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Comparative Experiments on Various Adfreeze Bond Strength Tests between Ice and Materials

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Abstract

This paper summarizes systematic experiments on the adfreeze bond strength between sea ice and construction materials used for offshore structures, such as steel and concrete, as well as various coating materials.

As a result of comparing test methods to determine the adfreeze bond strength between ice and the materials of structures, very little difference was observed among these methods. We also confirmed that the adfreeze bond strength depends more on the coarseness of the surface of construction materials than on the free surface energy on the surface.

1. Introduction

When ice sheets adfreeze to a structure in frozen sea waters, vertical ice forces are exerted on the structure due to fluctuations in the water level. Push-in forces act on the structure upward when the water level rises and act downward when it falls. These vertical ice forces have pulled out and buckled piles of piers.

To calculate the vertical ice forces on a pile structure generated by changes in the water level when ice sheets adfreeze to a structure, the following parameters have to be used: the diameter of the pile, the thickness of the ice sheet, the elastic constant, Poisson's ratio, the bending strength, the changes in the water

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level, and the adfreeze bond strength between the ice sheet and the surface material of the structure. The adfreeze bond strength is an especially important parameter to determine vertical ice forces. For instance, when the adfreeze bond strength between an ice sheet and the surface of a structure is high, adfreeze bond failure does not take place at the interface between the ice sheet and the surface, but bending failure occurs on the ice sheet (Figure 1 (a)). Also, when the adfreeze bond strength between an ice sheet and the surface of the structure is low, adfreeze bond failure occurs at the interface between the ice sheet and the structure (Figure 1 (b)). These two instances prove that when the ice sheet adfreezes to the structure and the water level is fluctuating, the vertical ice forces exerted on the structure are greatly affected by the adfreeze bond strength.

This paper summarizes our past experimental results of adfreeze bond strength tests between ice and structural materials to evaluate those tests and to analyze factors related to the adfreeze bond strength.

Figure 1 (a): Bending failure of an ice sheet

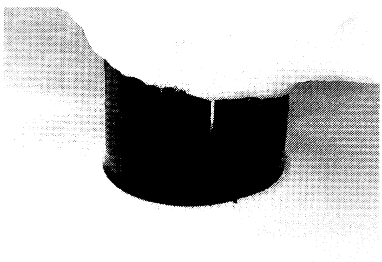

Figure 1 (b): Adfreeze bond failure at the interface between an ice sheet and a structure

2. Adfreeze Bond Strength Tests Between Ice and Structure Materials

(1) Test Methods

Figures 2 (a) and (b) show that with an ice sheet adfreezing to the surface of a structure, failure can be caused by external forces. Figure 2 (a) shows that not only the free surface energy between the sea ice and the structure material, but also the shear strength of the ice and the surface roughness of the materials, affect the adfreeze bond strength. Figure 2 (b) shows that the area of contact relevant to the free surface energy and the surface roughness of the material influences the adfreeze bond strength. However, when an ice sheet adfreezes to an offshore structure, the possible external forces in general are vertical

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forces acting along the surface of structure created by fluctuations in the water level or horizontal forces of the adfreezing ice sheet acting on the surface of the structure driven by wind and waves. Both types fall into the category shown in Figure 2 (a). It is extremely rare for the forms of failure shown in Figure 2 (b) to occur to sea ice adfreezing to an offshore structure.

Therefore, we assumed Figure 2 (a) as a typical form of failure to measure the adfreeze bond strength by the following four tests, and we evaluated the accuracy of each test. Figure 3 demonstrates the concept of each test.

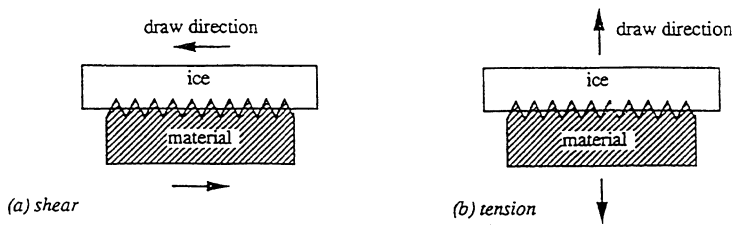

Figure 2: Forms of failure of an ice sheet adfreezing to a structure

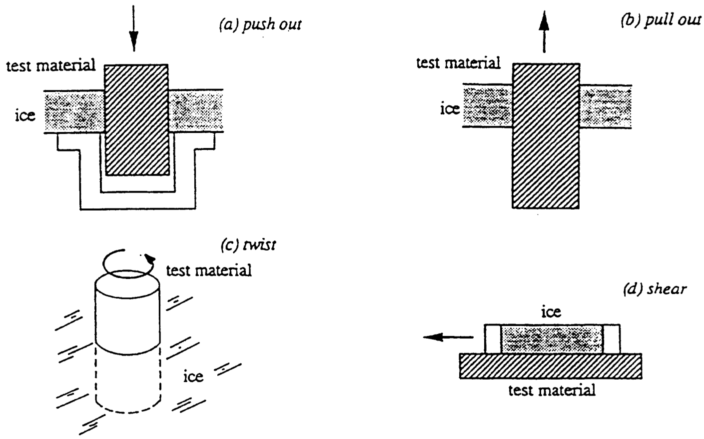

Figure 3: Conceptual figure of adreeze bond strength test

1) Push-out test

When the ice sheet adfreezing around a test pile reached a certain thickness, the ice sheet was cut and shaped so that the thickness of the ice round the test pile was uniform and the pile was perpendicular to the ice sheet. The specimen was turned upside down for the smooth upper surface to touch a steel box. Then a steel cap was placed on the specimen, and the specimen was enclosed in the steel box. The upper surface of the specimen was pressed by a hydraulic jack, and the ice sheet adfreezing to the pile was pushed out, to measure the

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adfreeze bond strength. The adfreeze bond strength was measured by a load cell connected to the steel cap. The rates of loading and push-out were changed arbitrarily by adjusting the hydraulic pump connected to the jack (Figure 4).

The adfreeze bond strength can be calculated by equation (1):

$$\tau_B = \frac{P}{\pi \phi h} \qquad (1)$$

where
τ_B: adfreeze bond strength
P: push-out force
ϕ: diameter of the test pile
h: ice thickness

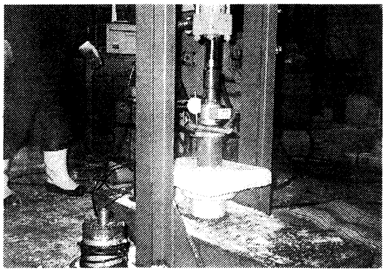

Figure 4: Push-out test device

2) Pull-out test

When the ice sheet adfreezing around the test pile reached a certain thickness, the pull-out test device was placed on the test pile, and a wire extending from the pile was connected to the load cell to pull out the pile by a hydraulic jack (Figure 5).

The adfreeze bond strength can be calculated by equation (2):

$$\tau_B = \frac{P}{\pi \phi h} \qquad (2)$$

where
P: pull-out force

3) Twist test

An ice sheet with a specified thickness adfreezing to the test pile with a square hole installed on top of the pile was cut out as a rectangular specimen. The four corners of the cut-out specimen were fixed by a steel frame, and a steel lever arm was set on the hole to horizontally rotate the pile to measure the adfreeze bond strength (Figure 6).

The adfreeze bond strength can be calculated by equation (4):

$$\tau_B \cdot \pi \phi h \cdot \phi / 2 = P'' \cdot l \qquad (3)$$
$$\tau_B = 2P'' \cdot l / \pi \phi^2 h \qquad (4)$$

where
P": rotation force
l: length of the steel lever arm

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4) Shear test

This test was to mainly measure the adfreeze bond strength between the ice and the material surface generated by free surface energy. Figure 7 shows the test device used to measure the adfreeze bond strength. With the ice inside a mold adfreezing to the steel plate, a collar was put on the mold, and the collar and a load cell were joined by a connecting bar. During the experiment, the collar was pulled by a screw jack through the connecting bar to shear the ice. The shear force, which is regarded as the adfreeze bond strength, was measured by the load cell.

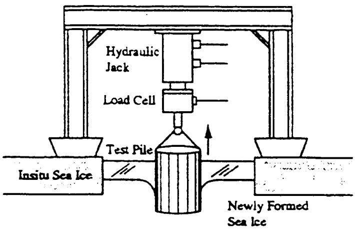

Figure 5: Pull-out test device

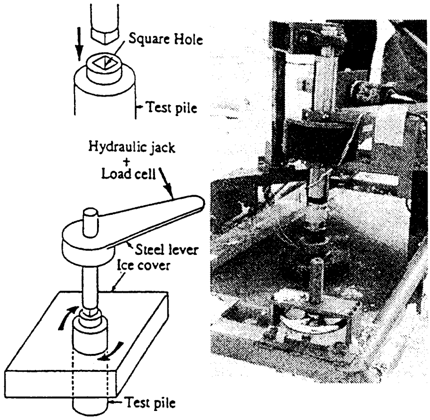

Figure 6: Twist test device

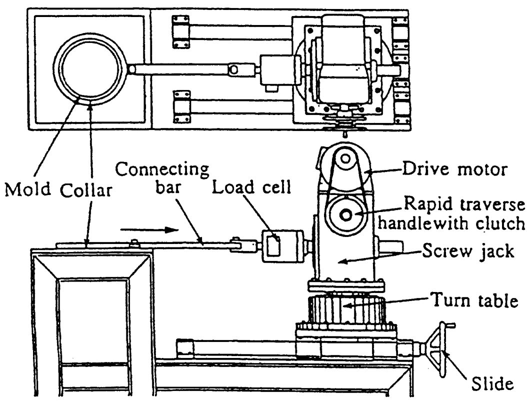

Figure 7: Shear test device

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The adfreeze bond strength can be calculated by equation (5):

$$\tau_B = \frac{4P}{\pi\phi'^2} \qquad (5)$$

where
P: force exerted on the load cell at the moment of adfreeze bond failure
ϕ': inside diameter of the mold

In experiments on the adfreeze bond strength of ice, the rates of push-out and loading should not be dismissed because ice is a visco-elastic body. Nakazawa et al. (1988) made experiments on the relationships between the adfreeze bond strength and the rates of push-out and loading of uncoated steel piles. The adfreeze bond strength is described by a moderate curve with a peak, as the rates of push-out and loading increased. However, the adfreeze bond strength was not greatly affected by the rate of push-out or the rate of loading. This result agrees well with that of the shear strength test on sea ice by Saeki et al. (1985). Thus, we can conclude that the rate of push-out or the rate of loading during our tests have no major effects on the adfreeze bond strength. Furthermore, experimental data of the relationship between the adfreeze bond strength and the ice thickness showed some deviations, but the adfreeze bond strength increased with increase in ice thickness and was constant when the ice thickness exceeded 8 cm (Nakazawa et al., 1988).

(2) Effects of the test methods on the adfreeze bond strength

1) Comparison of the push-out test, the pull-out test, and the twist test
We compared the adfreeze bond strength of the three tests (Figures 3 (a), (b), and (c)).

The test piles used was uncoated and rustless steel piles. The diameters (ϕ) of the pile were 1) 3, 5, 10, and 15 cm for the push-out test; 2) 3, 10, 15, 27, and 41 cm for the pull-out test; and 3) 5, 10, 15, 27, and 41 cm for the twist test.

Figure 8 shows the relationship between the dimensionless circumference of the cross-section of the test pile (the circumference of the test pile, $\pi\phi$, divided by the mean diameter of grains, D_{gr}) and τ_B. The D_{gr} is a mean diameter of a grain when a grain's area is calculated in terms of a circular area. The D_{gr} of the ice sheets used in the experiments was 0.8 cm, and the experimental ice temperature was -1.7 °C.

Figure 8 shows that although the adfreeze bond strength of the grains with an identical diameter was a little dispersed, it was almost constant regardless of the test method. This was also true for piles with any diameter. Thus, we

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can conclude that the difference between the above three test methods has little effect on the adfreeze bond strength. In addition, the adfreeze bond strength decreased as the diameter of the pile increased, and was constant when $\pi\phi/D_{gr} \geqq 80$.

2) Comparison between the push-out test and the shear test

We compared the adfreeze bond strength of the push-out test and the shear test (Figures 3 (a) and (d)). The test pile of the push-out test was a cylindrical titanium pile with a diameter of 5 cm. Specimens for the push-out test have to be in the water for 3-4 days, but those for the shear test can be made in only a couple of hours. Since the degree of corrosion is likely to be affected by the time the specimen is exposed to water, titanium was chosen for its high corrosion-resistance.

Figure 9 shows the results of the push-out test and the shear test by the relationship between the dimensionless circumference of the cross-section of the test pile and the adfreeze bond strength. This propensity of the curve is identical with the experimental results of the above three tests. The behavior of the curve representing the experimental values shows that the adfreeze bond strength decreased as the diameter of the pile increased. Also, the experimental values of these two tests were closely distributed along the curve. The adfreeze bond strength produced by the push-out test was not very different from the adfreeze bond strength by the shear test.

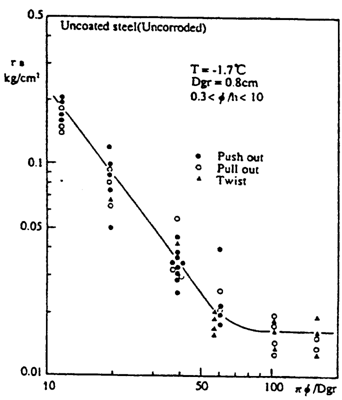

Figure 8: Relationships between the steel pile diameter and the adfreeze bond strength from the three tests

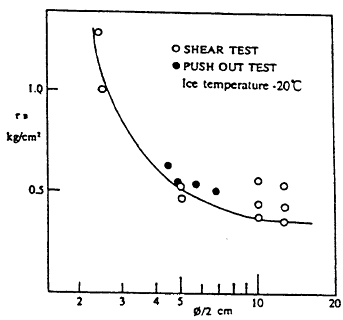

Figure 9: Relationships between the titanium pile diameter and the adfreeze bond strength from the two tests

According to these comparisons, the adfreeze bond strength of the four tests was nearly the same, so we can use any of the four at our convenience. Besides, the adfreeze bond strength tended to be greatly dependent on the

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diameter of the pile, in other words, the area of ice adfreezing to the structure. The adfreeze bond strength decreased as the diameter of the test pile increased and was constant when the diameter exceeded 20-25 cm.

3. Factors Related to the Adfreeze Bond Strength

(1) Effects of materials on the adfreeze bond strength

Since various strengths of ice are largely influenced by ice temperature in general, so should the adfreeze bond strength be affected by the ice temperature. Figure 10 demonstrates the relationships between ice temperature and the adfreeze bond strength of the following materials: concrete, low-density polyethylene (LDPE), uncoated steel (uncorroded), and coated steel (INERTA 160). The figure clearly shows that as the ice temperature decreases, the adfreeze bond strength of all the above materials increases. The adfreeze bond strength of uncoated steel and concrete, whose surface is relatively rough, increases steeply with a decrease in the ice temperature. On the other hand, the adfreeze bond strength of LDPE and coated steel, whose surface is smooth, increases moderately. The unevenness of the adfreeze bond strength of concrete at the same temperature seems to be caused by surface roughness. This is proven by the inconsistent measurements of the coefficients of static friction between an ice sheet and uncoated steel, between an ice sheet and coated steel, and between an ice sheet and concrete. Therefore, when the area of the material is somewhat large, the adfreeze bond strength is affected by ice temperature, and it is also influenced not by the material itself, but by the physical condition of the material surface.

(2) Effects of surface roughness on the adfreeze bond strength

Figure 11 shows the relationship between the adfreeze bond strength at -5 °C and the surface roughness of various materials. The surface roughness was measured by a high-accuracy surface roughness meter, and the mean value of the measured values was set at 10. The surface roughness and the adfreeze bond strength were closely correlated. The adfreeze bond strength increased sharply when the surface roughness increased and decreased when the surface roughness decreased. The figure obviously shows that the adfreeze bond strength was almost constant regardless of the surface roughness when the surface roughness was below 20 μ. The cause appears to be that factors other than surface roughness affect the adfreeze bond strength when the surface was smooth.

Murase and Nanishi (1985) experimented on the free surface energy and adfreeze bond strength of high polymer compounds. They reported that the

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adfreeze bond strength increases with an increase in free surface energy of the material and that the adfreeze bond strength between high polymer materials and fresh water ice have a linear relation to the free surface energy of a material surface. The experimental results of only high polymer compounds, whose surface is smooth, indicate a close correlation between free surface energy and adfreeze bond strength. Therefore, despite the absence of measurements of the surface roughness of materials, we can conclude that the adfreeze bond strength is affected by the free surface energy when the surface roughness is small.

Forms of failure caused by sea ice adfreezing to a structure can be roughly classified into two: 1) adfreeze bond failure of sea ice at dents on a structure with a rough surface; and 2) exfoliation failure on a smooth surface when the shear force exceeds the free surface energy of the material surface.

Our experimental results prove that the adfreeze bond strength is determined by the surface roughness when the roughness is larger than 20 μ and by the free surface energy of the material surface when the roughness is smaller than 20 μ. However, the adfreeze bond strength of materials used for offshore structures is in general determined by the roughness of the material surface.

4. Conclusions

1) The adfreeze bond strength of four tests (push-out, pull-out, twist, and shear tests) was almost equal, although with a little dispersion, so we can use any of the four at our convenience.

2) The adfreeze bond strength is prone to be greatly dependent on the diameter of a pile, i.e. the area of ice adfreezing to the structure. It decreases as the diameter of the test pile increases and is nearly constant when the diameter exceeds 20-25 cm.

3) Ice temperature affects the adfreeze bond strength, which increases as the temperature decreases. However, the adfreeze bond strength is influenced by the roughness of the material surface, not by the material itself.

4) The forms of failure of sea ice adfreezing to a structure can be roughly classified into two cases. One case is adfreeze bond failure of the sea ice at the dents on a structure with a rough surface. The other is exfoliation failure on a smooth surface when the shear force exceeds the free surface energy of the material surface.

5) Our experimental results prove that the adfreeze bond strength is determined by the surface roughness when the roughness is larger than 20 μ and by the

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free surface energy of the material surface when the roughness is smaller than 20 μ.

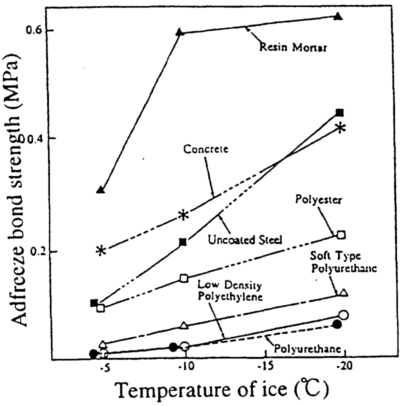

Figure 10: Relationships between the ice temperature and the adfreeze bond strength of various materials

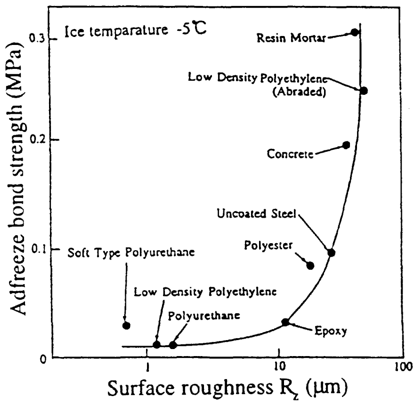

Figure 11: Relationships between the surface roughness and the adfreeze bond strength of various materials

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