Validation of wind loading codes by experiments

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Between 1994 and 1997, full scale measurements of the wind and wind induced pressures were carried out on the main building of Eindhoven University of Technology. Simultaneously, a comparative wind tunnel experiment was performed in an atmospheric boundary layer wind tunnel. In this paper, the transition from wind velocity into wind loading is studied from both experiments. This transition is expressed by three quantities: the pressure coefficient, the pressure admittance and the coherence. The results of the experiments show that the wind loading, defined in building codes, is based on assumptions, which are generally not valid for buildings. The errors, made in these assumptions, work in opposite direction, thus giving an unknown, but generally small error.

Key words: **wind loading; dynamic response; full scale testing; wind tunnel tests.**

1 Introduction

Wind loading is the dominant horizontal force on buildings, and the most relevant loading for cladding. In building codes, the wind loading is based on the wind climate characteristics at meteorological stations. This is translated into the loading on buildings by multiplication of the dynamic pressure with a pressure or force coefficient and several modification factors, e.g. the factors to account for the effects of the pressure fluctuations.
In this paper, the pressure coefficient, the pressure admittance and the coherence are studied, which are relevant parameters to describe the transition of wind velocity into wind induced pressures on buildings. These quantities are defined as follows:

- The pressure coefficient is the ratio between the wind-induced pressures and the undisturbed mean dynamic pressure at a reference height.
- The pressure admittance is the normalized ratio between the spectral density of the wind velocity and the spectral density of the pressures.
- The coherence of the pressures describes the relation between the pressures over the building = s envelope in the frequency domain.

The pressure coefficients used in building codes are often based on wind tunnel research. Both internal and external coefficients are defined.

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The modification factors for the fluctuating wind loading are based on spectral analysis of the loading and the response of a structure. The following assumptions are made in this calculation, which follow from the quasi-steady theory [1]:

1. The fluctuations of the wind induced pressures are proportional to the fluctuations in the wind velocity;
2. The coherence of the wind induced pressures is similar to the coherence of the wind velocity;
3. The peak values in the pressures on windward and leeward side of a building act simultaneously. This means that these pressures are perfectly correlated.

In a study, carried out at Eindhoven University of Technology, the choices for the pressure coefficients and modification factors in the building codes are validated against full scale and wind tunnel measurements of the wind induced pressures [2].

In this paper, the local pressure difference between external and internal pressure, as measured in full scale, is discussed. Also, the mean pressure coefficients, as measured in the wind tunnel are presented. Finally, results of the measurements of the spectrum and coherence of the wind induced pressures and their implications for the modification factors for the fluctuating loading in building codes are discussed.

2 Background

In the Dutch code NEN 6702 [3], the wind loading on a structure is expressed as:

$$p_{\mathrm{rep}} = C_{\mathrm{dim}} C_{\mathrm{index}} C_{\mathrm{eq}} \phi_1 p_{\mathrm{w}} \tag{1}$$

$$F_{\mathrm{index}} = A p_{\mathrm{rep}} \tag{2}$$

with:

p_{rep} is the representative wind loading in N / m^2;
C_{dim} is a reduction factor for large objects;
C_{index} can be the pressure coefficient C_{p} or the force coefficient C_{t}. The pressure coefficient can be an internal or external coefficient and can be positive or negative;
C_{eq} is the pressure equalisation factor;
ϕ_1 is the dynamic amplification factor;
p_{w} is the dynamic pressure in N / m^2;
F_{index} is the wind loading on the area *A*, in *N*; this can be an external force, or a total force, depending on the type of coefficient C_{index};
A is the area of the surface on which the loading is applied, in m^2.

In the Eurocode 1, part 2-4 [4], a similar approach is used. The modification factors C_{dim} and ϕ_1 are included in one factor c_d, incorporating both the effect of large objects and the dynamic amplification.

The pressure and force coefficients are given in codes and depend on the shape and size of the buildings. These factors are based on measurements in wind tunnels, mostly in relatively smooth boundary layers. Buildings, however, are seldom built in such conditions, but mostly in rough terrain conditions.
For wind loading on building cladding, the difference between the pressure outside and inside the buildings is relevant. This can not be measured easily in wind tunnel experiments, so validation of the codes by full scale measurements is very useful.

In building codes, different reference heights are defined. The pressure coefficients C_p, which are presented in this paper, are defined relative to the dynamic pressure at roof height of the building:

$$C_p = \frac{p_s - p_{ref}}{\frac{1}{2}\rho v_m^2} \tag{3}$$

with:

p_s is the local pressure on the surface;
p_{ref} is the reference pressure in N / m^2; in the ideal case, this should be the atmospheric pressure;
v_m is the mean wind velocity at roof height, in m / s;
ρ is the mass density of air, 1.25 kg / m^3.

Pressure coefficients can be defined for the instantaneous pressures or the mean, extreme or rms values of the pressures. In building codes, only the mean pressure coefficients are used, and therefor, in this paper, only this mean pressure coefficient is used, denoted by C_{pm}.

The modification factors C_{dim} and ϕ_1 represent the fluctuating part of the wind loading in NEN 6702. For Eurocode 1, this is given by c_d. These modification factors are defined as:

$$(C_{dim}\phi_1)_{NEN} = (c_d)_{Eurocode} = \frac{1 + 2gI(h)\sqrt{B+E}}{1 + 7I(h)} \tag{4}$$

with:

$I(h)$ is the turbulence intensity at building height H, this is the ratio of the standard deviation and the mean value of the wind speed;
B is a function of the dimensions of the building;
E is a function of the dimensions, the natural frequency f_e, and the damping ratio ζ of the building;
g is the peak factor; it has a value 3.5 in NEN 6702, and is calculated in appendix B of the Eurocode.

The functions B and E are derived from the spectrum of the fluctuating response $S_{xx}(f)$ on buildings. The relation between B and E and $S_{xx}(f)$ is:

$$B \propto \int_0^\infty S_{xx}(f)df \tag{5}$$

$$E \propto f_e S_{xx}(f_e) \tag{6}$$

with:
f_e is the natural frequency. Note that for different modes of vibration, a value for ϕ_1 can be defined;
x is the response of the structure, in terms of displacements.

The spectrum of the response is calculated from the spectral characteristics of the wind induced pressures and the structural properties of the building. The spectrum of the total force on the loaded surface is found by integration of the local pressures, using the coherence of the local pressures, which takes into account, the spatial correlation of the pressures. This calculation is the basis for the estimation of the factors B and E. In this procedure, the quasi-steady theory is assumed valid. In this case, the following relations between wind velocity and pressures are found:

$$p' = C_{pm} \rho \upsilon_m \upsilon' \tag{7}$$

$$\sigma_p = C_{pm} \rho \upsilon_m \sigma_v \tag{8}$$

$$S_{pp}(f) = (C_{pm} \rho \upsilon_m)^2 S_{vv}(f) \tag{9}$$

with:
$S_{pp}(f)$ is the spectrum of the pressures;
$S_{vv}(f)$ is the spectrum of the wind velocity;
σ_v, σ_p are the standard deviation of the velocity and the pressures, respectively.

This means, that the pressure spectrum is proportional to the spectrum of the undisturbed wind velocity. Integration of the pressure spectrum over the surface of the building gives the spectrum of the overall force. It is found by:

$$S_{FF}(f) = \int_A \int_A S_{pipi}(f) S_{pjpj}(f) coh_{pjpj}(f) dA dA \tag{10}$$

dA is the area, represented in the points i or j;
$S_{pipi}(f)$ is the autospectrum of the pressures in point i;
$S_{pjpj}(f)$ is the autospectrum of the pressures in point j;
$coh_{pipj}(f)$ is the coherence of the pressures in points i and j.

The spectrum of the response S_{xx} is found by multiplying $S_{FF}(f)$ with the dynamic admittance function. This leads to expressions for the coefficients B and E, as used in the codes, which depend on the spectrum of the response as given in equations 5 and 6.

3 Experiments

A full scale experiment is performed on the main building of Eindhoven University of Technology. In figure 1 and 2, an outline of this building is given and the location of the pressure taps is indicated. A detailed description of this experiment is given in [2] and [3]. The relevant characteristics are given here.

Fig. 1. Picture of the main building of Eindhoven University of Technology seen from the north-west.

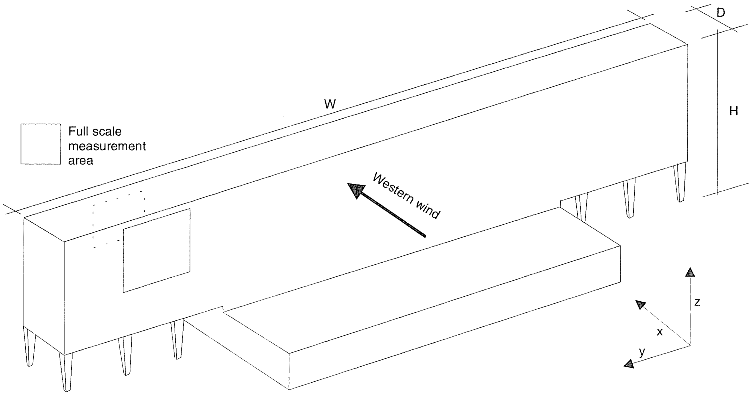

Fig. 2. Outline of the test building, and positions of pressure taps: H = 44.9 m, W = 167 m, D = 20 m.

The building is located in a densely built-up area in the centre of Eindhoven, surrounded by merely low rise buildings. The building has dimensions of 45 metres high, 20 meters deep and 167 metres wide. The building is north-south oriented. The prevailing wind directions are south-west and west. Western wind is exactly perpendicular to the western facade, see figure 2. A meteorological tower is built about 3 times the building height upstream. Wind velocity and direction are measured at roof height, and two lower heights on this tower.

The wind tunnel experiments were performed in the atmospheric boundary layer wind tunnel of Aerodynamik im Bauwesen at the Ruhr University in Bochum, Germany. The wind field in the wind tunnel was tuned to the upstream full-scale observations [5]. The building was scaled 1:350, and the model was equipped with pressure taps at four heights, including the positions of the pressure taps in the full scale experiment. It was concluded in [1] that the wind tunnel measurements do not represent the fluctuating pressures well. Therefore, only the mean pressures are discussed in this paper.

4 Results

4.1 *Pressure coefficients*

Pressure coefficients have been determined in full scale for a wide range of wind directions, on a limited area of the windward and leeward facade. In the wind tunnel experiment, results are available for three wind directions, and distributed over the full facades.

Two aspects of the pressure coefficients are discussed here, based on the observations in the current experiment, the values of the local pressure difference in full scale over the facade of the building, and secondly the distribution of the external pressure coefficients, as measured in the wind tunnel experiment.

First, the local pressure difference over the facade is studied in the full scale experiments. For two pressure taps, the pressure coefficient is given as a function of the mean wind direction in figures 3 and 4 at windward side, and for one tap at leeward side in figure 5.

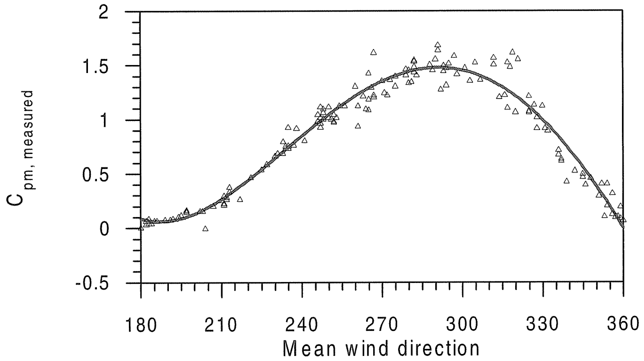

Fig. 3. Mean pressure coefficients in full scale, at windward facade, at h/H = 0.72.

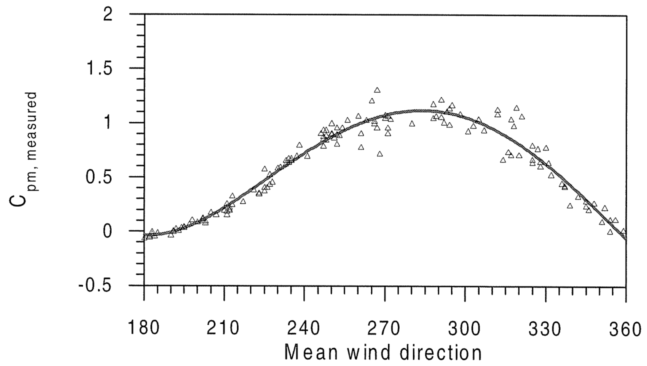

Fig. 4. Mean pressure coefficients in full scale, at windward facade, at h/H = 0.97.

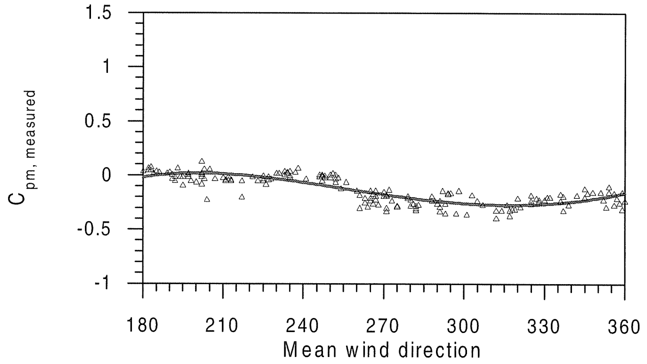

Fig. 5. Mean pressure coefficients in full scale, at leeward facade, at h/H = 0.75.

The mean pressure coefficient depends on the wind direction. The maximum values are found for wind almost normal to the facade. This maximum value is about 1.2 for the windward side at h/H = 0.97, and is about 1.5 for h/H = 0.72. This is higher than the value found, when the Dutch code is applied. Then, a maximum pressure difference over the facade of 1.1 is found.

In the near past, some windows of this building have collapsed, while a strong wind was coming from a wind direction of about 300 degrees. The results of these measurements show, that probably the local pressure difference over the window was much higher than predicted by the code in the design stage. It was concluded from the comparison of these full scale data with the wind tunnel results, that the internal pressure coefficient was in the order of -0.4 [1]. For the comparison of the full scale and the wind tunnel results, first, the full scale data have to be corrected for this internal pressure coefficient.

At leeward side, the mean coefficients are in the order of –0 to –0.3. If the internal pressure coefficient is added to this value, an external coefficient for suction of –0.7 is found. This is much higher than given in the current codes of practice.

The sum of the local pressure coefficients at windward and leeward side is about 1.8, which is higher than the sum of the local coefficients in the codes. This is mainly caused by the higher negative pressures at the leeward side. It was concluded, that these high negative values occur, because the flow, which separates along the sides of the building, is not yet separated, and causes a relatively large zone at the back of the building, which contributes to the overall drag. This is conform the conclusions, given by Akins et.al. [6], for buildings with a relatively high aspect ratio, about the pressure coefficients.

From the wind tunnel measurements, the distribution of the pressure coefficients over the facades is given for three heights in figures 6 and 7. The data are given relative to the parameter y_{no}, which is the relative distance of the tapping to the northern facade. Therefore, this parameter lies between 0 and 1.

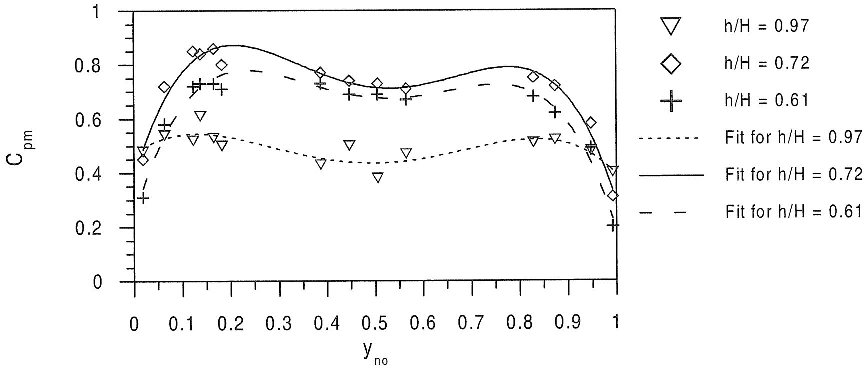

Fig. 6. Wind tunnel measurements of C_{pm} at windward side.

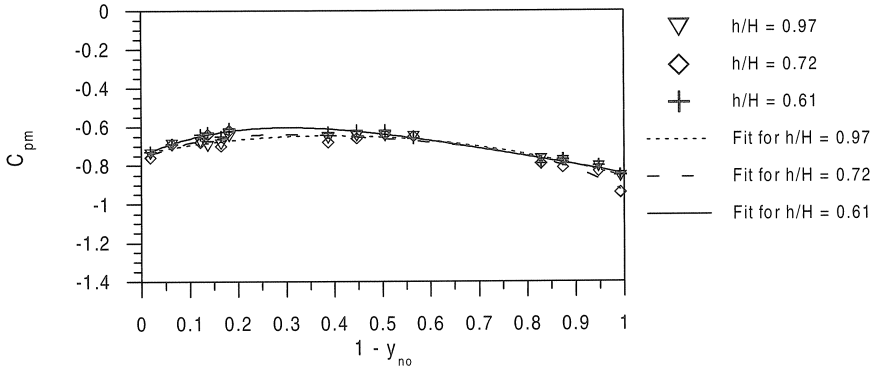

Fig. 7. Wind tunnel measurements of C_{pm} at leeward side.

The main observations from both full scale and wind tunnel experiment of C_{pm} are:

- At windward side, $C_{pm}(H)$ varies from 0.4 to 0.9, depending on the position on the surface and wind direction. The largest values for wind normal to the facade are not found in the centre of the windward facade on the wind tunnel model, but at a relative distance of $y_{edge} / W = 0.2$ from the vertical edges, at $h / H = 0.72$.
- In full scale, the highest value for $C_{pm}(H)$ at windward side was found for $\phi = 290°$, near the northern end of the facade, for all four measurement heights studied.
- The presence of a neighbouring upstream building, with a height of about 50 metres, probably affects the pressure coefficients for $y / W < 0.2$ at the southern part of the facade in the wind tunnel.
- At leeward side, values for $C_{pm}(H)$ in the order of –0.6 are found. This indicates that the flow around the building is not fully reattached to the sides or the top of the building [6].

4.2 *Spectral characteristics of wind induced pressures*

The spectra and coherence of the wind induced pressures have been obtained only from the full scale measurements. Since these only depend on the fluctuating pressures, the internal pressures does not affect the results.

Spectra of wind induced pressure

The single-point pressure spectra are compared with the spectra of the wind velocity at roof height through the definition of a pressure admittance function:

$$|\chi(f)|^2 = \frac{S_{pp}(f)}{(C_{pm}\rho v_m)^2 S_{vv}(f)} \tag{11}$$

with:

$\chi(f)$ is the pressure admittance function

If the quasi-steady theory is valid, equation 11 is equal to equation 10, and $|\chi(f)|^2$ has a value 1 for all frequencies. Results for $|\chi(f)|^2$ and the product of $|\chi(f)|^2$ and $C_{pm}{}^2$ are presented in figures 8 and 9, for pressure taps at windward and leeward side of the building. In figure 8, the results are compared with a model, presented by Sharma [7]. The windward side data show that $C^2_{pm}|\chi(f)|^2$ is constant for reduced frequencies lower than a given cut-off frequency. For higher frequencies, $C^2_{pm}|\chi(f)|^2$ decreases to zero. The cut-off frequency lies at $fH / u = 0.4$. In the model of [7], which was derived from observations in a wind tunnel on a low rise building, the cut-of frequency is found at a lower value.

At leeward side, the value fort $C^2_{pm}|\chi(f)|^2$ is much lower than at windward side. Here, also, it decreases with increasing frequency.

Both windward side and leeward side results show, that quasi-steady theory is not valid for the higher frequency range. The main conclusions from the full scale observations are:

- The graph for $|\chi_p(f)|^2 C_{pm}^{\ 2}$ can be divided in two parts, separated by a cut-off frequency at $nH/u_m(H)$ in the order of 0.4.
- At frequencies below the cut-off frequency, the value for $|\chi_p(f)|^2 C_{pm}^{\ 2}$ is constant, for higher frequencies, the value decreases with frequency.
- At leeward side, the function $|\chi_p(f)|^2 C_{pm}^{\ 2}$ is less than 20% of the value at windward side. This means that $S_{plpl} < 0.2\ S_{pwpw}$.

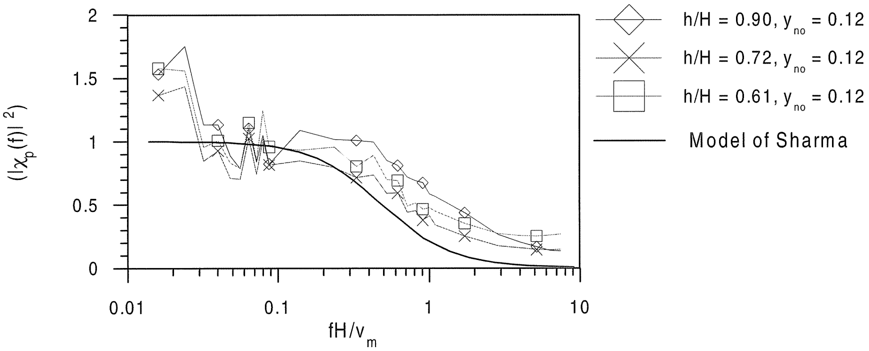

Fig. 8. Pressure admittance at windward side at three positions, comparison with model by Sharma.

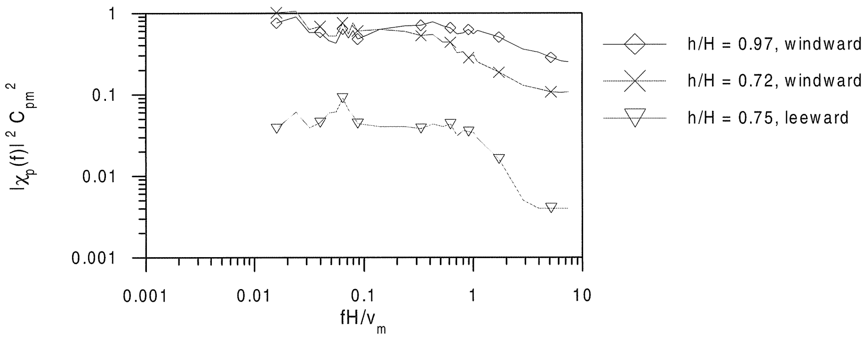

Fig. 9. Comparison of pressure admittance at windward and leeward side of the building.

This means, that for higher frequencies, the quasi-steady theory gives an overestimate for the spectrum of the pressures. Also, this theory overestimates the value for the spectrum of the pressures at leeward side. This is also found in earlier research, done by Kawai, on models of a large building in a wind tunnel [8].

Coherence of pressures

The coherence of the pressures is investigated for all combinations of full scale pressure taps. These combinations can be divided into three groups: The coherence of pressures at windward side, the coherence of the pressures at leeward side, and the coherence of the pressures between windward and leeward side. The coherence of the pressures at windward side, and the coherence at leeward side are usually represented by an exponential decay function of the following type:

$$coh = \exp\left(-K\frac{fD}{v_{\mathrm{m}}}\right) \tag{12}$$

The coherence of pressures between the windward and leeward side is investigated very little in the past and no engineering models are available. It is not used in the definition of the loading in the codes, since it is assumed that the peaks in the loading at windward and leeward side act simultaneously.

The coherence of the pressures was analysed from the full scale data in Eindhoven for flow normal to the windward facade. In figures 10 and 11, the results for the windward facade and leeward facade are presented. These are represented as a function of a reduced frequency, and compared to a model for the wind velocity coherence, which is presented by Simiu [9]. The coherence of the pressures between the windward and leeward side is given in figure 12.

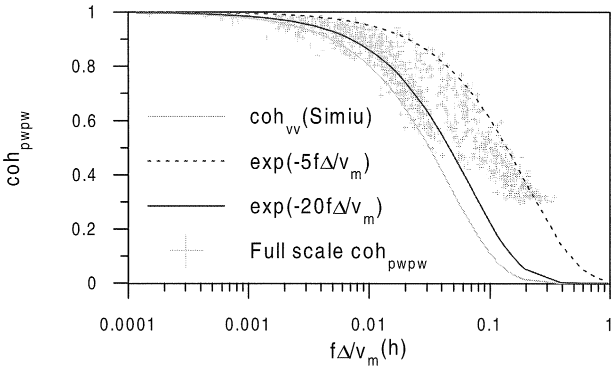

Fig. 10. Comparison of observed coherence of the pressures at windward side with the model for the coherence of the wind velocity by Simiu [9], and two exponential functions.

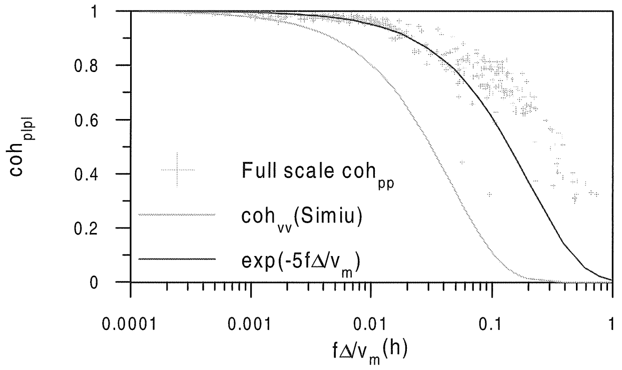

Fig. 11. *Comparison of observed coherence of the pressures at leeward side with the model for the coherence of the wind velocity by Simiu, and two exponential functions.*

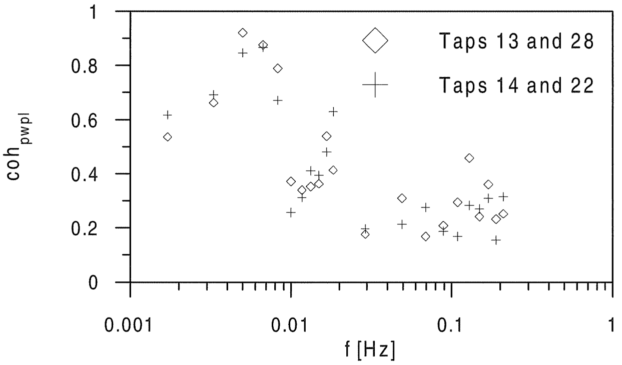

Fig. 12. *Coherence of the pressures between windward and leeward side for western wind. Taps 13 and 14 are on windward side, taps 22 and 28 are on the leeward side.*

The relevant conclusions, based on these observations are:

- The coherence of wind-induced pressures at windward side and at leeward side can be expressed by an exponential decay function of mean wind velocity v_m, distance between the pressure taps Δ and frequency f.
- The wind tunnel measurements do not correspond to the full scale data, both at windward and at leeward facade.
- In full scale, the coherence of the pressures on the windward facade is higher than predicted with models for the coherence of the wind velocities.
- The coherence of the pressures on the leeward facade is higher than the coherence of the pressures on the windward facade, for similar values of $f\Delta / v_m(h)$.

- The coherence of the pressures between the windward and leeward facade in full scale is higher than in the wind tunnel. A lower value for the coherence was found in the full scale experiment, than found with the only relevant expression in literature.

Effects on the total wind loading of buildings
The observations of the spectra and the coherence of the pressures lead to the following conclusions for the overall loading on buildings. These conclusions are described in more detail in [2]:

1. The spectrum of the pressures is overestimated above a certain cut-off frequency. This may lead to a slightly lower total force and response spectrum, and thus to a lower value for *B* and *E*, for the application in building codes. The differences, however, are negligible.
2. The effect of the higher coherence of the pressures on windward and leeward side, is rather large. It leads or a higher value for both factors *B* and *E*, which causes a higher wind load to be taken into account.
3. The effect of the coherence of the pressures at windward with the pressures at leeward side leads to a lower overall loading, compared to the calculation based on the quasi-steady assumptions. This effect counteracts to the error, described under conclusion 2.
4. Other factors, which are not described in this paper, can have an effect on the total loading, assumed in the calculations. The choice for a wind velocity spectrum can have a relatively large effect on the coefficient E, which is relevant for buildings sensitive to dynamic loading.
   The choices of wind climate and terrain parameters on the modification factors *B* and *E* is relatively small. These parameters do have a larger effect on the static loading.

5 Conclusions

Pressure coefficients

- Mean local pressure coefficients, measured in full scale, are modified by the reference pressure by about –0.4, which is a measure for the internal pressure coefficient inside the building. In the wind tunnel, the mean pressures are measured relative to the ambient pressure, so the wind tunnel pressure coefficients are not modified.
- Mean pressures at windward side correspond to data measured in earlier experiments.
  The leeward side values are lower (there is more suction), probably caused by the geometry of the building.
- Peak wind-induced pressures are represented by the peak factor. The peak factor for the windward side pressures is higher than the peak factor for the upstream wind velocity. The peak factor for the leeward side pressures is smaller than for the wind velocity.

Spectral characteristics

- The pressure spectrum in a point on the facade is calculated from the wind velocity spectrum using a pressure admittance function. This function depends on building shape and dimensions, turbulence characteristics and the position of the pressure tap on the facade. Existing models, based on wind tunnel data, are modified to describe the full scale observations at windward side in this study.

- The spatial distribution of the fluctuating wind field is taken into account by the coherence of wind-induced pressures. The coherence of the pressures is described by an exponential function of a reduced frequency, with two exponential decay factors. The observed coherence at windward and leeward side is higher than the coherence of the wind velocity at the same value for the reduced frequency.
- The coherence of the pressures at leeward side is larger than the coherence of the pressures at windward side, for equal values of this reduced frequency.
- The pressures at windward side are poorly correlated with the pressures at leeward side.
- Based on the above conclusions, it follows that the quasi-steady theory, which is the basis for the wind loading codes, is not valid for bluff bodies, like buildings. Modifications on this quasi-steady theory may be used to define a convenient description of the fluctuating wind-induced pressures. These modifications need to be quantified by experimental data, of which very little are available. Full scale data of the fluctuating pressures are a necessary validation tool for the quantification of models to predict the wind loading on buildings.

6 Acknowledgement

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