Neural network approach to characterize the atmospheric ice compressive strength

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Abstract:

Atmospheric icing of structures is a phenomenon that hampers human activities in cold climate regions. Coupled with environmental effects such as wind and temperature fluctuations, accumulated ice can shed, which may lead to serious damage to equipment.

Characterizing the compressive strength of atmospheric ice is important 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 under different environmental and structural parameters.

In order to simulate the natural processes of atmospheric icing, ice was accumulated in the closed loop wind tunnel of CIGELE (*Industrial Chair on Atmospheric Icing of Power Network Equipment*), , Three temperatures were considered (-20 ^{o}C, -15 ^{o}C and -5 ^{o}C) in this experiment. The wind speed inside the tunnel was set to 20 m/s in order to obtain a mean volume droplet diameter of 40µm and a water liquid content of 2.5 g/m^3. Each type of ice was tested at the same temperature at which it had been accumulated. A tomographic analysis was carried out on a small specimen (cylinder of 1 cm diameter × 2 cm length) for each temperature in order to quantify the porosity and determine the grain size and their distribution.

The neural network approach was used to predict the compressive strength of atmospheric ice as function of strain rate and temperature. Four strain rates ($10^{-4}s^{-1}$, $10^{-3}s^{-1}$, $10^{-2}s^{-1}$ and $10^{-1}s^{-1}$,) and three temperatures (-20°C, -15°C and -5°C) were considered. The obtained results show the capability of the used neural networks to reproduce the compressive behavior of atmospheric ice under different conditions.

Keywords: ***Atmospheric ice, ice shedding, compressive strength, neural networks, brittle failure.***

INTRODUCTION

The study of ice accretion on structures is an issue of paramount importance in cold climate regions. Coupled with wind, accumulated ice on structures may impair their operation, and result in significant damage, [1]–[3]. The accumulation of ice on the power transmission lines may create a variety of problems: collapse of transmission towers under excessive load, breaking of electrical cables and wires due to dynamic loading (fatigue), ice-covered insulator flashover, etc.[1], [4].

Atmospheric icing is a meteorological phenomenon that is manifested by a deposition of water drops or snowflakes on a cold surface exposed to the ambient air [2], [4], [5].Although the dangers caused by ice accretion on structures are considerable, ice shedding is as much important. This mechanism, which corresponds to the reduction of accumulated ice on a surface, is the source of several dynamic and structural instabilities on the power lines network[6]. The understanding of this phenomenon imposes 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[7], few works on the mechanical properties of atmospheric ice have been reported in the literature, [8], [9]. The compressive strength of atmospheric ice is considered to be the most significant property of icing engineering, especially as concerns the understanding of ice shedding by mechanical breaking which is affected by environmental and structural parameters such as strain rate, temperature, wind speed, porosity, liquid water content, etc.[10].

In order to characterize the ice fracture under different types of loading, researchers have proposed different failure criteria[11]. However, the explicit expression of these laws is complex, most of the time not including some basic environmental and structural parameters.

Algorithms associated with the artificial neural networks can prove to be an interesting alternative to the classical algorithms, as they can model and predict systems behavior without the necessity of explicit relationships between its components. The neural networks have been recently used in many engineering fields[12], and showed their capacity to adapt to problems of different nature.

In this paper, the backpropagation neural network is used to predict the compressive strength of atmospheric ice as function of strain rate and temperature. The experimental data is used to train and test the neural network. A comparison with other sets of experimental data shows the good predictive capacity of the proposed model.

I. ATMOSPHERIC ICE COMPRESSIVE STRENGTH EXPERIMENTAL DATA

Mechanical properties of atmospheric ice are subject to changes under several parameters such as temperature, strain rate, anisotropy and porosity. Therefore, one of the mean objectives of the present study is to elucidate the effect of those parameters by carrying out compressive tests on cylindrical ice specimens prepared under different laboratory conditions.

Atmospheric ice was prepared under specific conditions in the atmospheric icing research wind tunnel.

The following technique was used to simulate the natural atmospheric icing process. Warm water was injected into a cold airstream through the nozzles located at the trailing edge of a spray bar. Three independent supply lines provide air and water to the nozzles. Using a computer program allowing to control the flux and velocity of airflow inside the tunnel, air speed was controlled to have a mean volume droplet diameter (MVD) of 40 µm and liquid water content (LWC) of 2.5 g/m^3. Atmospheric ice was accumulated on a rotating aluminum cylinder (diameter 78 mm and length 590 mm). The cylinder was carefully cleaned with hot water and soap before each set of experiment, placed in the middle of the test section of the wind tunnel, and fixed by each edge against a rotor making 1 rpm, the rotation of the aluminum cylinder making the thickness distribution of ice uniform as illustrated in Figure 1. The distance between the cylinder and spray nozzles is large enough for the droplets to reach kinetic and thermodynamic equilibria.

Figure 1 Accumulated atmospheric ice on the rotating cylinder

Depending on accumulation conditions such as air velocity and liquid water content, the time needed to grow a sufficient thickness of ice on the cylinder varied from 2 to 4 hours, sometimes up to 8 hours.

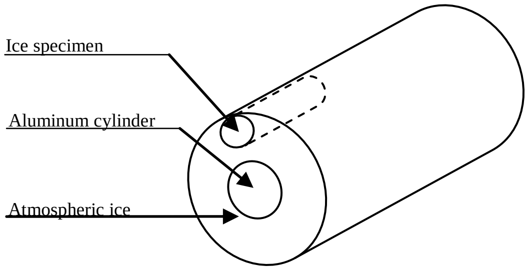

Figure 2 Schematic illustration of accumulated atmospheric ice and the specimen cut

Figure 2 shows the specimen orientation according to the accumulated ice. Once a thickness of 60 mm was obtained, prismatic blocks were cut using a warm aluminum blade in order to avoid any mechanical stress, and then machined into a cylindrical shape with a diameter of 40 mm and a length of 100 mm.The specimen dimensions are chosen in order to avoid any influence of grain size on the compressive behavior of ice[13].

The atmospheric ice specimen were prepared at three different temperatures; -20, -15 and -5 °C. A closed-loop electrohydraulic testing machine was used to carry out all the compressive tests. The machine had two load cells of capacity 250 KN and 25 KN, the latter chosen for ice testing. The whole system was located inside a controlled cold room, with temperature ranging from -40 °C to 0 °C, with an accuracy of ±0.5 °C.

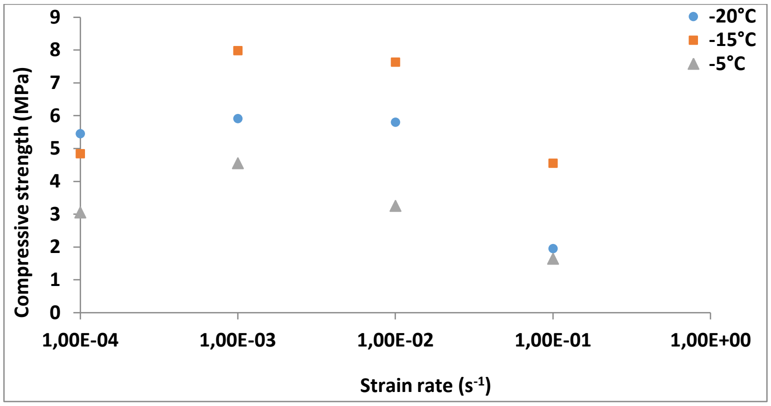

Figure 3 Compressive strength evolution versus strain rate for different temperatures

In each test, the compressive stress versus strain was recorded as function of time, temperature and strain rate. Figure 3 shows the evolution of ice compressive strength versus strain rate for the three different temperatures.

II. COMPRESSIVE STRENGTH MODELING USING NEURAL NETWORKS

A. The neural networks approach

Recently, neural networks have been used in many areas including classification, pattern recognition, speech synthesis, diagnosis, identification and control of dynamic systems[14].

The use of neural networks is justified by the fact that they can approximate nonlinear functions without having to specify explicit relationships between different variables. Their performance keeps improving continuously while relying on dynamic learning, which provides a robust neural identification towards the parametric variations and disturbances that can affect the operation of the studied system.

In the present work, neural networks are exploited the reproduce and predict atmospheric ice compressive strength as function of temperature and strain rate. The well-known multilayer perceptron is used for this application.

B. Type, structure and training algorithm

The used neural network is composed of one input layer, many hidden layers, and one output layer. The input layer contains two neurons (temperature and strain rate), the output layer contains one single neuron, while the number of the hidden layers varies depending on the experimental set and the needed modeling accuracy.

Figure 4 illustrates the architecture of the used neural network: 60% of the experimental data is used for training, 20% is used for validation, while 20% is kept for testing purposes. In order to minimize the error between the desired value and the network output, a back propagation learning algorithm is used, combined with the Levenberg-Marquardt optimization algorithm. In addition, the sigmoid function is selected as activation function of the hidden layers.

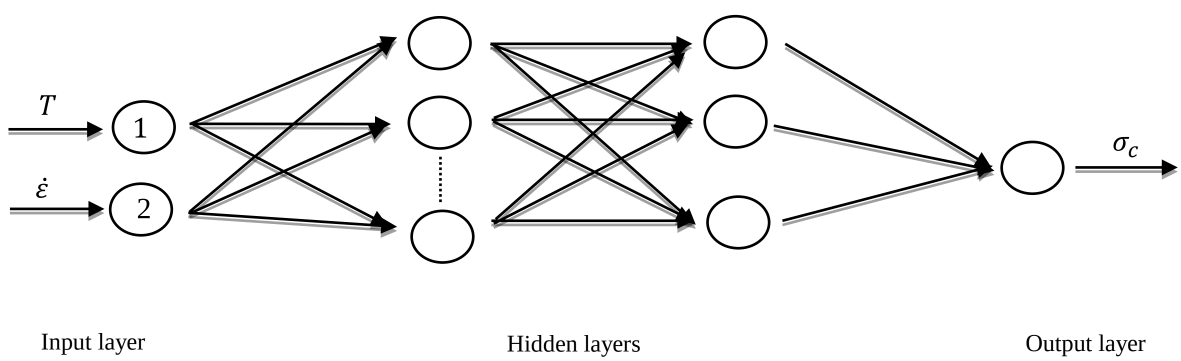

Figure 4 The architecture of the neural network model

III. ICE COMPRESSIVE STRENGH PREDICTION USING NEURAL NETWORKS

The training of the neural network involves three stages: the feed forward of the input training pattern, the back propagation of the associated error, and the adjustment of the weights. After the training completes, the convergence tests is carried out. To avoid overtraining, the convergence criterion used in this study is the root mean-square error of the testing data.

A comparison was made between the experimental values of the compressive strength and those obtained by the artificial neural network model. The results obtained before the training phase are shown as well in Figures 5, 6 and 7, below.

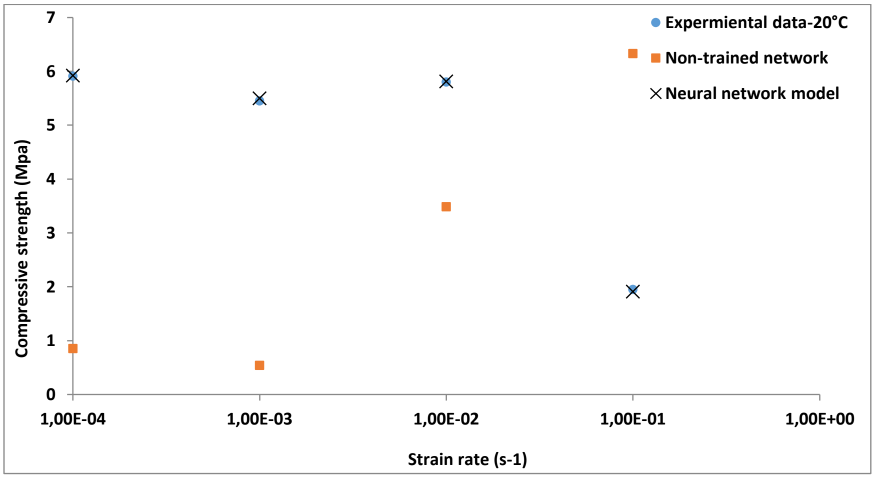

Figure 5 Predicted compressive strength at -20°C

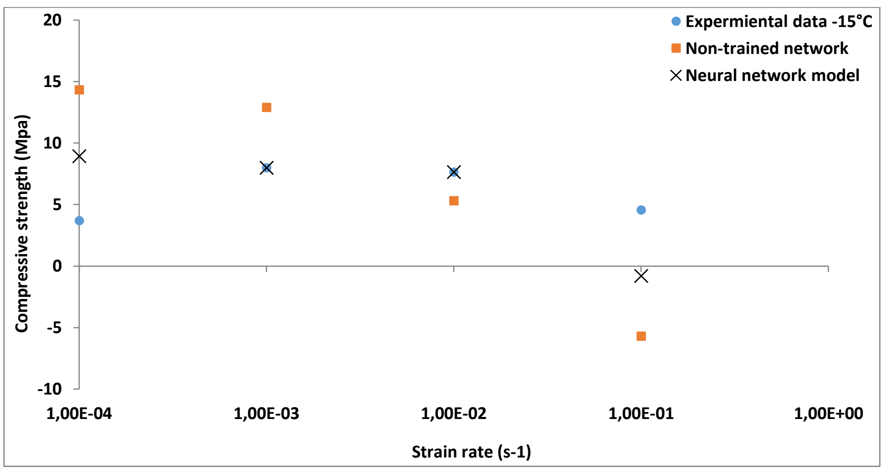

Figure 6 Predicted compressive strength at -15°C

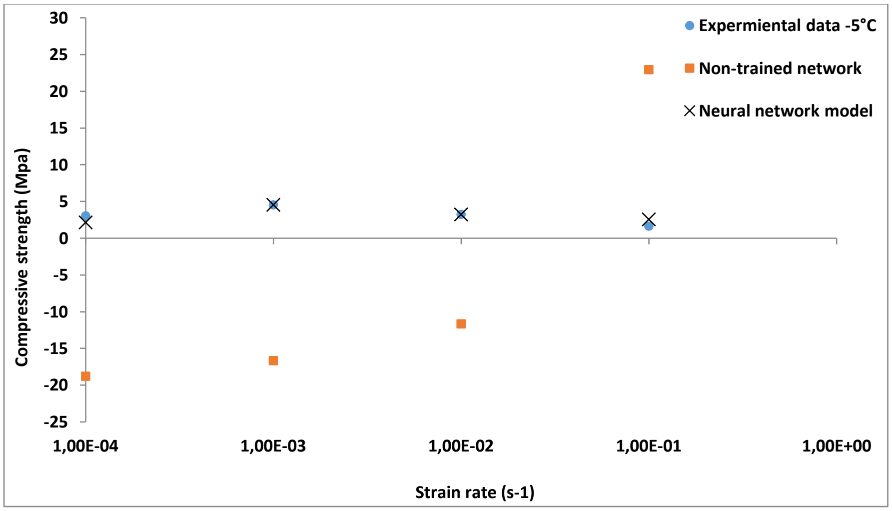

Figure 7 Predicted compressive strength at -5°C

In Figures 5, 6 and 7, results from experiments, non-trained and trained networks are compared. The accuracy level of the learning algorithm is also shown.

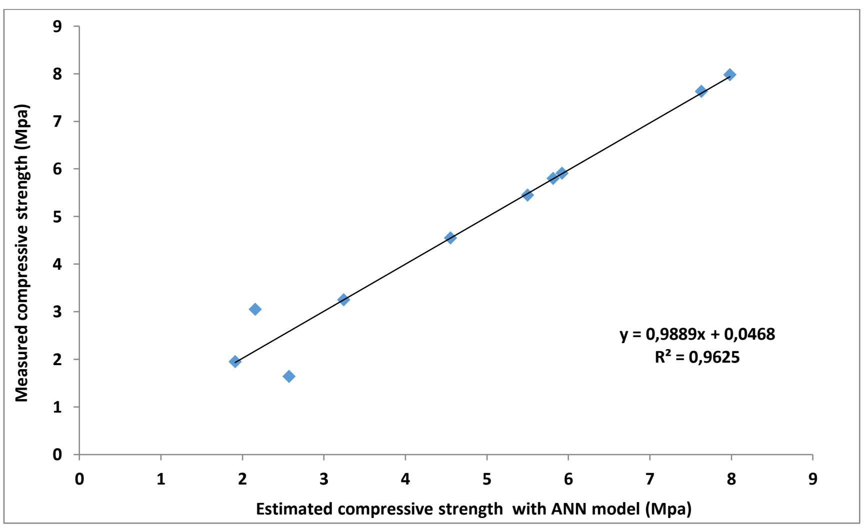

Figure 8: Comparison of the measured compressive strength and the estimated values by the ANN model

In Figure 8, the measured values of the ice compressive strength and estimated values by the neural network model are compared. It is to be noticed that the compressive strength values used do not belong to the data base used to train the network.

The estimated values by the ANN model show a very good correlation with $R^2 = 0.9625$, where R is the linear correlation coefficient. The relative error is 1.71% for -20 °C, 5.37 % for -15 °C and 0.22 % for -5 °C.

CONCLUSION

The objective of this study was to investigate the compressive strength of atmospheric ice as function of different parameters such as temperature and strain rate. It was shown that the predictive accuracy of the neural network approach used for that purpose was very good for compressive strength of atmospheric ice. The relative error was 1.71 % for 20 °C, 5.37 % for -15 °C and 0.22 % for -5 °C.

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