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Probability based calibration of pressure coefficients

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ABSTRACT: Normally, a consistent basis for calculating partial factors focuses on a homogeneous reliability index neither depending on which material the structure is constructed of nor the ratio between the permanent and variable actions acting on the structure. Furthermore, the reliability index should not depend on the type of variable action.

A probability based calibration of pressure coefficients have been carried out using pressure measurements on the standard CAARC building modelled on scale of 1:383. The extreme pressures measured on the CAARC building model in the wind tunnel have been fitted to Gumbel distributions, and these fits are found to represent the data measured with good accuracy. The pressure distributions found have been used in a calibration of partial factors, which should achieve a certain theoretical target reliability index. For a target annual reliability index of 4.3, the Eurocode partial factor of 1.5 for variable actions agrees well with the inherent uncertainties of wind actions when the pressure coefficients are determined using wind tunnel test results. The increased bias and uncertainty when pressure coefficients mainly are based on structural codes lead to a larger partial factor of the order of 1.8.

In order to put the partial factors determined into perspective, calculations have also been carried out for structures exposed to snow load. Assuming a target annual reliability index of 4.3, the partial factors for snow load may become as high as approx. 3.0 when the characteristic shape coefficients are based on mean values as specified in background documents to the Eurocodes.

Importance of hidden safeties judging the reliability is discussed for wind actions on low-rise structures.

KEY WORDS: Probabilistic design method; partial factors; wind actions; pressure coefficients; wind tunnel tests; snow load; Eurocode.

1 INTRODUCTION

Partial factors in structural codes may be calibrated by probabilistic methods using a certain target reliability index. The main objectives are generally to obtain a uniform reliability with respect to different types of materials (concrete, steel, timber, masonry, soil, …), different types of loads (permanent loads, wind actions, snow loads, imposed loads) and different load combinations.

A fully probabilistic design method for wind loaded structures is based on stochastic distributions of the individual parameters used in the wind action calculation and it follows the well-known wind load chain. Typically, the main uncertainties of the wind actions calculated originate from the velocity pressure of the incoming undisturbed wind and from the pressure or force coefficients. This paper includes a full probabilistic design method based on distributions of the velocity pressure and distributions of pressure coefficients determined in the wind tunnel.

A snow load chain is presented and the uncertainties on snow load and wind load are compared. This comparison is crucial in order to determine appropriate quantiles for snow shape coefficients under the assumption that codified partial factors for variable wind actions and snow loads should be the same, and also assuming the same required reliability index.

2 RELIABILITY MODEL

As basis for calibrating partial factors a simple, representative probabilistic model has to be formulated, see e.g. [1]. The following limit state equation is used, see e.g. [2]:

$$g = zX_R R - \left((1-\alpha)G + \alpha C c_{pe} q_{ref} A_{ref}\right) \tag{1}$$

where

R	resistance
X_R	model uncertainty for resistance model
z	design variable, e.g. cross-sectional area
G	permanent load

q_{ref}	maximum annual velocity pressure under reference terrain conditions
c_{pe}	pressure coefficient
C	wind factor equal to the product of exposure coefficient c_e, structural factor $c_s c_d$ and model uncertainty J_F
A_{ref}	reference area
α	models the ratio between variable and permanent loads. $\alpha = 0$ corresponds to no variable load and $\alpha = 1$ to no permanent load

The design equations corresponding to the limit state equation, based on eq. (6.10a) and (6.10b) in [14] are written:

STR (6.10b): $$z_b X_{R,k} R_k / \gamma_M - \left((1-\alpha)\gamma_{Gb} G_k + \alpha\gamma_Q C c_{pe,k} q_k A_{ref}\right) \geq 0 \quad (2)$$

STR (6.10a): $$z_a X_{R,k} R_k / \gamma_M - (1-\alpha)\gamma_{Ga} G_k \geq 0 \quad (3)$$

The design variable is obtained as $z = \max\{z_a, z_b\}$. Index k indicates characteristic value.

The stochastic model shown in Table 1 is based on the uncertainty modelling applied for calibration of partial factors in [2]. It is noted that the characteristic value of the product $X_R R$ is determined as a 5% quantile.

Table 1. Stochastic model

		Distribution	Coefficient of variation, V	Characteristic value, k
Loads				
Permanent load	G	Normal	10 %	50 %
Maximum annual velocity pressure	q_{ref}	Gumbel	23 %	98 %
Pressure coefficient	c_{pe}	Gumbel	See below	78 %
Wind factor	C	Lognormal	5 %	50 %
Resistances				
Material parameter	R	Lognormal	Steel: 7 % Concrete: 14 % Timber: 20 %	5 %
Model uncertainty	X_R	Lognormal	Steel: 5 % Concrete: 11 % Timber: 5 %	5 %

The partial factors in (2)-(3) shown in Table 2 are from [2] and the Danish National Annex to [14].

Table 2. Partial factors assumed.

Partial factors [-]		
Permanent load in (6.10a)	γ_{Ga}	1.2
Permanent load in (6.10b)	γ_{Gb}	1.0
Variable load	γ_Q	See below
Steel	γ_R	1.23
Concrete	γ_R	1.38
Timber	γ_R	1.37

Figure 1 shows the reliability index, β for structural components where the yield strength of steel, the compression strength of concrete or the bending strength of timber are governing for the resistance. β is shown as function of the load influence factor α for the Coefficient Of Variation (COV) for the pressure coefficient, $V_{C_{pe}} = 0.20$ and partial factor for variable load $\gamma_Q = 1.5$.

The reliability index is obtained by the First Order Reliability Method (FORM), see [3], and is related to the annual probability of failure by

$$P_F = \Phi(-\beta) \quad (4)$$

where $\Phi(-\beta)$ is the standard Normal distribution function.

From Figure 1 it is seen that the average reliability index is approx. uniform and equal to 4.3 for the ranges of α relevant for steel, concrete and timber structures, respectively. It is noted that the partial factors in the Danish National Annexes to the Eurocodes are calibrated to a target annual reliability index equal to 4.3, see [2].

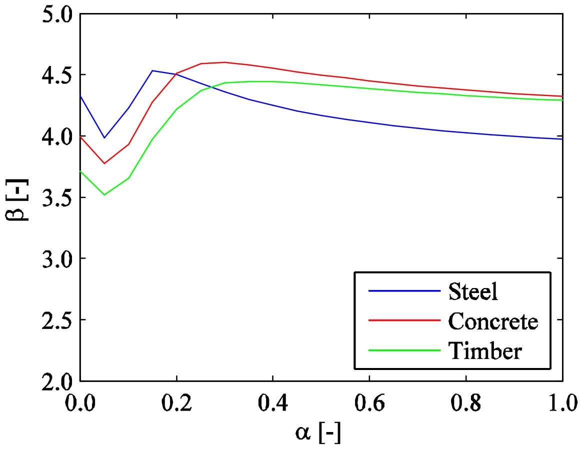


Figure 1. Reliability index β as a function of load influence factor α for the coefficient of variation for the pressure coefficient, $V_{C_{pe}} = 0.20$ and partial factor for variable load $\gamma_Q = 1.5$.

3 PROBABILISTIC APPROACH - WIND ACTIONS

In the Eurocode [16], the specification of the characteristic wind action is structured in accordance with the wind load chain originally introduced by Alan G. Davenport, see [4], [5] and Figure 2. This was decided in order to make the presentation as user friendly as possible.

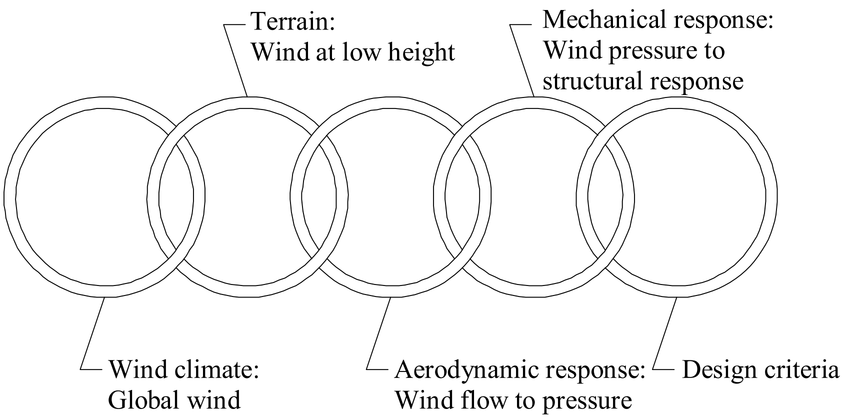


Figure 2. Wind load chain introduced by Alan G. Davenport.

The elements of the wind load chain are as follows:

1. The wind climate is specified by the basic wind velocity defined as the 10-minute mean wind velocity at 10 m height above reference terrain with a roughness length of 0.05 m and having a return period of 50 years corresponding to an annual probability of exceedance of 0.02.
2. The terrain effects are specified by 5 standard flat terrains spanning from category 0 with a roughness length of 0.003 m to category IV with a roughness length of 1 m. Simplified rules for transition between terrains having different roughness and the effect of orography are included in the Eurocode. The extreme winds and terrain effects specified are used to calculate the peak velocity pressure, q_p , which is the basic parameter describing the incoming undisturbed airflow approaching the structure.
3. The aerodynamic response is determined by multiplying the peak velocity pressure by pressure coefficients and force coefficients specified for the different structural geometries.
4. The mechanical response defines the response of the structure, e.g. in form of deflections, accelerations and stresses.
5. The design criteria define the dimensioning criteria used to evaluate the mechanical response calculated.

There are 3 fundamental different factors contributing to the wind load uncertainties:

A. *The statistical uncertainty* caused by the random nature of the load process. This uncertainty cannot be avoided. For instance the wind climate and the turbulence of the wind are described in statistical terms.
B. *The physical uncertainty* tied up with our knowledge of the wind load on the structure. When our knowledge about the load process is increased through research, the physical uncertainty decreases.
C. *The model uncertainty* caused by the simplifications applied in the load description. The uncertainty depends on the model simplifications chosen. The model uncertainty may be reduced by a precise and accurate load model.

Pressure coefficients based on wind tunnel tests will introduce errors due to the difference between full-scale and model-scale values. Errors will also arise when wind velocity pressures measured at a given site are applied to other sites. The estimated parameters in the distribution describing the extreme winds are encumbered with uncertainty. The above mentioned conditions are all together called model uncertainties.

According to the Eurocode, see [16], the wind action on the structure is given by

$$F_w = q_b c_e c_f c_s c_d J_F A_{ref} \tag{5}$$

q_b	wind velocity pressure. The 10 minutes mean velocity pressure at a height of 10 m above rural terrain with a roughness length of 0.05 m
c_e	exposure coefficient taking into account the terrain roughness and the height of the structure
c_f	force coefficient depending on the geometry of the structure
$c_s c_d$	structural factor taking into account the effect on wind actions from the non-simultaneous occurrence of peak wind pressures on the surface together with the effect of the vibrations of the structure due to turbulence. The structural factor depends on the structural area considered.
J_F	model uncertainty
A_{ref}	reference area

In the subsequent tests described in chapter 4 it is assumed that $c_f = c_{pe}$, where c_{pe} is the pressure coefficient, and $c_s c_d = 1$.

The parameters mentioned in the wind load expression are stochastic variables with a certain mean value and coefficient of variation. This appears from Figure 3. The 3 *c*-factors might be correlated. However, the correlation will often be moderate. If the parameters mentioned in the wind load expression are uncorrelated, the mean value and the coefficient of variation of the annual extreme wind load may be determined by:

$$\mu_{F_w} = \mu_{q_{bref}} \mu_{c_e} \mu_{c_f} \mu_{c_s c_d} \mu_{J_F} \tag{6}$$

$$\left(1+V_{F_w}^2\right) = \left(1+V_{q_{ref}}^2\right)\left(1+V_{c_e}^2\right)\left(1+V_{c_f}^2\right)\left(1+V_{c_s c_d}^2\right)\left(1+V_{J_F}^2\right) \tag{7}$$

μ_{F_w} is the mean of annual extreme wind loads. q_{ref} is the annual extreme velocity pressure under reference conditions.

Normally, the wind velocity pressure fits the well to the extreme value distribution of type 1. The distributions of the other parameters in the expression are usually not known in detail. However, the Central Limit Theorem implies that the product of a number of independent factors will tend towards a lognormal distribution regardless of the distribution of the individuals factors. Mean value and standard deviation are sufficient to define the distribution.

In the Eurocodes partial factors are used to convert characteristic values to design values. For structures exposed to wind actions these partial factors should take the uncertainties of all elements of the wind load chain properly into account. Detailed calibration studies, see e.g. [6], have shown that the partial factor on wind actions should be of the order of 1.7 and that the Eurocode partial factor for wind action specified to be 1.5 may actually underestimate the inherent uncertainties. This result is discussed thoroughly in the subsequent chapters.

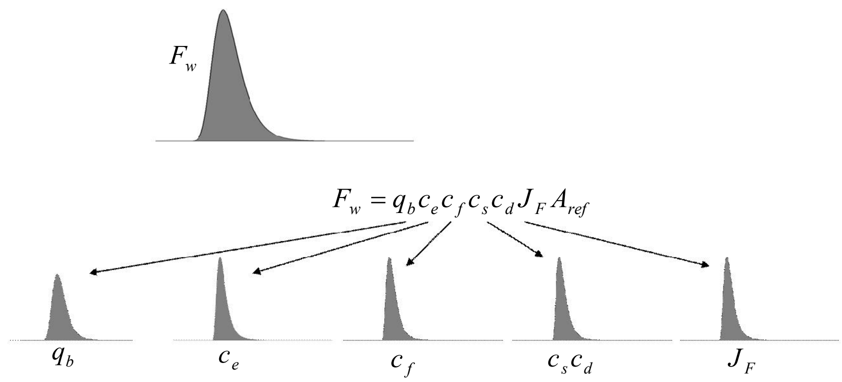


Figure 3. Stochastic distributions of individual wind action parameters.

A large number of wind tunnel measurements and simulations have been carried out by [7] in order to answer the following question: *What is the value of the loading coefficient that results in a design load of the desired design risk, given a wind speed of the same risk.* Thus, for the external pressures the question is: *Which pressure coefficient* c_{pe} *provides a characteristic wind pressure calculated by* $w_e = c_{pe} q_p$, *in which* q_p *is the characteristic peak velocity pressure.* [7] found that the pressure coefficient should be obtained as the 78% quantile in the Gumbel distribution of pressure extremes.

4 CASE STUDY - PRESSURES ON CAARC BUILDING

Following a meeting of the Commonwealth Advisory Aeronautical Research Council Coordinators in the Field of Aerodynamics in 1969, [8] prepared in 1970 a specification for a CAARC standard tall building model for the comparison of simulated natural winds in wind tunnels. A simple model experiment was proposed for comparison between the techniques being established in various wind tunnels for the simulation of natural wind characteristics. The CAARC building is of rectangular prismatic shape, it has the horizontal full-scale dimensions of 30.48 m x 45.72 m, and the height is 183.88 m. Some of the test results obtained have been reported by [9].

The test results reported in this chapter is obtained on a 1:383 scale model of the CAARC building. The tests were carried out in a turbulent boundary layer with a roughness length of approx. 0.6 m in full scale.

Blockage ratio of the model is approx. 2 %. The pressures reported have been corrected for blockage in a way facilitating that the largest extreme pressure on the wide windward façade is 1. In Figure 4 the scale model of the CAARC building used for wind tunnel tests is shown. In Figure 5 the size of the scale model and the location of the pressure taps are shown. 256 pressure taps have been used. The facades are named North, East, South and West. Facade North and South are the widest facades.

Figure 4. Wind tunnel model of the CAARC standard tall building with pressure taps.

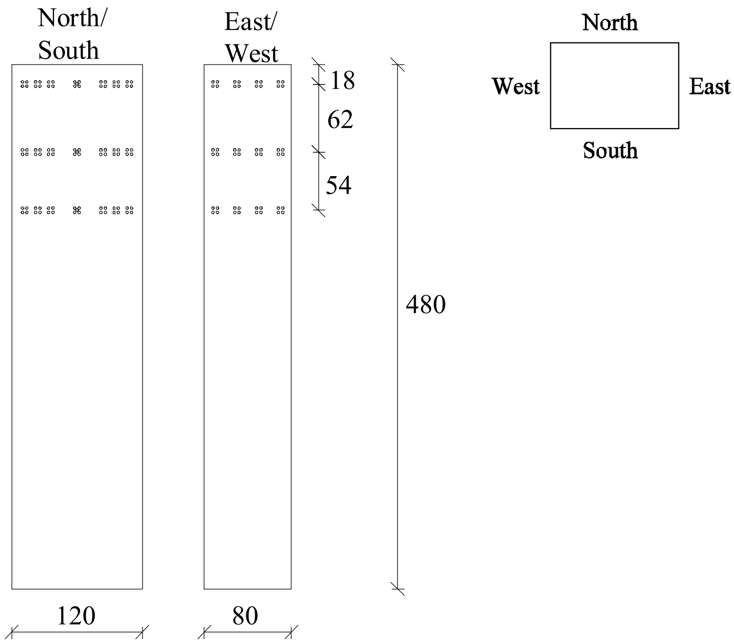


Figure 5. CAARC building model with pressure taps. Scale 1:383. Measurements are in mm.

For wind perpendicular to the North and East facade the measured pressure coefficients for the four facades are depicted in Figure 6 and Figure 7, respectively. The shown pressure coefficients have been based on interpolations using the measurements in the point of the pressure taps.

The figures show the Eurocode zones, see [16]. The Eurocode and the extreme measured pressure coefficients are tabulated on each facade.

The pressure measurements shown indicate that the Eurocode may be non conservative. Furthermore the Eurocode zoning for the CAARC building facades parallel with the wind direction do not follow the extreme suction distributions measured. There seem to be a need for updating the Eurocode values and zoning, especially for buildings with heights of more that approx. 5 times the cross wind dimension similar to the CAARC building.

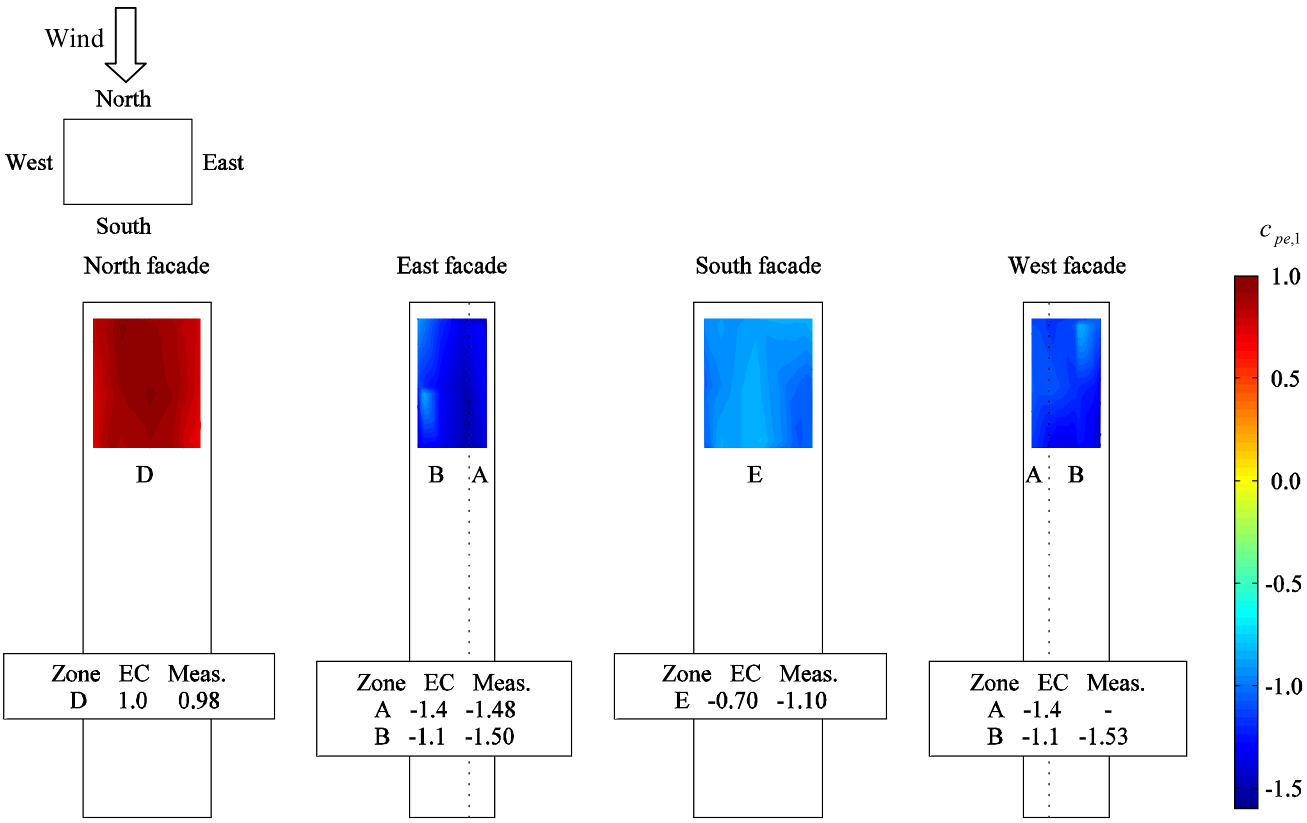


Figure 6. Pressure coefficients $c_{pe,1}$ for wind on the North facade.

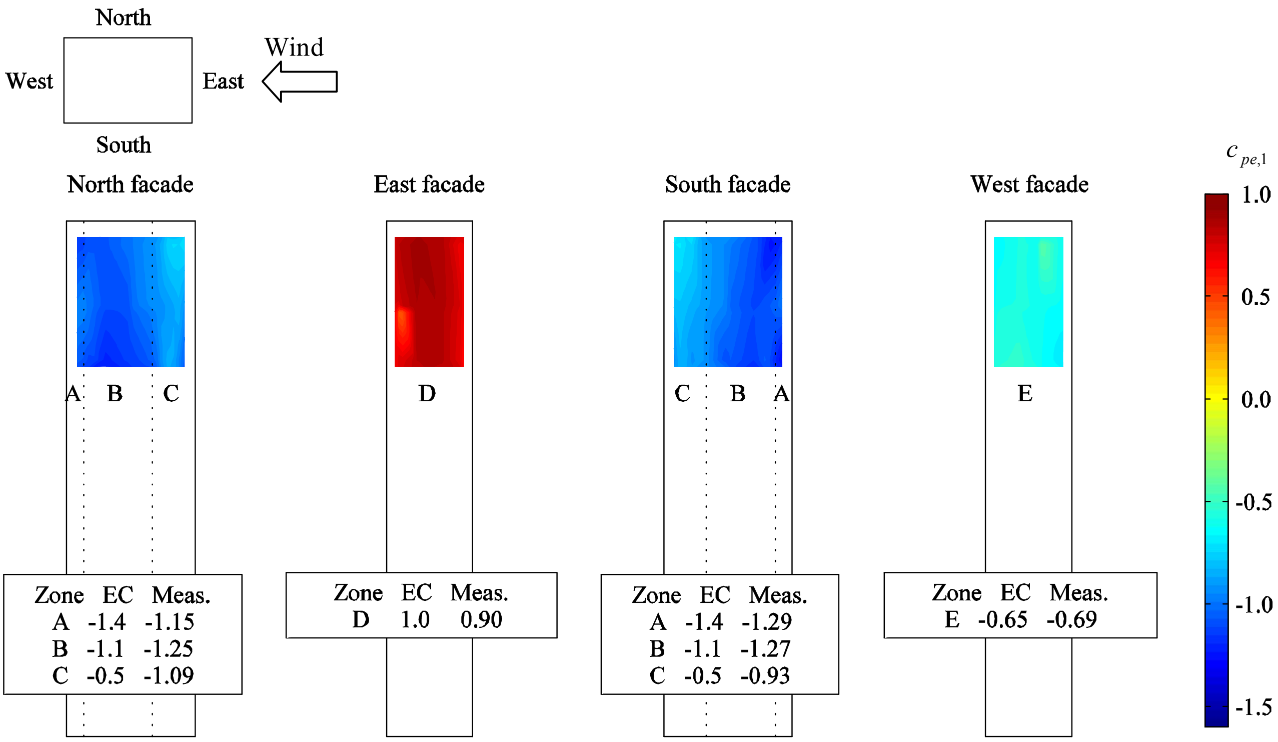


Figure 7. Pressure coefficients $c_{pe,1}$ for wind on the East facade.

For wind perpendicular to the North facade of the CAARC building the probability function is determined for the pressure coefficients for the Eurocode zone A and B on the facades parallel to the wind. Selected pressure taps in these zones are used to illustrate the fit of the probability function, see Figure 8 to Figure 13.

In Figure 8, Figure 10 and Figure 12 the probability function for the pressure coefficient are shown for full-scale loaded areas of 1 m^2, 10 m^2 and 72 m^2, respectively, for zone A. In Figure 9, Figure 11 and Figure 13 the probability function for the pressure coefficient are shown for full-scale loaded areas of 1 m^2, 10 m^2 and 33 m^2, respectively, for zone B. For larger areas in a zone the extreme suctions are reduced. The correction due to reduced measurement time based on [10] has not yet been included.

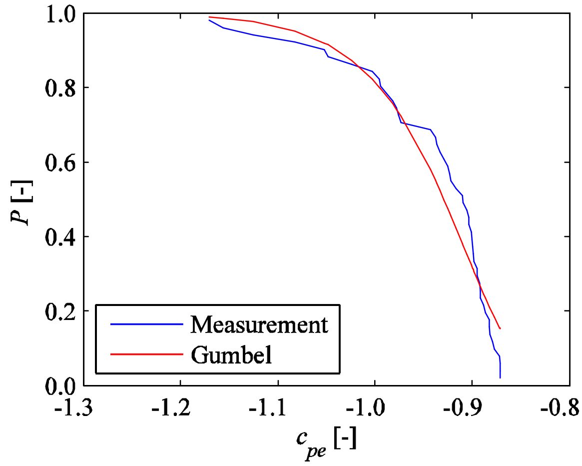


Figure 8. Probability P as a function of pressure coefficient c_{pe} in zone A in the Eurocode for a loaded full-scale area of 1 m^2.

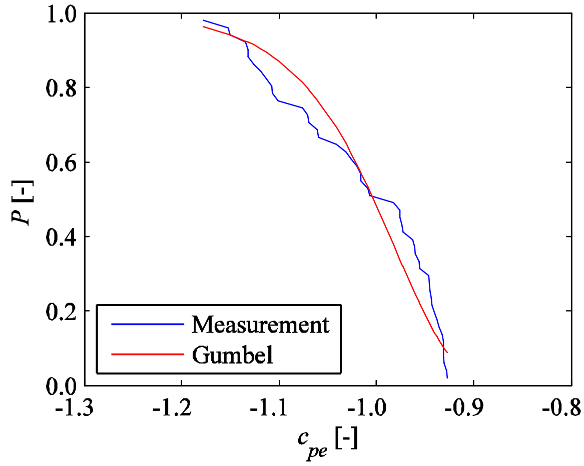


Figure 9. Probability P as a function of pressure coefficient c_{pe} in zone B in the Eurocode for a loaded full-scale area of 1 m^2.

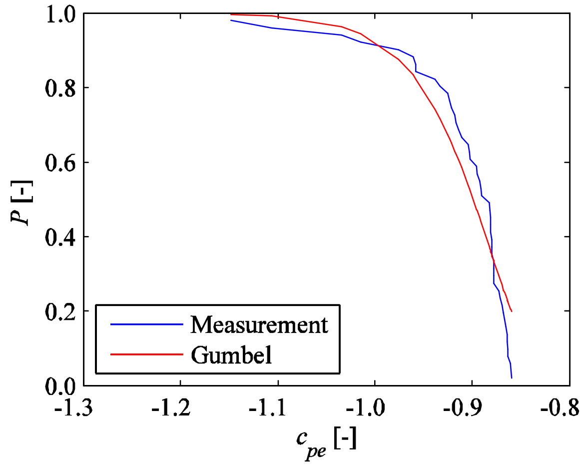


Figure 10. Probability P as a function of pressure coefficient c_{pe} in zone A in the Eurocode for a loaded full-scale area of 10 m^2.

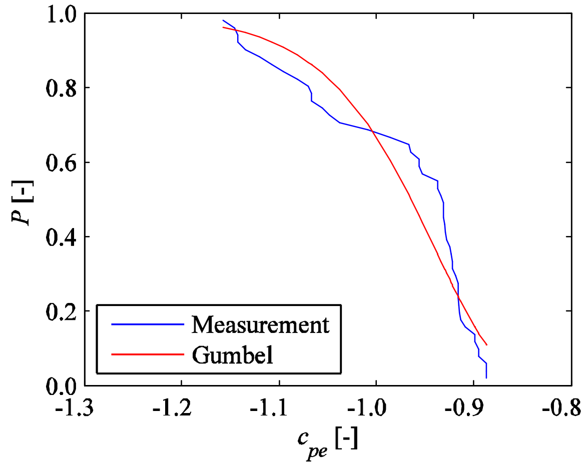


Figure 11. Probability P as a function of pressure coefficient c_{pe} in zone B in the Eurocode for a loaded full-scale area of 10 m^2.

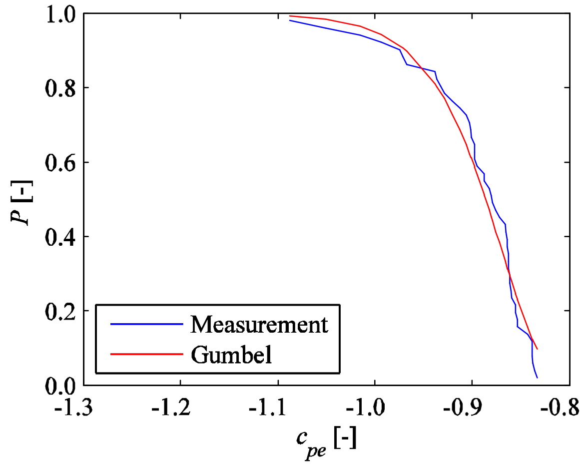


Figure 12. Probability P as a function of pressure coefficient c_{pe} in zone A in the Eurocode for a loaded full-scale area of 72 m^2.

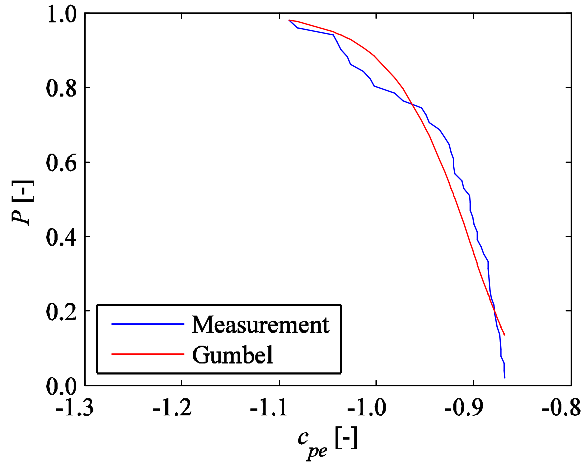


Figure 13. Probability P as a function of pressure coefficient c_{pe} in zone B in the Eurocode for a loaded full-scale area of 33 m^2.

Table 3 shows the mean characteristic pressure coefficients (10 m^2 areas) obtained as the mean value of the characteristic 78% quantiles for the respective zones. The 78% quantiles are determined from the distribution function of the maximum pressure coefficient over a 10 minutes period, which is obtained assuming a Gumbel distribution and by adjusting for the number of measurements per 10 minutes periods, see [10].

The partial factors on wind actions are shown in Figure 14 to Figure 16 under different assumptions. The Eurocode [14] target reliability of 4.7 and a target reliability of 4.3 as specified in the Danish application of [14], see the National Annex, are depicted in Figure 14 and Figure 15. For a target reliability index of 4.3 and 4.7, the partial factors are determined, to be approx 1.5 and 1.8, respectively, for a steel structure using the coefficient of variation of 0.14 measured for zone A. When a wind tunnel test is not carried out, the coefficient of variation of approx. 0.25 may be representative for pressure coefficients and this increase the partial factors to approx. 1.9 and 2.2.

Table 3. Pressure coefficients.

Zone	Mean characteristic pressure coefficient, c_{pe} for 10 m^2	Coefficient of variations, V	Partial factor γ_Q for wind action alone acting on steel structures	
			β =4.3	β =4.7
A	1.05	0.14	1.54	1.78
B	1.14	0.17	1.62	1.89
C	0.80	0.13	1.51	1.74
D	0.88	0.06	1.44	1.65
E	0.66	0.18	1.65	1.93

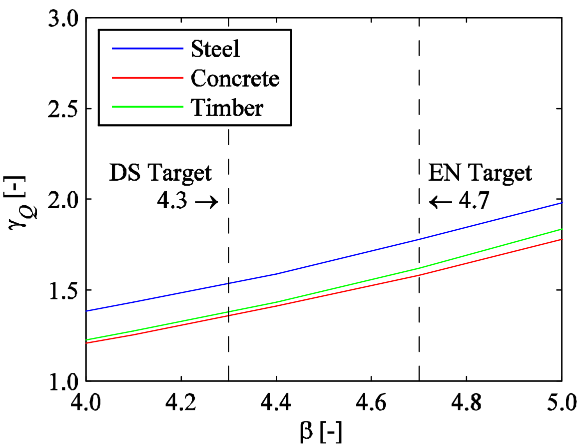


Figure 14. Partial factor for variable wind load alone (α =1), γ_Q as a function of reliability index β for coefficient of variation $V_{c_{pe}}$ = 0.14. Based on wind tunnel tests results for Eurocode zone A.

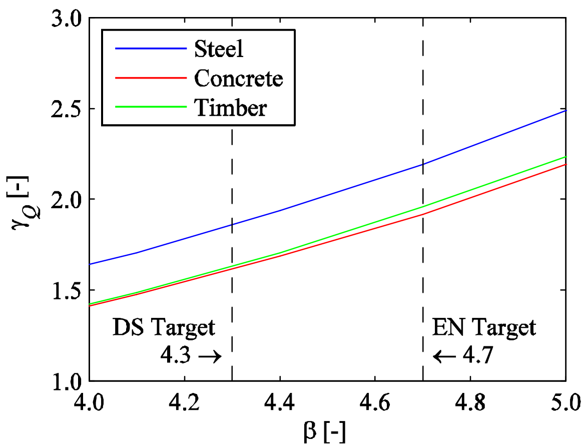


Figure 15. Partial factor for variable wind load alone (α =1), γ_Q as a function of reliability index β for coefficient of variation $V_{c_{pe}}$ = 0.25. Based on rough evaluation of uncertainty of wind pressures using codes.

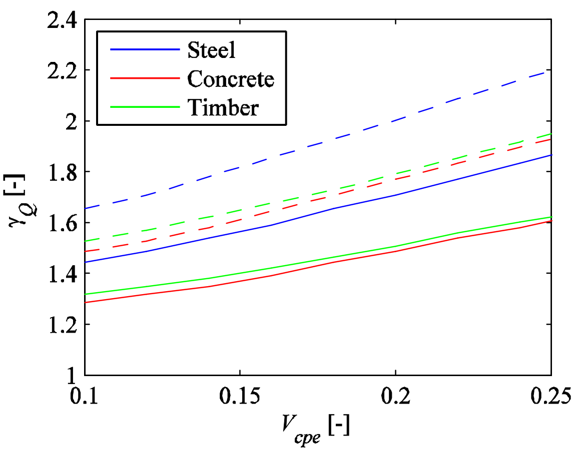


Figure 16. Partial factor for variable wind load alone (α =1), γ_Q as a function of coefficient of variation $V_{c_{pe}}$. Reliability index β = 4.3 (full lines DS Target) and β =4.7 (dashed lines EN Target).

Figure 14 shows the partial factor for variable wind load alone (α =1), γ_Q as a function of the annual reliability index β for the coefficient of variation $V_{c_{pe}}$ = 0.14 based on the wind tunnel test results for Eurocode zone A. It is seen that a higher partial factor is required for steel than for concrete and timber components considered. Figure 15 shows the partial factor for the coefficient of variation $V_{c_{pe}}$ = 0.25 based on a rough evaluation of uncertainty of wind pressures using codes. It is seen that the higher uncertainty implies higher partial factors. Finally, Figure 16 shows the partial factor as a function of the coefficient of variation $V_{c_{pe}}$ for the annual reliability index β = 4.3 used for calibration of partial factors in the Danish National Annex to the Eurocodes, and for the annual reliability index β =4.7 recommended in Eurocode, see [14].

5 PROBABILISTIC APPROACH - SNOW LOAD

Similar to the categorising of wind actions, the snow load chain may be defined as shown in Figure 17.

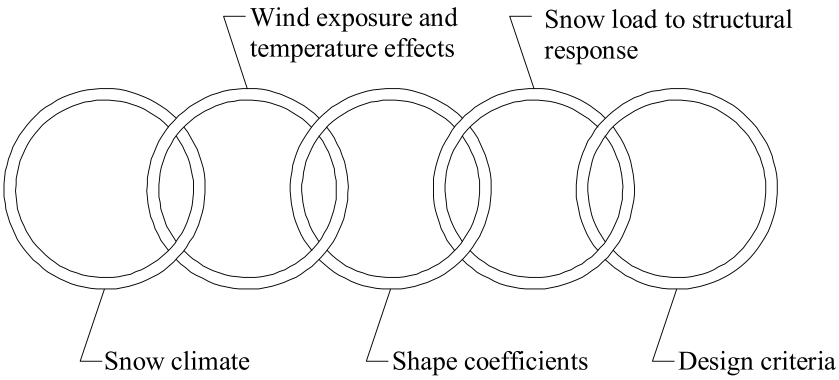


Figure 17. Snow load chain.

According to the Eurocode, see [16], the snow load on the structure is given by

$$s = s_k c_e c_t \mu_i J_s \tag{8}$$

s_k	characteristic value of snow load on the ground.
c_e	exposure coefficient
c_t	thermal coefficient
μ_i	snow load shape coefficient
J_s	model uncertainty

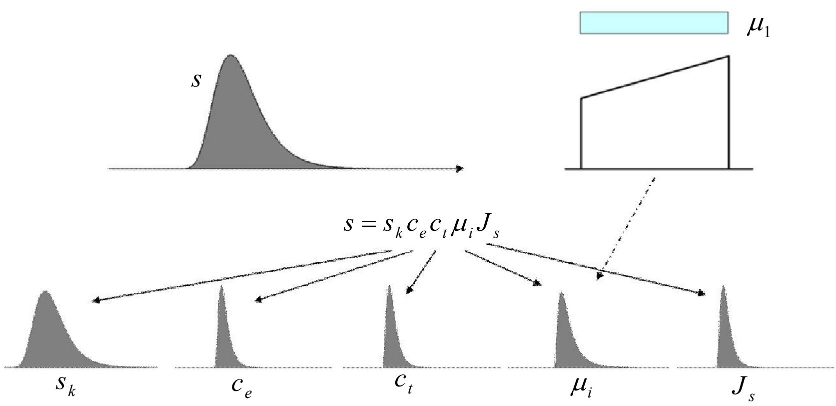


Figure 18. Sketch showing the snow load distribution on a monopitch roof as well as the distribution of the individual parameters.

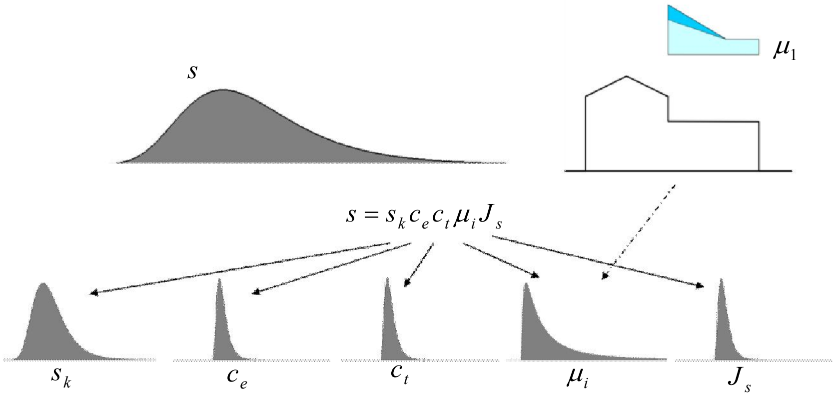
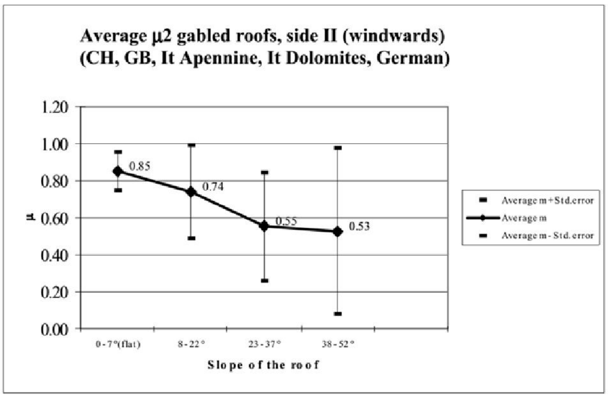


Figure 19. Sketch showing the snow load distribution on a roof abutting to a taller construction works as well as the distribution of the individual parameters.

Similar considerations as for wind actions can to some extend be stated for snow loads. However, the available documentation/measurements of snow loads are very limited. Some information can be found in [11] indicating large variations in characteristic snow loads compared to observations. As described in [12] snow loads have been observed in the winter 2010 in Denmark exceeding the design snow loads in the Eurocodes.

Figure 18 illustrates possible uncertainties related to the factors used to estimate the snow load on a monpitch roof (and similarly for a gabled roof). Figure 19 indicates the uncertainties for a more 'complicated' roof, namely a roof abutting to a taller construction work. It is seen that the uncertainties are much larger than for a pitched roof. Figure 20 shows examples of the mean and standard deviations of the roof shape coefficient for gabled roofs with different slopes for different European sites. It is seen that the shape coefficient has a large scatter and that a shape coefficient equal to 0,8 does not account for this uncertainty. A larger shape coefficient corresponding to a quantile of the order of approx. 90% could be appropriate.



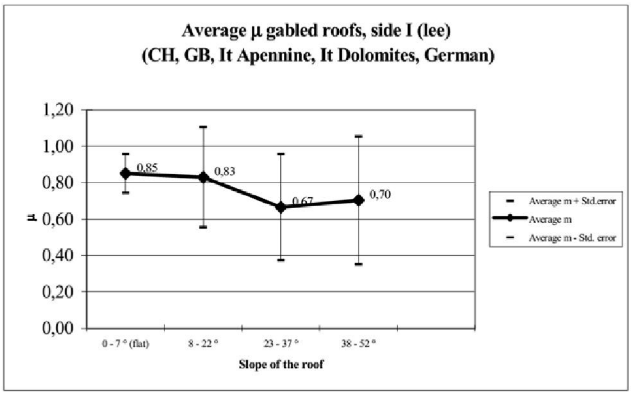


Figure 20. Mean and standard deviation of the roof shape coefficient for gabled roofs with different slopes for Swiss, Italian Apennine, Italian Dolomites, United Kingdom and German sites. From [11].

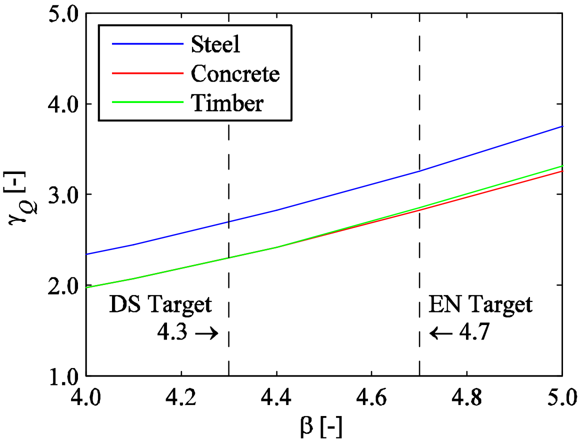


Figure 21. Partial factor for variable snow load alone (α =1) γ_Q as a function of reliability index β. Coefficient of variation for snow on ground V_s = 0.40. Coefficient of variation of shape coefficient V_μ = 0.30. Characteristic shape coefficient equal to mean value.

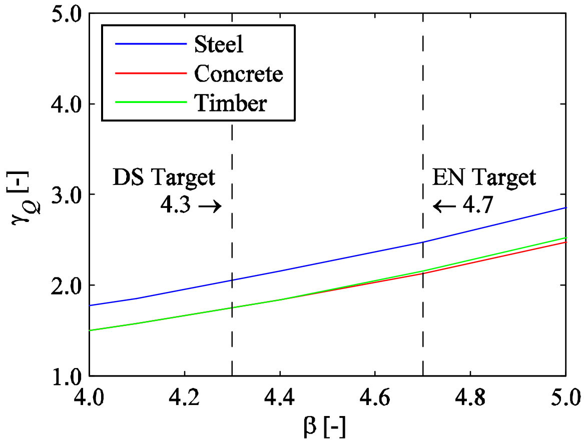


Figure 22. Partial factor for variable snow load alone (α =1) γ_Q as a function of reliability index β. Coefficient of variation for snow on ground V_s = 0.40. Coefficient of variation of shape coefficient V_μ = 0.30. Characteristic shape coefficient equal to 1.25 times mean value.

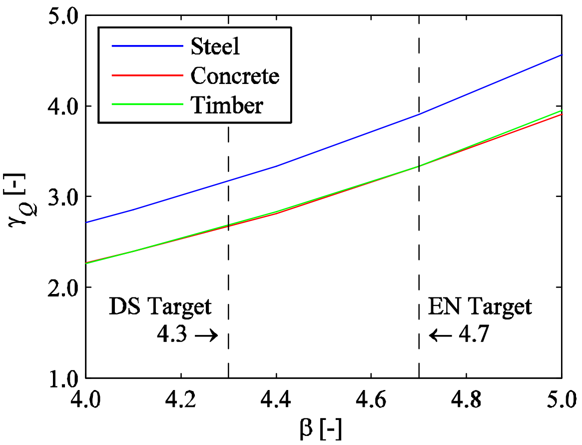


Figure 23. Partial factor for variable snow load alone (α =1) γ_Q as a function of reliability index β. Coefficient of variation for snow on ground V_s = 0.60. Coefficient of variation of shape coefficient V_μ = 0.80. Characteristic shape coefficient equal to mean value.

Figure 21 shows the partial factor for variable snow load alone (α =1), γ_Q as a function of the annual reliability index β for the coefficient of variation for snow on ground V_s = 0.40, the coefficient of variation of shape coefficient V_μ = 0.30 and the characteristic shape coefficient equal to mean values as indicated from [11]. It is seen that quite high partial factors are required to obtain a target reliability index corresponding to an annual reliability index in the range from 4.3 to 4.7. Figure 22 shows that the partial factor for snow load can be reduced significantly if a 95% quantile is used for the shape coefficient. Figure 23 shows, as expected, that if the coefficient of variation of the shape coefficient is increased to 0.8, then even higher partial factors are required.

6 COMPARISON BETWEEN WIND ACTION AND SNOW LOAD

In order to provide an overview the uncertainties of wind actions and snow loads are summarised in Figure 24.

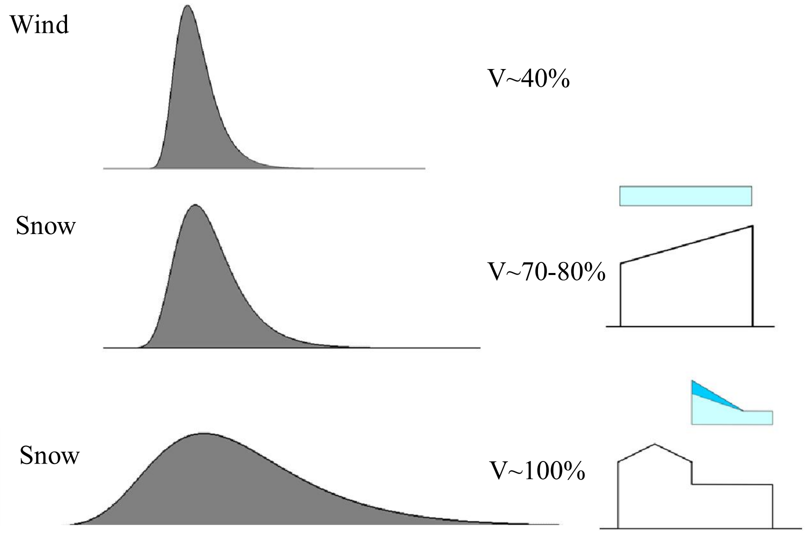


Figure 24. Comparison of uncertainty level for wind actions and snow loads.

Wind actions and snow loads are generally obtained as a product of various contributions including wind pressure, snow load on ground and shape coefficients. Figure 24 illustrates the relative uncertainty level for wind actions, snow load on 'simple' monopitch roofs and 'complicated' roofs abutting to taller buildings.

7 SPATIAL AVERAGING AND LOAD DURATION - HIDDEN SAFETY FOR LOW RISE STRUCTURES

It is important to identify and describe additional / 'hidden' safety elements in the load calculation models for several reasons:

- when reliability assessments are performed using probabilistic methods, e.g. for existing structures.
- when additional tests and measurements are made, e.g. wind tunnel tests. Here it is important not to 'use' the additional safety when decreasing the characteristic wind action as a result of the measurements (more than what corresponds to the reduction in uncertainty).
- when using advanced numerical calculation models. Here a similar consideration as for additional tests has to be made.

Since the publication of the EN 1991-1-4 in 2005 a large number of measurements have been carried out in our wind tunnel aiming at determining both 1 m² and 10 m² loads, as well as loads on intermediate areas, on a consistent basis. This has been accomplished by installing pressure tap clusters on the wind tunnel models, see Figure 25. The pressures in each pressure tap cluster have been measured simultaneously indicating that spatial averaging could be used to estimate the wind action on different areas of up to approximately 10 m². Thus, the procedure applied facilitates a determination of both 1 m² and 10 m² pressure coefficients, which could be compared directly to the same type of pressure coefficients specified in the Eurocode.

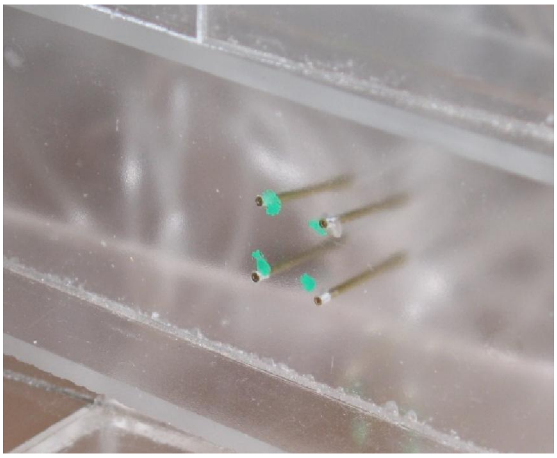


Figure 25. Photo of pressure tap cluster on model. Each pressure tap has an area of less than 1 m².

The measurements described below show two case studies, where the influence of both time averaging and spatial averaging of simultaneously measured external pressures in the separated zones with large suctions are illustrated.

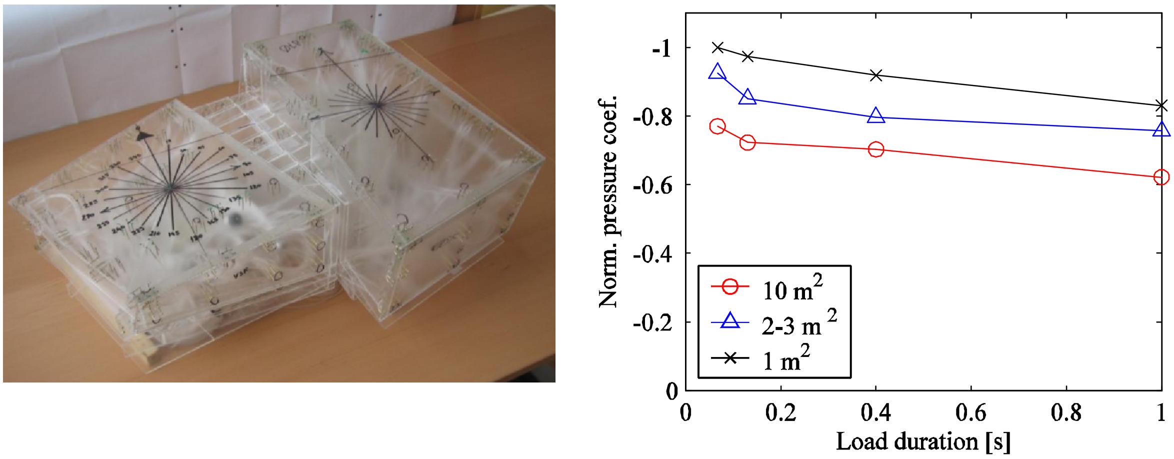


Figure 26. The Concert and Conference Centre “Harpa” in Reykjavik, Iceland. Left-hand side: Photo of 1:200 wind tunnel scale model. Right-hand side: Normalised pressure coefficients measured on the eastern facade in separated zones with large suctions as function of load duration and load area. Reproduced by permission of Ramboll Denmark, Consulting Engineers of the building.

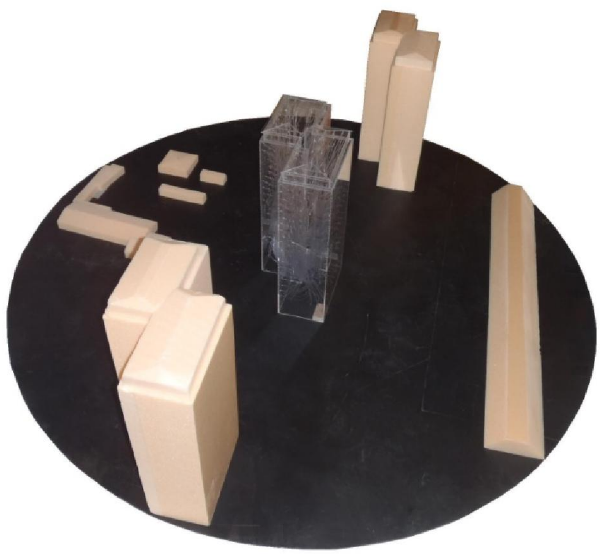


Figure 27. Photo of a 1:200 wind tunnel scale model of a block building in Søndermarken in Copenhagen, Denmark. The pressure tap model is situated in the middle of the circle. Reproduced by permission of Moe, Consulting Engineers, and the building owner KAB.

The effect of spatial averaging and time duration for pressures measured at Søndermarken is shown in Figure 28. In this illustration the time duration has been made non-dimensional by multiplying it with the mean wind velocity divided by the dimension e defined in the Eurocode, i.e. the minimum of 2 heights and the cross wind dimension, determining the sizes of the different zones on the structure. This choice of length scale has been found to be in reasonable agreement with measurements carried out in the separated zones with large suctions on different models.

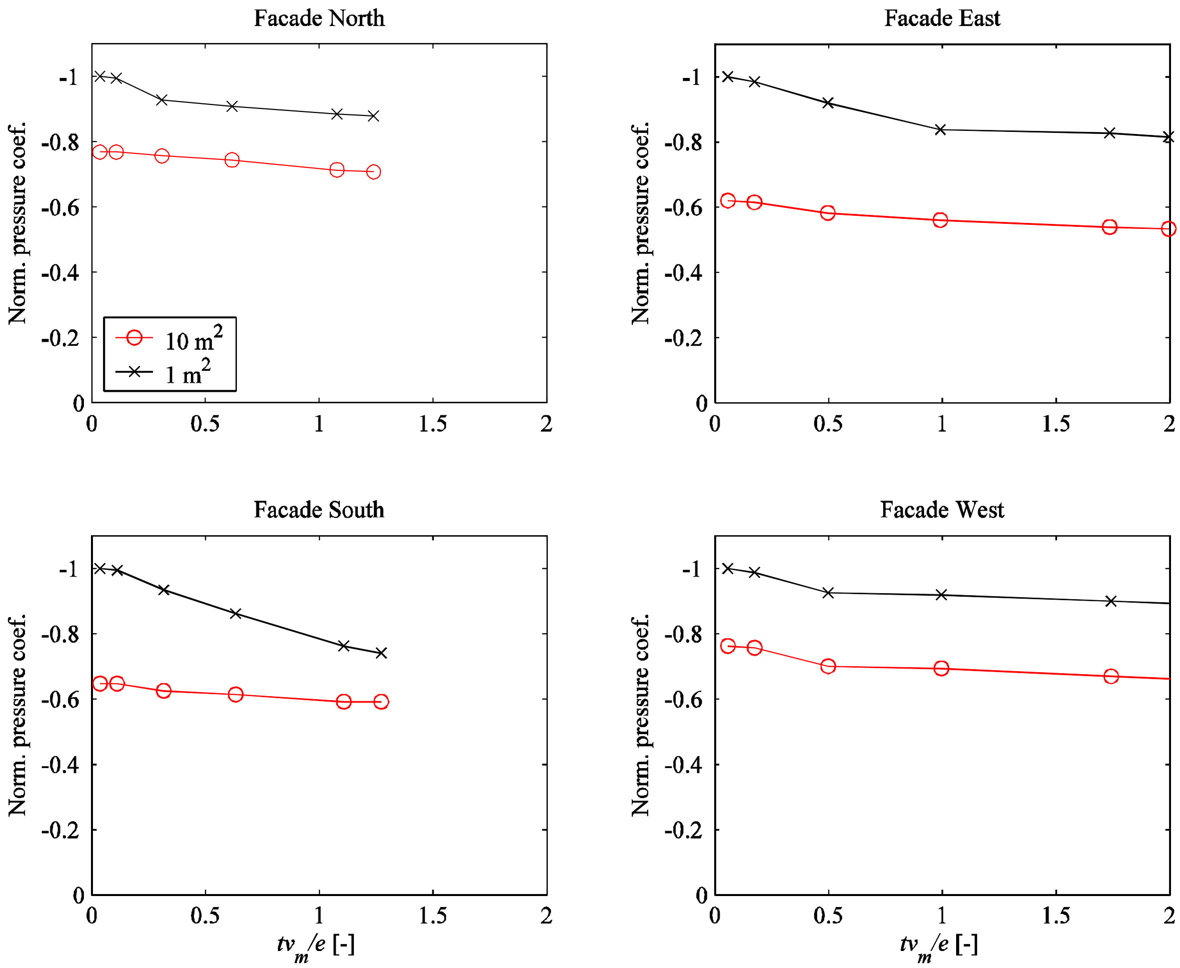


Figure 28. Normalised pressure coefficients from measurements of facade wind loads in separated zones with large suctions on a structure. The non-dimensional x-axis is averaging time t multiplied by the mean wind velocity v_m and divided by the Eurocode defined dimension of e. Reproduced by permission of Moe, Consulting Engineers, and the building owner KAB.

Figure 26, Figure 27 and Figure 28 show examples of characteristic pressure coefficients as function of load durations for loaded areas of 1 m², 2-3 m² and 10 m², respectively. The effect of load duration is significant for all loaded areas considered indicating that the largest suction peaks have very short durations of the order of 1/10 seconds. Especially for short durations the averaging effect is pronounced. It may be observed that the pressure coefficient is approximately 30-40% smaller for the 10 m² loads with duration of approximately 1 second compared to its value for 1 m² loads with duration of approximately 0.1 second. A consistent approach with data sets including both the effect of duration and loaded area are needed. The data presented show the importance of both load duration and spatial averaging.

It is noted that this comparison between the Eurocode and wind tunnel test results does not include the effect of whether short duration wind action fluctuations will lead to a structural failure. Most structures have a certain additional resistance for short duration action effects. Ductility of steel and the ductility of joints often average out the extreme short duration wind action effects and thereby provide an effective additional resistance of the structure. Concrete, masonry and wood materials have larger resistances for short duration action effects, and these effects are not included in the Eurocode specifications. Thus, the characteristic Eurocode resistance values in connection with short duration wind action effects often gives additional safety not taken into account in most structural design.

The pressure coefficients in many codes are based on the “equivalent static gust” concept where a moving time averaging filter is assumed to correspond to spatial averaging over a certain area. This procedure will not provide accurate pressure coefficients in all situations, and it is crucial to establish a more consistent approach including both spatial averaging and time averaging. The paper focuses on this approach in a full probabilistic design method.

As illustrated in Figure 29 Eurocode specifies external pressure coefficients as function of loaded area, and the tabulated values give $c_{pe,10}$ representing a loaded area of 10 m² to be used for the wind load on the main structural elements, and $c_{pe,1}$ representing a loaded area of 1 m² to be used in the design of fixings, smaller panels etc.

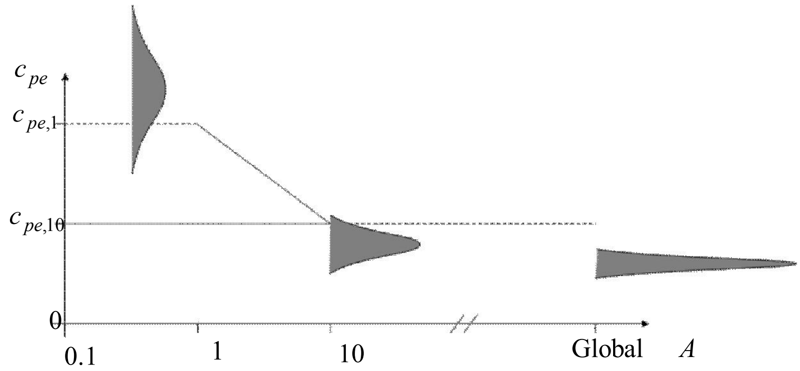


Figure 29. Recommended Eurocode procedure for determining the external pressure coefficient c_{pe} for buildings with a loaded area between 1 m^2 and 10 m^2. From EN 1991-1-4:2005. The distributions shown illustrate typical results obtained in wind tunnel experiments.

The experience gained from a large number of wind tunnel tests carried out with models of a variety of different low-rise building geometries is as follows:

1. The Eurocode 1 m² pressure coefficients often underestimate the wind action measured in the wind tunnel. An underestimation of more than 20% is often observed
2. The Eurocode 10 m² pressure coefficients often overestimate the wind action measured in the wind tunnel. An overestimation of more than 20% is often observed.
3. The Eurocode global wind action often overestimates the wind action measured in the wind tunnel. Often the overestimation is of an order of at least 40%.

Thus, for small structural elements and fixings the Eurocode may underestimate the wind action. For global wind load used to design the overall structural stability, the Eurocode normally overestimates the wind action considerably.

The majority of the Eurocode pressure coefficients are based on [7] and [13] for 10 m² and 1 m² loaded areas, respectively. [7] used time averaging for determining 10 m² wind loads indicating that these values have not been based directly on a spatial averaging. Thus, pressure coefficients in the Eurocode are based on the "equivalent static gust" concept where a moving time averaging filter is assumed to correspond to spatial averaging over a certain area. This procedure will not provide accurate pressure coefficients in all situations, and it is crucial to establish a more consistent approach including both spatial averaging and time averaging.

8 CONCLUSION

Normally, a consistent basis for calculating partial factors focuses on a homogeneous reliability index neither depending on which material the structure is constructed of nor the ratio between the permanent and variable actions acting on the structure. Furthermore, the reliability index should not depend on the type of variable action. In order to put the partial factors determined into perspective, calculations have been carried out for structures of steel, concrete and timber, and these structures have been exposed to both wind actions and snow load, one at a time.

In the present Eurocodes the uncertainties inherent in the snow load are much higher than the wind action uncertainties. In order to take this difference consistently into account it is proposed to change the definition of the characteristic snow load to an upper quantile of approx. 95%. This may facilitate that the partial factor on wind actions and snow loads could be maintained to be 1.5, if the corresponding reliability index is found to be appropriate.

Pressure measurements have been carried out the CAARC building model on a scale of 1:383. The Eurocode zoning for the CAARC building facades parallel with the wind direction do not follow the extreme suction distributions measured. There seem to be a need for updating the Eurocode zoning, especially for buildings with heights of more that approx. 5 times the cross wind dimension similar to the CAARC building.

The pressure coefficients in many codes are based on the "equivalent static gust" concept where a moving time averaging filter is assumed to correspond to spatial averaging over a certain area. This procedure will not provide accurate pressure coefficients in all situations, and it is crucial to establish a more consistent approach including both spatial averaging and time averaging.

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