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Reliability and code level

Michael Kasperski†

Ruhr-University Bochum, Department of Civil Engineering, Germany

Chris Geurts‡

TNO Building and Construction Research, The Netherlands

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Abstract. The paper describes the work of the IAWE Working Group WBG - Reliability and Code Level, one of the International Codification Working Groups set up at ICWE10 in Copenhagen. The following topics are covered: sources of uncertainties in the design wind load, appropriate design target values for the exceedance probability of the design wind load for different structural classes with different consequences of a failure, yearly exceedance probability of the design wind speed and specification of the design aerodynamic coefficient for different design purposes. The recommendations from the working group are summarized at the end of the paper.

Keywords: design wind load; design wind speed; design aerodynamic coefficient; structural classes; uncertainties; extreme values.

1. Introduction

Working group B was set up at the first International Codification Workshop held at the Ruhr University Bochum on September 15th 2000 to concentrate discussion on problems related to the reliability and level of accuracy of wind loading codes. The members of the working group are M. Kasperski (Germany) Convenor, C. Geurts (The Netherlands), A. Goliger (Republic of South Africa), R. Hoxey (Great Britain), J. Kanda (Japan), E. Simiu (U.S.A.) and T. Stathopoulos (Canada). The paper summarizes the discussed topics and presents some general recommendations on how to specify an appropriate design wind load.

2. Reliability and uncertainty

2.1. Basic definition

Reliability is defined as the probability that a system or component performs its required functions under stated conditions for a specified period of time. The complement of reliability is the failure

† michael.kasperski@rub.de
‡ c.geurts@bouw.tno.nl

probability, i.e., the probability that a system fails to perform its required function under stated conditions before the end of the specified target period of time. In structural engineering the required functions are primarily the structural safety and the serviceability. The stated conditions are the actions or more precisely the combined action effects that are expected to occur in the specified design working life.

For a mass product like e.g., a bulb the failure probability can be obtained by simply counting the number of failures that have occurred in a certain period and divide this number by the total number of observed systems. Structural reliability cannot be counted in this way but it has to be estimated based on models for the resistance R of the system and models for the combined action effects E. The distance between R and E is called the safety zone Z; if Z becomes smaller than 0, a failure is obtained. The failure probability is the integral over the safe region of the joint probability density function of the random variables defining the loads and the resistance. Since the information for the statistical models for R and E is imperfect the reliability is obtained as an estimated value within confidence bounds that can in principle be estimated.

Models are only approximate representations of the behavior of a system. The corresponding uncertainties in the estimation of the structural reliability are referred to as modeling uncertainties. A second group of uncertainties is associated with sampling errors that arise from the fact that the size of the samples used in the estimates is limited.

In practice, the complete structural reliability analysis is replaced by a simple comparison of two design values, one for the resistance and one for the combined action effect. The design values are introduced as appropriate fractile values of the respective probability distributions. The design value for action effects is given by specifying a target value for the exceedance probability. It is reasonable to specify target values for the ultimate limit state for the reference period of the design working life and to use for the serviceability limit state annual exceedance probabilities.

2.2. Coping with uncertainties

Uncertainties in estimating a parameter of a model or a probability of an event means that the estimated value may be smaller or larger than the 'true' value. Model uncertainties usually are dealt with by introducing estimations to the safe side or neglecting some favourable features of the analysed phenomenon. Statistical uncertainties can be expressed by specifying the probability or confidence that the true value is in a specific range around the estimated value. In structural engineering, confidence is usually introduced as a one-sided range. If a design value of the resistance is estimated, the confidence is introduced to avoid an overestimation, i.e., to avoid that a value larger than the 'true' design value for the resistance is used in the design calculations. For action effects, the purpose of a confidence is to avoid an underestimation of the 'true' value.

The inherent randomness in the estimated design value can be obtained from e.g., a Monte Carlo Simulation. In the following example, it is assumed that the extremes follow a type I extreme value distribution:

$$F(x) = \exp\left[-\exp\left(-\left[\gamma + \frac{\pi}{\sqrt{6}}\frac{x-m}{\sigma}\right]\right)\right] \tag{1}$$

m : mean value
σ : standard deviation
γ : Euler constant = 0.5772

There are different methods for estimating the two describing parameters m and σ based on the data from a confined ensemble. The easiest and straight-forward method is the method of moments, which estimates m and σ as the ensemble mean value and standard deviation as follows:

$$m = \frac{1}{N}\sum_{i=1}^{N} x_i, \qquad \sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - m)^2 \tag{2}$$

N: ensemble size

Alternatively, the parameters m and σ can be estimated from a least-square-fit in a probability paper. A probability paper is obtained by transforming the vertical scale for the non-exceedance probability so that the target distribution appears as a straight line. The trace of the observed non-exceedance probability is obtained from order statistics, i.e., the ensemble is sorted in ascending order. The position in the sorted list is the input-value to estimate the non-exceedance probability of the corresponding x_i value as follows:

$$p(x \le x_i) = \left(\frac{i - \alpha}{N + \beta}\right) \tag{3}$$

i : position or rank in list of ascending order
α, β : parameters for the plotting position

The simplest approach, which is used in the following example, is obtained with $\alpha = 0$ and $\beta = 1$, a more sophisticated approach introduces $\alpha = 0.44$ and $\beta = 0.12$ for acceptance tests with Gumbel probability paper (Gringorten 1963). The least-square fit is obtained from solving the following linear system of equations:

$$\begin{bmatrix} \sum_{i=1}^{N} x_i^2 & \sum_{i=1}^{N} x_i \\ \sum_{i=1}^{N} x_i & N \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{N} y_i \cdot x_i \\ \sum_{i=1}^{N} y_i \end{bmatrix} \tag{4}$$

where $y_i = -\ln(-\ln(p(x \le x_i)))$

The coefficients a and b are the parameters of a straight-line fit, i.e., it is assumed that:

$$y = a \cdot x + b \tag{5}$$

The mean value and the standard deviation are obtained with the least-square fit as follows:

$$\sigma = \frac{\pi}{\sqrt{6}} \cdot \frac{1}{a} \qquad m = b + \gamma / a \tag{6}$$

A further method has been introduced by Lieblein (1974) and is known as the Best Linear Unbiased Estimator (BLUE). Two weighted sums of the sorted values x_i lead to the parameters a and b of the straight line approach:

Table 1 BLUE-coefficients for the Gumbel Distribution and $N = 19$

i	1	2	3	4	5	6	7	8	9	10
A	0.117	0.101	0.089	0.080	0.073	0.066	0.061	0.056	0.051	0.047
B	-0.183	-0.116	-0.071	-0.041	-0.020	-0.005	0.007	0.016	0.023	0.028
i	11	12	13	14	15	16	17	18	19	Σ
A	0.043	0.039	0.035	0.032	0.029	0.025	0.002	0.019	0.015	1.000
B	0.033	0.036	0.039	0.041	0.042	0.043	0.043	0.043	0.041	-0.001

$$a = \sum_{i=1}^{N} A_i \cdot x_i \qquad b = \sum_{i=1}^{N} B_i \cdot x_i \tag{7}$$

The parameters m and σ of the Gumbel distribution again are obtained from Eq. (6). The weighting coefficients for the BLUE-method can be found in tables (Cook 1985), however, only for ensemble sizes below 25. The respective values for an ensemble size of $N = 19$ are given in Table 1.

For a confined ensemble, each estimation method will lead to different values of m and σ. The design value is obtained as:

$$x_{des} = m + g \cdot \sigma \tag{8}$$

where $g = F^{-1}(p_{target}) = [-\ln(\ln p_{target}) - \gamma] \cdot \frac{\sqrt{6}}{\pi}$

In Fig. 1, the inherent randomness of the estimated design values is shown for $N = 19$ and $p_{target} = 0.999$ applying the method of moments (mom), the least-square fit (lsq) and the best linear unbiased estimator (BLUE). The 'true' design value in terms of the reduced variate $x_{red,\,des}$ is:

$$x_{red,\,des} = \frac{x_{des} - m}{\sigma} = g = 4.936 \tag{9}$$

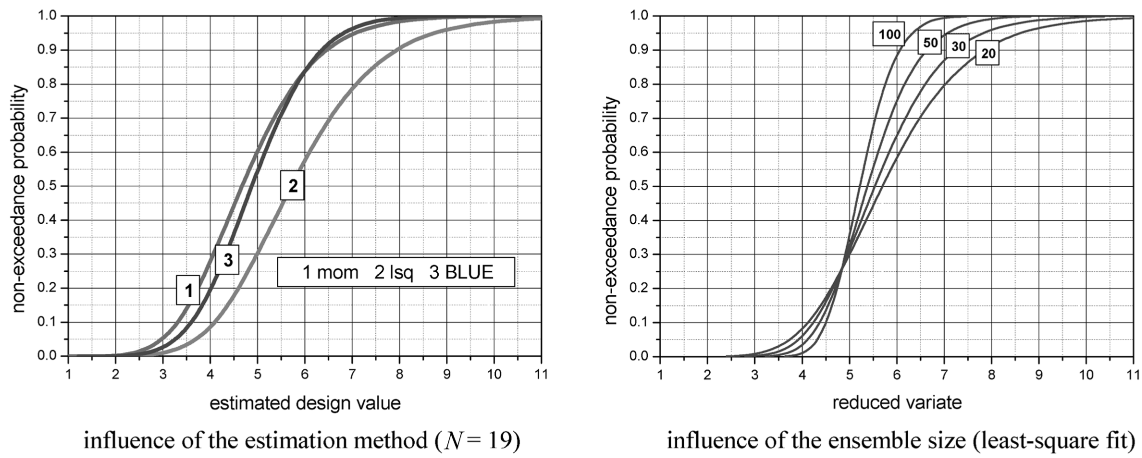

Fig. 1 Non-exceedance probability for estimated design values - random ensemble from extremes following a type I extreme value distribution

As indicated by its name, the BLUE-method leads on average to the true value (4.936), while on average the least-square fit leads to considerable overestimations (5.668) and the method of moments leads on average to underestimations (4.697). Although its name suggests that the BLUE-method is the best method to estimate the design value, it has to be understood that the probability of obtaining a too small design value with this method is 50%, while underestimations for the least-square method occur only with a probability of about 30%, i.e., the obtained one-sided confidence with the least-square fit is larger than with the BLUE-method.

The one-sided confidence of any estimation method can be improved by specifying an adjusting factor that simply shifts the trace of the estimated design values to the right side. However, it has to be understood that this approach increases the probability of an over-design. Furthermore, an adjusting factor can only be obtained if the theoretical model is known, i.e., if the type of the extreme value distribution and the variation coefficient is known.

The complement of the confidence probability is the error probability. Intuitively, one would expect a fairly small value as target for the error probability, e.g., $p_{error} = 1\%$ to 10%. A small error, however, results in expensive designs; the probability of an over-design is $1-p_{error}$. The smaller p_{error} is chosen, the higher the probability of an over-design becomes. As an appropriate value for the confidence, the Eurocode (CEN 2002) therefore recommends in its chapter ‘Design by Testing’ a confidence interval of 75%, i.e., the corresponding error probability is 25%. In other words: it is accepted that in one of four cases the resulting design will lead to a smaller reliability than the specified target reliability. It is worth mentioning that the least-square fit with an error probability of 30% requires almost no further adjustment to meet the target error probability of 25%, while applying the BLUE-method requires a considerable adjustment.

2.3. Target exceedance probabilities

Tentative target values for the exceedance probability of the design wind load are specified in the following either for the period of the design working life or in terms of annual exceedance probabilities. Approximately, the relation between these two values can be given as:

$$p_L = 1 - (1 - p_1)^L \tag{10}$$

p_L - exceedance probability in the design working life
p_1 - annual exceedance probability
L - design working life in years

It is reasonable to classify structures or structural elements in regard to the consequences of a failure. These consequences may be losses of life or economic losses. The following classes can be distinguished:

A - structures with a special post disaster function (hospitals, schools, transmission lines, bridges),
B - buildings which as a whole contain people in crowds (high-rise buildings, stadia, concert halls),
C - normal structures (office buildings, commercial buildings, factories, residential buildings),
D - structures presenting a low degree of hazard to life and other properties (farm buildings, house chimneys, roofing tiles)

The target value of the exceedance probability of the design wind load for the structural safety is

Table 2 Tentative target values of the exceedance probability of the design wind load for the ultimate limit state (reference period: ultimate limit state - design working life, serviceability limit state - one year)

Structural class	A	B	C	D
USL	0.025	0.05	0.10	0.20
SLS	0.01	0.02	0.05	0.10

Table 3 Tentative values for the design working life for different types of structures

Type of structure	Temporary structures	Industrial structures	Residential and office buildings	Bridges
Design working life	1−5 years	20−40 years	60−80 years	100 years

specified for the design working life. For serviceability, the tentative target values are given as annual exceedance probabilities. Respective tentative values are summarised in Table 2. Eventually, the owner of a structure may specify additional requirements for the serviceability, e.g., the maximum number of hours per year that a telecommunication tower is not able to keep a line connected due to vibrations induced by wind.

It is worth mentioning that usually the design working life in codes is not explicitly specified but is assumed implicitly to be 50 years. Some tentative values for the design working life are given in Table 3.

3. Sources of uncertainties

3.1. Wind climate

Meteorological data form the basis for extreme value statistics to describe the basic wind climate for a specific site. The first source of uncertainty is the quality of the recorded data. This topic has been addressed in WGF (Holmes, *et al.* 2005) and is here summarized briefly for sake of completeness. The quality of the data may be biased due to the use of imperfectly calibrated instruments. The data also may require corrections if the measurements are not performed in standard terrain or if the measurements are influenced by neighboring buildings. Such corrections are difficult to make.

Extreme wind conditions have to be expected for the following wind phenomena: tropical cyclones, synoptic storms, thunderstorms, tornadoes and gravity winds. Usually, tornadoes are not dealt with in codes since the wind forces they induce may be too large to be attended to in design. Downdrafts induced by heavy rain may occur in front of synoptic storms. They can be treated as a separated storm type.

If the extreme wind conditions at a specific location are influenced by more than one storm type, the observed extreme wind speeds should be sorted in appropriate ensembles for each storm type. The respective ensembles then have to be analyzed by an appropriate extreme value estimation method. Recommendations are given in the report of WGF (Holmes, *et al.* 2005).

Tropical and extratropical storms may have durations of extreme wind conditions that may last over several hours. Basically, the duration of strong wind conditions during a storm is an important parameter in the estimation of the exceedance probability of the design wind load. The longer the extreme wind conditions last, the higher will be the probability that the design wind load w_{des} is exceeded (Kasperski 2000). This accumulation of the exceedance probability over the duration of a storm can be described as follows:

$$p_{storm}(w > w_{des}) = \prod_{i=1}^{N_{hours}} (1 - p_i(w > w_{des})) \tag{11}$$

p_{storm} - exceedance probability in the whole storm
p_i - exceedance probability in the i-th hour of the storm
N_{hours} - duration of the storm

Thunderstorms and downdrafts on the other hand have durations of only a few minutes. The exceedance probability of the design wind load in this case is favorably affected. In relation to the case of an equivalent synoptic storm of one hour duration that leads to the same gust wind speed, the exceedance probability of the design wind load due to a downdraft is obtained as:

$$p_{downdraft}(w > w_{des}) = 1 - (1 - p_1(w > w_{des}))^{M/60} \tag{12}$$

$p_{downdraft}$ - exceedance probability induced by the downdraft
p_1 - exceedance probability in an equivalent synoptic storm of one hour duration
M - duration of the extreme wind conditions in minutes

The longest durations are obtained for the storm type gravity winds. The Mistral in the Provence, the Foehn in the Alpes or the Chinook in the Rocky Mountains may have durations from some hours to several days. Especially long durations are obtained for gravity winds in the Antarctic and in Greenland.

A further model uncertainty is obtained from assuming that the wind climate is not subject to long term trends. As a matter of fact, even for a perfect stationary wind climate random trends may be observed due to the confined observation period. These trends may occur for the number of storms per year and / or for the intensity of the storms. The statistical significance of these trends can be evaluated by assuming an appropriate probability distribution for the respective variable and by specifying an appropriate target confidence for accepting or rejecting the hypothesis of a stationary wind climate. Since the effects on the design wind speed may be large (Kasperski 1998) the confidence for accepting the existence of long-term trends should be larger than 95%.

3.2. The atmospheric boundary layer

The structure of the atmospheric boundary layer depends upon storm type. The most elaborate boundary layer models have been developed in recent decades for synoptic storms, e.g., (ESDU 1985). Less detailed models are available for tropical storms and downdrafts. So far, wind tunnel experiments only attempt to model synoptic boundary layers. All other storm types have therefore to be translated to equivalent synoptic storms. An equivalent synoptic storm is obtained by applying an appropriate gust factor to the characteristic gust wind speed and by taking into account the duration of the storm type and its relative intensity over the time.

The basic structure of the respective wind field is influenced by the roughness and topography of the terrain in the fetch the wind is traveling along. The fetch is relatively short for thunderstorms and is larger for tropical and synoptic storms. Therefore, one uncertain parameter is the appropriate length of the fetch that has to be analyzed in regard to predict the flow field conditions at a specific site.

The next uncertainty occurs in describing the friction effects along the fetch. Over land, the effective roughness may change with the season (winter with low vegetation and summer with high vegetation, winter eventually with snow cover) and may change over time due to changes in the land use during the projected life time of the structure under consideration. Eventually, the effective roughness may be influenced by the wind itself, e.g., in case of forests where during extreme wind conditions the trees may be blown over by the wind in large areas. Over sea, the wind velocity triggers the effective roughness directly by creating waves. The higher the wind speed, the higher the waves and therefore the effective roughness will be greater.

If the wind blows over a series of sub-fetches with different effective roughness, the next uncertainty is introduced by modelling the accumulated effect due to these multiple roughness changes. This source of uncertainty in regard to underestimate the design value can be accounted for by estimations to the safe side, e.g., specifying in a code only two standard terrain categories as follows: terrain 1 for flow over open sea or larger lakes and terrain 2 for flow over land.

Statistical uncertainties are induced by the fact that stationary conditions in nature will last - if they occur at all - only for relatively short periods. Therefore, some statistical parameters required to describe the characteristics of the turbulent flow field can be estimated from full-scale data only with a relatively poor statistical stability. The most prominent example is the integral length scale which has a coefficient of variation of the estimated value in the range of 30% if L_{ux} is estimated from a 10 minute period (ESDU 1985). Other parameters like the mean wind speed or the turbulence intensity do not suffer from such severe statistical uncertainties. Assuming stationarity, the respective variation coefficients are about 5%.

3.3. Building aerodynamics

Generally, a building or engineering structure will not be perfectly isolated but will stand in the vicinity of other buildings or structures. A model uncertainty may be obtained in evaluating the influence of the adjacent objects on the flow field of the object under consideration. Basically, these interference effects may lead to a decrease or an increase of the wind induced loads or load effects. If the influence is expected to be considerable, the further investigation will try to include these interaction effects; if the influence is regarded to be negligible, the object is treated as an isolated object. As an appropriate limit for ‘considerable’ or ‘negligible’, a range from 5% to 10% is recommended.

If the wind loads and wind load effects are obtained on the basis of model tests in a boundary layer wind tunnel, usually not all architectural details can be modeled. The corresponding effects on the flow fields are then not reflected in the tests.

A further group of model uncertainties is obtained from scale mismatches between the wind tunnel test and full-scale conditions. Basically, a scale λ is specified as the ratio of a specific variable in the wind tunnel to the corresponding variable in full-scale. The geometric scale λ_L of the wind tunnel flow is obtained by comparing the integral length scale L_{ux} in the wind tunnel flow to the expected value in full scale. Additionally, the ratio of the integral length scales (e.g. L_{ux} / L_{uy}) in the wind tunnel flow has to be similar to full-scale conditions.

Strictly speaking, the geometric scale of the model has to be the geometric scale of the flow; a mismatch will lead to biased results. From the geometric scale λ_L and the velocity scale λ_v the time scale λ_T is obtained as $\lambda_T = \lambda_L / \lambda_v$. Since the expected wind speeds in full-scale have a range, the velocity scale itself is specified by a range. As an engineering approach, the velocity scale can be estimated as the ratio of the mean wind speed in the wind tunnel to the mean design wind speed in full-scale (Kasperski 2000).

A further source of model uncertainty is obtained from the Reynolds number defect. For curved structures, this defect is corrected by applying additional roughness on the model's surface. For structures with sharp edges it is usually assumed that if a minimum Reynolds number is exceeded the results will not be influenced by the Reynolds number defect.

Statistical uncertainties theoretically can be avoided by a sufficient large number of repeated independent runs. Slight mismatches in the time scale can be corrected as proposed in Kasperski (2003). Further advices for appropriate procedures for the wind tunnel tests can be obtained from e.g., the ASCE Manual ‘Wind Tunnel Studies of Buildings and Structures’ (ASCE 1999).

3.4. Structure

A wind load code has to provide appropriate design values for the design of the cladding in terms of local loads and design values for the design of the load bearing structure and its support. Since the extreme of combined action effects are required for the design calculations, it may happen that the most severe wind induced action effect is not the wind load effect with the largest absolute value (Kasperski 1996). In its simplest application, the analysis of structural effects assumes a linear structural behavior. Additionally, for many buildings, the major contribution to the extreme structural effect will be due to the background component of the wind, i.e., the structural behavior can be described quasi-statically. A general method to identify and codify the effective wind load distribution that is inducing the extreme structural effect has been presented in Kasperski (1992). This method can be applied also for weak non-linear structural behavior as it is obtained from geometric non-linearities. The method has been extended to include the resonance response as well in Holmes and Kasperski (1996). It is worth mentioning that the effective load distributions may be considerably different from the mean load distribution or the enveloping distribution of local peaks.

A considerable model uncertainty is obtained if the effective load distribution is replaced by the simple rule to reduce favorable load contributions by a factor between 0 and 1. Depending on the load effect, this model uncertainty may be on the safe but uneconomic side or may lead to an unsafe design value. In most cases, an underestimation on the load effect can be avoided if favorable load contributions are set to zero. However, this may lead to artificial load distributions that cannot adequately reflect the underlying physics and therefore have low acceptance in the design practice. It is therefore recommended to introduce effective load distributions in the wind load codes and standards.

4. Basic variables and probabilistic concept

The exceedence probability of the design wind load is influenced by the following basic variables:

- The extremes of the mean wind speed or the gust wind speed for the contributing storm types
- The duration of the storm and its fluctuation in the intensity over time
- The wind direction in the strongest period and the possibility of directional changes during the

storm

- The extremes of the aerodynamic coefficients in terms of local or global wind loads or wind induced structural effects.

The extremes of the wind speeds and the aerodynamic coefficients have to be modeled to follow one of the three extreme value distributions. The remaining basic variables can be represented in an engineering approach by their respective mean values. Then, the basic equation to estimate the exceedance probability of the design wind load is as follows:

$$p(w > w_{des}) = \int_{v=0}^{\infty} f_v(v) \cdot \int_{c_{\lim}}^{\infty} f_c(c)dc\, dv$$

$$= \int_{v=0}^{\infty} f_v(v) \cdot (1 - F_c(c_{\lim}))dv \tag{13}$$

$f_v(v)$ - probability density of the extreme wind speeds
$f_c(c)$ - probability density of the extreme aerodynamic coefficient
$F_c(c)$ - cumulative probability distribution of the extreme aerodynamic coefficient

$$c_{\lim} = 2 \cdot w_{des} / (\rho \cdot v^2),\ \rho \text{ - air density}$$

The appropriate fractile of c which leads to the target exceedance probability of the design wind load depends on the extreme value distributions of v and c and on their respective variation coefficients. Using in a code the mean extreme aerodynamic coefficient introduces a model uncertainty to the unsafe side with considerable underestimation. A smaller model uncertainty is obtained if the 78%-fractile for c is introduced assuming an extreme value distribution type I as recommended in (Cook and Mayne 1980). The respective fractile value is obtained as follows:

$$\hat{c}_{78\%} = \hat{c}_{mean} + 0.636 \cdot \hat{c}_{sdev} \tag{14}$$

$\hat{c}_{78}$ - 78%-fractile of the extreme aerodynamic coefficient
$\hat{c}_{mean}$ - mean value of the extreme aerodynamic coefficient
$\hat{c}_{sdev}$ - standard deviation of the extreme aerodynamic coefficient

Strictly speaking, Eq. (13) has to be solved considering the duration of the storm. If the intensity of the storm reaches its maximum only in a single hour and the adjacent storm hours have smaller intensities, it is usually sufficient to consider only the strongest hour of a storm.

For codification, it seems to be reasonable, to introduce in Eq. (14) rounded values. This leads to the following proposal that has been adopted in the recent draft of the ISO 4354 - Wind actions on structures:

$$\hat{c}_{80\%} \cong \hat{c}_{mean} + 0.7 \cdot \hat{c}_{sdev} \tag{15}$$

$\hat{c}_{80\%}$ - 80%-fractile of the extreme aerodynamic coefficient corresponding to the reference period 1 hour

$\hat{c}_{mean}$ - mean value of the extreme aerodynamic coefficient from 1 hour samples
$\hat{c}_{sdev}$ - standard deviation of the extreme aerodynamic coefficient from 1 hour samples

5. Resulting uncertainty of the design wind load

The possible influences on the resulting uncertainty of the design wind load can be evaluated by specifying ranges for the single contributions for a normalised mean value of the respective variable and its variation coefficient. If the statistical uncertainty has to be balanced by an appropriate confidence, the normalised mean value of a parameter will be smaller than 1. The normalised mean value for a statistical uncertainty will become 1 if a sufficient number of independent samples are available or if a confidence for a range has been applied. In Table 4, some tentative values are specified for the model uncertainties and for the statistical uncertainties which are partially adopted from (Davenport 1987).

The largest contribution of uncertainty is obtained for the aerodynamic coefficients specified in wind load codes. This huge range reflects that not all aerodynamic coefficients presented in today's codes are extreme aerodynamic coefficients obtained in a boundary layer flow. Some coefficients have been obtained in low-turbulent flows, other coefficients are mean values from boundary layer flow experiments. Where extreme coefficients have been introduced they correspond either to the mean extreme or the 78%-fractile of the extremes or they are mistakenly specified as 80% of the largest observed extreme.

Aerodynamic coefficients are required for different design purposes: the design of the cladding, the design of the support of the load bearing structure and the design of the load bearing structure itself. An ideal code would specify for each task a separate set of aerodynamic coefficients, i.e., aerodynamic coefficients for different sizes of the influence area and simultaneous distributions for different command variables (drag, lift, structural responses like bending moments etc.), thus minimizing the model uncertainty. Today's codes usually consider the influence of the area size globally by an area reduction factor and/or a local pressure factor. The influence of the non-simultaneous actions on different surfaces is modelled by an action combination factor and/or a reduction factor for favourable loads.

Wind tunnel experiments may suffer from larger uncertainties since the effects of scaling mismatches and Reynolds number defects are still not fully understood and can therefore not be taken into account appropriately. The statistical uncertainties can be reduced to a mean of 1 by sampling extremes from a sufficient large number of independent runs. The number of required runs especially depends on the variation coefficient of the extremes. The variation coefficient usually lies

Table 4 Tentative values for the statistical parameters of the different uncertainties

Source		Model uncertainty		Statistical uncertainty	
		Mean	c.o.v.	Mean	c.o.v.
Wind climate	Stationary	1.0	0.1	0.9	0.1–0.2
	Trend	1.1	0.2	0.9	0.1–0.2
Boundary layer		0.9–1.1	0.1	1.0	0.05–0.3
Aerodynamic coefficient	Wind tunnel	0.8–1.2	0.2	1.0	0.05–0.3 (∞)
	Code	0–2	0.5	–	–

in the range from 5% to 30% but may become indefinite if the mean approaches zero. For variation coefficients below 20%, 60 runs are sufficient to estimate the mean value and the standard deviation of the extreme aerodynamic coefficients with an adequate statistical stability. A conservative approach then assumes that the extremes follow a type I extreme value distribution. If the experiments aims to identifying the type of distribution as well, a much larger number of independent runs is required Kasperski (2003), Holmes and Cochran (2003).

The model uncertainty for the boundary layer is 0.9 for synoptic storms and tropical cyclones if the influence of the terrain roughness is estimated to the safe side. For downdrafts, the model uncertainty is probably larger than 1 for the mean. The statistical uncertainties for the parameters describing the turbulent wind field generally have a mean value of 1 and a coefficient of variation in the range of 5% (mean value, turbulence intensity) to 30% (integral length scales).

For the wind climate the model uncertainties are large if long term trends have to be modelled. Additionally, model uncertainties are large if an inappropriate ensemble is used to specify the design wind speed. An additional uncertainty is obtained, if only the characteristic value of the wind speed is estimated and a more or less arbitrarily chosen partial safety factor is applied. Finally, the simplified code methods for directional effects may introduce further model uncertainties in the design wind loads.

6. Conclusions

Design values for the wind induced actions are required for different purposes, like, for example, the design of the cladding and its fixing, the design of the support of the load bearing structure and the design of the load bearing structure itself. It is recommended that for each task a separate set of aerodynamic coefficients is specified, i.e., aerodynamic coefficients for different sizes of the influence area and simultaneous distributions for different command variables (drag, lift, structural responses like bending moments etc.), thus minimizing the model uncertainty.

The consequences of a failure determine the target value of the exceedance probability of the design wind load. It is recommended to distinguish at least the four following structural classes:

A - structures with a special post disaster function
B - buildings which as a whole contain people in crowds
C - normal structures
D - structures presenting a low degree of hazard to life and other properties

In future codes, the design working life will become an explicit design variable. Therefore, appropriate target values for the exceedance probability are recommended for the reference period ‘design working life’. If the respective value is not specified explicitly as a design parameter, a value of 50 years can be used.

The target exceedance probability and the design working life determine the yearly exceedance probability of the design wind load. The same value is recommended for the specification of the design wind speed. The design wind speed should be estimated from an appropriate ensemble considering the statistical uncertainties which are inevitably introduced due to the confined observation period. It is recommended to use a 75% confidence interval.

The appropriate design value of the aerodynamic coefficient can be obtained by solving the convolution integral of the probability density distribution of the extreme wind speeds and the extreme aerodynamic coefficients. In a simplified approach, it is recommended to use the 80%-

fractile of the extreme aerodynamic coefficients, assuming a type I extreme value distribution. To avoid further statistical uncertainties, it is recommended to have ensembles of at least 60 independent runs.

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JH