Structural Safety 70 (2018) 115–127

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

# On the probabilistic representation of the wind climate for calibration of structural design standards

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ARTICLE INFO

*Article history:*
Received 28 April 2017
Received in revised form 25 October 2017
Accepted 28 October 2017

*Keywords:*
Wind actions
Probabilistic modelling
Code calibration
Partial safety factors
Extremes

ABSTRACT

The article presents a contribution to the current debate on the probabilistic representation of the wind speed extremes for calibration of the partial safety factor covering wind action. The requirements for the probabilistic model are formulated. The Gumbel distribution is shown to represents best the 10-min mean wind velocity yearly maxima based on theoretical considerations and analyses of real data with different statistical techniques. Data from locations across a large geographical region indicate that the coefficient of variation of the distribution varies over the territory. A method is proposed for accounting this variation in order to calibrate a single partial safety factor for the whole territory. The distribution location is indirectly given in design standards through the georeferenced characteristic wind speed values. A solution for including the uncertainty affecting these values is suggested. The findings are implemented in an illustrative calibration exercise. The proposed methods and concepts might be applied to other environmental actions such as the snow loads.

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## 1. Introduction

Modern structural design codes or standards as the Eurocodes [1] provide simple and safe basis for the design of structures. The simplicity is achieved mainly by the fact that structural safety is checked by comparing the design values of action effects with the design value of the resistance. Semi-probabilistic design equations in the Load Resistance Factor Design format (LRFD, see e.g. [2]) use partial safety factors (PSFs) applied on the resistance and action sides. These factors control the reliability of the corresponding design solutions. Their values are selected by code committees in order to achieve the desired level of safety [2–5]. In the present version of the European Standards (The Eurocodes [1]), for example, one single partial safety factor ($\gamma_Q = 1.50$) is recommended for all unfavourable environmental variable actions such as snow and wind. However, it has been shown in [6] that a wind load dominated structure designed with $\gamma_Q = 1.50$ has a reliability lower than the Eurocode target, which requires a yearly target reliability index $\beta_t$ equal to 4.70 (for consequence class 2). It also appears reasonable to differentiate the partial safety factors of the environmental actions, such as snow, wind and temperature, since these actions originate from different physical phenomena and are represented by different models involving various random variables.

Modern calibration methods are based on reliability theory considering fully probabilistic models [3,4,7]. If wind action is involved, this requires models representing the wind action on structures from the basic physical phenomenon (i.e. the geostrophic wind), and the representation of the governing variables, which may have a deterministic or a random nature. A widely accepted model is the Alan G. Davenport wind load chain [8] illustrated in Fig. 1. Many semi-probabilistic codes such as the Eurocode 1 [9] represent wind actions on structures based on this model. The chain model includes five fundamental aspects, shortly: i) the *wind climate* comprising the weather systems generating geostrophic winds due to temperature gradients on the Earth surface; ii) the *influence of terrain,* which modifies the wind flow in the atmospheric boundary layer; iii) the *aerodynamic effects* depending on the structure shape; iv) the *dynamic effects* of the structure, and v) the *criteria* for verifying the predicted load models. More details are given in [10,11].

Although the model is widely accepted, challenges are still faced when defining the probabilistic models representing different aspects. In fact, several probabilistic models for representing the aspects in the Davenport chain have been proposed for calibration of design codes, see e.g. [12]. Therefore, this article discusses some open issues related to the stochastic modelling of the 10-min mean wind velocity yearly maxima ($V_{b,\max}$) used for representing the *wind climate* for code-calibration purposes. In detail, the following aspects are addressed:

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https://doi.org/10.1016/j.strusafe.2017.10.012
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**Fig. 1.** Alan G. Davenport wind loading chain.

- *The selection of the type of distribution function representing* $V_{b,\max}$. This is still openly discussed in the scientific community since several distributions seem to fit well the available data, but they result in different calibrated safety factors due to the so-called tail sensitivity problem affecting the reliability analyses. Gumbel, Generalised extreme, Weibull, three-parameters Lognormal and other distributions are proposed in the literature, see for example [11,13,14].
- The estimation of the distribution parameters that are relevant for the calibration of partial safety factors. These parameters are the coefficient of variation ($COV$) and the uncertainty on the distribution location. The former should include the aleatory uncertainty (random nature of wind) and the epistemic uncertainties (originated by the lack of knowledge and a limited amount of information). The latter should include the uncertainties originated from the (surrogate) models utilised for creating the wind maps included in the design codes.
- *The representation and inclusion of the* $V_{b,max}$ *space-variation in the partial safety factor calibration*. This is required since a single partial safety factor for wind action is used for large geographical areas, although the wind climate is highly regional dependent.

The selection of the distribution type, the estimation of its parameters and their variation over a vast territory are addressed in Section 2 of the article. The second part of the article proposes a method for integrating, in the partial safety factor calibration, both the space-variation of the wind characteristics and the uncertainty on the distribution location. Wind speed records from five weather stations across Norway were analysed for catching the space-variation. The uncertainty on the distribution location was estimated based on measurements in several places over the territory. The findings are implemented in an illustrative calibration exercise.

## 2. Representation of the *wind climate*

### 2.1. Requirements of the model

The variation of the *wind climate* can be described by the wind velocity averaged over a period corresponding to frequencies in the spectral gap of the horizontal wind speed spectra [10,15]. Periods of 10 min to 1 h are typically used [16]. In the European Standard Eurocode 1 Part 1–4 (EC1-1-4) [9], the *wind climate* variation is represented by the basic wind velocity ($V_b$) which is defined as the 10-min mean wind velocity, irrespective of wind direction and time of the year, at 10 m above the ground level in open terrain. The reliability assessment of a structure exposed to wind actions is a time-variant problem since the wind is varying in time. The reliability problem can be simplified to a time-invariant problem, if it can be assumed that the resistance is independent of the wind process, by the so-called time-integrated approach (see [2]) considering the $V_b$ yearly maxima $V_{b,\max}$.

As any random variable, $V_{b,\max}$ might be represented by a distribution function, which is in general defined by the *type* of distribution and its *parameters*. The parameters determine the *location*, *scale* and *shape* of the distribution, while the *type* determines the tail behaviour.

The *type* of distribution and the *coefficient of variation COV* (i.e. the scale or scatter independent of the location) play an important role in reliability-based code calibration. This role can be observed in Eq. (1) where the partial safety factor for a Gumbel distributed variable $X$ is determined using the design value method [1]. In the Equation, $\beta_t$ is the target reliability, $\alpha$ is the sensitivity factor (see, e.g., [2]), $p_k$ is the fractile corresponding to the characteristic value, $\Phi(\cdot)$ is the standard normal cumulative density function and $a_{EM} \cong 0.5772$ is the Euler-Mascheroni constant. The analytical expressions of the distributions functions utilised in the article are given in Appendix A

$$\gamma_X = \frac{6\,COV_X \ln\{-\ln[\Phi(\alpha\beta_t)]\} + 6\,a_{EM}\,COV_X - \pi\sqrt{6}}{6\,COV_X \ln\{-\ln[p_k]\} + 6a_{EM}\,COV_X - \pi\sqrt{6}} \qquad (1)$$

The distributions *location* or magnitude is not affecting the partial safety factor when the extreme wind speeds are originated from a single physical phenomenon. In this case, standardised random variables can be used for PSF calibration as in [5]. For the wind, this is advantageous since the magnitude varies considerably in space due to different local climates and exposures. Design codes provide the regional magnitude or distribution location through the $V_{b,\max}$ characteristic value. In the Eurocode 1 [9], the characteristic value corresponds to the 98% fractile (i.e. $p_k = 0.98$) of the yearly extreme value distribution and is referred to as the fundamental value of the basic wind velocity $v_{b,0}$. The regional distribution of $v_{b,0}$ is given in the Eurocode 1 National Annexes in the form of tables or maps. It has to be highlighted that the uncertainties affecting $v_{b,0}$ do influence the calibration of the partial safety factor. Thus, a good probabilistic representation of these uncertainties is of importance.

Correspondingly, in the authors' view, the distribution function representing $V_{b,\max}$ should have the following properties:

a) The distribution function type should represent $V_{b,\max}$ in the whole geographical application area of the standard under consideration.
b) The distribution function type and parameters have to be validated by recorded time series over an adequate period, say, longer than 15 years [17].
c) The distribution function type must agree with the phenomena generating randomness.
d) The stochastic model should be suited for the reliability methods used in the calibration procedure. Usually, a parametric probability distribution is sought since the first order reliability method (FORM) is commonly used in calibration of partial safety factors because of its accuracy and its low computational cost.
e) It should include the statistical uncertainties which arise from the lack of data and the model uncertainties in order to estimate the predictive reliability index, see e.g. [18].
f) It should be accurate in the upper tail defined as the surroundings of the design point. The fractile corresponding to the design point is approximatively equal to $\Phi(\alpha \cdot \beta_t) = 5 \cdot 10^{-4}$, which is the fractile associated with the design point of the wind induced action obtained with $\alpha = 0.7$ and $\beta_t = 4.7$ according to [1].

In principle, different types of distributions can be fitted to the data upper tail, and the best one can be individuated by using statistical tools, probabilistic reasoning and judgment. Nevertheless, the point c) above is of particular importance especially due to the lack of observations in the surrounding of the design point. The application of extreme value theory (see e.g. [19,20]) does limit the choice of distribution function type correspondingly, see also [21] for further discussion.

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