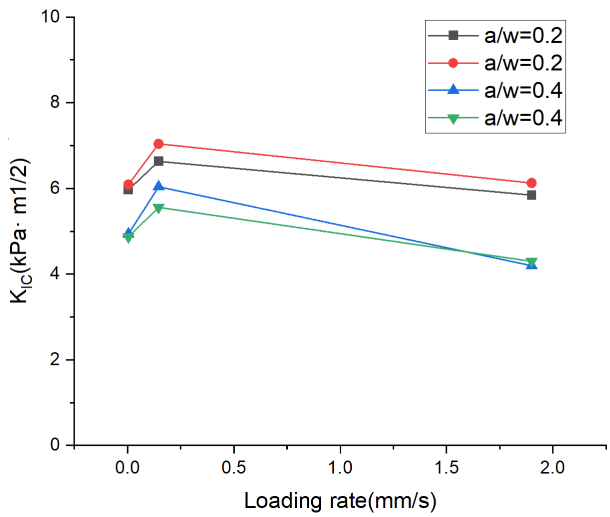


Figure 5 fracture toughness at different *a*/*h*

CONCLUSION

In this paper, taking the model ice in the small ice model basin in China Ship Scientific Research Center (CSSRC SIMB), using the ATSM empirical formula, the change of fracture toughness of model ice at different loading rates and notch depths were analyzed, and the fracture toughness of model ice was studied, and the following conclusions were obtained:

(1) The fracture toughness of the model ice changes with the change of loading rate. When the loading rate was greater than 0.146mm/s, the fracture toughness gradually decreases with the change of loading rate. However, when the loading rate was 0.045mm/s, the fracture toughness value was less than that when the loading rate is 0.146mm/s. It was inferred that in this range, the stress state of the ice sample changes from plane stress to plane strain.

(2) The ice pre-notched depth *a* of the model has no obvious effect on fracture toughness, and there was little difference between *a*/*h* at 0.2 and 0.4.

Through the study of the fracture toughness of the model ice, it can be obtained that the CSSRC ice tank model ice and polar sea ice have the same change trend in fracture toughness. In the later stage, the size of the ice sample, the loading direction and the incision direction will be further studied, and the fracture energy and brittleness index of the ice sample will be calculated to have an in-depth understanding of the mechanical characteristics of the model ice.

ACKNOWLEDGEMENTS

The study presented in this paper is part of a research project financially supported by the National Natural Science Foundation of China (Grant Nos. 52101331, 52192690, 52192694) and Ministry of Industry and Information Technology of China (No. [2021] 342).

REFERENCE

[1]. ASTM. Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials. Annual Book of ASTM Standards E399-81.

[2]. Dempsey J P，Defranco S J，Adamson R M，et al．1999，Scale effects on the in-situ tensile strength and fracture of ice，Part I:Large grained freshwater ice at Spray Lakes Reservoir，Alberta. International Journal of Fracture, 95: 325-345．

[3]. Dempsey J P. 1991, The Fracture Toughness of ice. Ice structure interaction, 109-144.

[4]. Defranco S J, Dempsey J P. 1994, Crack propagation and fracture resistance in saline ice. Journal of Glaciology. 40(136) : 451-462．

[5]. I.E. Gharamti, J.P. Dempsey , A. Polojärvi, J. Tuhkuri. 2021. Fracture energy of columnar freshwater ice: Influence of loading type, loading rate and size. Materialia. 20 (2021) 101188.

[6]. I.E. Gharamti, J.P. Dempsey , A. Polojärvi, J. Tuhkuri. 2021. Fracture of warm S2 columnar freshwater ice: size and rate effects. Acta Materialia 202 (2021) 22–34.

[7]. Gold, L W, Crack Formation in ice plates by thermal shock. Can. J. physics.41:1712-1728.

[8]. Griffith, A. A. 1921, The phenomena of rupture and flow in solids. Proceeding of the Transactions of the Royal Society, Vol. A221, pp.163-198.

[9]. JI Shunying, LIU Hongliang, XU Ning, etc. Experiments on sea ice fracture toughness in the Bohai Sea. ADVANCES IN WATER SCIENCE, 24:386-340. (in Chinese)

[10]. Kaplan M F．1961，Crack propagation and the fracture of concrete． Journal of the American Concrete Institute，58(5) : 591-610．

[11]. Nixon W A, Schulson E M．1987，A micromechanical view of the fracture toughness of ice. Journal de Physique，3(48) : 313-319．

[12]. Timco G W，2010， Weeks W F. A review of engineering properties of sea ice. Cold Regions Science and Technology, 60:107-129．

[13]. ZHANG Mingyuan, MENG Guanglin, YAN Decheng, et al. 1989, Plane strain fracture toughness KIC of sea ice. Oceanolgia et Limnologia Sinica, 20(4) : 338-342．(in Chinese)

[14]. ZHANG Xiaopeng, CHEN Kai，LI Feng，et al. 2010，Experimental study of the fracture toughness of natural freshwater ice. Journal of Glaciology and Geocryology，32(5) : 960-963. (in Chinese)

[15]. LIU Chun, CHEN Hong-niao, ZHAO Yan-bing, etc. Experimental Study on Fracture Properties of Concrete Based on Three Point Bending Tests. BULLETIN OF THE CHINESE CEＲAMIC SOCIETY, 35:4191-4211. (in Chinese)

[16]. Tian, Y., Ji, S. , Zhang, X. , Wang, Y. , & Wu, W. . 2018 , Experimental Analysis of Uniaxial Compressive Strength for Columnar Saline Model Ice. (in Chinese)

[17]. Yukui, T., Shaopeng, J., & Yinghui, W. 2021, Research on sea ice simulation and measurement in small ice model basin of CSSRC. Marine Environmental Science, 40 (2), 277-286. (in Chinese)