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Bending strength and effective modulus of atmospheric ice

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Abstract

Bending strength and the effective modulus of atmospheric ice accumulated in a closed loop wind tunnel at temperatures −6 °C, −10 °C and −20 °C with a liquid water content of 2.5 g/m^3 have been studied at different strain rates. More than 120 tests have been conducted. Ice samples, accumulated at each temperature, have been tested at the accumulation temperature. In addition, tests have been performed at temperatures of −3 °C and −20 °C, for the ice accumulated at −10 °C. These tests showed a clear dependency of bending strength of atmospheric ice on test temperature at low strain rates. Strain rate effects are implied because the spread in bending strength for the different temperatures diminishes as strain rate increases. The results also reveal that, in most cases, the effective modulus of atmospheric ice increases with increasing strain rate. The bending strength of atmospheric ice accumulated at −10 °C has been found to be greater than that of ice accumulated at −6 °C and −20 °C. The results show that the effective modulus of ice accumulated at −20 °C at higher strain rates is less than that of the two other types.

Keywords: Atmospheric ice; Beam; Bending strength; Effective modulus

1. Introduction

One of the most important causes for the increase in vulnerability of a power transmission network in cold climate regions is atmospheric ice accretion on ground wires and phase conductors. Atmospheric ice is the result of supercooled water droplets in the atmosphere impinging on exposed surfaces. Basic understanding of the mechanical properties and behaviour of atmospheric ice has potential applications in many fields such as de-icing techniques to remove ice from wires and conductors and the effects of the resulting transient forces on power network elements.

One of the few studies on the mechanical properties of atmospheric ice is the research of Druez et al. (1986) on compressive strength of ice. In their study, ice accumulated at various air temperatures and air speeds was tested at the same temperature as it had been accumulated. The liquid water content (LWC) of the air flow was set at 0.4 g/m^3 and 0.8 g/m^3. The mean volume droplet diameter for these two values of LWC was set at 20 μm and 40 μm, respectively. Also, two strain rates were used for strength tests, and several wind velocities for the ice accumulation. Druez et al. (1989) also measured the tensile strength of atmospheric ice

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accumulated at temperatures ranging from −3 °C to −20 °C where the LWC was set at 0.8 g/m^3 and 1.2 g/m^3 and the droplet diameter for these two values of LWC was set at 40 μm.

In contrast to the few studies on atmospheric ice, the flexural strength of other types of ice has been studied by many investigators. For example, Timco and Frederking (1982) performed a series of cantilever beam tests on freshwater ice. They confined themselves to testing only S2 ice at a test temperature of −10 °C. Cantilever beam tests were conducted by those authors in the push-down mode, and the simply supported beams were tested isothermally at −10 °C in both the push-down and pull-up modes. As another example, Frederking and Svec (1985) studied the stress concentration relief at the root of cantilever beams. Their tests were conducted in the top-in-tension mode of fine-grained ice in an outdoor pool at temperatures ranging from −5 °C to −20 °C. Also, Dempsey et al. (1989) studied the effects of specimen size on the flexural strength and effective modulus of columnar freshwater ice using four-point-bend tests in two sizes. The larger beam thickness and length in one size were almost 1.5 times greater than the corresponding dimensions of the smaller specimen. Considering the differences in the bending results, they concluded that the specimen size can overshadow the results of flexural strength and effective modulus. Gow and Ueda (1988) performed some bending tests with both cantilever and simply-supported beams of freshwater ice sheets. Their tests within the temperature range −1 °C to −19 °C revealed that macrocrystalline (S1) and columnar (S2) ice have different flexural characteristics. They ascribed these differences to variations in the size and orientation of the crystals in the ice as well as to the thermal condition of the beams. The results of the above mentioned works were used for comparison with the results of the present study on atmospheric ice.

We could find no report on the bending strength of atmospheric ice in the literature. Lack of comprehensive information about the strength and mechanical properties of atmospheric ice under various loading conditions led to the present study. In this paper, the bending strength and effective modulus of atmospheric ice for various accumulation temperatures and strain rates are investigated.

2. Ice accumulation

The meteorological conditions prevalent during ice formation, such as wind velocity, liquid water content of air, mean volume droplet diameter and air temperature, can influence the structure of atmospheric ice and, consequently, its mechanical properties. Therefore selection, monitoring and control of the ice accumulation conditions are very important and will be discussed in the following section.

2.1. Ice accumulation equipment

The ice accumulation conditions for this study were created in the CIGELE (Industrial Chair on Atmospheric Icing of Power Network Equipment at Université du Québec à Chicoutimi) atmospheric icing research wind tunnel which is a closed-loop (air-recirculated) low-speed icing wind tunnel. Three main systems inside the wind tunnel, the fan, the refrigeration unit, and the nozzle spray-bar systems were used to simulate icing conditions as those encountered during various icing processes in nature. Air speed and air temperature in the wind tunnel are adjustable with appropriate accuracy. Atmospheric icing processes are simulated by injecting warm water into a cold air stream through nozzles located at the trailing edge of the horizontal spray bar, designed in the shape of a NACA0012 airfoil. The droplet size distribution depends on the combination of air and water pressures and, within a certain range of the temperature, on the flow rate of water in the supply line. The absolute and relative humidity were measured using a humidity probe placed inside a plastic/aluminum fairing specially designed to resist freezing.

Atmospheric ice was grown from supercooled water droplets impinging on a rotating aluminum cylinder 78 mm in diameter and 590 mm in length. It was placed in the middle of the test section where the distance between the spray nozzles and the cylinder was long enough for thermodynamic equilibrium to be reached between the air flow at its highest velocity and the largest droplets.

The cylinder was cleaned with alcohol before ice accumulation and set in place for 2 h while the system was cooling down. After ice accumulation, the accumulated ice was cut with a warm aluminum blade to avoid any mechanical stress that might cause cracks. The resulting ice slices were then carefully prepared using a microtome to avoid crack formation. The guidelines recommended by the IAHR working group on test methods (Schwarz et al., 1981) were used for preparing the specimens. For the purpose of preparing ice samples and thin sections, the microtome was adjusted carefully to prevent any crack formation. Any sample with broken edges was discarded. The position of specimens extracted from the accumulated ice on the cylinder and load direction in mechanical tests are shown in Fig. 1. The average interval between ice accumulation and bending tests was 5 h.