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Determining ice loads for tower structure design

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ABSTRACT

Ice load is a major design criterion of tall towers. International Standard ISO 12494 gives a method to assess ice loads and combined ice and wind loads on complex structures by Ice Classes. The method has not been directly verified, however. Here, we present an analysis of the applicability of the ISO method based on field data on rime icing. The data include ice amounts simultaneously measured on the ISO Standard ice collector, a 7.5 m tall self-supported lattice structure and a 127 m tall guyed lattice TV-tower. We compare ice masses on these objects within specific Ice Classes and calculate the ice masses calculated for the structures based on the ISO method. The results show that ISO Ice Classes are a useful tool in assessing rime ice loads on structures, but that systematic errors arise. These errors tend to be on the safe side in regard to structural design and are, at least partly, related to poorly known ice shedding mechanisms.

1. Introduction

Ice is a major design criterion for tall structures in cold climates. Lattice structures, such as TV and telecommunication towers as well as power line towers, are particularly vulnerable to icing. Moreover, their wind load considerably increases with accreted ice (Fig. 1). More than 140 ice related collapses of TV and communication towers occurred in the latter part of the 1900s in the United States alone [1]. Some of the collapsed towers were among the tallest structures in the world. Many of the ice induced cascade failure events of power line towers, such as those in Canada in 1996 and in China 2008, have reached catastrophic consequences.

Lattice towers are "bare" structures, directly imposed to loading. The design loading is normally the wind load, and in cold regions, the atmospheric ice load combined with wind. Structural reliability analyses have indicated that a 10% increase in the load factor would produce an approximately ten-fold increase in the probability of failure [2]. Moreover, ice reduces the natural frequencies of the tower and may induce galloping of the guy wires [3,4]. These processes may cause fatigue and thus contribute to the failure risk.

In order to assess the design ice loads for towers, theoretical models to estimate icing have been developed [5–7]. However, cloud physical data required by in-cloud icing modeling are not routinely measured, and simulation of them by high resolution atmospheric boundary-layer models is only taking its first steps [8]. Of course, icing measurements have been made for assessing the loads in many countries for a long time [9]. However, this approach is hampered by the poor representativeness of a measurement device when considering icing of a large structure [10] and the poorly known height dependence of ice loads [11,12].

In 2001 the International Standardization Organization issued an International Standard ISO 12494 "Atmospheric icing of structures" [13] that presents a detailed methodology for assessing ice loads on structures. The standard defines *Ice Classes* and estimation methods for both ice loads and combined ice and wind loads, separately for rime ice (in-cloud icing) and glaze ice (freezing precipitation). In this paper, we only consider in-cloud icing, i.e., rime ice. The ISO Ice Classes for rime ice are shown in Table 1. They are defined in terms of ice mass per unit length of an object.

According to ISO 12494, an Ice Class corresponds to an ice mass per unit length on a vertically oriented slowly rotating 30 mm diameter cylinder that is at least 0.5 m long. Accordingly, such a standard collector is recommended to be used when determining the Ice Class for a site by direct icing measurements.

ISO 12494 provides a systematic approach for assessing ice loads on structures and is meant to be used worldwide. However, due to the lack of field data on ice on towers the method has been poorly verified. The ISO method assumes that a rime ice mass is independent of the dimensions of a structural component. This is only a crude approximation based on numerical modeling [14], laboratory experiments [15] and observations [16]. The height dependence of rime ice loads in the ISO Standard is also a crude

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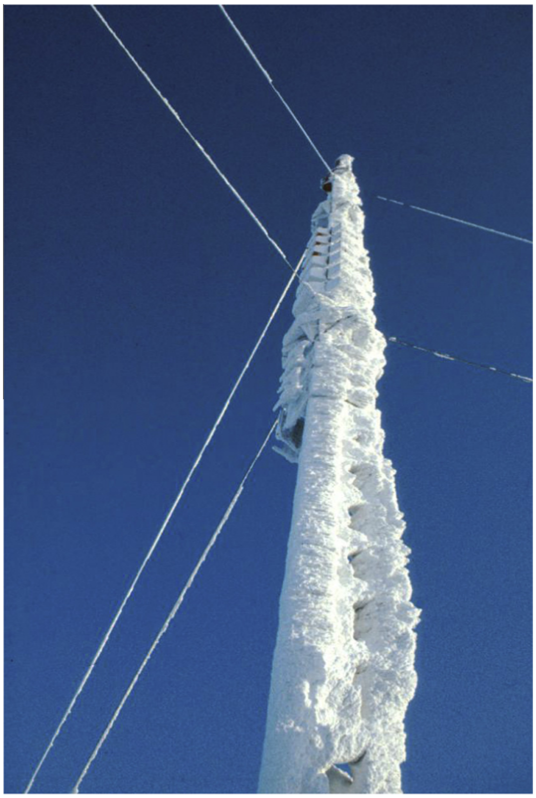

Fig. 1. Rime ice on the 127 m lattice tower at Ylläs.

Table 1
ISO Ice Classes for rime ice [13].

Ice Class	Ice mass (kg/m)
R1	0.5
R2	0.9
R3	1.6
R4	2.8
R5	5.0
R6	8.9
R7	16
R8	28
R9	50
R10	Extreme case

approximation based on very limited field data [17]. Furthermore, ice shedding is not taken into account in the method.

Therefore, it is extremely important to test the applicability of the ISO method in estimating design rime ice loads on tall lattice structures. Here, we present results from simultaneous field measurements of rime icing on an ISO Standard ice collector and two lattice structures, a 127 m tall guyed TV-tower and a 7.5 m tall self supported lattice tower. These data allow us to study the applicability of the ISO method to assessing rime icing on full-scale structures in a large range of ice loads.

2. Measurements

The measurements were made in 1998–2002 on top of Ylläs hill in Northern Finland. The site is at 700 m asl and about 500 m above the mean level of the surrounding terrain.

The 127 m tall guyed TV tower at Ylläs (Fig. 1) is standing on a specially prepared vertical force measurement system based on strain gages. The 7.5 m tall self-supported tower (Fig. 2) was constructed to serve as a test structure for icing and wind load studies. It has the same structural details as a section of the 127 m tower. It was also erected on a strain gage based load cell system. Our one meter long ISO ice collector is standing on a commercial load cell and includes an electric motor and a gear for rotation at 4 rpm. This device, when heavily iced up, is shown in Fig. 3.

All the ice load data, together with meteorological parameters such as wind speed and air temperature, were recorded using an automatic measurement system. The measurements were recorded as 10 min mean values once every 3 h. The resolution of the mass measurements is determined by the maximum capacity of the load cells. The ISO collector at Ylläs had a load cell with the maximum capacity of 500 kg. Therefore, ice masses in the smallest Ice Classes R1 and R2 cannot be reliably measured by this system since they represent only 0.1% and 0.2% of the maximum capacity of the load cell.

The measurements by weighing the two towers include a similar relative accuracy. The guy ropes of the 127 m tower cause a temperature dependent error in the measured weight because the tension of the ropes increases as the temperature decreases. This error was corrected by an algorithm in the structural analysis software for the tower, and was verified using situations where no ice existed on the tower. The geometric nonlinearity of the guy ropes may cause errors that are proportional to the ice mass on the guy ropes. An ice accumulation on the ISO ice collector includes, in extreme cases, a “cap” (see Fig. 3) that increases the measured ice mass.

3. Comparisons and calculated loads

Our purpose here is to compare the simultaneously measured ice masses on the two full-scale structures and the ISO ice collector. In particular, we wish to make comparisons of such ice masses that correspond to specific ISO Rime Ice Classes. According to the ISO 12494 philosophy, a measured ice mass on the ISO collector is used as the reference that determines the Ice Class for a comparison.

Although we have ample data, it was not easy to find icing cases where the ice masses could be directly compared within a specific Ice Class. This is because, for a meaningful comparison one needs a case in which the ice mass starts from zero on all the objects considered. This is rarely the case at Ylläs because, during the icing season, the air temperature is persistently below 0 °C, so that the structures are very infrequently free of ice.

All cases where the data showed, within the resolution of the measurements, zero mass on all three objects, were utilized here. In many icing cases there was only one observation that was within a certain Ice Class, i.e., the previous observed ice mass on the ISO collector was well below the limit given in Table 1 and the next observation well above it. There were, however, also cases, where the icing rate was so low that several consecutive observations fell within the same Ice Class. In such cases all observations, where the ice mass on the ISO collector was within ±5% of the Ice Class boundary, were included by using the mean of these observed ice masses. The corresponding mean was then used to represent the ice mass on the two tower structures.

Ice mass calculations were made in order to compare the ISO-method with observations on the lattice towers. In these calculations, the 127 m tower and the 7.5 m tower were considered in detail so that each tower component was included in the ice load calculation. This included antennas, cables, ladders, etc. The ISO method provides the rime ice mass per unit length and ice density, based on Table 1 and a height correction. Ice dimensions are then obtained by the figures given in the ISO Standard for components of different shapes. No shadowing by the other components of