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Directional design of a high-rise building

M. Kasperski and Y.-L. Lo[2]

[1]Department of Civil and Environmental Engineering Sciences
Ruhr-Universität Bochum, 44780 Bochum, Germany

[2]Department of Civil Engineering
Tamkang University, New Taipai City 251, Taiwan

Abstract

Many strong wind climates around the world show distinct dependency on direction. However, exploiting the favourable directional effects for the wind resistant design requires a consist approach which considers the directional distribution of extreme wind speeds, the possibility of direction change over the storm duration and the directionality of the aerodynamic coefficients. The actual study presents the general approach for a consistent specification of the design values and discusses the different aspects on the example of a high-rise building for the wind climate of Germany.

Introduction

Consistent wind resistant design requires the convolution of the probability densities of the extreme wind speeds v and the extreme aerodynamic coefficients c. Both random variables show a distinct dependency on the direction. Extremes of v have to be sampled for independent events, i.e. one individual storm gives one entry to the ensemble of extreme wind speeds. Extremes of aerodynamic coefficients have to be sampled for a reference period appropriate to the duration of the considered storm type. For synoptic storms, this reference period is one hour; for tropical cyclones, the corresponding duration is 10 or 15 minutes [1]. Basically, extreme storms last longer than the reference period. Then for the wind speed two different directionalities have to be considered. The first directionality effect is obtained from the wind direction of the strongest storm period; the second directionality effect covers the change of direction over the storm duration, sorting the additional storm periods in descending order. Usually, it is sufficient to consider a mean duration for the individual storm, which can be expressed as an integer multiple of the reference period [2].

The basic equation to specify the design value for the aerodynamic coefficient c_{des} is obtained in an implicit form from:

$$p(w > w_{des}) = \int_{\Phi=0}^{360} f_{rel}(\Phi) \cdot p_{\Phi}(w > w_{des})\, d\Phi \overset{!}{=} p_{target} \qquad (1)$$

P_{target} – target value for the annual exceedance probability

w_{des} – design wind load = $0.5 \cdot \rho \cdot v_{des}^2 \cdot c_{des}$

ρ - air density

v_{des} – design wind speed having the same p_{target} value

f_{rel} – relative frequency of extreme wind speeds for wind direction Φ

The contribution p_{Φ} from a specific wind direction is obtained as:

$$p_{\Phi}(w > w_{des}) = \int_{v=0}^{\infty} f_v(v) \cdot \left[1 - \prod_{k=1}^{k_{av}} F_c(c_{lim}, \Theta, \Phi_k) \right] dv \qquad (2)$$

f_v - probability density of the extreme wind speeds

F_c – cumulative probability distribution of the extreme aerodynamic coefficient

c_{lim} – $v_{des}^2 \cdot c_{des} / v_k^2$

Θ - orientation of the building

Φ_k – wind direction in k-th strongest reference period

v_k – wind speed in k-th strongest reference period

If the direction change in the k-th reference period is treated as a random variable, the individual $F_{c,\,k}$ values are obtained from the weighted sum over all possible wind directions:

$$F_{c,\,k} = \sum_{\Phi} f_{\Phi,\,k}(\Phi_k) \cdot F_c(c_{lim,\,k},\ \Phi_k) \qquad (3)$$

$f_{\Phi,\,k}$ - probability density of the wind direction in the k-th strongest extreme wind speeds

Object of the study

The actual object of the study is a high-rise structure with quadratic cross section and height H = 240 m; the aspect ratio is b/H = 6. The model with a geometric scale of 1:400 is tested at the Tamkang University in a boundary layer with a power law exponent of 0.25 for the mean wind speed [3]. The velocity scale is 1/6.67; the sampling frequency is 200 Hz. A single run corresponding to one hour in full scale conditions then consists of 12000 data. The local pressures are measured at 15 levels; each level has 4 x 7 pressure taps. For flow direction 0° the front face is face A, the downwind face is face C and the side faces are B and D. The angle of attack is varied from 0° to 45° in 5° steps. For each flow direction, 60 independent runs are performed. All pressure coefficients are normalized to the mean velocity pressure at building height.

Wind induced local and global actions

Based on the local pressures, global wind induced forces F and corresponding bending moments M can be obtained via integration for different levels along the building height. The respective values are normalized as follows to dimensionless aerodynamic coefficients:

$$c_F(z) = \frac{F(z)/q_H}{b \cdot (h-z)},\ c_M(z) = \frac{2 \cdot M(z)/q_H}{b \cdot (h-z)^2} \qquad (4)$$

For each random variable, 60 extreme values are used to identify the corresponding parameters of the generalized extreme value distribution which is given as:

$$F(x) = \exp\left[-\left(f_1 - \mathrm{sign}(\tau)\cdot f_2 \cdot \frac{x-m}{\sigma}\right)^{1/\tau}\right] \qquad (5)$$

m - mean value, σ - standard deviation, τ - shape parameter

The coefficients f_1 and f_2 depend on the actual shape parameter τ and are given as follows:

$$f_1 = \Gamma(1+\tau),\ f_2 = \sqrt{\Gamma(1+2\cdot\tau) - f_1^2} \qquad (6)$$

Γ - Gamma function

Positive τ-values correspond to the extreme value distribution type III. This distribution is limited to the right side, i.e. it has a largest value which cannot be exceeded. Negative τ-values lead to the extreme value distribution type II. If τ becomes zero, the Gumbel distribution is obtained:

$$F(x) = \exp\left[-\exp\left(-\left[\gamma + \frac{\pi}{\sqrt{6}}\,\frac{x-m}{\sigma}\right]\right)\right] \qquad (7)$$

γ - Euler constant = 0.577216

In figure 1, the identified parameters for the generalized extreme value distribution are shown for the bending moments with reference to the building-oriented coordinate system x and y. Depending on the angle of attack, the extremes may follow the most unfavourable extreme value distribution type II.

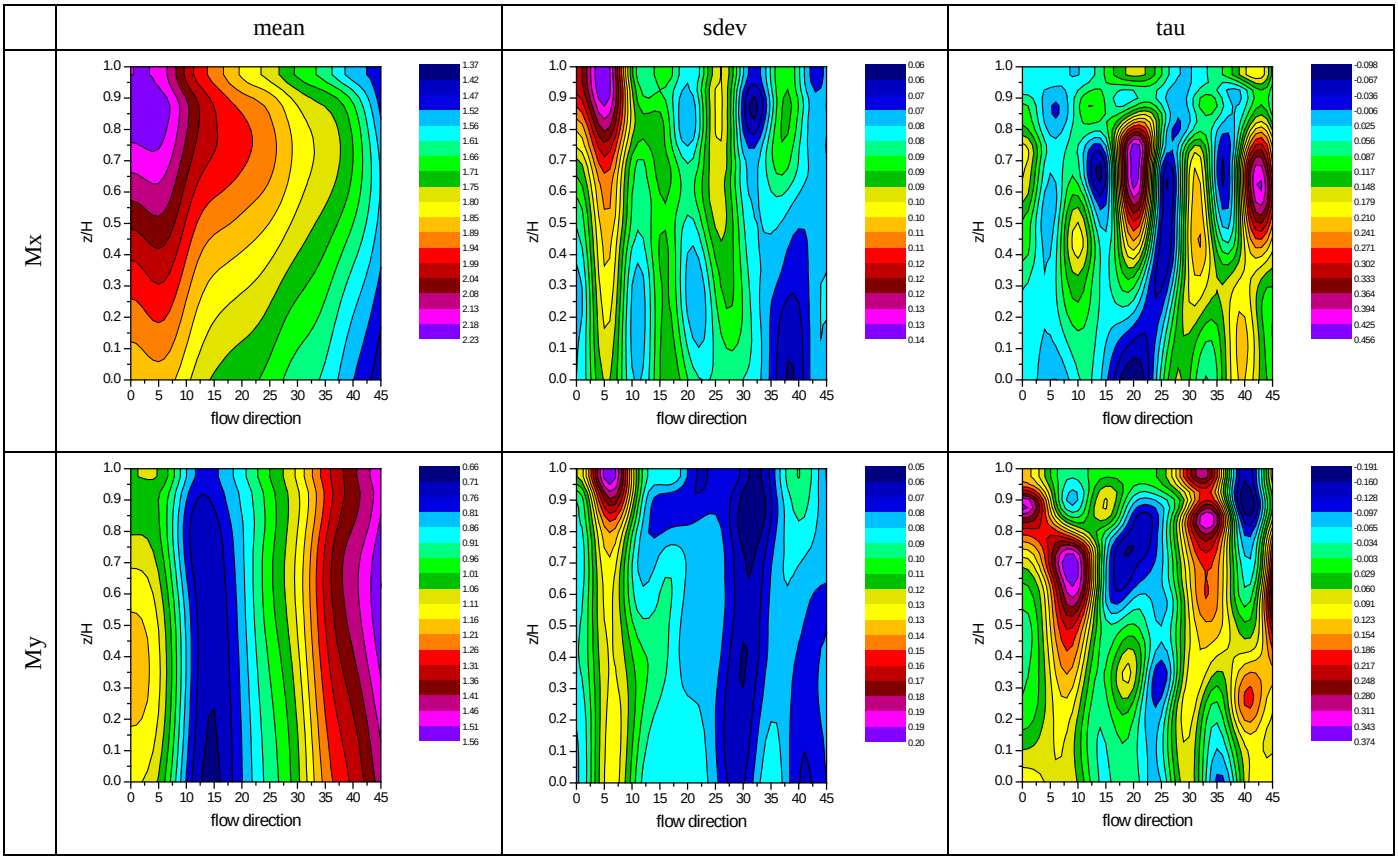

Figure 1. Parameters of the generalized extreme value distribution for the wind induced bending moments

Directionality of the wind climate

The design of high-rise structures in Germany is governed by storms induced by strong frontal depressions. A conservative approach assumes that the annual non-exceedance probability of the largest hourly mean wind speed of independent storms follows the extreme value distribution type I. Figure 2 shows the respective trace for the station Düsseldorf airport based on observations between 1952 and 2007, applying a threshold value of 14 m/s. The independent extremes are sampled for Aeolian years starting on 1st of May and extending to the 30th of April of the consecutive year. The annual exceedance probability is obtained by combining the probability of the number of events per 12 month cycle and the non-exceedance probability per event as follows:

$$p(v \le v_{ref} \mid \text{year}) = \sum_{N=0}^{\infty} p(N) \cdot p(v \le v_{ref})^N \qquad (8)$$

p(N) - probability of N storms per year, N = 0, 1, 2, 3, 4, …

$p(v \le vr_{ef})$ - non-exceedance probability per independent event

Large wind speeds from this storm type usually are limited to a few sectors of wind directions. An appropriate probabilistic model is given with the Beta-Distribution which is limited to both sides. The corresponding probability density is given as:

$$f(x) = \frac{(x-a)^{r-1}\cdot(b-x)^{t-1}}{(b-a)^{r+t-1}\cdot B(r,t)} \quad \text{for } a \le x \le b \qquad (9)$$

a - lower bound, b - upper bound, r, t exponents

The constant B is defined as:

$$B(r,t) = \Gamma(r)\cdot\Gamma(t)/\Gamma(r+t) \qquad (10)$$

Figure 3 shows the relative frequency of wind directions of the 30 strongest storms at Düsseldorf for the observation period 1952-2007. The storms are limited to the sector from 180° to 330°. The storm wind speeds are assumed to follow the Gumbel distribution with mean value of 16 m/s and standard deviation of 2 m/s. The lower threshold value is 14.1 m/s, i.e. the complete wind climate model has to demand that the largest possible wind speeds in the non-storm sectors meets this threshold value. Then, the extreme wind speeds in non-storm sectors have to follow the extreme value distribution type III. A pragmatic approach identifies the corresponding parameters based on annual extremes of the hourly mean wind speeds per sector.

On average, extreme storms at Düsseldorf last for four hours. The relative intensities of the second, third and fourth strongest storm hour are 0.96, 0.92 and 0.89. From the 30 strongest storms, altogether 542 hours are available to describe the probability of the direction change in the k-th hours of a storm. The mean value of the direction change strongly depends on the direction of the strongest hour and slightly depends on the rank k. For the second strongest hour, three typical cases are shown in figure 4. If the strongest storm hour occurs for 240°, the second strongest storm hour is likely to occur in the same sector. The probability of a direction change smaller than ± 5° is about 60%. If in the strongest hour the wind blows from 210°, the second strongest storm hour occurs in the same direction with a probability of about only 20%. Finally, if the wind direction for the strongest storm hour is 270°, the second strongest storm hour will have the same direction with less than 10%.

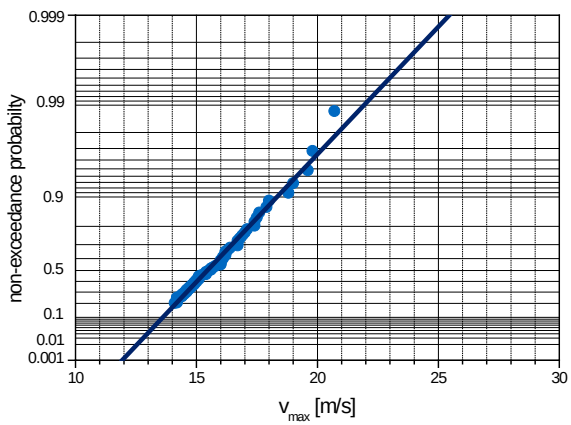

Figure 2. Annual non-exceedance probability of the largest hourly wind speed in independent storm events (Düsseldorf airport 1952-2007)

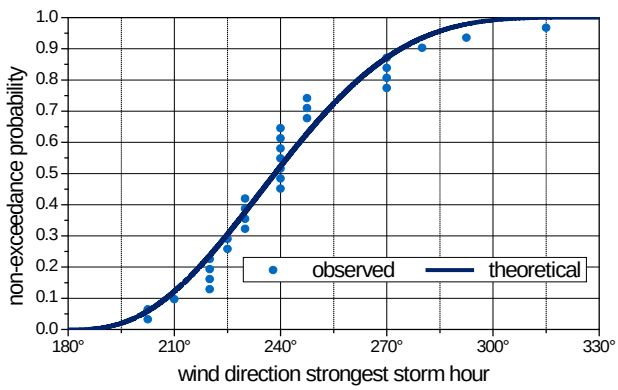

Figure 3. Directionality of the largest hourly mean wind speed during an independent storm event (Düsseldorf airport 1952-2007: m = 240°, σ = 25°, r = 3.04, t = 4.59, a = 180°, b = 330°)

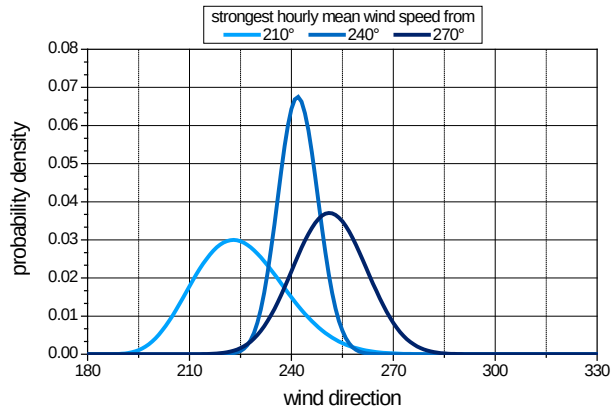

Figure 4. Probability density of direction change in the second strongest storm hour (Düsseldorf 1952-2007)

Thunderstorms and other convective processes are neglected in this study. This approach is appropriate for the design of the stiffening core. However, the design values of the local pressures in the lower third might be affected by these two storm types.

Non-directional design

The German wind load Standard DIN-EN 1991-1-4 conservatively promotes the non-directional design, i.e. it is assumed that all storm events occur for the most unfavourable direction. For dimensioning the stiffening core, the wind induced bending moments in x and y direction have to be combined to the maximum stress considering the corresponding section moduli in x and y direction which are given for a rectangular shape as:

$$w_x = b \cdot d^2/6, \; w_y = b^2 \cdot d/6 \qquad (11)$$

The ratio d/b is varied in 0.1-steps from 1.0 to 3.0, keeping the cross section area constant as b·d = 1.

Solving equation (1) with a target value of 0.001 for the annual exceedance probability of the design wind load identifies the design values for the local pressures and the stresses. Without directional effects, the square cross section is optimum. The critical angle of attack is 5° for all analysed levels. The height-dependent design values are shown in figure 5.

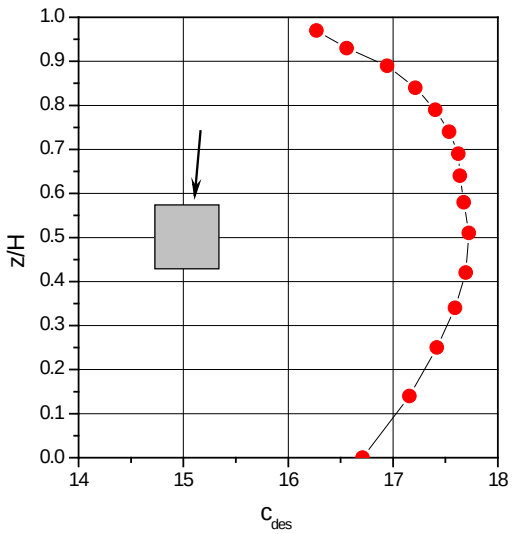

Figure 5. Non-directional design values for the maximum corner stress of a square stiffening core

Directional design

Directional effects on the local pressures are discussed on the example of the centre tap at level 11, which has the relative height z/H = 0.82. In figure 6, the maximum and minimum design values for varying orientation are compared to the values applying the non-directional design. Considering the directionality in the wind climate and the aerodynamic coefficients reduces the design value for the positive pressure by 6% and for the negative pressure by 15% irrespective of the orientation of the building.

For face A, the optimum orientation is 180° in regard to the smallest positive design pressure. Compared to the non-directional design, the reduction is 27%. The minimum design pressure is reduced by 20%. The corresponding reductions for the minimum pressures are 24% for face B, 40% for face C and 47% for face D.

Considering the maximum suction as criterion leads to 190° for the optimum orientation. The reductions for face B and C are 28%, the reduction for face D is 40%. However, the positive design pressure at face A is only reduced by 20%.

Figure 6 also shows the results considering the additional storm hours without and with direction change over the duration of the storm. The influence of the additional storm hours is negligible when the additional storm hours have the same direction as the strongest storm hour. However, for the real storm behaviour with direction change over the duration, the influence on the design values exceeds 5%.

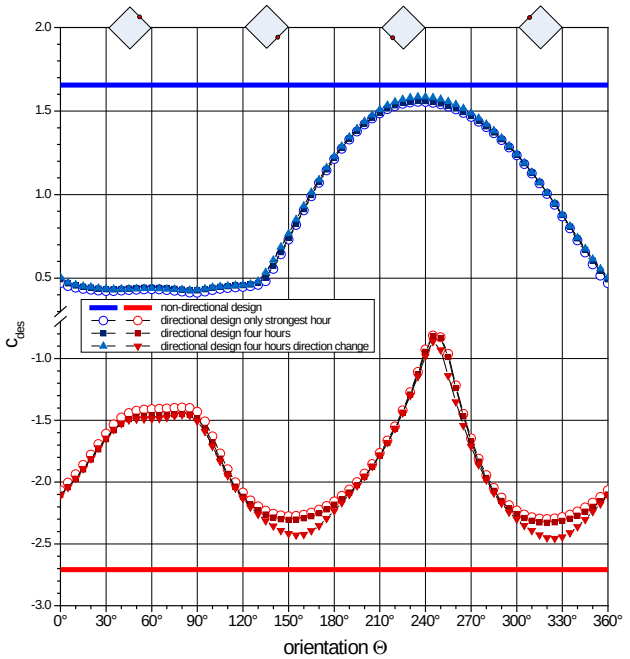

Figure 6. Directional design values for the central tap at z/H = 0.82

For the base, the directional design shows almost no influence of the orientation if the cross section of the stiffening core is a square (fig. 7). The ratio between the largest and the smallest design value is 1.007. This results in a ratio of the final cross section area of $1.007^{2/3} = 1.0046$. However, the difference of the design values to the non-directional design is considerable with a ratio of 0.909 for the most favourable orientation of 9° and 0.915 for the most unfavourable orientation of 70°. Considering the directionality in the aerodynamic coefficients and the wind climate reduces the cross section area of the core at base level by 5.8% to 6.2% .

The optimum cross section of the core at the base is obtained with the side ratio of 1.4:1. For the most favourable orientation of 60°, the ratio to the non-directional design value becomes 0.898, thus reducing the required cross section by 7%. With increasing relative height z/H of the design level, the favourable effects decrease to 5 % at the top level of z/H = 0.97.

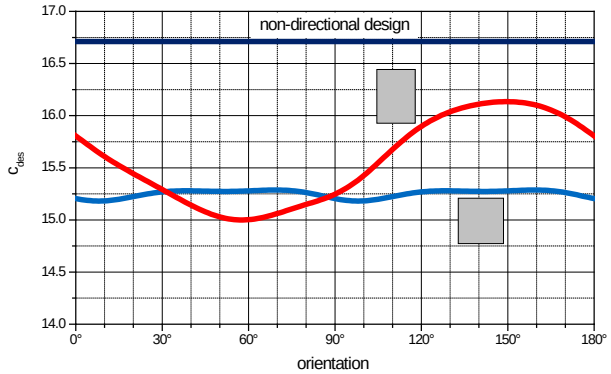

Figure 7. Directional design values for the stiffening core at the base for two core geometries, the straight line correspond to the non-directional design

Conclusions

The German wind load standard does not provide information for directional design. Instead it is conservatively assumed that all storms come from the most unfavourable direction. As can be shown on the example of the strong wind climate at Düsseldorf, considering directionality leads to more economic design values even if the orientation of the building is not taken into account. For the example the general reductions lie between 6% and 15%. If the orientation of the building can be chosen, the design values can be reduced further to a total of 20% to 40%. However, the model for the extreme wind climate has to be refined in regard to direction change over the duration of a storm.

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