PROGRESS AND TRENDS IN AIR INFILTRATION
AND VENTILATION RESEARCH

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Paper 15

WIND PRESSURES ON LOW-RISE BUILDINGS
AN AIR INFILTRATION ANALYSIS

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ABSTRACT

The distribution of wind pressure on a building envelope is governed by the size and shape of the structure and the turbulence characteristics of the wind. Observation of the mean wind pressures shows that surfaces are divided into pronounced zones of positive and negative pressure. The turbulence gives rise to fluctuating pressure components of appreciable magnitude. This fact changes the prerequisites of the ventilation for a given volume.

The pressure in the cavity behind the facade materials depends on the external pressures over the facade. A levelling, or smoothing, of the pressure fluctuations can take place, depending on the cavity design and permeability distribution.

The wind pressure spectrum shows that the greater part of the turbulent energy is concentrated at frequencies below 1 Hz. Full–scale measurements have shown that the fluctuations, which are quantified by the calculated variance of the spectrum, are of the same order of magnitude as the mean pressure. The degree of correlation between fluctuating components of the wind pressure on different parts of the building envelope is low. Because of this, the interchange of air is at all times based on a varying pressure distribution, and the participation of different leakages is variable. In the case when air infiltration can be expected to account for a considerable part of the total air exchange rate, the methods of calculation used should take into account the real wind characteristics and the response of the building to wind fluctuations.

LIST OF SYMBOLS

$H(f)$	transfer function
$S_{cav}(f)$	the power spectrum for the pressure difference between the cavity pressure and the internal pressure (Pa^2/Hz).
$S_P(f)$	power spectrum for wind pressure (actually the spectrum for the difference between external pressure and internal pressure) (Pa^2/Hz).
$S_{p,cav}(f)$	cross spectrum between wind pressure and pressure in the cavity (Pa^2/Hz)
f	frequency (Hz)
$\gamma^2(f)$	coherence function
σ_P	standard deviation for wind pressure fluctuations (Pa)
τ	time lag (sec)

1 INTRODUCTION

The rate of air exchange is determined by the degree of air tightness, the distribution of the leaks on the surface of the building and the indoor and outdoor climatic conditions. Wind environment, temperature–based variations of air density and the driving mechanisms in ventilation systems give rise to pressure differences across the building surface, resulting in air flow through existing leakages. The interplay between climate and technical systems can sometimes result in undesirable consequences regarding hygiene, durability and damages.

The purpose of this paper is to elucidate the problem of air infiltration by considering air flow–structure interaction. Wind pressure distributions on low–rise buildings are exemplified especially for moderate wind speeds and the importance of pressure fluctuations is analysed.

The work is concentrated upon the wind, acting as a driving force for air infiltration. In this respect, special attention is paid to the influence of fluctuations in wind speed and direction. Methods of spectral analysis are used to describe the energy content of the fluctuating parts of the wind pressure at different frequencies and wavelengths. Comparisons between wavelengths and the dimensions of existing leakage areas can give information concerning the contributions of fluctuations to the rate of air infiltration. The transformation to the frequency domain makes it possible to study the effects on air infiltration due to variations of wind pressures. In addition, the analyses provide conditions for describing existing connections between pressures on different surfaces of the building.

2 FULL–SCALE MEASUREMENTS OF WIND PRESSURES

A measurement program, embracing full–scale measurements on four single –unit dwellings, has been carried out. The objects, which are comparatively newly built, comprise one one–storey building, two buildings of 1½ storeys, and one of 3 storeys. The insulation standard and the levels of air–tightness corresponds to the Swedish Code of Practice. The measurements include registration of pressure differences between external and internal pressure on facade units and roofs. Measurements have also been performed in cavities, attics and crawl spaces and pressure differences between different storeys were recorded. The measurements were carried out during relatively calm weather conditions.

A survey of problems related to low wind pressure registrations includes an assessment of the qualities of the equipment, the difficulty of calibration and choosing relevant reference pressures. Besides the qualities of the measuring system, the characteristics of the measurement points are of great importance. In a situation where measurement errors can be considerable, a well– hought–out strategy for the experiments and a careful design of the measurement method with regard to all possible influencing factors is required in order to improve the accuracy.

3 RECORDED WIND PRESSURE DISTRIBUTIONS BASED ON STATIONARY WIND PRESSURES

The distribution of pressure over a 1½–storey building is illustrated in Figure 3.1.

For steady flow conditions, the pressure distribution over the building can be described by mean pressures representing different periods of time and different elements of the building envelope. The pressure distribution on the building becomes that expected for a given wind direction. Definite zones with positive and negative pressures arise. The mean pressures on different parts of the building surfaces are correlated. Calculations show that there is a balance between the air volumes which move in and out of the building.

The internal pressure is determined by the pressure distribution, the outdoor and indoor temperatures, the air tightness of the building and the effect of a mechanical ventilation system, if present. The internal pressure of the building is estimated from the state of equilibrium for the inflow and outflow volumes, whereby differences in density for the flows are taken into consideration. This model for describing the air exchange is usually used for the calculation of energy losses through ventilation and it gives a simplified description of the air infiltration process.

There are several weaknesses inherent in the calculation procedure, which appear when it is applied with input data from full–scale measurements. There is a need for additional information about the pressure distribution for different climatic conditions and the distribution of leaks over the building envelope. Input data based on pressure coefficients obtained from the Swedish Code of Practice give, in comparison with data from full–scale measurements, a larger number of calculated air changes.

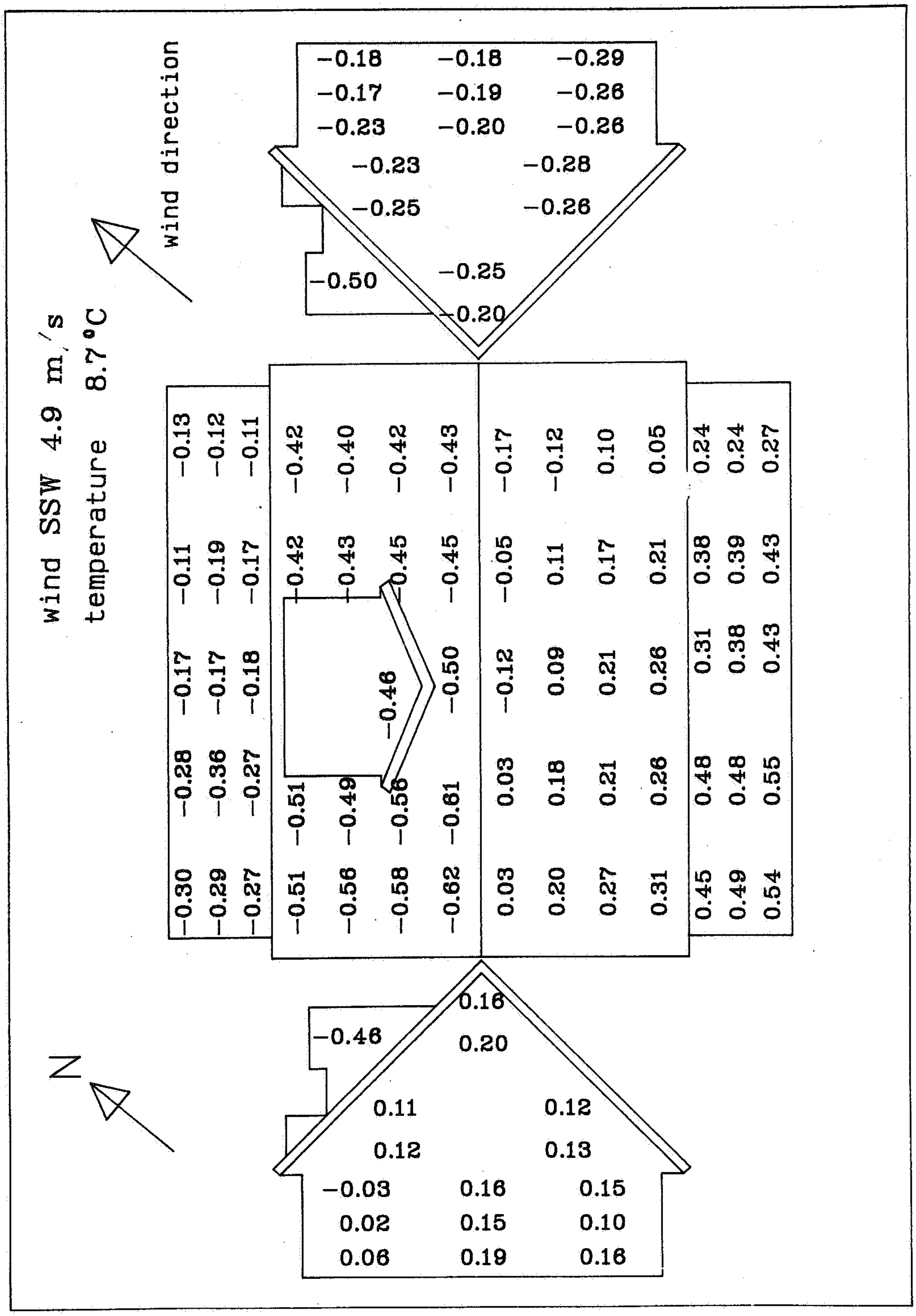


Figure 3.1 Pressure coefficients, example of pressure distribution.

4 REGISTERED FLUCTUATIONS OF PRESSURE DIFFERENCES

4.1 External pressures

The wind pressure distribution on a building is in reality characterized by large variations about the mean pressure. Changes in speed and direction give rise to a continually varying pressure distribution without any distinct zones of positive and negative pressure. The fluctuations of the wind speed and their relation to the wind pressures on a surface vary stochastically, like the wind pressure. Time–related and spatially–related fluctuations in wind speeds and direction characterize the level of turbulence, which can be described by means of fundamental statistical methods. The external pressure on a surface, for example, can be described by three quantities: mean value, variance, and the spectrum of the fluctuating component. The mean and the fluctuating pressure on the surfaces give rise to an exchange of outdoor and indoor air through leaks in the construction. Measurements show that magnitude of the fluctuations, can be of the same order as the mean pressure.

The degree of turbulence in the oncoming wind, together with the effect of the shape and size of the building, the surroundings and the terrain, determines the characteristics of the pressure fluctuations of the external pressure on a facade. A quasi–steady approach to wind loads gives adequate results only for pressures on the windward side. The separated flow on the roof and the leeward sides of the building can be described by eddies of different size. Their scale is generally less than that of the atmospheric turbulence. Large eddies give a comparatively uniform pressure distribution, while small eddies have a local effect.

If the variations in wind speed are known, it is possible, on the windward wide of a structure, to calculate pressure distributions by employing Bernoulli's equation. This situation cannot be applied to the leeward side. Because of friction, characterized by a broad, extremely turbulent boundary layer, the air flow separates from the building surface. Thus, the fairly simple relation between wind speed and wind pressure on the windward side becomes more complicated on the leeward side.

The degree of correlation between the pressures at any two arbitrarily selected points depends on the relation between the dimensions of the building and the length scales of the energy contained in turbulence eddies. The scale of turbulence is usually considerably larger than the size of the building. The building can be observed in a wind pattern of almost uniform structure of varying intensity. The pressure differences, caused by eddies acting on the windward and leeward sides, will be correlated. This is not so for the differences generated by the building. Because of this, the resulting wind pressures on the windward and leeward sides do not become fully correlated. A study of external pressures on different parts of walls, exemplified by the windward and leeward sides in Figure 4.1.1, gives for all cases a very low – in most cases an almost non–existent – degree of correlation.

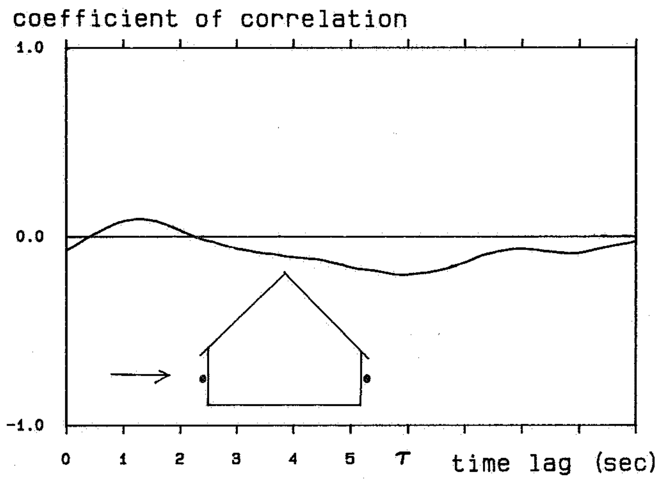


Figure 4.1.1 Coefficient of correlation between external pressures on windward and leeward sides

The low degree of correlation between windward and leeward sides is only of interest when the fluctuating parts of the wind pressure are taken into consideration. Mean pressures between different building surfaces are correlated, due to the long averaging period.

Pressures over a measurement object are exemplified in Figure 4.1.2 where density functions, based on measurement data, have been determined. The pressure differences are those expected with positive pressures on the windward side and negative pressures on the leeward side. The variation of the pressure differences is considerable. The random variation of wind in speed and direction with time indicates that the external wind pressure on facades and roof is a noisy process. The fluctuations are unequal in size on different parts of the building. The deviation from the mean value is, for example, larger on the windward than on the leeward side.

Spectra for wind pressures on the facades are exemplified in Figure 4.1.3. The dominating energy content is found in frequency intervals below 1 Hz. Shapes and amplitudes are comparable for spectra representing different surfaces. However, the coherence function for opposite facades has low values. For surfaces with similar orientation, for example facade and roof, the coherence rises.

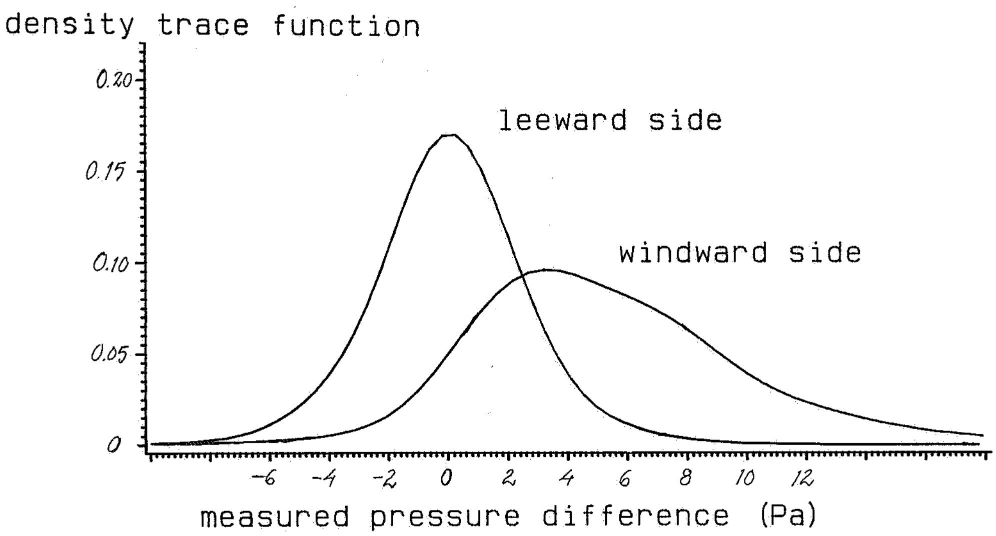


Figure 4.1.2 Probability density functions (density trace functions) describing wind pressure on windward and leeward sides

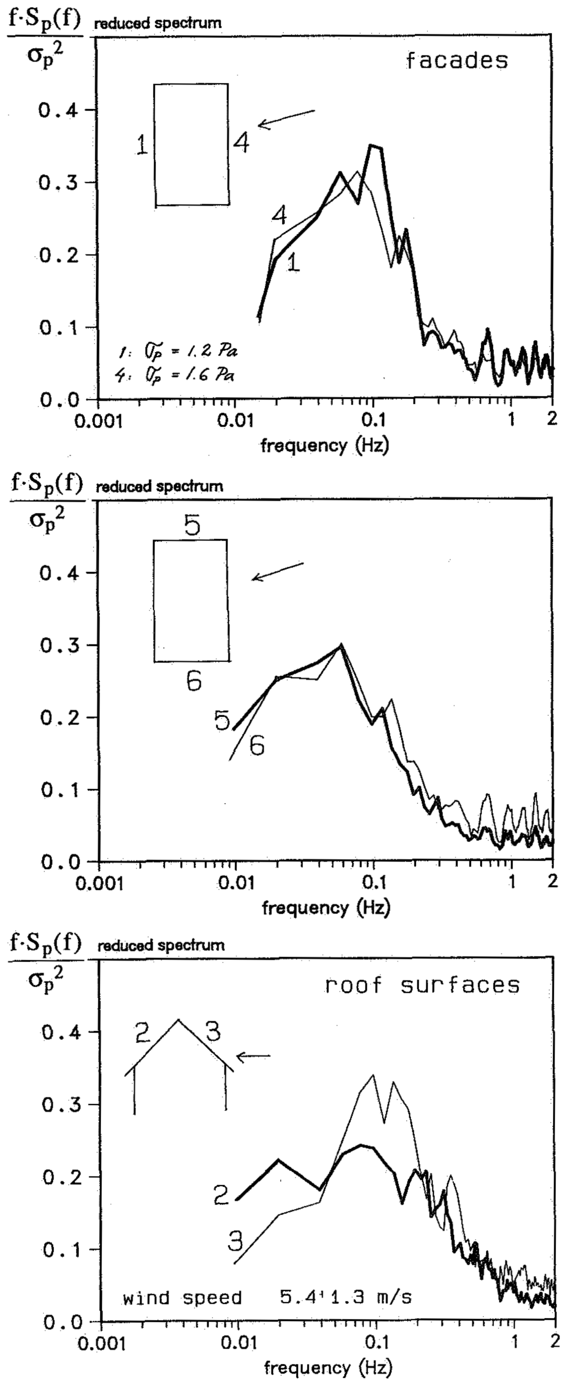


Figure 4.1.3 Comparisons between spectra of wind pressures on facades and roof

4.2 Ventilated cavities behind the external walls

Normally, external walls are designed with a cavity behind the facade material. The cavity is supposed to have an equalizing, and in most cases also a reducing, effect on the external pressures. The degree of smoothing is determined by the distribution of leakages on the facades and the design of the cavity, especially with respect to air intakes and exhausts. Hence, the cavity has an important influence when wind is acting as a driving force for air exchange.

Generally, the pressure is reduced and damped in the cavity. However, measurements show that this is not always the case. For a one–storey dwelling, the external pressures on facades have been compared with pressures in the cavity. The measurement point in the cavity is situated just behind the corresponding point on the facade. The construction of the cavity with horizontal nailing battens restricts the vertical air flow, see Figure 4.2.1. In practice the air layer is thereby divided into a number of bays.

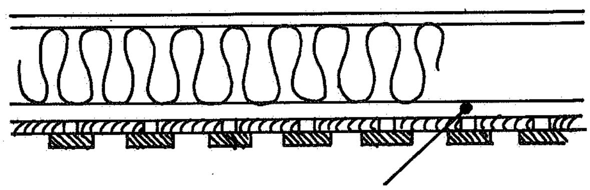


Figure 4.2.1 The appearance of the air cavity, horizontal section

On the windward side, the expected pressure reduction across the exterior facade material fails to appear. As a result of the design of the cavity, the pressure increases behind the facade. The mean value of the pressure difference between the pressures in the cavity and inside the building increases from 1 to 2 Pa compared with the difference between external and internal pressure. No appreciable damping of the fluctuations in the cavity is indicated.

On the leeward side, slightly negative pressure differences on the facade change into positive ones in the cavity, as shown in Figure 4.2.2. The curves indicate a smaller variation around the mean value in the cavity as compared to facade pressure.

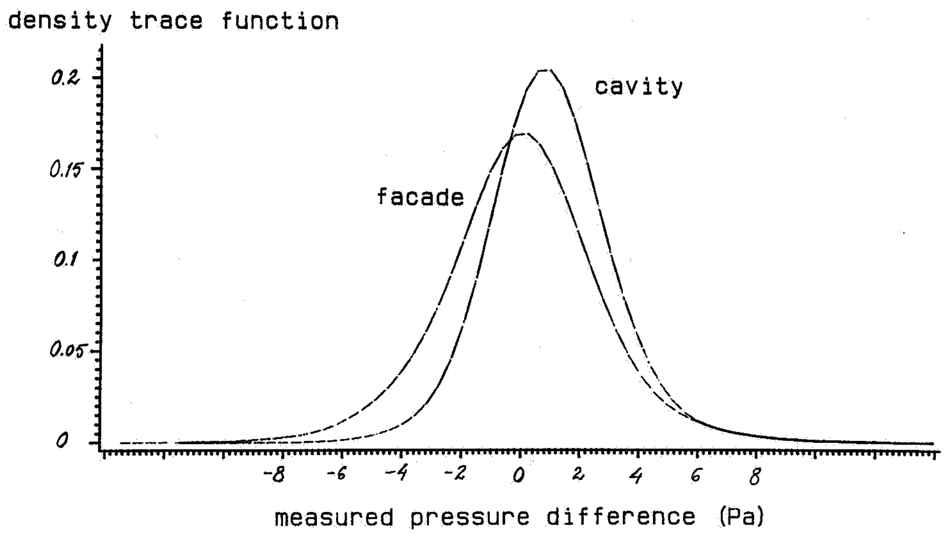


Figure 4.2.2 Probability density functions (density trace functions) describing wind pressure on the facade and in the cavity, leeward side.

Fluctuations of pressure differences are illustrated in the form of reduced spectra in Figure 4.2.3. On the windward side, the spectra for facade and cavity become almost equal. A peak is noted near to the frequency 0.1 Hz. A high degree of similarity between facade and cavity is also found on the leeward side. The shapes of the spectra are similar in character on the two sides.

The connection between facade and cavity is good for all facades, as can be seen from the degree of coherence exemplified in Figure 4.2.4. The coherence function, $\gamma^2(f)$, is defined as

$$\gamma^2(f) = \frac{|S_{p,cav}(f)|^2}{S_P(f)\ S_{cav}(f)} \qquad (4.1)$$

The relation between external pressure on the facade and the corresponding pressure in the cavity has also been estimated in terms of transfer functions, H(f). These functions, illustrated in Figure 4.2.5, make it possible to describe the pressure conditions as

$$S_{cav}(f) = |H(f)|^2 \cdot S_P(f) \qquad (4.2)$$

where

$S_P(f)$	is the spectrum for the pressure difference between facade and internal pressure,
$S_{cav}(f)$	for that between cavity and internal pressure, and
$S_{p,cav}(f)$	the cross spectrum between facade and cavity.

For the frequency range of interest, the magnitudes of the transfer functions are approximately 0.7 – 0.9.

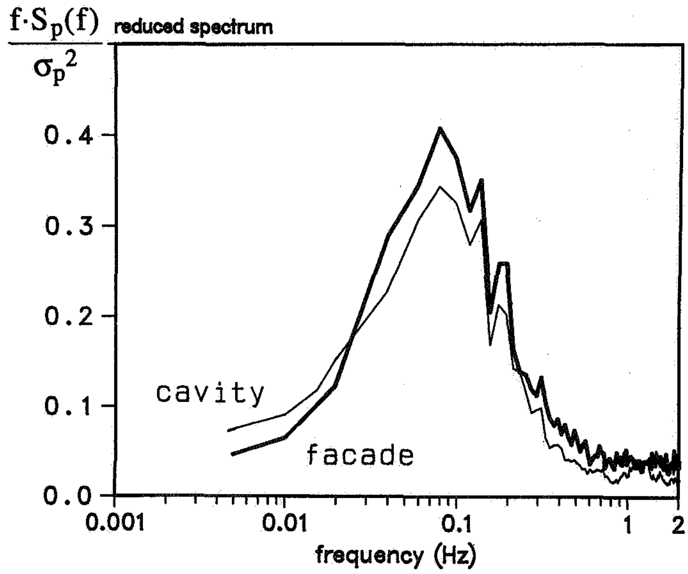


Figure 4.2.3 Spectra illustrating the variations in pressure difference for facade–cavity on the windward side.

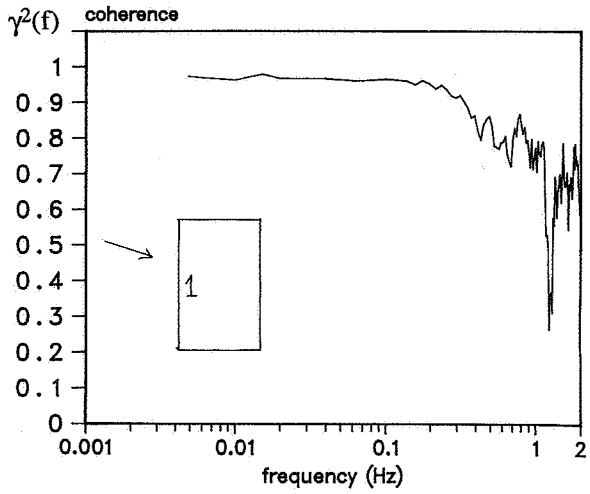


Figure 4.2.4 Coherence functions between facade and cavity for the windward side of the building

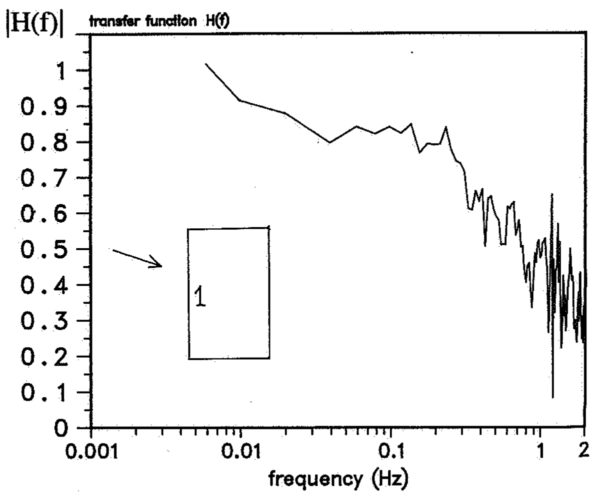


Figure 4.2.5 Transfer functions between facade and cavity, windward side

The strong relation between wind pressure on a facade and the pressure in a cavity just inside the wall is illustrated by the cross–correlation between the pressures. A sampling of recorded pressures at a sampling frequency of 50 Hz, i.e. equivalent to 0.02 seconds, shows that the cavity pressure on the leeward side of the building has a time delay of about 0.2 seconds with respect to the local external pressure (see Figure 4.2.6.). This delay is not observed on the windward side.

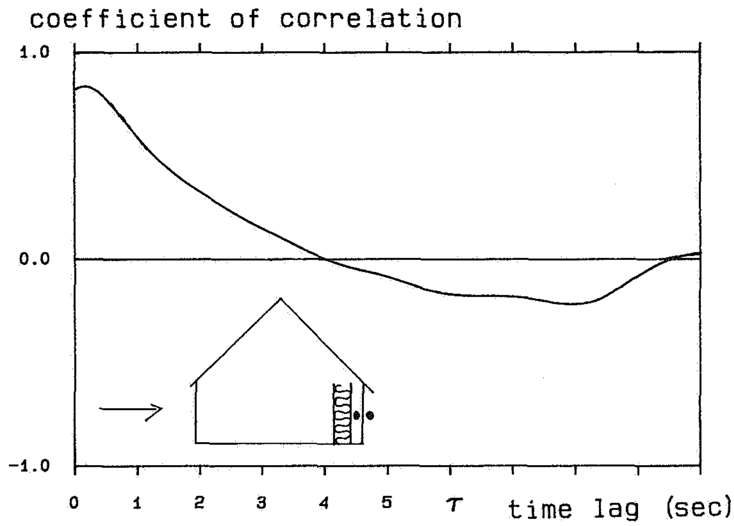
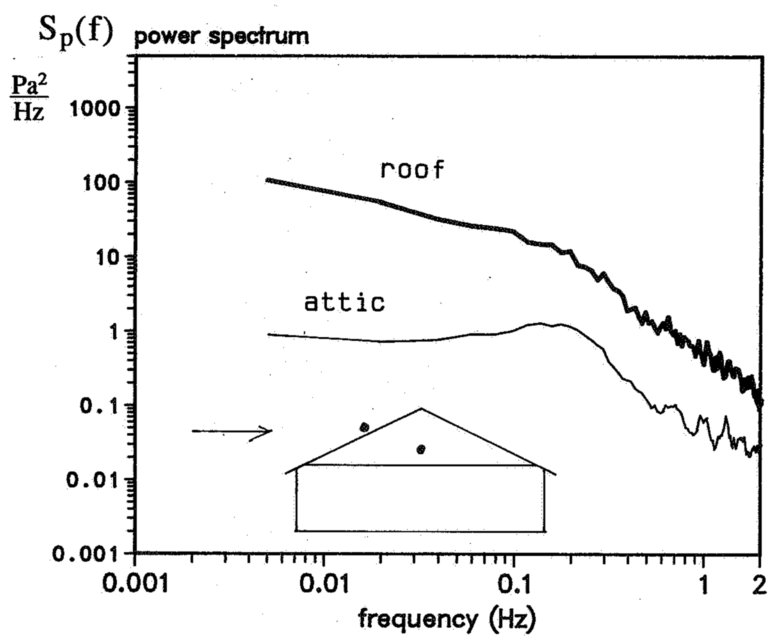


Figure 4.2.6 Coefficient of correlation between pressures on the facade and in the cavity, leeward side

The attic gives a marked smoothing and damping of the fluctuating parts of the pressure differences acting over the roof of the building. The energy content for the fluctuating wind pressure on the roof is greatly reduced in the attic, illustrated by spectra in Figure 4.2.7. The number of air changes in the space is in most cases large. The ventilation of the attic is to a large extent dependent on wind conditions with regard to both speed and direction.



Figur 4.2.7 Spectra representing fluctuations in pressure on the roof and in the attic

5 AIR INFILTRATION CAUSED BY FLUCTUATING WIND PRESSURE, CONCLUSIONS

Low degrees of correlation and coherence between the pressure fluctuations on different parts of the building surfaces indicate a continually varying pressure distribution. A more exact assessment of the contribution from the fluctuating wind pressure to air infiltration requires information about the characteristics of the fluctuations of external pressures and the geometry of the leaks and current air flows in front of and through the leaks.

Spectral methods can be used to estimate the parts of the fluctuations of wind speed and wind pressure which contribute to the rate of air infiltration. Wind spectra describe the frequency interval containing the major part of the energy content. By means of spectra for the pressure differences across a wall, the extent of the fluctuations can be compared with the dimensions of the structure and the leaks. It thereby becomes possible to judge the degree to which the fluctuations have an influence on the air flow through leaks. The exchange of air through openings, for example round windows, is caused by a pulsating flow, which is complicated by the fact that air is transferred in and out simultaneously.

The majority of cracks in facades can be presumed to have a width of between 0.5 and 3 mm. For a wind speed of 2 m/s, the gust wave length has a magnitude of between 20 metres at 0.1 Hz and 2 metres at 1 Hz. A comparison with the size of a leak through an external wall indicates that a uniform field of pressure is built up over the leak (compare Figure 5.1). High frequencies are needed, e.g. a wavelength of 0.1 metres corresponding to the frequency 20 Hz, to obtain a number of local pressure fields developed over the leak, without any mutual relation or correlation.

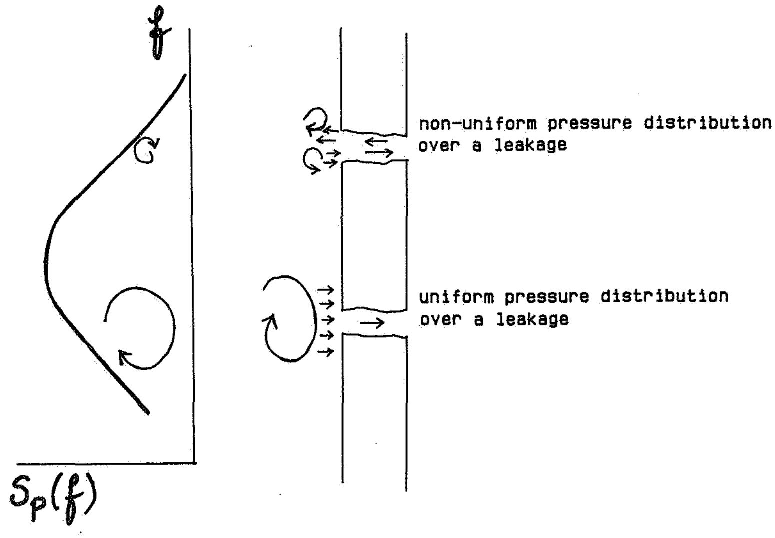


Figure 5.1 Illustration of local pressure fields

Full–scale measurements show that the pressure fluctuations can be characterized as extremely low–frequency, in the frequency range below 1 Hz, and the majority can therefore give contributions to air infiltration. The geometric form and dimensions of the leakages give the conditions for the air flow to penetrate through a construction and subsequently be mixed with the inside air. A part of the pressure fluctuations which are squeezed into the opening, or the leak, is not transmitted the whole way and does not take part in the exchange of air between the inside and the outside.

In the case where air infiltration can be expected to give rise to a considerable part of the total air exchange rate, the methods of calculation used should take into account the known characteristics of wind and the building's response to wind fluctuations.

REFERENCES

GUSTÉN, J *Wind pressures on low–rise buildings. An air infiltration analysis based on full–scale measurements.* Publication 1989:2, Division of Structural Design, Chalmers University of Technology, Gothenburg.

Discussion

Paper 15

Earle Perera (Building Research Establishment, UK)

1. Could you describe briefly your pressure measuring system including what you use as your reference back-off pressure?

2. What is the correlation between external windward pressure and internal pressure?

Jan Gustén (Chalmers University, Sweden)

1. The measuring system consists of electronic pressure transducers and anemometers for wind speed and wind direction, plastic tubes of length 25 metres and FM tape recorders. A transfer function H(f) has been determined for the tubes. The results are either related to the internal pressure and/or to a static reference pressure at the height of 10 metres.

2. For the objects measured the variations in the internal pressure are very small.

J-M Fürbringer (EPFL, Switzerland)

If you measure pressure difference you have the influence of the stack effect. How do you treat this point?

Jan Gustén (Chalmers University, Sweden)

Registrated pressure differences between the external and internal pressures include wind loads as well as variations in air density. During each measuring period the outdoor and indoor temperatures are constant. Consequently, the pressure fluctuations depend only on variations in wind speed and wind direction.