Summary of the Test Methods for Icing Strength of Freshwater and Seawater

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Abstract. Polar navigation ships, offshore platforms, and amphibious aircraft sometimes need to work in low temperature environments, which will inevitably form varying degrees of icing on the surface of structures such as cabin doors. In order to ensure their normal working conditions, it is advisable to choose reasonable anti-icing and deicing methods to prevent icing or effectively remove icing. Therefore, it is necessary to study the mechanical properties of ice to provide a reference for the selection of anti-deicing methods. This article summarizes the common methods for measuring the shear strength and tensile strength of ice, which can provide some guidance for the freezing strength test of fresh water and sea water.

1. Introduction

Polar navigation ships and offshore platforms need to work in low temperature environments in polar regions. Seawater splashing[1] is the main reason for icing. Frozen will bring different degrees of risk to the normal operation of these equipment. Decrease the strength of the main structure. Excessive icing quality may even cause damage. In addition, icing will make communication navigation antennas, life-saving facilities and ventilation equipment more prone to failure. An amphibious aircraft needs to take off and land on the water. When the ambient temperature is low or when flying at high altitudes, the water attached to the landing gear compartment and the fuselage will freeze and affect flight safety. For the above two cases, the hidden safety hazards can be eliminated by using the correct anti-icing and deicing methods. To this end, it is necessary to determine the shear and tensile strength of ice to provide a reasonable basis for the selection of anti-icing and deicing methods. In this paper, the common methods for measuring the shear strength and tensile strength of ice are summarized.

Ice has complex material properties. Its crystals exhibit anisotropy, and loading in different directions will show different strengths. The shear strength of ice is affected by many factors such as ice crystal structure, salinity, temperature, and loading direction, and it can show different modes of destruction such as buckling, stretching, extrusion, shearing, and bending[2]. Since there is no reliable and convenient method and related test standards to measure the shear strength of ice by realizing the pure shear state of ice in the experiment, the shear strength measurement of ice in most existing studies uses shear tests of metals or rocks, including single-sided shear without side restriction, single-sided shear with side restriction, and double-sided shear, etc., the tensile strength of ice is generally measured using the Brazilian test method. According to the Griffith strength criterion, the tensile strength of ice can be obtained through analytical algorithms.
2. Preparation of Ice Test Pieces
At present, the ice test pieces used for testing the mechanical properties of ice are mainly collected and processed manually from natural conditions, and the preparation methods are various. Zhang Hongbiao[3] and others cut the collected ice billet through a cutting machine, and then turned it into a column shape using a machine tool and processed a loading platform for measuring tensile strength. In addition, you can use tools such as a saw to process ice into cubes to measure shear strength. See Figure 1[3].

3. Test Method for Mechanical Properties of Ice
3.1. Single-sided Shear Without Side Restriction
The single-sided shear without side restriction is an experimental method to measure the shear strength of ice. Jia Qing[4] and others used the unconfined single-sided shear method to study the shear strength of fresh water ice in the reservoir. The experiment was carried out in a low temperature environment and the experimental device is an electric hydraulic ice pressure tester. During the test, keep the shear plane of the test piece coincide with the axis of the sensor and the geometric axis of the center of the tester platen to ensure the uniformity and symmetry of the load. See Figure 2[5].

Due to the differences in the icing environment, the types of ice crystals will also be different, there are two types of ice test pieces, columnar ice and granular ice. Columnar ice crystals grow vertically downward, and the crystal extension direction is perpendicular to the horizontal plane. Its crystal structure determines the anisotropy of mechanical properties. The mechanical properties of granular ice are basically isotropic. For two different types of ice samples, you can take different loading methods to load. See Figure 3 and 4[4].

Figure 1. Processing of ice test pieces[3]

Figure 2. Electro-hydraulic ice pressure testing machine[5]
The strength of single-sided shear without side limitation is the ratio of the ultimate shear force to the shear area, which can be calculated using the following formula\[5\]:

\[\sigma_s = \frac{P_{\text{max}}}{bh}\] (1)

In the formula: \(P_{\text{max}}\) is the maximum load for breaking the ice sample, \(b\) is the width of the sheared surface of the sample, and \(h\) is the height of the sheared surface of the sample.

Figure 3. Granular ice loading direction  Figure 4. Columnar ice loading direction

3.2. Single-sided Shear With Side Restriction
Because the tensile strength of ice is low, the smaller tensile stress in the test will cause larger experimental errors. Therefore, it is necessary to avoid the generation of tensile stress in the test. Compared with unconfined single-sided shear, a limit plate is added on the side parallel to the sheared surface to limit the deflection of the ice sample to the side under the load. This method can get better results of pure shear test. The method of single-sided shear with side restriction test can analyze the relationship between the shear force and the lateral force, and obtain the pure shear strength. Ji Shunying and Li Zhijun\[6\] carried out sea ice shear strength experiments using this method, and analyzed the influencing factors of sea ice shear strength. It was pointed out that temperature, brine volume and shear rate will affect the sea ice shear strength. The sea ice shear strength in the test can be calculated using formula (1). See Figure 5.

Figure 5. Schematic diagram of single-sided shear with side restriction
3.3. Double-sided Shear

The difference between double-sided shearing and single-sided shearing is that it has two shearing surfaces. This method is more convenient to implement, but it is easy to generate bending tensile stress on the shearing surface. Butkovich[7] conducted double-sided shear tests on sea ice, Zhang Mingyuan[8][9] and others carried out double-sided shear experiments of sea ice and river ice at different temperatures and different loading rates, and studied the relationship between ice temperature and deformation rate and ice shear strength. The shear strength of ice can be calculated from the experimentally recorded load-time curve:

$$\tau = \frac{P}{s}$$

In the formula: $P$ is the load when the sample is broken, $s$ is the shear area when the sample is broken. See Figure 6.

![Figure 6. Schematic illustration of double-sided shear](image)

3.4. Test Method for Tensile Strength

For the testing of ice tensile strength, the Brazilian test method is currently commonly used. Wang Qizhi[10] and others proposed the platform Brazil disc test method, placing the processed disc-shaped sample between the pressure plates of the press, and the platform of the sample was in contact with the upper and lower pressure plates of the press, respectively. In this way, the concentrated force load is changed to uniform load force load. When the loading angle corresponding to the platform satisfies $2\alpha \geq 20^\circ$, the central cracking condition can be guaranteed according to the Griffith strength criterion, so the sample can be considered to be cracking failure. The tensile strength formula[11] determined by the platform disc sample is:

$$\sigma_t = k \frac{2P}{\pi Dt}$$

In the formula: $P_c$ is the critical load, the maximum load at the end of the elastic deformation in the test; $D$ is the diameter; $t$ is the thickness, and $k$ is the coefficient related to the sample loading angle $\alpha$, which can be approximated by the following formula:

$$k = \left(\frac{2\cos^2\alpha + \cos\alpha + \sin\alpha/\alpha}{8\cos\alpha + \sin\alpha/\alpha}\right)^2$$

In the formula: $\alpha$ is the loading angle. In this way, based on the measured diameter, thickness, and experimental critical load data, the tensile strength of ice can be calculated. See Figure 7.
In addition, Wang Qizhi and others studied the validity of the test. By analyzing the mechanism of cracks on the ice sample during the experiment, an effective platform Brazil test load-displacement curve was obtained, which played a guiding role in subsequent experiments. To ensure that ice is brittle, the strain rate should be controlled in the range of $(10^{-5} \sim 10^{-1}) \text{s}^{-1}$. See Figure 8[10]. Chen Xiaodong and others studied the effects of loading rate, sample thickness and temperature, and porosity[12] on the experimental results, and found that the porosity has the most significant effect.

4. Conclusion
At present, the development and utilization of water resources continue to develop. The measurement of the shear strength and tensile strength of seawater ice and freshwater ice is an important part of studying the mechanical properties of ice. The research results of ice mechanical properties can be applied to the selection of anti-icing and deicing methods, design and construction of water conservancy projects and utilization of water resources. Among them, the single-sided shear with side restriction can obtain better pure shear test results, while the Brazilian test method is easier to
implement than direct stretching, and it shows strong advantages for both static and dynamic tests. This article summarizes the current common methods of ice shear and tensile experiments to provide convenience for future research work.

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