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Probabilistic Analysis of Interaction of Atmospheric Icing with Wind

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Climatic actions are correlated with each other as they are generated by phenomena related to the physics of the atmosphere. However, this correlation is poorly reflected in codified rules for their combinations. This is why the partial factors and other reliability elements provided in CEN and CENELEC standards for specific types of structures such as masts, towers, and chimneys – sensitive to the effects of climatic actions – are analysed using probabilistic methods. Currently valid and new drafts of prescriptive documents are considered in this study. It appears that the application of recommended values of partial factors for design of these structures may lead to a significantly lower reliability level than that accepted for other types of structures. The reliability elements should be calibrated against specified target reliability levels for different consequence categories of structures. Obtained low reliability levels might suggest that the design procedures could involve some "hidden safeties" that will be investigated within further research.

Keywords: Climatic actions, interactions, partial factors, target reliability level, masts, towers.

1. Introduction

Climatic phenomena differ in the way how they interact with the structure. Wind exerts pressure or suction perpendicular to exposed surfaces while snow and atmospheric icing act similarly as gravitational loads. The duration and occurrence rate of load renewals is specific to each of them. Wind actions have several time scales, each associated with one physical phenomenon contributing to the wind dynamics. Maxima of snow and icing loads are commonly associated with a reference period of one year as they often result from the accumulation process. The duration of a load phase of the leading climatic action such as wind storm, significant roof snow load or icing is important for its combination with other climatic actions, thus affecting partial and combination factors and the total load effect.

Climatic actions are correlated with each other as they are all generated by phenomena related to the physics of the atmosphere. For example, it is expected that if there is snow or icing, then the temperature is low. However, this correlation is poorly reflected in codified rules for combinations of climatic action effects.

Climate changes influence climatic phenomena and increase uncertainties concerning climate action effects on building materials, structures, and building processes in the future.

A climatic action F can be generally defined as

$$F = F(C, c_e, c_i, c_d) \qquad (1)$$

where the c_i factors transform the climatic variable C into the climatic action F, c_e denotes an exposure factor for the effects of the environment surrounding the structure, the height from the ground, and the exposure to the solar radiation; c_i denotes an interaction factor that covers the effects from the interaction of the climatic phenomenon with the structure, and c_d is a dynamic factor accounting for possible vibrations induced to sensitive structures by the short-term variability of the action.

The climatic actions can be described considering the loading chain, CEN/TC 250/ SC1.T6 (2022). For atmospheric icing five links are illustrated in Fig. 1 - climate characteristics of the region, the characteristics of construction works, properties of the atmosphere, mechanism of icing development, and design criteria.

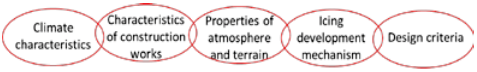

Fig. 1. The icing loading chain.

2. Structures Sensitive to Icing with Wind

Civil engineering works such as masts and towers, various steel members of high-rise structures, and also electrical transmission lines are sensitive to atmospheric icing and wind. The procedure for determination of ice loads and their effects on structures is given in the international standard ISO 12494 (2017) which was implemented in some countries including the Czech Republic where supplementary national provisions including specific rules for combinations of icing with wind are given in the new national standard CSN 73 0034 (2017).

In the presently valid Eurocodes, the basic guidelines for the design of ice loads on civil engineering structures such as steel masts and towers are included in EN 1993-3-1 (2006). In the second generation of Eurocodes, the new Eurocode EN 1991-1-9 (2022) for atmospheric icing has been developed from the conversion of ISO 12494 in the technical subcommittee CEN/TC 250/SC1. The basis of design including combinations of actions and serviceability criteria currently given in EN 1993-3-1 (2006) has been transferred during the revision of Eurocodes to the new Annex A.3 of prEN 1990 (2023) for the basis of the design of towers, masts, and chimneys. The design working life of a tower or mast made of different materials can be considered to be in a broad range from 30 to 100 years depending on the category of structure and purpose of its use.

For overhead electrical lines, the basis of design, various types of actions including climatic actions are within the scope of EN 50341-1 (2012) where selected provisions of Eurocodes concerning actions on structures were incorporated.

However, a considerable difference between the rules for the design of masts, towers, and other specific structures provided in both CEN and CENELEC standards remains including models for icing and wind, reliability differentiation of structures, partial factors, combination factors, and target reliability levels.

3. Atmospheric Icing Data

Annex C2 in EN 1991-1-9 (2022) states the need for standardized ice measuring devices to obtain suitable data for atmospheric icing. Accretion of atmospheric icing is commonly not measured in the stations of national weather services, although freezing fog, rain, and drizzle are observed as they can cause significant issues to the air traffic. Ice accretion should be measured by using a cylinder of 3 cm diameter and a length of 50 to 100 cm (reference collector) and by recording the ice mass on the cylinder; see Fig. 2. The cylinder should be placed vertically, 10 m above the ground surface, and slowly rotating around its axis. In some countries such as in the Czech Republic, the reference collector for ice accretion is placed horizontally and is not rotating.

Fig. 2. Rotating cylinder for ice measurements itself without ice while other structural parts can be further affected by wind.

The measurement frequency may be adjusted to local meteorological conditions, but should at least record the seasonal maximum. Measurements should be collected for a sufficiently long period to form a reliable basis for extreme value analysis. For the purposes of structural reliability verifications, the length of the period could be from a few years to several decades, depending on conditions, commonly e.g. at least 20 years.

The probabilistic model for the fundamental ice load can be based on the extreme value distribution, e.g. on Gumbel or Generalized Extreme Value distribution.

The fundamental value of the basic ice load $m_{b,0}$ is given by the characteristic value of rime mass or glaze thickness obtained on a reference collector which is expected to occur with an annual probability of exceedance of 0.02. The fundamental values of the basic ice loads $m_{b,0}$ are either defined based on Ice Classes (IC) or from the characteristic rime ice mass or characteristic glaze ice thickness, irrespective of wind direction, of the ice collector, and the orientation of the ice collector.

In addition to atmospheric icing, ambient air temperature, humidity, wind velocity and its direction should be measured.

4. Reduction Factor *k*

Guidance for the combination of icing with wind is given in prEN 1991-1-9 (2022). The reduction factor *k* is used to decrease the wind pressure due to low probability that the wind action of a 50-year return period will occur simultaneously with heavy icing conditions.

The values of the reduction factor *k* for glaze classes (ICG) and rime classes (ICR) are given in Table 1. For the higher rime classes R6 to R8, the factor *k* increases by 0.1 and for the classes R9 and R10, $k = 1$ should be applied (no reduction). The same values of the reduction factor *k* are given in ISO 12494 (2015).

Table 1. Factor *k* for reduction of wind pressure.

ICG	*k*	ICR	*k*
G1	0.40	R1	0.40
G2	0.45	R2	0.45
G3	0.50	R3	0.50
G4	0.55	R4	0.55
G5	0.60	R5	0.60

However, when considering the combined effect of icing and wind on a structure, it should also be taken into account the changed geometric characteristics of the iced structural members. It could be different to have an iced rod only or an iced object from which the ice affected by wind will not fall so quickly having a potentially harmful effect on the structural member.

It is also necessary to consider whether to apply the combination factor ψ_0 with the reduction factor *k* simultaneously as it is presently recommended in Eurocodes and ISO 12494 (2015), but it is not assumed in EN 50341-2-19 (2015).

The extent of the interdependence of icing load and wind velocity was analysed for several locations in Germany and Sweden. The interdependency of icing load (q_{icing}) and wind velocity (v_{wind}) for the southwest location in Sweden is illustrated in Fig. 3. A weak positive correlation is observed for icing load and wind velocity, CEN/ TC 250/ SC1.T6 (2022).

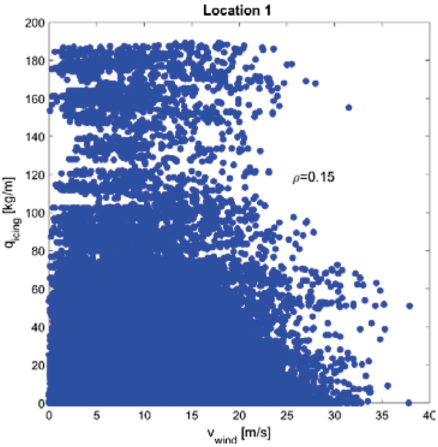

Fig. 3. Interdependency of icing load and wind velocity (period 1979-2018).

5. Reliability Differentiation

Principles of reliability differentiation for structures are given in the Eurocode prEN 1990 (2023) for the basis of structural design. Target reliability indices β_t are recommended for five consequence classes CC0 to CC3. The consequence class CC2 (for $\beta_t = 3.8$) is recommended for common types of structures for the Ultimate limit states verification with a reference period of 50 years. More detailed reliability differentiation is further given in ISO 2394 (2015) considering also the failure consequences and relative costs needed for safety measures.

Currently valid EN 1993-3-1 (2006) gives three consequence classes CC1 to CC3 with examples without indicating specific target reliability indices; the standard refers to EN 1990 (2002). This indicates that the same values of target reliability indices as provided in EN 1990 (2002) should be considered for towers and masts categorized into individual consequence classes; no further information is available.

A new classification of towers and masts into different consequence classes from CC0 to CC3 as proposed in the final draft of prEN 1990 (2023), Annex A3 is indicated in Table 2 considering a range of possible failure consequences – injuries or loss of human lives, economic or environmental consequences. The values of partial factors for unfavourable action effects can be differentiated using the consequence factor k_F depending on the consequence class of the structure.

Table 2. Reliability differentiation and the consequence factor k_F for towers, masts, and chimneys in Annex A.3.

Consequence class	Description of consequences	Consequence factor k_F
CC3	high	1.1
CC2	normal	1.0
CC1	low	0.9
CC0	lowest	0.8

The same values of partial factors as for buildings given in Annex A.1 of prEN 1990 (2023) are considered for towers, masts, and chimneys; unfavourable effects of permanent and variable actions are then multiplied by an appropriate k_F-value.

It should be noted that EN 50341 (2012) gives three different reliability levels for overhead lines, related to the consequence classes CC1 to CC3 and return periods of climatic actions (50, 150, and 500 years, respectively).

An overview of the recommended partial factors for permanent actions, wind, and ice loads provided in EN 50351 (2012), and also partial factors of EN 1993-3-1 (2006) for the consequence classes CC1 to CC3 is provided in Table 3.

Table 3. Partial factors in EN 50351 and EN 1993-3-1.

Action	EN 50341-1			EN 1993-3-1		
	CC1	CC2	CC3	CC1	CC2	CC3
Permanent	1	1	1	1	1.1	1.2
Wind	1	1.2	1.4	1.2	1.4	1.6
Icing	1	1.25	1.5	1.2	1.4	1.6

The unusually low value $\gamma_G = 1$ recommended for the partial factor for self-weight and permanent load in EN 50341-1 (2013) does not comply with the guidance of prEN 1990 (2023), Annex C.

The combination factor ψ_0 with reduction factor k provided in ISO 12494 (2017) and also in EN 1991-1-9 (2022) for accompanying load effects of wind and icing are given in Table 4.

Table 4. Comparison of combination factors ψ_0.

Action	ISO 12494	EN 1993-3-1	EN 50341-1
Icing	0.3	0.5	0.35
Wind	$0.6k$	$0.5k$	0.4

6. Models for Icing

EN 50341-1 (2012) distinguishes ice regions while ISO 12494 (2017) provides ice classes, Wichura B. & Makkonen L. (2009). The mass density of icing may be in a broad range from 300 to 900 kg/m^3.

The specification of ice classes and ice regions in CEN and CENELEC standards resulted in the need for the development of different icing maps for practical applications for civil engineering structures and energetic devices including power lines in some countries including the Czech Republic. The map of ice classes in the nationally implemented ISO 12494 (its National Annex given in CSN 73 0034 (2018)) is illustrated in Fig. 4. The map was prepared in the cooperation of the Czech Meteorological Institute with the authors of this study.

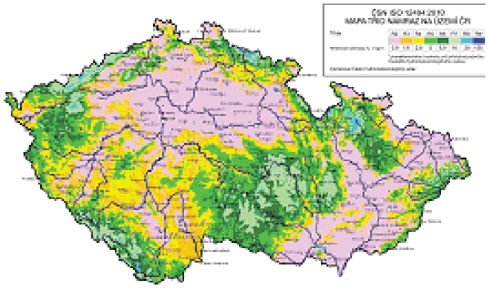

Fig. 4. Czech map of ice classes in CSN 73 0034.

Another national map for the Czech icing regions for the structural design of electrical power lines is given in EN 50341-2-19 (2017), see Fig. 5. The database of measurements of icing is based on collected data from the Czech company EGU Brno dealing with power engineering.

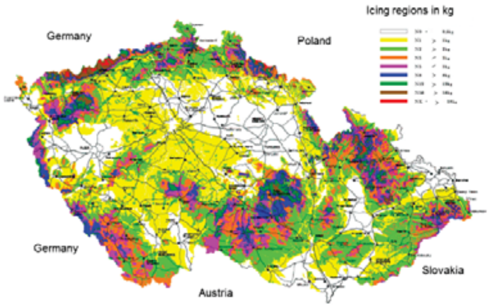

Fig. 5. Map of icing regions in CSN EN 50341-2-19.

Presently the new Eurocode EN 1991-1-9 (2022) is available where it is allowed to directly specify the characteristic ice load instead of an ice class, see Nygaard (2019).

The rime ice shape model for various structural components in prEN 1991-1-9 (2022) is considerably simplified in comparison to ISO 12494 (2017).

7. Load Combination for ULS verifications

It was shown that the reliability of some construction works sensitive to icing and wind such as steel masts and guided towers designed according to current European and international standards may be considerably lower than the reliability level of other types of structures, Markova J. (2011) and Markova & Holicky (2015).

In this study, the probabilistic methods of the theory of structural reliability are applied for the reliability analysis of a selected steel member designed according to currently valid and new prescriptive documents.

The combination of three actions is considered in the reliability assessment of a steel member: a permanent action G, ice load I, and wind W. Two load cases of wind and icing need to be considered. In the first load case, the main action is an ice load which is combined with wind considered as an accompanying action. In the second load case under consideration, the wind pressure is a dominating variable load.

The combination of actions in the permanent design situation given in prEN 1990 (2023) is considered. Assuming the linear behaviour of structural members, the actions G, I, and W and their characteristic values G_k, I_k, and W_k denote appropriate load effects. Considering the icing as a leading action, the design value of action effect E_d is given as (+ denotes in combination)

$$E_d = \gamma_G G_k + \gamma_I I_k + \gamma_W k \psi_W W_k \qquad (2)$$

In case that the leading action is wind W, then the wind W will be reduced by reduction factor k, and the icing I should be reduced by the appropriate factor ψ_I. Factors γ_G, γ_I and, γ_W denote the partial factors of actions G, I, and W.

To investigate resulting load effects under various intensities of variable actions, see Markova (2018), the characteristic values of actions G_k, Q_k, and W_k are related using quantities χ given as the ratio of both the characteristic values of climatic actions $I_k + W_k$ to the total load $G_k + Q_k + W_k$, and ratio κ of the characteristic values of wind and icing

$$\chi = (I_k + W_k)/(G_k + I_k + W_k),\ \kappa = W_k/I_k \qquad (3)$$

Commonly a realistic range of χ for lightweight steel structures may be considered from 0.5 up to 0.8.

Reliability analysis is based on the limit state function g($\boldsymbol{X}$) corresponding to the load effect of permanent and variable actions and resistance R of a steel member (for simplicity considered here as a tie) expressed as

$$g(\boldsymbol{X}) = \theta_R R - (G + I + W) \qquad (4)$$

where $\boldsymbol{X}$ denotes the vector of basic variables (random variables entering the right-hand side of this equation) and θ_R is the factor expressing the uncertainty of the resistance model. The model uncertainty of the action effect is not considered here for a steel tie.

It is necessary to specify the probabilistic models for the basic variables. The limit state function (see Eq. (4)) has five basic variables that describe the actions G, I, and W, the resistance R and the model uncertainty θ_R. Simplified (e.g. averaged over a common loaded area) probabilistic models are indicated in Table 5. These models are considered in time-invariant reliability analysis of a structural member using Turkstra's combination rule where a combination of 50 years maximum of a leading action with an annual action of a non-dominant action is considered.

Table 5. Probabilistic models of basic variables for time invariant reliability analysis

Basic variable	Distr.	X_k	μ	V
Permanent	N	G_k	G_k	0.03
Wind (1 year)	GUM	W_k	0.3 W_k	0.50
Wind (50 years)	GUM	W_k	0.7 W_k	0.35
Icing (1 year)	GUM	I_k	0.6 I_k	0.25
Icing (50 years)	GUM	I_k	1.9 I_k	0.10
Resistance steel	LN	280	235	0.06
Res. uncertainty	N	1.0	1.1	0.05

The mean μ_X and coefficient of variation V_X of each variable are intentionally related to the characteristic value X_k used in the design calculations. The coefficient of model uncertainty θ_R is described by a random variable having a coefficient of variation of 0.05.

The probabilistic model for ice load is based here on the selected results of the cooperation of the Klokner Institute CTU with the Czech Hydrometeorological Institute during the development of the icing map to the National annex of the Czech Republic to nationally implemented ISO 12494 (2001) and preparation of its National Annex.

Presently only limited systematic long-term measurements are available worldwide for ice loads, often having values of the coefficients of variation of ice loads from 0.4 to 1 depending on the site location. Long-term measurements of icing, spanning over about 60 years, are also available in some places of the Czech Republic.

8. Probabilistic Reliability Analysis

The probabilistic reliability analysis is based on the design condition given as

$$\theta_R \, R(\boldsymbol{X}) > \theta_E \, E(\boldsymbol{X}) \tag{5}$$

where $\boldsymbol{X}$ is the vector of random variables. The probability of failure P_f determined from the reliability analysis describes the likelihood that condition (5) is not met.

The reliability index β is considered in the following analyses instead of the failure probability P_f given as

$$\beta = \Phi^{-1}(1 - P_f) \tag{6}$$

where Φ is a standardized normal distribution function.

The target value of the reliability index β_t = 3.8 recommended in prEN 1990 (2023) for the Consequence Class CC2 (common structures) corresponds to the probability of failure $P_f = 7.24 \times 10^{-5}$. It should be noted that a higher Consequence Class (CC3, β_t = 4.3) and a lower Consequence Class (CC1, β_t = 3.3) are also provided in Annex C of prEN 1990 (2023).

It is assumed that the ice load I is a leading variable action and the wind W is an accompanying action, where the load ratio χ = 0.5.

In the design of a steel member, the partial factors γ and combination factors ψ_0 for actions are accepted based on the recommendation of codes indicated in Tables 2 and 3 and probabilistic models of basic variables given in Table 5.

Fig. 6 indicates significantly low values of the reliability index β as a function of the load ratio χ between the characteristic values of variable loads to total loads assuming the design of a steel member according to currently valid Eurocode EN 1993-3-1 (2022) and relevant sets of partial factors given for the consequence classes CC0 to CC3 (partial factors for permanent loads from 1 to 1.2, and for variable actions from 1.2 to 1.6).

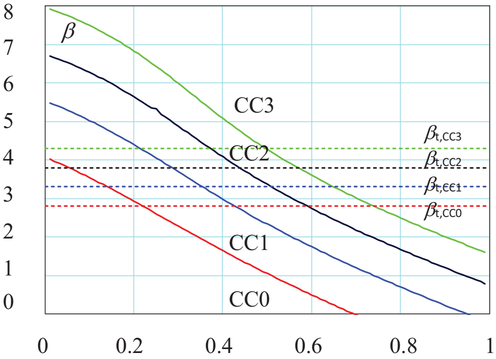

Fig. 6. Variation of 50-year reliability index β with the load ratio χ, the load combination based on a set of partial factors in EN 1993-3-1 (2006) recommended for the consequence classes.

Fig. 7 shows the reliability index β versus the load ratio χ for a steel member assuming the design according to new Annex A.3 of prEN 1990 (2023), EN 1993-3-1 (2006), and EN 50541 (2012) for the relevant sets of partial factors and reduction factors recommended for the common reliability level CC2. The reliability level achieved by the application of the original Czech standard CSN 73 1430 (1984) is also indicated.

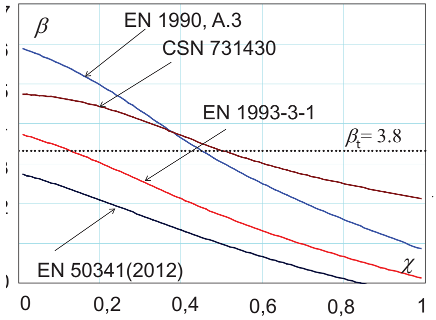

Fig. 7 The 50-year reliability index β versus the load ratio χ considering icing as leading action and reliability elements for structural class CC2 in standards of CEN, CENELEC, and also in original Czech standard CSN 73 1430.

It follows from Fig. 7 that the reliability levels associated with the design according EN 1993-3-1 (2006) and EN 50541 (2012) are very low.

As part of the national implementation of the current generation of Eurocodes in all CEN Member countries, the partial factors and other reliability elements for towers and masts have been already calibrated at the national level to meet the requirements for national safety and also the economy of the design. In addition, the power-producers whose structures of electrical overhead-lines sometimes fall down during a winter storm have the experience that the structural failure is often caused by an accidental fall of a tree into the power-line. It should be noted that a heavy atmospheric icing is not a very common phenomenon in Central Europe, which occurs only in some specific mountainous regions without many structures and usually for a short-term period only.

9. Concluding Remarks

For the specification of models of icing, further research and data collection are needed in CEN Member countries.

The sample results of analyses of data from Germany and Norway confirm asymptotical independence between the investigated icing and wind actions on structures. To obtain a more general conclusion about the cross-correlation of icing and wind actions on structures, the analyses should be further extended to different regions. The values of reduction factor k for a decrease of wind actions in combination with icing recommended in current prescriptive documents should be checked. It appears that for the reduction of wind on the iced structure provided by the reduction factor k recommended in EN 1991-1-9 (2022) for different categories of ice classes, the characteristics of the structure with its geometry should also be considered. While the ice can fall easily from a power line in the wind, the accredited ice on a significantly frozen steel member could lead to severe effects of the interaction of icing with wind and potentially could lead to the failure of the structure.

The reliability level of structural members of towers, masts, and chimneys, designed according to the current European standards EN 1993-3-1 (2006) and EN 50341 (2012) is significantly lower than recommended in prEN 1990 (2023).

Presently, no recommendations for the target reliability level of steel masts, towers, and other similar structures are provided in EN 1993-3-1 (2006) and EN 50341 (2012).

It appears that the reliability level of a steel member in CC2 class designed based on reliability elements recommended in the subclause A.3 of prEN 1990 (2023) and in Czech national code CSN 73 1430 for the common range of the load ratio χ comply with requirements for the target consequence class CC2 in prEN 1990 (2023).

The models for actions and their combinations recommended in CEN, CENELEC, and ISO standards should be further calibrated and harmonized. The combination factors ψ_0 and reduction factor k should be further verified for recommended target reliability levels. For the specification of models of icing, further research and data collection are needed in CEN Member countries.

In connection with the preparation of the 2nd generation of Eurocodes, it will be necessary to propose a new National Annex to prEN 1990 for the basis of design of towers, masts and chimneys, in which it will be selected the partial factors for actions and also the combination factors including the reduction factor for simultaneously effect of wind with icing. New data on climate loads are currently being collected and evaluated, and new updated icing map is planned to be developed in the Czech Republic.

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