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An atmospheric ice empirical failure criterion

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ABSTRACT

Characterizing the compressive strength of atmospheric ice is very significant to understand the ice shedding phenomenon. For this purpose, several tests were carried out in order to study the behavior of atmospheric ice under compression and tension, and under different experimental conditions.

Ice was accumulated in a closed loop wind tunnel in order to simulate the natural processes of atmospheric icing. Four temperatures were considered (− 20, − 15, − 10 and − 5 °C), the wind speed inside the tunnel was set to 20 m/s in order to obtain a mean volume droplet diameter of 40 μm, and a water liquid content of 2.5 g/m3.

An empirical failure criterion for the atmospheric ice was proposed based on the experimental observations, taking into account the porosity, strain rate and temperature.

1. Introduction

Atmospheric icing of structures is a phenomenon that affects human activities on many levels, and causes damages of different nature (Farzaneh, 2008). This phenomenon is manifested by a deposition of water drops or snowflakes on a cold surface (Farzaneh, 2000; Farzaneh, 2009). Structures in northern environments are often exposed to atmospheric icing. Wet snow, freezing rain, freezing fog, or hoarfrost are some of meteorological events resulting from atmospheric icing. Although the dangers caused by ice accretion on structures are considerable, ice shedding is particularly important. Ice shedding, which corresponds to the weight reduction of accumulated ice on a surface, is the source of several structural instabilities on overhead power line networks (Farzaneh, 2009)–(Fuheng & Shixiong, 1988). Understanding this phenomenon requires a deep knowledge of the structural and rheological properties of atmospheric ice.

Unlike other types of ice such as fresh water ice or sea ice (Michel, 1978), few works on the mechanical properties of atmospheric ice are reported in the literature (Eskandarian, 2005)–(Druez et al., 1986). These contributions concern the study of the rheological characteristics of this type of ice, rather than providing quantification to its failure limits. Therefore, a presentation of failure criteria seems to be indispensable to understand the ice shedding phenomenon.

The presentation of ice failure criteria was generally based on approaches concerning brittle materials, such as the maximum normal stress criterion (Schulson, 2001), the Mohr Coulomb criterion presented by Schulson (Schulson, 2001) or recently by Farid et al. (Farid et al., 2017), the criterion of the maximum strain suggested by Hamza (Hamza, 1984), the strain energy criterion proposed by Cole (Cole, 1988), or the fracture toughness criterion for columnar grained ice S2 presented by Dempsey et al. (Dempsey & Wei, 1989). The failure of atmospheric ice involves many parameters that should be taken into account, this is more suggestive to the development of an empirical failure criterion specific to atmospheric ice.

The compressive and tensile strength of atmospheric ice are considered to be the most significant properties for ice engineering, especially for the understanding of ice shedding mechanisms. These properties are highly affected by many environmental and structural parameters such as strain rate, temperature, wind speed, porosity, liquid water content, etc. (Kermani et al., 2007). Consequently, as compressive and tensile strength give a global image of the resistance of ice to different loads, they must be taken into account when considering the failure criterion.

The present contribution concerns the development of an empirical failure criterion for atmospheric ice, which takes into account porosity, strain rate, and temperature effects. A significant correlation between the actual strength values and those predicted by the model was observed. The proposed criterion was validated in the case of compressive and tensile loadings.

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2. Experimental procedure

2.1. Atmospheric ice preparation

The technique adopted to prepare atmospheric ice has an aim to reproduce the natural atmospheric icing process, specific conditions to generate this process were created in the atmospheric icing research wind tunnel at CIGELE Laboratories (Eskandarian, 2005; Kermani, 2007). Although the process has been detailed in a previous work by the same authors (Farid et al., 2016), explanation of the experimental procedure and setup seems important for the sake of clarity.

Three independent supply lines provided air and water to the nozzles. Distilled water was injected into a cold airstream through nozzles located at the trailing edge of a spray bar. Air speed, water and air flux, all were controlled to generate droplets with a mean volume droplet diameter (MVD) of 40 μm and a liquid water content (LWC) of 2.5 g/m^3. A computer program allowed the control of these different parameters. Atmospheric ice was accumulated on a rotating aluminum cylinder (78-mm diameter and 590-mm length) making 1 rpm making the thickness distribution of ice uniform. The cylinder was carefully cleaned with hot water and soap before each set of experiment. Then it was placed at the middle of the test section of the wind tunnel. The distance between the cylinder and spray nozzles was large enough for the droplets to reach kinetic and thermodynamic equilibria.

The time needed to grow a sufficient thickness of ice on the cylinder varied depending on accumulation conditions such as air temperature, velocity and liquid water content, it ranges from 2 to 4 h, sometimes up to 8 h. The atmospheric ice specimens were prepared at four different temperatures: − 20, − 15, − 10, and − 5 °C.

The specimen orientation according to the accumulated ice is illustrated in Fig. 1. Once a thickness of about 60 mm was obtained, prismatic blocks were cut using a warm aluminum blade in order to avoid any mechanical stress. Then, the blocks were machined into cylindrical shape with a diameter of 40 mm and a length of 100 mm. These specimen dimensions were adopted in order to avoid any influence of the grain size on the compressive behavior of the ice (Schwarz et al., 1981).

Before each test, the ice specimen ends were cleaned and smoothed to assure their parallelism. The specimen were fixed against the stainless steel platen using a thin piece of paper, the use of paper relax the triaxial stress field in the end of the specimen, and allowed to the test system to transfer the axial load perfectly.

Once prepared, cylindrical specimens have been tested on uniaxial compression at the same temperature at which they have been accumulated. As strain rate in natural ice shedding is not more than $10^{-2}\,s^{-1}$ (Kermani et al., 2007), hence, four strain rates were chosen for the experimental tests: $10^{-4}\,s^{-1}$, $10^{-3}\,s^{-1}$, $10^{-2}\,s^{-1}$ and $10^{-1}\,s^{-1}$. The considered strain rates were calculated by dividing the test system cross head speed by the sample's length. The test system is considered infinitely stiff, so the system's compliance was negligible during the compressive tests (Farid et al., 2016).

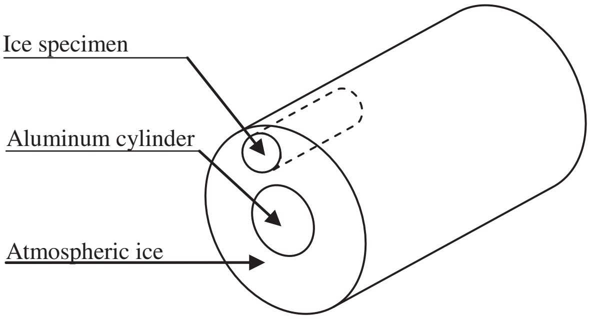

Fig. 1. Schematic illustration of accumulated atmospheric ice and the specimen cut.

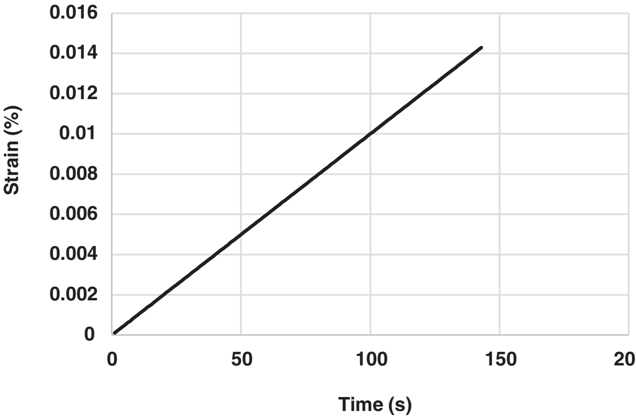

Fig. 2. Strain-time plot for a strain rate of $10^{-4}\,s^{-1}$ at a temperature of − 5 °C.

Plotting the strain versus time validated the claim that the specimen strain rates were constant during tests, this is shown in Fig. 2 below.

In order to assure the results reproducibility, each test was repeated a minimum of five time, more details about the presented results are available in (Farid et al., 2016).

2.2. Microstructure observation and porosity evaluation

Compared to other types of ice, atmospheric ice shows relatively high porosity and lower densities depending on the type of the accretion regime. In the present study, a Micro CT (Computed Tomography) has been used to quantify, with better accuracy, the porosity in the prepared samples (Farid et al., 2016).

Based on the binary images presented in Fig. 3, one can note the influence of the accumulation temperature on the porosity, as temperature decreases, pores become smaller and their distribution become more uniform. The obtained values of porosity were 0.288 ± 0.079% at − 5 °C, 1.062 ± 0.082% at − 15 °C and 2.253 ± 0.089% at − 20 °C.

3. Experimental results

For each experimental condition (temperature and strain rate), the stress versus strain curves were plotted, and the compressive strength, which corresponds the maximum stress reached before failure, was recorded.

Fig. 4 shows the evolution of compressive strength of atmospheric ice as a function of strain rate for three temperatures: − 20, − 15 and − 5 °C. The compressive strength of ice increases until it reaches a maximum value, which is then followed by a decrease as the strain rate increases. This transition characterizes the ductile-brittle transition, after which, the brittle failure takes part as dominant mode of failure, and the ice fractures without apparent plastic deformation.

Fig. 5 illustrates the evolution of the compressive strength as a function of temperature at different strain rates. The highest values of atmospheric ice compressive strength were obtained for a temperature of − 15 °C. After this temperature is reached, the compressive strength decreases, which is related to the presence of more pores and cavities at temperature lower than − 15 °C. The evolution of porosity versus temperature is showed in Fig. 6.

Porosity increases as the accumulation temperature decreases. This can be mainly related to the accretion mode; as temperature decreases, supercooled droplets reach the accumulation surface and freeze immediately upon contact, air particles get trapped in the interstices during this process, which therefore increases ice porosity.