Experimental study of Nominal Normal Bond strength between Conductor cable and Ice

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Abstract— **The deicing-induced jumping frequently occurred in conductor cables is likely to cause collision, wear, short-circuit between wires, and even tower collapse. It is found that the deicing is strongly related to the cohesive strength of the ice deposit, and the conductor cable-ice bond strength. However, previous studies are mainly concerned with the adhesive strength in the shear direction. The bond strength in the normal direction, between the conductor cable and the ice, are not well explored. This paper presents an innovative purpose-built testing apparatus, which is capable of measuring the conductor cable-ice bond strength in the normal direction. To account for the influences of both the ice temperature and the ice wrap angle, a total of 32 cases, associated with 832 specimens, were investigated in the laboratory tests, thereby the corresponding nominal normal bond strength are obtained. It is found that the nominal normal bond strength increases with the decrease of the ice wrap angle, as well as the decrease of the ice temperature.**

Keywords— ***ice-coated cable; laboratory test; ice temperature; ice wrap angle; nominal normal bond strength***

I. Introduction

The super-cooled water droplets in the air, continually colliding the cables, would result in the ice-coated conductor cables that are prone to deicing-induced jumping of large amplitude [1-2] due to the natural wind force, rising temperature, and ambient vibration. Consequently, it is likely to cause the collision, wear, short-circuit between wires, and even tower collapse. In both the numerical and experimental approaches for the investigation into the deicing-induced jumping, the ice-shedding is commonly simulated by removing the equivalent ice loading dynamically. However, the deicing mechanism was not well considered in these simulations, which results in the paucity of considering the interaction of the ice-shedding with the cable's vibration. As of now, the study of the mechanical mechanism behind the deicing remains inadequate, and it is necessary to perform a further study to gain insight into it.

Many studies were conducted to attain the mechanical properties of the ice. For illustration, Druez et al. [3] investigated the elastic modulus, tensile strength, compressive strength of the ice formed in the wind tunnel. Guo and Meng [4] studied the influence of the ice temperature and the loading rate on the compressive strength of the ice, via the cylindrical specimens. Kermani et al. [5] attained the bending strength of the accumulated atmospheric ice body experimentally. It is found that the bending strength of ice increases with decrease of the ice temperature at a low loading rate. It is worth noting that Schwarz et al. [6] summarized the testing methods on the ice's mechanical properties, and provide recommendations for conducting a standard test.

Nevertheless, for the ice-shedding, we are more concerned with the bond strength lying in the interfaces of the ice and the conductor cable. It is found that most of the previous relevant studies focused on the adhesive strength in the shear direction. For example, Jellinek [7] conducted shear tests on the ice to the stainless-steel disk. Druez et al. [8] investigated the effects of the roughness on the shear strength of the ice, focusing on the ice-covered conductor cables. With regard to the shear testing apparatus, Chu and Scavuzzo [9] developed a quasi-static experimental technique to determine the adhesive shear strength of impact ices formed inside an icing wind tunnel. Lou et al. [10] designed and fabricated a shearing test device to investigate into the fracture process along the ice interfaces.

This paper aims to investigate into the normal bond strength between the conductor cable and the ice, and it is organized as follows. The second section shows the apparatuses especially designed for the normal bond strength test, along with the experimental setup and the corresponding test protocol. The third section presents the experimental results, mainly the nominal normal bond strength varied with the ice temperature and the ice wrap angle, and the discussion was made. The conclusions are summarized in the fourth section.

II. EXPERIMENTAL PROGRAM

A. Experimental setup and apparatuses

The testing device mainly incorporates the ice-cable mold, the test table fixed to the base, and the loading equipment. The ice-cable mold, as shown in Fig. 1, is made of stainless steel, and is capable of providing the reaction force while the cable is under an elevating load. The ice-cable mold consists of two side plates, one bottom plate, and two end plates with a semi-circular groove. Usually, the radius of the semi-circular groove is a little bigger than the radius of the conductor cable.

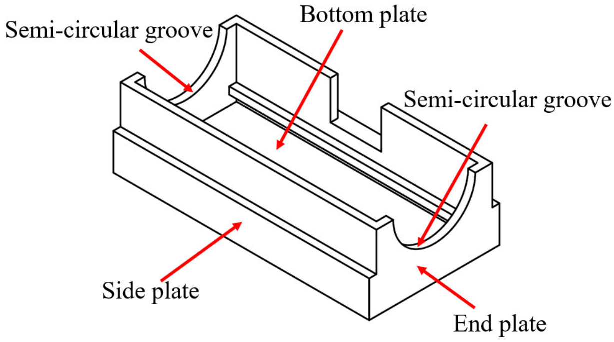

Fig. 1 Ice-cable mold

The conductor cables employed fo the tests are JL/G3A-

630/45 with a diameter of 33.6 mm, and each of them in the test is 200 mm long, as shown in Fig. 2. The intermediate part (with length of 100 mm) of the cable is ice-coated. And the two ends of the conductor cable are bounded by using the steel rings. To prevent the water seepage from the ice-cable mold, the ends of the cable are sealed with waterproof plasticine, sine it is hard to make the conductor cable completely fitted with the semi-circular groove due to the cable's rough surface. Note that the additional adhesive force due to the sealing would be subtracted in processing the test data. Moreover, the waterproof plasticine is also used to fill the gap between the conductor cable and the semi-circular groove, while the conductor cable diameter is smaller than the diameter of the semi-circular groove. Note that for the conductor cables with a larger diameter, the radius of the groove of the end plate should be correspondingly enlarged. In addition, the surface of the conductor cable needs to be cleaned before forming the specimen of the ice-coated cable.

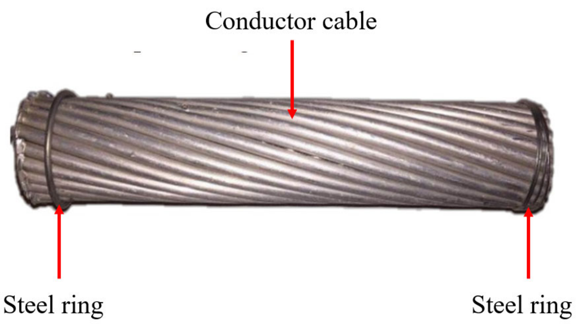

Fig. 2 JL/G3A-630/45 conductor cable

Fig. 3 shows the test table, which would be fixed to the base via the bolt holes on its bottom plate in the test. This design would efficiently facilitate the test, thereby reducing the error caused by the ambient temperature.

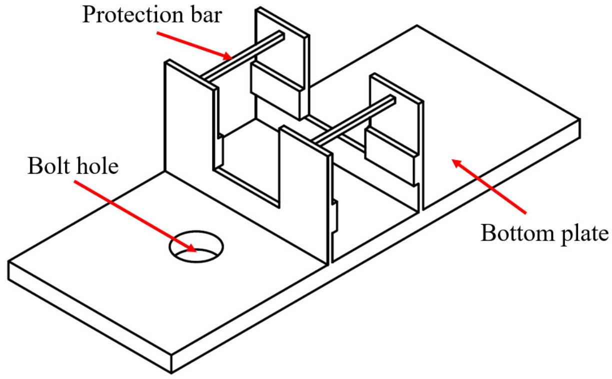

Fig. 3 Test table

Fig. 4 shows the experimental setup. In the tests, the ice-cable mold with the ice-coated cable specimen in it would be fed into the test table directly, as shown in Fig. 4. The loading protocol is realized by elevating the conductor cable via the steel rings at the two ends of the cable. The loading would not be terminated till the ice is complete de-bonded from the cable.

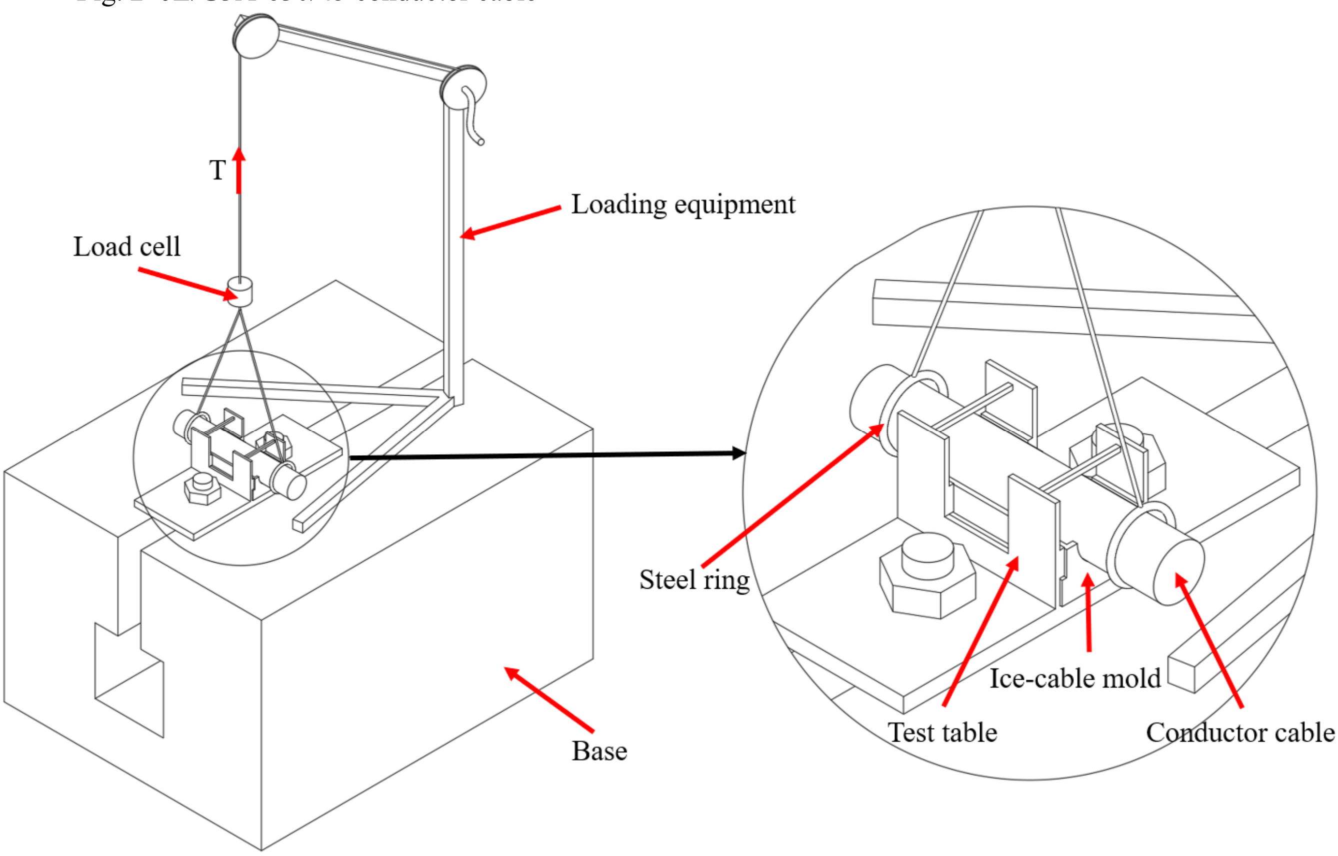

Fig. 4 Experimental setup

B. Specimens and test cases

As shown in Fig. 5, define the wrap angle, α, as the central angle of the contact area of the cable and the ice. In this paper, four wrap angles were adopted, namely 30°, 60°, 90°, and 120°.

The ice-coated region (area of the contact face) was controlled by manually adjusting the level of the liquid. The temperatures set in the refrigerator (freezing temperature), at which the water in the mold froze, were -3℃, -5℃, -7℃ and -9℃. Each specimen was put in the refrigerator for at least 24 hours. In addition, to simulate the ice melting due to the rising temperature, selected specimens were exposed to the environment with a temperature of 1℃, and the corresponding time of exposure to the environment is one hour.

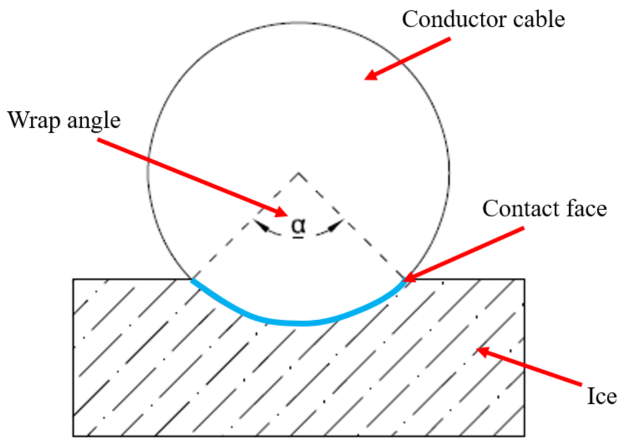

Fig. 5 Parameters of ice-coated cable

Table 1 lists all the 32 cases considered in the tests, along with the corresponding number of the repetitive specimens tested. A total of 832 specimens were tested. The large number of the repetitive tests adopted in each test case is to reduce the data scatter as much as possible. The data scatter is mainly due to the inherent stochastic nature of ice, and is usually found in the test for ice.

TABLE I. NUMBER OF SPECIMENS

Temperature (℃)		**Wrap angle (°)**			
24h	**1h**	**30°**	**60°**	**90°**	**120°**
-3℃	/	40	40	40	40
-5℃	/	40	40	40	40
-7℃	/	40	40	40	40
-9℃	/	40	40	40	40
-3℃	1℃	12	12	12	12
-5℃	1℃	12	12	12	12
-7℃	1℃	12	12	12	12
-9℃	1℃	12	12	12	12

III. RESULTS

A. Failure mode

Fig. 6 shows a typical time history of the loading imposed on the cable. In the figure, the peak load corresponds to the separation of the ice and the conductor cable, after which the load on the specimen rapidly drops to zero. The results show that the failure mode of ice is a kind of brittle failure. Figs. 7 and 8 show the contact faces of the ice and the cable after the deicing respectively. It is found that the contact surfaces are relatively clean, which implies that the adhesive force within the force is greater than the bond strength in this case. The white frost on the conductor cable's surface is largely attributed to the condensation of the moisture in the air on the conductor cable's surface.

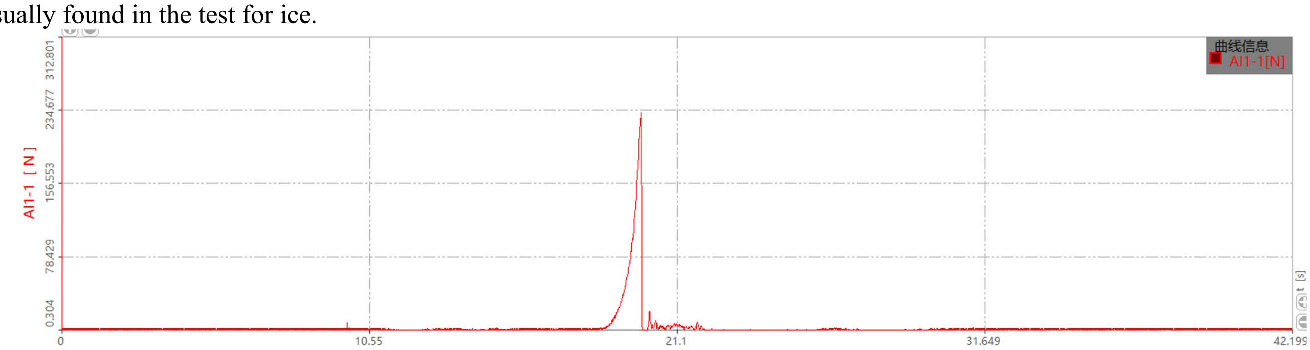

Fig. 6 Time history of loading

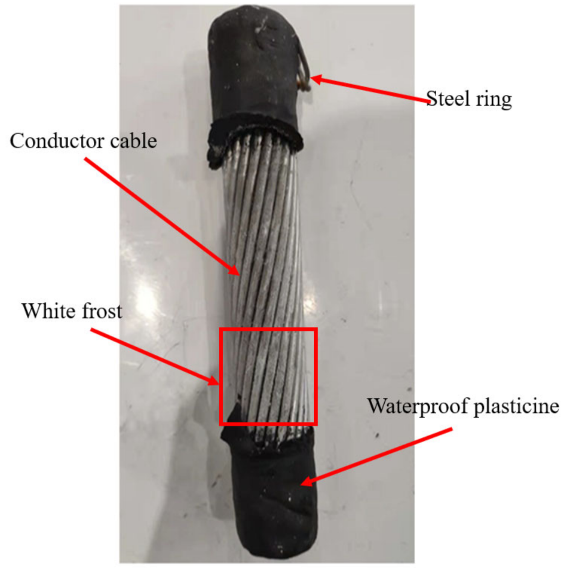

Fig. 7 Contact surface of ice after de-bonding

B. *Nominal normal bond strength*

Commonly, in the analysis of the deicing-induced jumping, we are mainly concerned with the unidirectional ice-shedding. Therefore, to focus on the unidirectional de-bonding force in the global coordinate system, the nominal normal bond strength, f, is defined herein, which is actually the average strength in the vertical direction and can be computed by

$$f = \frac{2\sum_{i=1}^{n} F_i}{n\alpha D l} \tag{1}$$

where, F_i is the de-bonding force (peak load in Fig. 6) of the ith specimen, n is the number of the specimens, α is the wrap angle, D is the diameter of the conductor cable, and $l = 100$ mm is the length of the ice-coated part of the cable. Table 2 lists the nominal normal bond strength of the specimens.

TABLE II. NOMINAL NORMAL BOND STRENGTH

Temperature (℃)		Wrap angle (°)			
24h	**1h**	**30°**	**60°**	**90°**	**120°**
-3℃	/	0.181	0.143	0.137	0.130
-5℃	/	0.298	0.198	0.173	0.156
-7℃	/	0.374	0.214	0.184	0.170
-9℃	/	0.413	0.238	0.210	0.180
-3℃	1℃	0.168	0.121	0.096	0.101
-5℃	1℃	0.188	0.167	0.128	0.156
-7℃	1℃	0.205	0.133	0.131	0.154
-9℃	1℃	0.197	0.160	0.127	0.159

Figure 9 shows the three-dimensional (3D) contour map of the nominal normal bond strength, without consideration of the melting. It is found that the nominal normal bond strength increases with the decrease of the temperature, provided the same wrap angle. Moreover, with the increase of the wrap angle, the nominal normal bond strength decreases, given the same temperature. It is also found that the nominal normal bond strength is more sensitive to the temperature in the case of a small wrap angle, compared to the case of a large wrap angle.

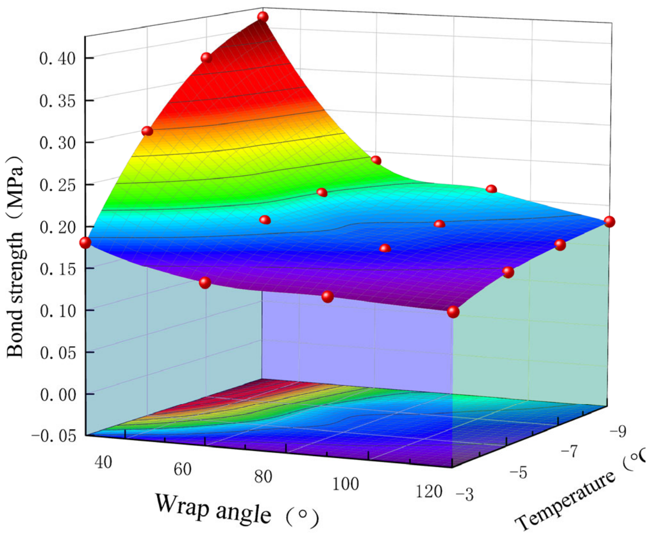

Fig. 9 Nominal normal bond strength without melting

Fig. 8 Contact surface of cable after de-bonding

For the specimens which were exposed to the environment temperature of 1℃ for one hour, Fig. 10 shows the nominal normal bond strength obtained via the tests. It is found that the influence of the melting occurred in the vicinity of the contact face of the ice (see Fig. 11) seems to be pronounced, particularly in the case of small wrap angles. Generally, the melting reduces the de-bonding force, thereby reducing the nominal normal bond strength.

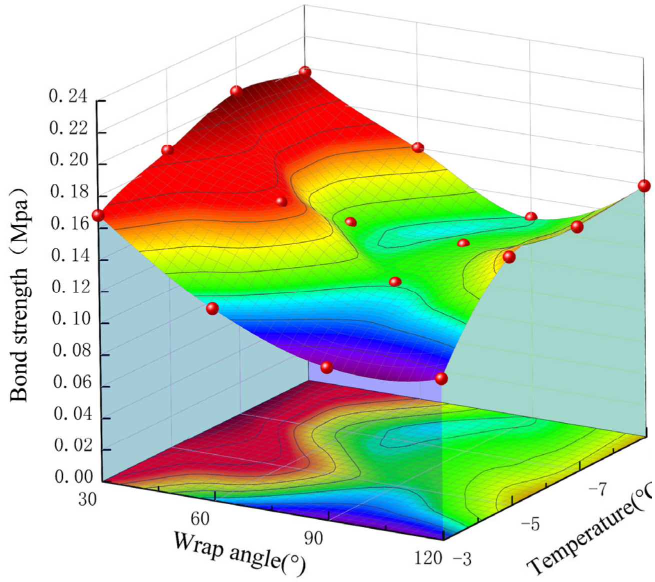

Fig. 10 Nominal normal bond strength with melting

Fig. 11 Contact face of ice after de-bonding

In addition, it is observed that the influence of the melting becomes small, if the original temperature of the specimen is lower than -5℃ and the wrap angle is greater than 90°. However, this phenomenon may be largely attributed to that the duration of the heat exchange is really short (one hour), and the environmental temperature causing the melting is not very high (1℃). There is a need of further study on the relationship between the bond strength and the rate of the rising temperature, which may benefit the prediction of the occurrence of the ice-shedding.

IV. CONCLUSIONS

An innovative purpose-built device for the experimental study of the nominal normal bond strength was designed and fabricated, thereby the tests were conducted with consideration of the influences of the ice temperature, and the presence of the melting. The conclusions are summarized as follows.

1) The nominal normal bond strength increases with the decrease of the temperature, provided the same wrap angle. With the increase of the wrap angle, the nominal normal bond strength decreases, given the same temperature. The nominal normal bond strength is more sensitive to the temperature in the case of a small wrap angle, compared to a large wrap angle.

2) Generally, the melting reduces the de-bonding force, consequently reducing the nominal normal bond strength. The reduction is relatively pronounced, while the wrap angle is small and the original ice temperature is low.

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