Ice Loads on a Lattice Tower Estimated by Weather Station Data

EVA SUNDIN

Division of Water Resources Engineering, Luleå University of Technology, Lulea, Sweden

LASSE MAKKONEN

VTT Building Technology, Technical Research Centre of Finland, VTT, Finland

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ABSTRACT

Atmospheric ice loads are a major design criterion of tall structures in cold regions. In this paper the possibility to derive the design ice loads using analysis of meteorological observations made routinely at a weather station is studied. Ice loads calculated by extrapolating weather station data and using simplistic ice loading and unloading models are compared with those measured on a 323-m-height lattice TV tower. The comparison is made cumulatively in 3-h intervals over seven winter periods. The results show reasonable agreement in the time of the icing events and in overall loads. In the cases where the cumulative ice loads differ, the discrepancies are mostly due to incorrectly predicted unloading events. This study points out the importance of on-site temperature data for successfully estimating cumulative ice loads over long cold periods.

1. Introduction

Atmospheric icing frequently causes tower failures in cold regions. Sundin and Mulherin (1993) report 13 TV towers that collapsed due to ice loads in the United States alone during the last 20 years. All these towers were more than 300 m high and the economical losses were, consequently, significant. Apparently, there is need for better methods to predict the expected ice loads for tower design.

The use of direct ice load measurements in design of towers is very limited for two reasons. First, a statistically meaningful extreme value analysis requires data from more years than what the broadcasting companies usually can afford to wait, and second, icing measurements that represent levels high above the ground cannot usually be made before the tower has been erected. Therefore, much attention has been paid to estimating atmospheric ice loads based on meteorological data from weather stations (e.g., Rudneva 1962; McKay and Thompson 1969; Mihel 1971; Strauss 1986; Haldar et al. 1988; Makkonen and Ahti 1995). This approach has the advantage that meteorological data are available for many years with relatively good spatial coverage. However, major problems are that the data must be extrapolated to the site of the mast and that largely unverified methods must be used to derive the ice loading and unloading rates and times from weather observations.

In this paper a systematic verification of ice loads derived for a mast using weather station data is presented by comparing them on a 3-h interval basis with ice loads measured on a 323-m-high lattice TV tower.

2. Measured loads

a. Measurements

In Sweden there are 50 high lattice towers for distribution of radio and television signals. About half of these 300-m masts are affected by atmospheric icing in the winter.

The tower in Arvidsjaur on the mountain of Akkanålke, 753 m above sea level, was equipped to serve as a test mast for atmospheric icing in 1988. The surroundings of Akkanålke are woodlands that transform into bare mountain regions at the treeline at about 650 m above sea level. The 323-m-high mast is one of the masts that experiences the most severe atmospheric icing in Sweden; see Fig. 1. A typical situation is shown in Fig. 2. The mean level of the terrain surrounding the tower within a distance of 10 km is estimated to be 550 m above sea level. The three-legged lattice tower with the side width of 2.9 m was built in 1986. It was designed considering exceptional wind and ice loads. The design of the mast allows a total additional load in the legs of 9300 kN (Fahleson 1995). Since the winter of 1988–89 measurements of loads in the legs and guys as well as some meteorological parameters have been

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Corresponding author address: Eva Sundin, Division of Water Resources Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden.
E-mail: Eva.Sundin@sb.luth.se

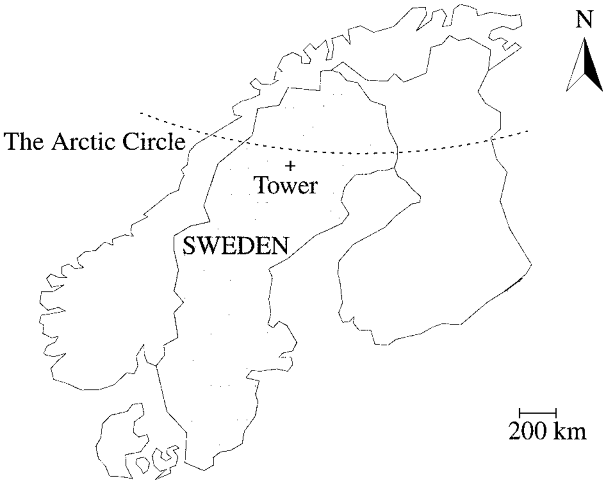

FIG. 1. Tower location, the mountain of Akkanålke (65°32′N, 19°00′E), about 110 km south of the Arctic Circle.

made. The loads in the legs are measured by strain gauges. Interference from the transmitters and the hard climatic conditions have complicated the measurements and sometimes interrupted them. Over the years the equipment and the methods for data recording have been improved and supplemented. The measurements are recorded once every hour from 1 October to 31 March.

The prevailing wind direction during icing events is from the southwest and the wind speeds sometimes exceed 50 m s^{-1} (Fahleson 1995). The wind speeds fit to a Weibull distribution with $k = 2.1$ and $a = 14.5$ at 110-m measurement height (Fahleson 1995).

b. Data processing

The sum of the loads that are registered in the three legs is the total gross load. Additional load due to wind is neglected since Fahleson (1995) found that wind contributes very little to the vertical load in the legs. Additional ice on the guy wires increases the vertical load. The more ice, the higher the vertical load due to the suspension of the guys. This was eliminated by multiplying the total load by 0.5 (Fahleson 1995). To correlate with weather station data the analyses were based on instantaneous values every 3 h.

3. Calculated loads

a. Meteorological data

Meteorological data were obtained from the weather station at Storberg operated by the Swedish Meteorological and Hydrological Institute. The station is located 453 m above sea level and 3 km southwest of the mast (see Fig. 3). Thus the level at which the weather parameters are measured is 300 m lower than the base of the mast and more than 600 m lower than the top of the mast. The weather parameters used and their observation intervals are shown in Table 1. The precipitation rate for each 3-h calculation interval was derived from the 12-h observations, assuming continuous unchanged precipitation rate throughout the 12-h period.

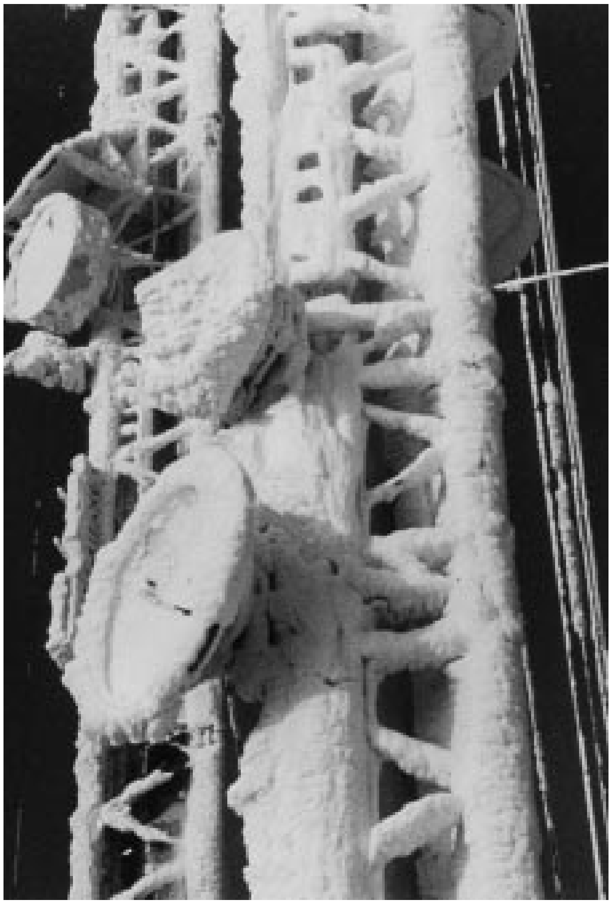

FIG. 2. Typical icing situation of the tower of Akkanålke.

b. Calculation methods

For ice load calculations, the lattice tower was separated into six vertical sections of 53.9 m each. A total projected cross-sectional area of 500 m^2 was determined from all parts of the trunk of the tower. Sections 1–5 were estimated to include an area of 80 m^2 each and the top section, section 6, was estimated to include 100 m^2. The middle of each section was considered as the level for which the meteorological parameters and the ice loads were derived. Icing and deicing were determined for each section separately and then summed up to get the total load.

1) IN-CLOUD ICING

The estimation of ice loads due to in-cloud icing from the meteorological parameters was based on the procedures developed by Makkonen and Ahti (1995). Ac-

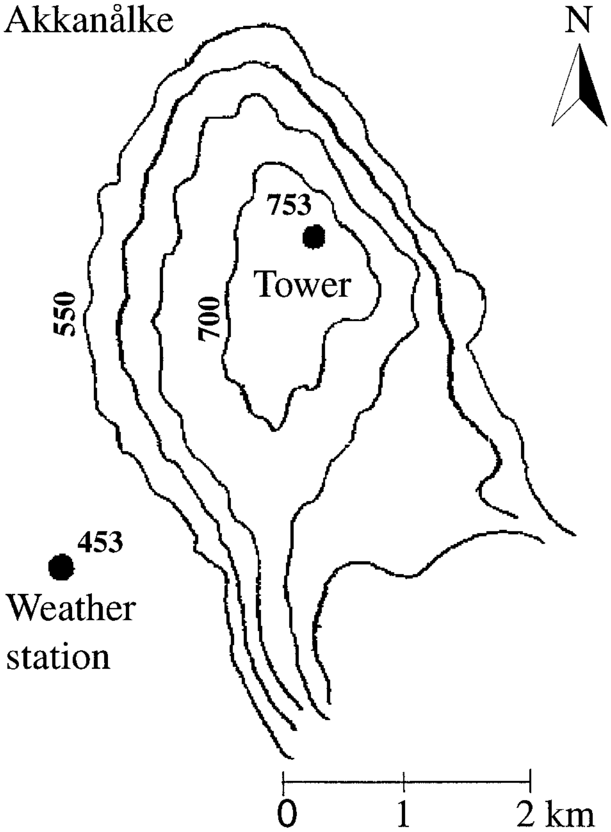

FIG. 3. Location of Storberg weather station in relation to the tower of Akkanålke. The numbers are heights of ground level in meters.

cording to these, in-cloud icing occurs when the structure is found to be in a cloud, that is, the height of cloud base is lower than the height of interest. The criteria for in-cloud conditions are thus

$$H_b < H_i$$

and

$$-15°\text{C} < t_{a,i} < 0°\text{C},$$

where H_b is the height of cloud base, H_i is the height of interest, and $t_{a,i}$ is the air temperature at the level of interest. Here, H_b and H_i are related to the mean level of the surrounding terrain. It was assumed that clouds are so thick that when the cloud base is at low levels, then the top of the mast is also in the cloud. The lower limit of $-15°$C for $t_{a,i}$ is adopted to ensure that clouds containing mainly ice crystals (see Pruppacher and Klett 1978, 9) are not included as a source of icing.

The air temperature at all levels on the tower is assumed to be equal to the one measured at the weather station; that is, no temperature gradient is applied in the modeling. This simple assumption is supposed to reflect the situation in the mean, as detailed data are not available. The real instantaneous temperature gradient varies significantly, of course, and can be either negative or positive. For instance, the standard adiabatic lapse rate would give poor modeling results because an inversion layer typically prevails in this region in winter. On the other hand, during severe weather systems with potentially heavy icing such a temperature inversion does not typically exist.

TABLE 1. Meteorological parameters used in the estimation of ice loads on the tower.

Parameter	Frequency
Air temperature (°C)	3 h
Height of cloud base (code)	3 h
Wind speed (m s^{-1})	3 h
Wet bulb temperature (°C)	3 h
Precipitation (mm)	12 h
Weather type (code)	3 h

The wind speed at each level of interest was determined by the simple power-law relation (see, e.g., Cook 1985)

$$v_i = [(H_i - 25\text{ m})/10\text{ m}]^{0.27}v, \qquad (1)$$

where the zero-plane displacement of 25 m and the exponent of 0.27 are appropriate to this densely forested area. Equation (1) is a rough approximation for the wind speed on average. More detailed estimates for H_i are not possible in this case and in most similar applications because atmospheric stability conditions vary significantly and there are no data to determine them.

The in-cloud ice load, M_i^{IC} (N m^{-1}), for each event was estimated following Ahti and Makkonen (1982),

$$M_i^{\text{IC}} = 5.5 \times 10^{-3}v_iT_ig, \qquad (2)$$

where 5.5×10^{-3} is an empirical constant, v_i is the wind speed (m s^{-1}) at the level of interest, T_i is the event duration (h), and g is the gravity constant (9.81 m s^{-2}). Equation (2) is based on measurements on a 0.05-m-diameter cylinder. Differences in tower component dimensions and changes in dimensions due to ice were not taken into account for three reasons. First, the cloud drop size and liquid water content necessary for such calculations are not part of routine weather observations. Second, the droplet collision efficiency theory is mostly outside its verified range (Makkonen and Stallabrass 1987) under our conditions, as the iced structure dimensions are quite large. Finally, field measurements by Druez at el. (1988) and small-scale tests in a wind tunnel (Makkonen and Oleskiw 1997) indicate that the ice loading rate per unit length is rather insensitive to the dimensions under these conditions.

2) FREEEZING PRECIPITATION ICING

The following criteria of Makkonen and Ahti (1995) are used to describe the freezing precipitation events,

freezing rain or freezing drizzle observed

or

rain or drizzle observed and $t_w < 0°$C, where t_w is the wet bulb temperature. Under these conditions the heat balance of the fallen precipitation particles is negative, making freezing possible. The initial temperature of the drops cannot be used as separate criterion because it is unknown. Thus, it is implicitly assumed that the drop temperature is 0°C. The loading rate of freezing precipitation, I (mm h^{-1}), on a vertical surface is

$$I = wv_i, \tag{3}$$

where w is the liquid water content. The liquid water content w is derived from the precipitation rate following Stallabrass (1983) as $w = 0.26R^{0.88}$, where R is the precipitation rate (mm h^{-1}). Equation (3) assumes the freezing fraction, $n = 1$. This assumption is based on the lack of shed water, as indicated by the fact that icicles have never been observed on the tower or on trees in this area. Considering the actual water flux that impinges on the vertical components of the mast the upper limit of the freezing precipitation load, M_i^{FP} (N m^{-1}) is determined by

$$M_i^{\mathrm{FP}} = 0.26R^{0.88}v_i T_i A_i g, \tag{4}$$

where v_i is the wind speed (m s^{-1}) and T_i is time of precipitation (h) at the weather station.

3) WET SNOW ACCRETION

The criteria for wet snow events used were (Makkonen 1989)

snowfall or sleet observed

and

$$t_{w,i} > 0°\mathrm{C}.$$

The loading rate wet snow, I (mm h^{-1}), is assumed to be

$$I = R, \tag{5}$$

based on Makkonen (1989). That I is independent of the wind speed, according to Eq. (5), is because at high wind speeds the higher impinging snow flux is compensated by more efficient rebouncing of the snow particles at impact. Makkonen (1989) justified this relation for wet snow on horizontal wires. Since little is known on wet snow accretion on vertical surfaces, Eq. (5) was used here. The wet snow load, M_i^{WS} (N m^{-1}) was accordingly determined by

$$M_i^{\mathrm{WS}} = RT_iA_ig. \tag{6}$$

4) UNLOADING

The measured loads show that spontaneous unloading of structures appears at temperatures below melting as well as above. Only unloading due to melting was considered in the model due to unknown mechanisms of other types of unloading events. The unloading criterion used was

$$t_{a,i} > 0°\mathrm{C} \quad \text{for 3 h or more,}$$

where $t_{a,i}$ is the air temperature at each section. At the deicing criterion the cumulative icing is interrupted and the section is totally deiced in 3 h.

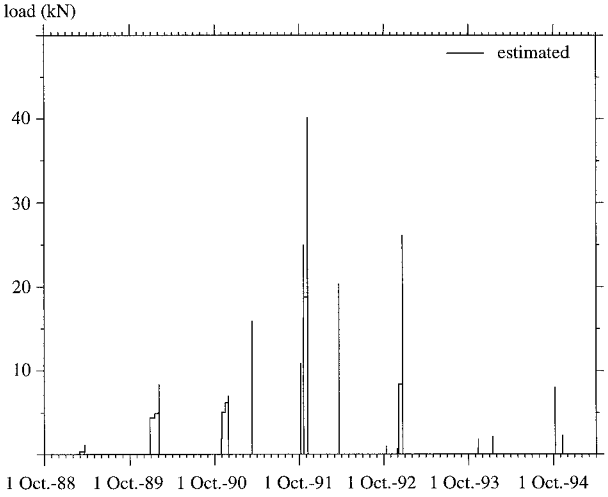

FIG. 4. Freezing precipitation loads of the tower estimated from weather station data of Storberg. Years 1988–89 to 1994–95. These loads, as well as loads due to wet snow, are insignificant compared to those caused by in-cloud icing.

4. Results

The result show that in-cloud icing is the entirely dominant type of ice on this tower. Freezing precipitation is both less frequent and also lower in magnitude compared to in-cloud icing (Fig. 4). Significant loads due to wet snow did not occur at all and, consequently, detailed results are shown only for the total load.

Overall results are shown in Figs. 5–12. Figure 5 shows all seven seasons, while Figs. 6–12 show year by year results. The results show reasonable agreement in the time of the icing events and mostly the loads also agree. Only loads heavier than 500 kN should be considered significant icing events. Below this limit ice is hardly traceable, according to on-site observations (Fahleson 1995). There are some unpredicted significant icing events. These are mostly due to incorrectly predicted ice melting in the modeling. In the other cases where the modeled cumulative ice loads are too high, the discrepancies are mostly due to unpredicted unloading.

The measurements of the loads during the first season, 1988–89, were limited to the last part of the winter. Icing may have occurred in November to January. In 1989–90 the load measurements were very limited. Except for two very short measurements, a few days in December and January, the measuring period only lasted for 3 weeks in February. There was an interruption in the measurements of the loads from 21 November to 17 December 1991. In February and March 1991 the mea-

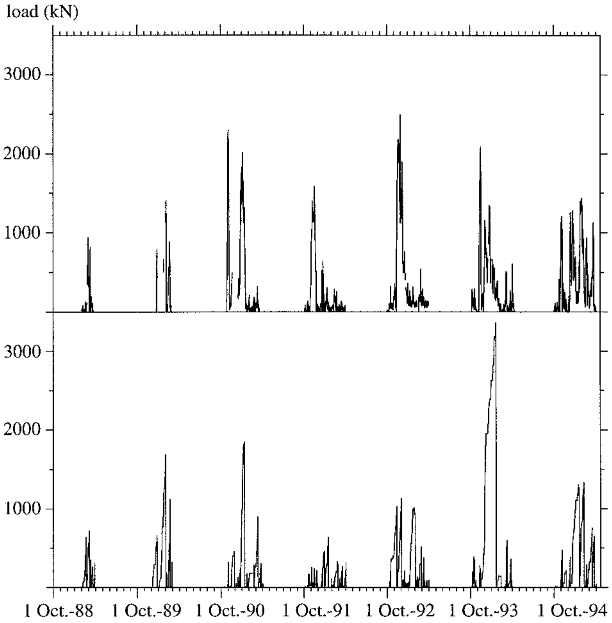

FIG. 5. Ice loads of the tower, measured and estimated from weather station data. Years 1988–89 to 1994–95.

sured loads were very low or zero. Two short interruptions of the load measurements occurred in 1991–92: 9–11 November and 21–24 December. In February and March, the measured loads were very low or none. In 1992–93 there was one interruption in the load measurements, 11–17 February.

In the other years measurements were almost continuous. The measured ice loading rates are up to 15 kN h^{-1}. Lehtonen et al. (1991) measured ice loading rates, up to the same value, on a 127-m-high TV tower located at a higher elevation in northern Finland. Estimated ice loading rates are mostly quite similar to the measured loading rates. Unloading events are simulated as instantaneous and only when caused by melting. The shedding rates induced by wind at temperatures below zero were found by Lehtonen et al. (1991) to be 10–20 times lower than deicing rates due to melting but become significant in estimating loads for long periods. This limitation of our estimation method is clearly shown by Fig. 11. During the period of December 1993 and January 1994 estimated icing without unloading disagree with the measurements that show unloading events. During these periods the measured air temperature was continuously below zero.

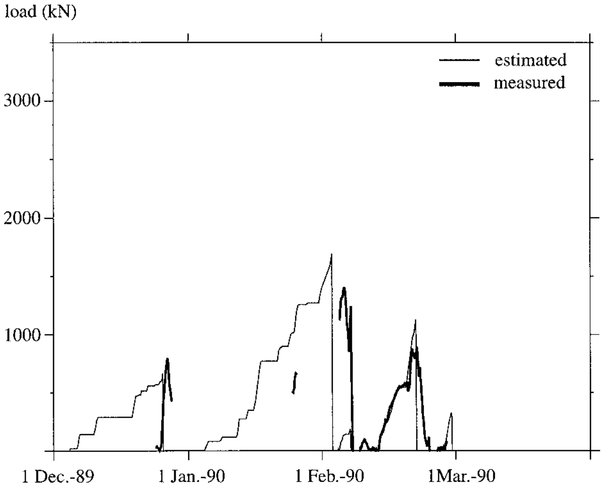

FIG. 7. Estimated ice loads based on weather station data and measured ice loads on the tower. Year 1989–90.

5. Discussion

The estimation procedure of this paper has obvious limitations. Evolution of ice loads on a complex tower structure involves complicated phenomena and is sen-

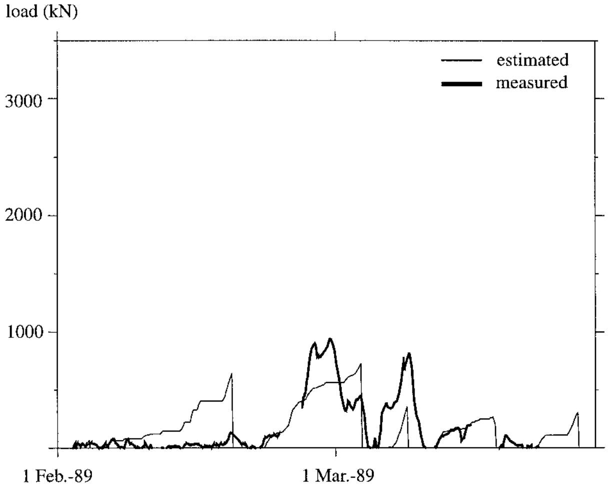

FIG. 6. Estimated ice loads based on weather station data and measured ice loads on the tower. Year 1988–89.

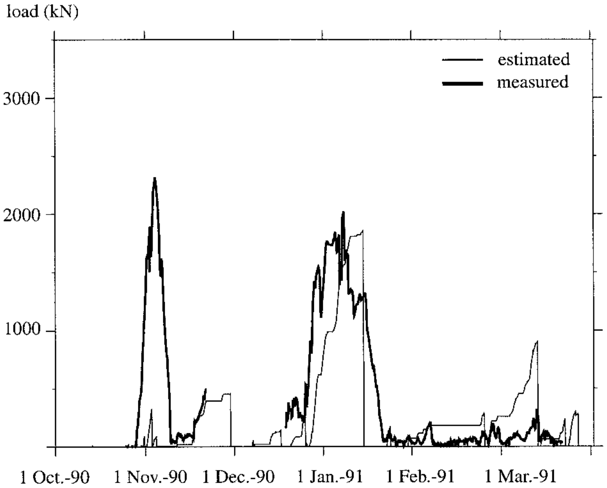

FIG. 8. Estimated ice loads based on weather station data and measured ice loads on the tower. Year 1990–91.

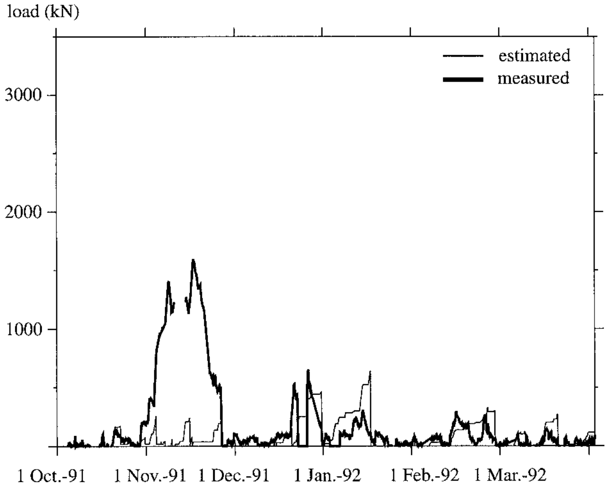

FIG. 9. Estimated ice loads based on weather station data and measured ice loads on the tower. Year 1991–92.

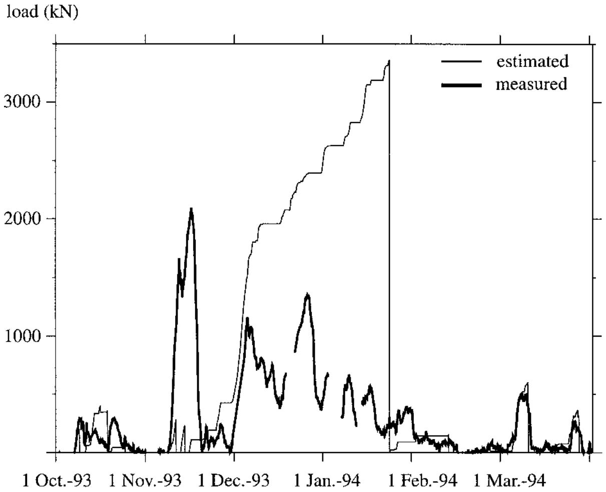

FIG. 11. Estimated ice loads based on weather station data and measured ice loads on the tower. Year 1993–94.

sitive to atmospheric conditions. To predict such a process for long periods cumulatively using rough icing calculation methods, incomplete simulation of ice shedding, and weather data extrapolated from ground observations at another site is a brave attempt. On the other hand, motivation for this attempt is strong. There are no other systematic ways by which site-specific design ice load estimates for high towers can be made.

Ice loads caused by precipitation turned out, in this study, to be insignificant and below the measurement detection limit. The method used can, therefore, be quantitatively verified in this study only in regard to in-cloud ice. For this, the results support the feasibility of the method but point out many problems. Most major icing events are well detected and the predicted icing rates are generally of the right magnitude.

The mean annual maximum load for the 7 years studied is 1750 kN as predicted and 1550 kN as measured. The overprediction, as well as most of individual discrepancies between the predicted and measured loads, are related to undetected or incorrectly predicted unloading events. This is to be expected because no attempt was made to model shedding mechanisms other than melting and because correct prediction of melting would require very accurate temperature estimates at various heights up to 300 m—a task impossible using ground temperature measured at the weather station. An example of these problems can be seen in Fig. 9, where the ice load in November 1991 is not modeled because of the estimated temperature being repeatedly above 0°C. A further cause of unpredicted unloading events may be that the measured load data involves an effect of the guy wires. As shown by Fahleson (1995), the condition that the load on the shaft is half of the total

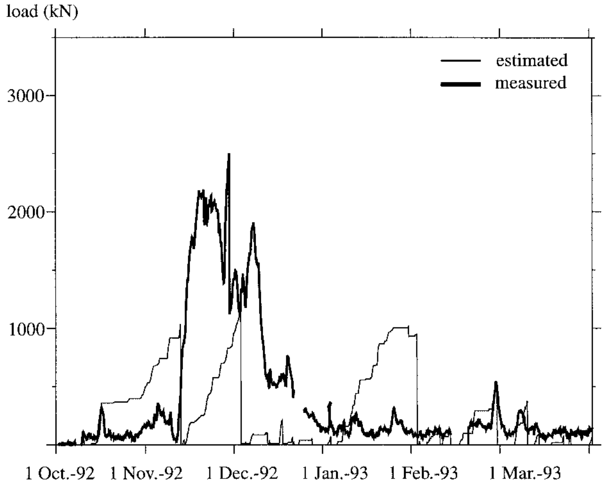

FIG. 10. Estimated ice loads based on weather station data and measured ice loads on the tower. Year 1992–93.

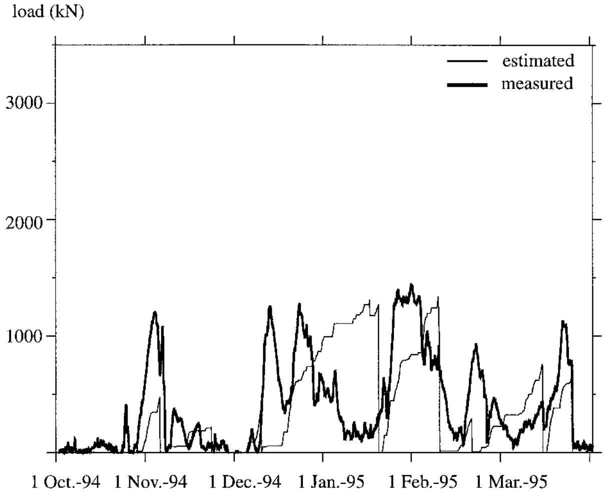

FIG. 12. Estimated ice loads based on weather station data and measured ice loads on the tower. Year 1994–95.

load may not apply to all those cases where shedding occurs from vibrating guy wires but not from the shaft. There is indication of this during the major modeled icing period in Fig. 11.

As the estimation method applied in this paper shows promise, attempts should be made to improve it. One possibility would be to make a multicorrelation analysis to find relationships between various weather parameters and loading and unloading events. Such an analysis might produce curves in even better agreement than those in Figs. 4–10. We chose, however, not to try such an approach here for the danger of it; application of purely statistical relationships to other structures at different locations might result in serious errors as long as the loading and unloading mechanisms are incompletely understood.

A way to improve the understanding of icing and shedding phenomena on complex structures is to continue model developments and measurements of ice loads combined with on-site meteorological observations. One of the lessons from this study is that it appears to be particularly difficult to predict ice melting and shedding using extrapolated weather data. The on-site air temperature is particularly important for the ice melting events and, consequently, the cumulative loads to be correctly modeled. More sophisticated icing modeling would include liquid water contents and droplet size inputs and would simulate time-dependent aspects of the icing process (see, e.g., Makkonen 1984; Lehtonen et al. 1991).

While making such developments one should keep in mind, however, that the main application of this methodology is not to simulate accurately individual icing and shedding events but to derive from long-term routinely measured meteorological data representative ice load statistics. In this regard the results in Fig. 5 are quite promising. Using such statistics an engineer can then derive, say, 50-yr return period ice loads for optimized structural design.

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