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Annex V Air Infiltration Centre

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CONTENTS

Corrigenda

Page 62 $Re_H = \frac{\bar{V}_\infty . H}{\nu} = 360000$ $H = 3M$

Page 118 Mean local CP's (= Cp(ℓ))

Page 154 $P = \frac{\rho}{2}.Cp.(\bar{u}^2 + \sigma^2)$

PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Program was formulated among a number of industrialised countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Program, the Participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

Energy Conservation in Buildings and Community Systems

The International Energy Agency sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, etc. The difference and similarities among these comparisons have told us much about the state of the art in building analysis and have led to further IEA sponsored research.

Annex V Air Infiltration Centre

The IEA Executive Committee (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous agreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and to increase the world pool of knowledge on infiltration and ventilation. Much valuable but sporadic and uncoordinated research was already taking place and after some initial groundwork the experts group recommended to their executive the formation of an Air Infiltration Centre. This recommendation was accepted and proposals for its establishment were invited internationally.

The aims of the Centre are the standardisation of techniques, the validation of models, the catalogue and transfer of information, and the encouragement of research. It is intended to be a review body for current world research, to ensure full dissemination of this research and based on a knowledge of work already done to give direction and a firm basis for future research in the Participating Countries.

The Participants in this task are Belgium, Canada, Denmark, Finland, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States.

INTRODUCTION

During the course of the Air Infiltration Centre's model validation programme, it became apparent that one of the major areas of weakness was the characterisation of wind pressures acting on the surface of buildings. Currently, two methods for determining wind pressures are common, these being to measure the pressure distribution directly or to perform wind tunnel tests on scale models. To date, the results of full-scale measurements have not been used successfully in validation exercises. Some success, however, has been achieved with wind tunnel investigations but an insufficient range of data, coupled with a diversity of measurement techniques, has meant that the full potential of this approach has yet to be realised.

As a consequence of these uncertainties, the Air Infiltration Centre held a specialist wind pressure workshop at which both wind engineers and those closely involved in infiltration studies had the opportunity to discuss techniques for improving the prediction of wind-induced air infiltration. In advance of this meeting, the AIC prepared and circulated a state-of-the-art review of the problem to be used as a basis for discussion (AIC Technical Note No.13). Topics covered at the meeting included the development of wind pressures, turbulent fluctuations, measurement methods, wind tunnel studies and data requirements for air infiltration calculations. The structure of the workshop was informal but a number of contributors were invited to present keynote papers introducing each topic. Written contributions from other participants were also requested. This report contains a record of the contributions received and edited discussion notes. It concludes with views on the future deployment of wind pressure data in air infiltration models and suggestions for further research. A short bibliography of additional papers recommended for further reading is also included.

AIR INFILTRATION CENTRE - WIND PRESSURE WORKSHOP
Brussels, Belgium
21-22 March 1984

PAPER 1

THE ESTIMATION OF INTERNAL PRESSURES DUE TO WIND WITH APPLICATION TO CLADDING PRESSURES AND INFILTRATION

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THE ESTIMATION OF INTERNAL PRESSURES DUE TO WIND WITH APPLICATION TO CLADDING PRESSURES AND INFILTRATION

1.0 INTRODUCTION

Internal pressures in buildings due to wind have assumed more importance recently for several reasons. First in the design of exterior cladding, the much improved definition of external pressures through boundary layer wind tunnel testing, has shifted the spotlight onto the accompanying internal pressures as a remaining source of uncertainty. As will be pointed out in this paper, wind tunnel studies of exterior pressures can be misleading in certain circumstances unless a parallel investigation is made of the internal pressures. Second in energy conservation, the estimation of leakage through the building envelope (a major contributor to energy loss) depends on the internal pressure. Ventilation studies (representing the other side of the air infiltration issue) likewise depend on the internal pressures.

The evaluation of internal pressures has never been an exact science and sometimes has been rather baffling to code committees attempting to specify safe values which are not at the same time excessively conservative. Part of the problem is the indefinite character of the leakage paths through the building envelope. This is compounded by difficult questions such as whether or not doors or windows will be open during a wind storm or even whether they will be accidently broken. Yet another aspect is the complex distribution of pressures over the surface of the building. Finally, there is the question of the role played by the significant dynamic component of the exterior pressures in developing dynamic interior pressures.

This paper attempts to address these various questions and to suggest the routes towards their solution for design. Considerable progress can be made if there is acceptance of the fact that the uncertainties have to be expressed in statistical terms.

2.0 BACKGROUND

Amongst the earlier studies on internal pressures were those by Malmer (1925) and Irminger and Nokkentved (1930). The latter measured the internal pressure on model buildings uniformly perforated with holes of varying diameter; in some experiments the holes were partially plugged with silk threads. The authors concluded from the experiments that:-

"a) In a permeable building the internal pressure will be substantially different from the atmospheric pressure, and will vary with the wind velocity in proportion to newton (i.e. $\frac{1}{2}\rho U^2$).

b) The internal pressure is constant for a constant wind velocity, irrespective of the number and size of the holes, and whether they communicate direct (entirely open holes) or indirect (silk thread), provided only they are uniformly distributed.

The internal pressure is moreover directly dependent upon the external pressure and its distribution".

The authors went on to note that: "Calculation of the internal pressure is simple. If the leak has an area a and the difference between internal and external pressure is Δp, then the amount of air which passes through the opening per second must be proportional to $a\sqrt{\Delta p}$. The volume of the air inside the building is constant, therefore:-

$$\sum a_j \sqrt{\Delta p_j} = 0 \qquad (1)$$

where the sign for $\sqrt{\Delta p_j}$ is plus if the external pressure is greater than the internal and minus for the reverse condition."

This result has been adopted by several subsequent authors (Chen, Davenport, Vickery). It is of considerable value in determining the mean internal pressure but is less adequate to deal with the fluctuating components and the distributed leakage through rather small openings. A major uncertainty concerns the nature and distribution of the leakage paths. In the following we consider distributed leakage as well as leakage due to openings such as windows and doors. We first consider the mean internal pressure and subsequently the fluctuating. We discuss some of the implications for wind tunnel testing. Finally, we deal with the question of air infiltration due to leakage.

3.0 MEAN INTERNAL PRESSURE: DISTRIBUTED LEAKAGE

Some valuable information on the leakage of Canadian buildings was developed experimentally by Tamura and Shaw (1976) and Shaw (1981) using measurements of the flow rate into buildings from a fan pressurization system. From these experiments they deduced that flow through a building envelope depends on the type of construction, and conforms generally to a relationship

$$Q = c\,A\,(\Delta p)^{n} \tag{2}$$

where Q = air leakage rate through the exterior wall; c = a flow coefficient; A = the area of exterior walls; Δp = the pressure difference across exterior walls; and n = a flow exponent. Although the flow exponent can vary over the range 0.5 to 1.0, buildings with HVAC systems appear to converge on a value of 0.65. The value of c varies over the exterior of the building and the average varies from building to building. Shaw's results give the following values for the mean and range of c:

TABLE 1

	number	c m/s/(kPa)$^{-0.65}$	$(a/A_w)_{equiv}$
High rise bldgs	(8)	0.018 ± 0.010	0.0006
Schools	(11)	0.043 ± 0.018	0.0015
Supermarkets	(10)	0.081 ± 0.056	0.0028

Examples of these results are shown in Fig. 1.

Equation (2) is clearly an extension of the leakage law leading to equation (1). The departure from the "square-root pressure difference" relation is probably due to the contribution of very small leakage paths whose resistance may be closer to a linear viscous resistance ($n = 1$). Although these results were developed for heat loss study they are of direct value in the study of internal pressures for wind loading as well.

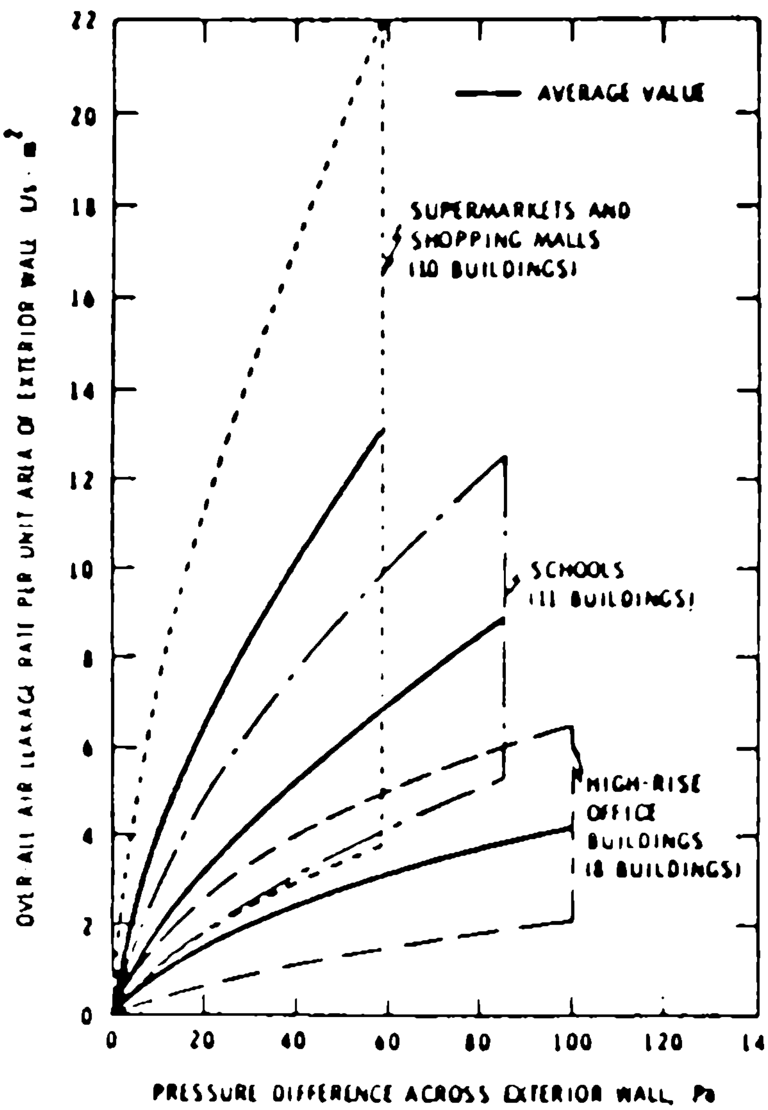

FIG. 1 COMPARISON OF OVERALL AIR LEAKAGE OF VARIOUS BUILDING GROUPS
(after Tamura and Shaw - 1981)

The time average internal pressure can be found from equation (2) by using the continuity condition $Q = 0$.

$$\int_A c(r)\,|(p(r) - p_i)|^{0.65}\, sign(p(r) - p_i)\, dA = 0 \qquad (3)$$

In this $p(r)$ is the mean external pressure at position r and p_i the mean internal pressure we are seeking. The exact distribution of $c(r)$ is unknown and even the average values of c vary considerably from building to building. This is justification for basing an estimate of the mean internal pressure on a somewhat simpler, linear leakage law with $n = 1$. This leads to a first approximate expression for the constant mean internal pressure coefficient.

$$Cp_i \approx (1/A) \int_A Cp(r)\, dA \qquad (4)$$

that is, the spatial average of the exterior mean pressure. (In this, the pressure coefficient $Cp_r = p_r/q$ where q is a reference velocity pressure, i.e. $\frac{1}{2}\rho U^2$, U being the mean velocity and ρ the density of air).

In Fig. 2 we represent the distribution of time averaged exterior pressure coefficients on a tall building model in a turbulent boundary layer in two ways - in the upper diagram, in the usual way, as contours on the building exterior and in the lower diagram it is represented as a statistical distribution. According to equation (4), the mean internal pressure coefficient for uniform leakage is simply the mean or expected value of the distribution.

If we wish we can find a more exact solution to the internal pressure using the following which avoids the linearization of the pressure difference:

In general, with the statistical distribution of Cp given by $f_{Cp}(Cp)$,

$$Q(m) = Ac \int_{-\infty}^{\infty} (Cp - Cp_i)^{1-m}\, f_{Cp}(Cp)\, dCp = 0 \qquad (5)$$

where $m = 1 - n$. The first term of a Taylor expansion on m, is,

$$Q(0) = Ac \int_{-\infty}^{\infty} (Cp - Cp_i)\, f_{Cp}(Cp)\, dCp = 0$$

$$\text{or} \quad Cp_i \simeq \int_{-\infty}^{\infty} Cp\, f_{Cp}(Cp)\, dCp \qquad (6)$$

$$\simeq E\,(Cp)$$

This expected value of Cp is a first approximation to Cp_i.

The next term of the Taylor expansion provides a further correction which can be easily shown to be

$$Cp_i = E(Cp) - m\ \sigma_{Cp} \int_{-\infty}^{\infty} \theta \ln|\theta|\, f_\theta(\theta)\, d\theta \qquad (7)$$

in which the reduced pressure term is represented by

$$\theta = (Cp - E\,(Cp))/\sigma_{Cp}$$

where σ_{Cp} is the standard deviation of the Cp distribution.

The form of the weighting function $\theta \ln|\theta|$ is shown in Fig. 3. It shows that the principal influence on the correction is made by differences in the tails of the distributions. If the distribution is symmetrical, clearly no correction is required. On several examples of tall buildings, using wind tunnel data, the correction has been found to be of the order of 10 to 15 percent.

The standard deviation of the distribution of the mean external pressures in Fig. 2 (in this case 0.29), also provides us with a first approximation to the variability or uncertainty of the mean internal pressure coefficient - specifically, for the situation in which one window, selected at random, is left open in an otherwise sealed building. Because of background leakage and other practical considerations this is a severe assumption even in a building in which windows can be opened. A proposition of N independent leakage paths thus reducing the standard deviation by $1/\sqrt{N}$, is probably closer to the mark. If $N = 4$ the standard deviation is halved; for $N = 25$ the standard deviation is reduced to 20%.

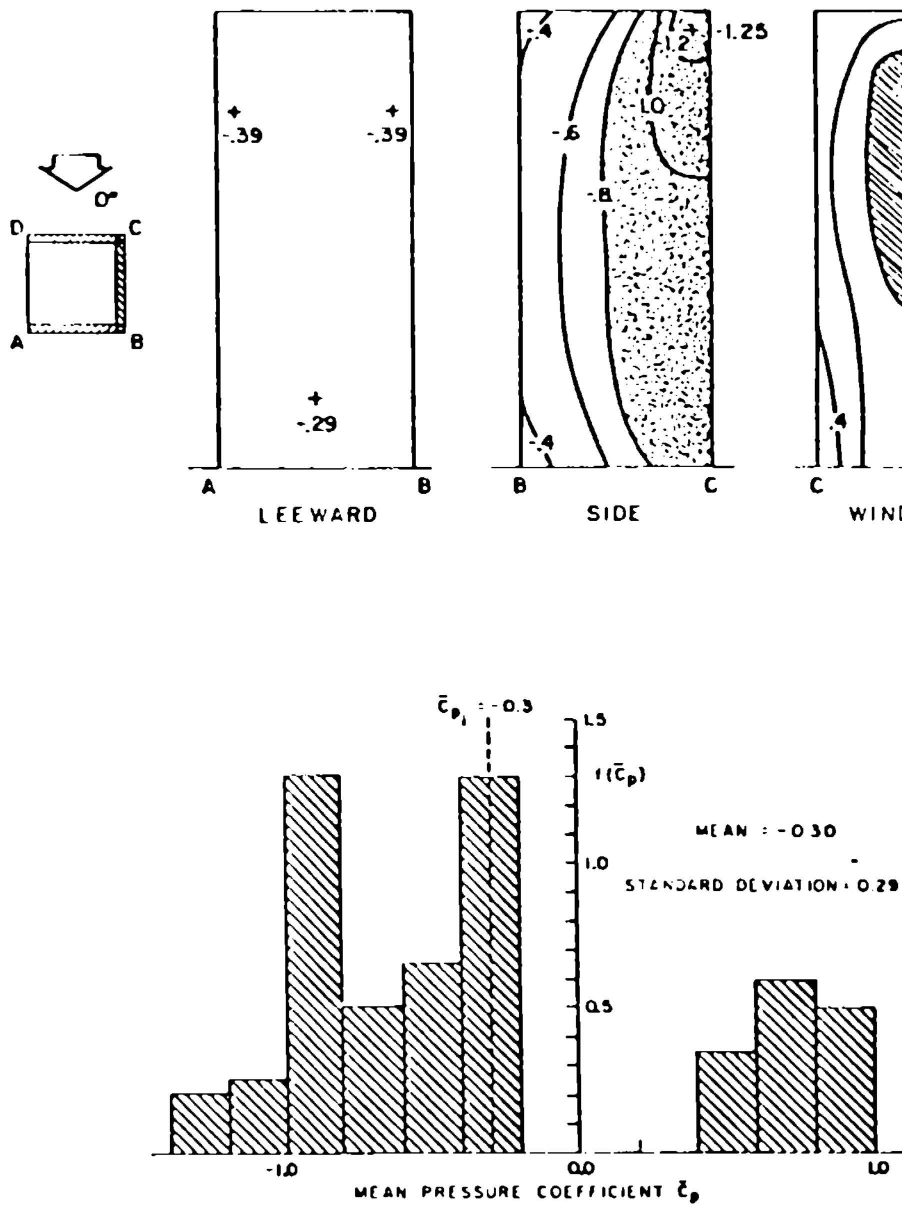

FIG. 2 **DISTRIBUTION OF TIME AVERAGED EXTERIOR PRESSURE COEFFICIENTS ON A TALL BUILDING IN BOUNDARY LAYER FLOW REFERENCED TO ROOF HEIGHT**

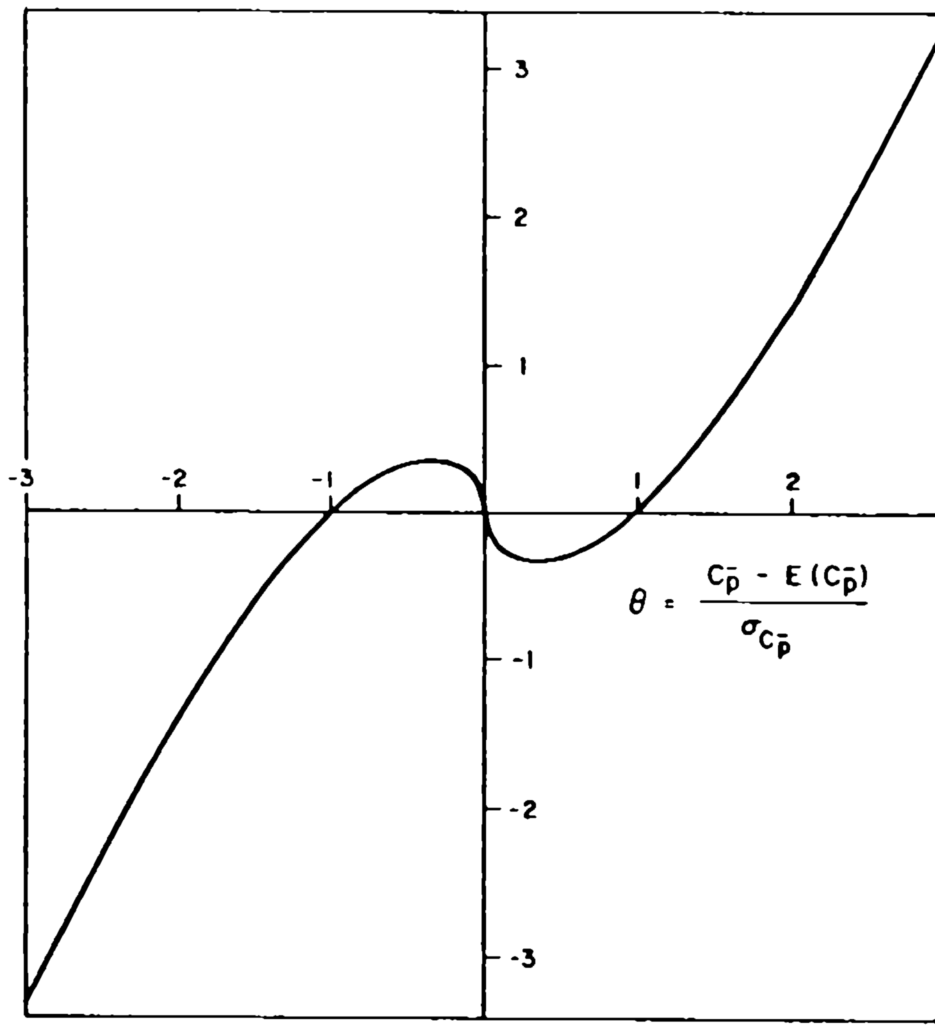

FIG. 3 WEIGHTING FUNCTION FOR ESTIMATION OF INTERNAL PRESSUR
FROM STATISTICAL DISTRIBUTION OF PRESSURE COEFFICIENTS

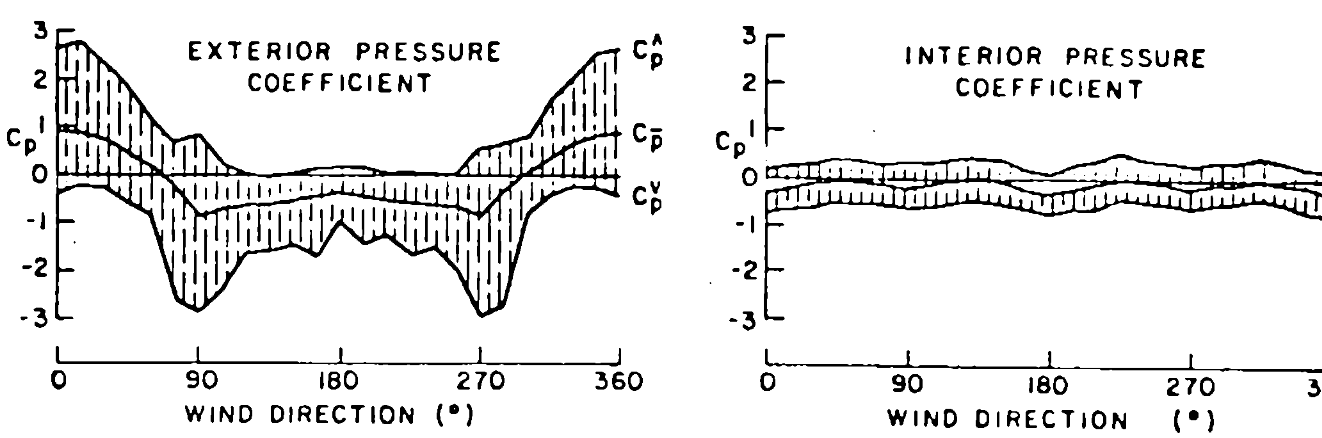

FIG. 4 COMPARISON OF INTERNAL AND EXTERNAL PRESSURE COEFFICIEN

For buildings in which the windows do not open, the variability depends only on the variability in the leakage distributions (suggesting an interesting line of investigation). The standard deviation of Cp_i would under most practical circumstances appears to be much smaller, even negligible.

3.1 MEAN INTERNAL PRESSURES: LARGE OPENINGS

Flow through a larger opening of area a is partly described by the expression in equation (1), but is more accurately described by

$$Q = k\,a\,\sqrt{2(\Delta p/\rho)} \tag{8}$$

$$= k\,a\,\sqrt{2q\,(Cp - Cp_i)/\rho}$$

where k is a coefficient of discharge often taken as 0.65. (This relation has been used by Holmes, 1979.)

By comparing the more general leakage law in equation (2) with equation (8), we can straightforwardly show that the opening of area a having the same gross leakage as a wall of area A_w with flow coefficient c, is given by

$$k\,a\,\sqrt{2/\rho}\;\Delta p^{0.5} = c\,A\,\Delta p^{0.65}$$

or

$$\left(\frac{a_{equiv}}{A_w}\right) = \frac{c}{k}\sqrt{\frac{\rho}{2}}\;\Delta p^{0.15} \tag{9a}$$

For example, when $\Delta p = 0.5\ kPa$, $k = 0.65$, $n = 0.65$, $\rho = 1.25\ kg/m^3$

$$\left(\frac{a_{equiv}}{A_w}\right) = 0.035c \tag{9b}$$

Thus referring to the values of c in Table 1 we find the equivalent openings shown in the same table.

If a building has a large opening a_1 under a local mean pressure coefficient Cp_1, as well as distributed leakage with an equivalent area a_{equiv}, then the resulting internal pressure Cp_i is given approximately by

$$a_{equiv} \sqrt{Cp_{i_o} - Cp_i} = a_1 \sqrt{Cp_1 - Cp_i} \qquad (10)$$

In this Cp_{i_o} is the mean internal pressure without the large opening. Since Cp_i must lie between Cp_{i_o} and Cp_1, the sign of one of the terms is negative and we can easily show that,

$$Cp_i = \frac{a_1^2 \, Cp_1 + a_{eq}^2 \, Cp_{i_o}}{a_1^2 + a_{eq}^2} \qquad (11)$$

Through this relation we can compare the statistical properties of the internal pressure coefficient due to the presence of the large opening at some unspecified location, both with and without the background leakage.

Without the background leakage the expected value of the mean internal pressure coefficient is $E(Cp)$, that is the mean value of the external pressure coefficient. The standard deviation is σ_{Cp} i.e. that of the mean external pressure coefficients. With the distributed leakage the expected internal pressure is again $E(Cp)$ but the standard deviation of the internal pressure coefficient is $\sigma_{Cp}\, a_1^2/(a_1^2 + a_{eq}^2)$. Clearly if the position of the opening is known and it can be linked systematically with the wind direction this range in the pressure coefficient can be cut down.

4.0 FLUCTUATING PRESSURES: GENERAL

Due to the fluctuating nature of the external pressures some of these fluctuations will be transmitted to the internal pressure. The exact nature of the transmission will depend on the leakage path and size of openings and, to some extent, on the flexibility of the structure. Experimental and theoretical work on the fluctuating pressures has been undertaken by Holmes (1979) and by Stathopoulos, Surry and Davenport (1979), and by Davenport (1983).

To explore this question we consider the case of uniform leakage and subsequently the behaviour of a large opening, for a rigid building.

4.1 FLUCTUATING PRESSURES: DISTRIBUTED LEAKAGE

Because of the variability in the leakage paths it is justifiable to work with a linearized model. We will assume a model where we have a linearized leakage coefficient $\gamma = c\,(\Delta p_o)^{n-1}\,n$ where Δp_o is an effective value of the mean pressure difference.

$$Q \quad = \quad \gamma A \Delta p \tag{12}$$

It can be shown that the dynamic equation for the fluctuating internal pressure, p_i', in response to a fluctuating external pressure, p_e', is of the form

$$p_i' + \frac{1}{\omega_c}\,\frac{dp_i'}{dt} + \frac{1}{\omega_o^2}\,\frac{d^2 p_i'}{dt^2} = p_e' \tag{13}$$

In this ω_c is a damping term, related to the leakage resistance of the wall through the expression

$$\omega_c \quad = \quad A\ \gamma\ \rho\, c_s^2/V_o \tag{14}$$

where V_o is the volume, c_s the velocity of sound in air (345 m/s) and ρ the air density ($1.24\ kg/m^3$). The frequency ω_o is the internal frequency of the space inside the building and roughly speaking

$$\omega_o \quad \propto \quad 2\pi c_s\,(V_o)^{-1/3} \tag{15}$$

where the proportionality is of order unity.

If we compare values for ω_c and ω_o we find first (with $\rho\, c_s^2$ = 147 kPa; γ = 0.1 m/s/kPa), that

$$\omega_c = 14.7\ A/V_o\ rad/sec \tag{16}$$

For a tall building, 200 x 50 x 50m, this represents an upper frequency of about 1.2 rad/s or 0.2 Hz.

The value of ω_o on the other hand is likely to exceed 10 rad/sec. For buildings without large openings we then conclude that the leakage damping overwhelms any resonance effect. It also suggests that the leakage will effectively filter out high frequency response from the internal pressure.

A further reduction in the fluctuating internal pressure arises from the spatial correlation of the external pressures, or lack of it. In dealing with an entire building the equation (13) reduces to

$$Cp_i^2(\omega)\{1 + i\omega/\omega_c - \omega^2/\omega_o^2\}^2 = \frac{1}{A^2}\int_A\int Cp(\omega,r_1)Cp(\omega,r_2)\,dA_1\,dA_2 \qquad (17)$$

The average covariance of external pressures on the right hand side can be represented in the form $R(\omega)\ 1/A \int \{Cp(\omega,r)\}^2\ dA$ in which $R(\omega)$ is an overall correlation which is undoubtedly a function of building size and turbulence (or pressure fluctuation) scale. Some preliminary indications are that the integral value of R over all frequencies is of the order 0.5.

In Fig. 4 we show some direct measurements of external and internal pressures on the model in Fig. 2 with uniform porosity scaled to represent that of a full scale building. The external pressure tap coincides with the +0.9 pressure point. Note the significantly lower amplitude of the internal fluctuating pressure. Since the fluctuating pressures add more or less as the square root of sums of squares, the amplitude of the fluctuating pressure difference will differ little from the external fluctuating pressure. The mean pressure difference is inferred directly from the difference in mean pressure coefficients.

4.2 FLUCTUATING PRESSURES: LARGE OPENING

This case has been considered both experimentally and analytically by Holmes (1979) for the case of low building models. Consider a rigid building with a large opening, but without background leakage, e.g. a loading door having an area of say 10% or more of the total wall area. In this case the mean internal pressure is the same as the external pressure at the opening. Thus the significant questions relate to the fluctuating pressures.

Holmes treated this as a Helmholtz resonator with square law damping, the equation of motion being of the form

$$\frac{1}{\omega_o^2}\frac{d^2C'p_i}{dt^2} + \frac{1}{D^2}\frac{dC'p_i}{dt}\left|\frac{dC'p_i}{dt}\right| + C'p_i = C'p \tag{18}$$

Here the primes refer to the fluctuating components. For sinusoidal pressure fluctuations, the second term can be linearized and the values of ω_o, the resonant frequency of the building, and D, the damping coefficient, can be shown to be respectively

$$\omega_o = 1.062\ c_s\ a^{\frac{1}{4}}/V_o^{\frac{1}{2}} \tag{19}$$

and

$$D = k\ c_s\ (\sqrt{\rho\ c_s^2/q})\ (a/V_o)\ \sqrt{\frac{3\pi}{4}} \tag{20}$$

where a is the size of the opening. With $c_s = 345$ m/sec, $k = 0.65$ and $q \simeq 1$ kPa this reduces the above to (S.I. units)

$$\omega_o = 366\ a^{\frac{1}{4}}\ /V_o^{\frac{1}{2}} \tag{21}$$

$$D = 4173\ (a\ /\ V_o) \tag{22}$$

With a typical warehouse with dimensions of say 50m x 50m x 10m and an opening of 10m^2 we find

$$\begin{aligned} \omega &= 366 \times 10^{\frac{1}{4}}/(25{,}000)^{\frac{1}{2}} \\ &= 4.12 \text{ rad/sec} \\ D &= 4173 \times 10\ /\ 25{,}000 \\ &= 1.67 \text{ rad/sec.} \end{aligned} \tag{23}$$

This suggests that the pressures are critically damped $(D < \omega_o)$. If the area of the opening was increased by a factor of 4, say, the natural frequency would increase to 5.83 rad/sec and the damping factor would increase to 6.7 rad/sec. This indicates a mild resonance would occur.

The condition for resonance is basically

$$\omega_O < D$$

That is

$$1.062\ c_S\, a^{\frac{1}{4}}/V_O^{\frac{1}{2}} < k\, c_S(\sqrt{\rho c_S{}^2/q})\ (a/V_O)\sqrt{\frac{3\pi}{4}}$$

or

$$(a^{3/2}/V_O) > \frac{0.48}{k^2}\left(\frac{q}{\rho c_S{}^2}\right) \qquad (24)$$

With the same substitutions as above this gives approximately

$$a \quad > \quad 0.04\ V_O{}^{2/3} (25)$$

For a warehouse of 10,000 m^3 for example this means an opening greater than $25 m^2$.

The usefulness of these results is that it suggests a yardstick for determining whether the interior pressure fluctuations will experience resonant amplification. If they do not then the interior pressure fluctuations should be the same as the exterior pressure fluctuations but attenuated at the high frequencies above "D".

5.0 "CANYON EFFECT" ON INTERNAL PRESSURES

Measurements of the wind induced external pressures on buildings are normally referenced to the pressure at some location where the flow is undisturbed by the buildings themselves. In wind tunnel studies it is common to determine both the static (p_S) and dynamic (q) reference pressure in the free stream just upstream of the building in question. This is sometimes referred to as the "gradient level" after the "gradient wind speed" in the atmosphere. The pressure coefficients derived from the experiments for some position, r, on the building are then defined by

$$Cp(r) = \quad (p(r) - p_S) / q$$

Pressure coefficients defined in this way have been conventional for a number of years. In estimating the pressure difference, nominal values of internal pressure have been adopted, (to which may have been added the mechanical pressurization and "stack effect" pressures).

The procedures referred to in this paper allow some of the guesswork to be taken out of these estimates of internal pressure. For tall buildings with controlled air conditioning inside and more or less uniform air leakage the estimation of interior pressure coefficients should be reliable. These will again be referenced to "gradient level" reference pressures.

This procedure then allows a new set of "pressure difference coefficients" to be established defined by

$$C_{\Delta p} = Cp - Cp_i \tag{26}$$

This closes the loop on the pressure difference and allows the pressure coefficients themselves to define the proper interior pressures.

This step appears to be particularly important in circumstances when there is a high density of taller buildings and the building in question is somewhat submerged in the familiar city "canyon". While the canyon tends to reduce the general levels of wind speed - it may accelerate them locally - it also can depress the ambient static pressures so that the entire region is below the gradient level reference pressures and all the exterior pressures on the cladding will appear to be shifted down as well.

Since all the venting of the interior of the structure also must feed on this pocket of lower pressure the interior pressures will be depressed as well. If purely nominal values of interior pressure are used the pressure differences estimated from the exterior pressure coefficients referred to gradient level will be biased downwards reducing the apparent positive pressures and increasing the apparent suctions.

This effect is illustrated in Fig. 5 which show the spatially averaged exterior pressure coefficients, $E(Cp)$, computed for three tall buildings. This as we have

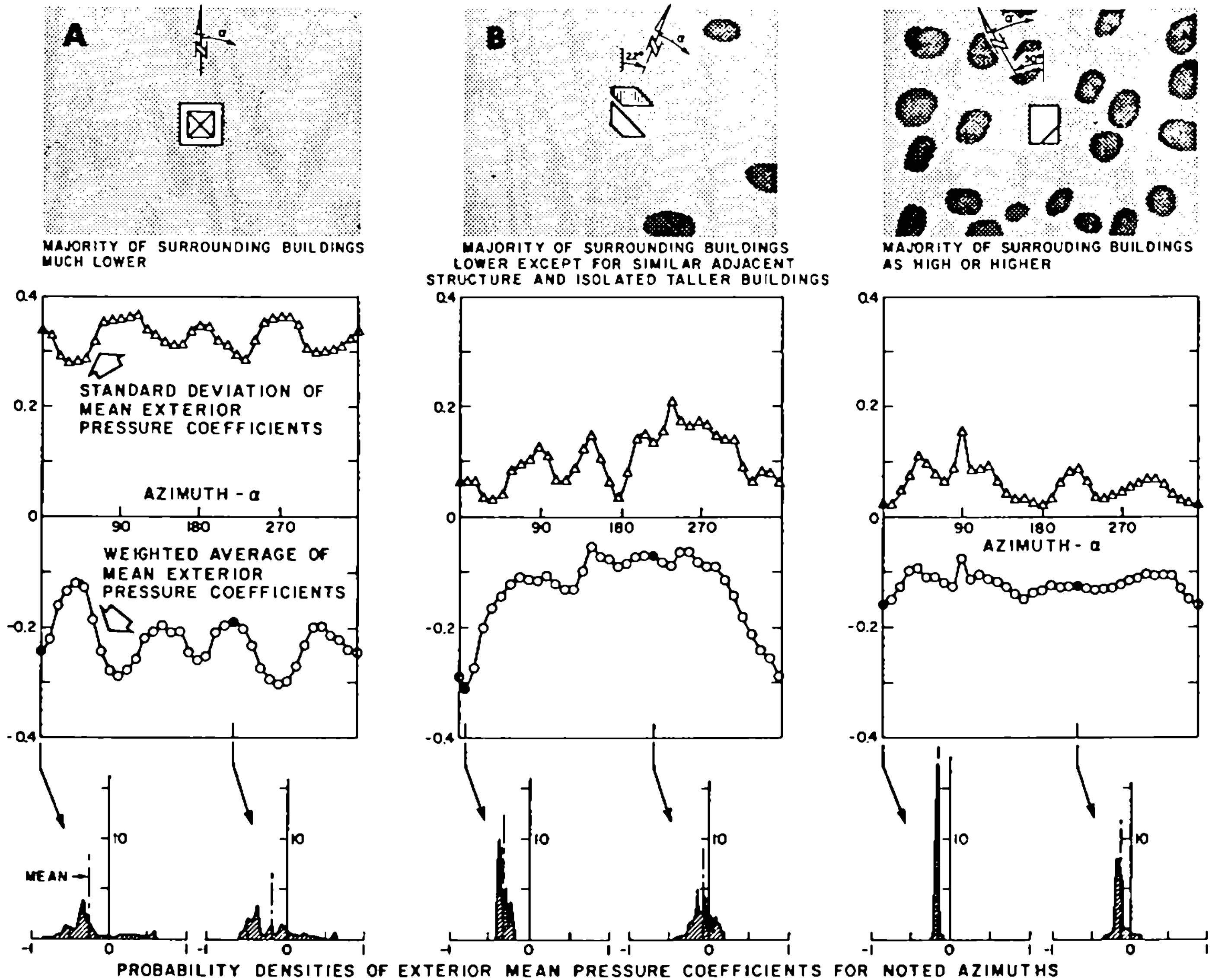

FIG. 5 COMPARISON OF MEAN EXTERIOR PRESSURE COEFFICIENTS REFERENCED TO GRADIENT HEIGHT FOR THREE TALL BUILDINGS

noted is a good estimate of the interior mean pressure coefficients. Building A is 860 ft. high and comparatively isolated; Building B is 210 ft. high, in close proximity to a neighbour lying in its wake for some wind directions and Building C is 465 ft. high and situated in a "canyon" surrounded by taller buildings, . The significant variations in the mean interior pressure coefficients (computed from the exterior pressure coefficients referenced to gradient height) are noteworthy. They arise both with wind direction as well as from building to building.

In addition to the mean exterior pressure, Fig. 5 also shows the standard deviation. This is an indication of the possible variability in the mean interior pressures but is larger by a significant factor. This is far less sensitive to wind direction.

6.0 AIR INFILTRATION

Air infiltration is closely related to the question of interior pressures. Equation (2) indicates the airflow across the building envelope, the direction being indicated by the sign of the pressure difference. Consider any point on the building's surface. If the mean and standard deviation of the fluctuating exterior pressures are $\bar{p}_e$ and σ_{p_e}, and the mean and standard deviation of the interior pressures are $\bar{p}_i$ and σ_{p_i}, then the instantaneous difference in pressure can be represented by

$$\Delta p = \bar{p}_e - \bar{p}_i + z\sqrt{\sigma^2_{p_e} + \sigma^2_{p_i} + r\,\sigma_{p_e}\sigma_{p_i}} \qquad (22)$$

r is a correlation coefficient between interior and exterior and z is a random variable with mean zero and standard deviation of unity. Inflow will take place when $\Delta p > 0$, that is

$$z > (\bar{p}_e - \bar{p}_i)/(\sigma^2_{p_e} + \sigma^2_{p_i} + r\,\sigma_{p_e}\sigma_{p_i})^{\frac{1}{2}} \qquad (28)$$

This will occur for a fraction of the time, θ, given by

$$\theta = \int_{z_1}^{\infty} f_z(z)\,dz \qquad (29)$$

The value z_1 corresponds to the righthand side of the inequality above and will vary with position on the surface, r. The inflow per unit area is $c\Delta p^n$. The total infiltration over the entire surface is then

$$Q_{in} = \int_A \int_1^{\infty} c(r) \, \{\Delta p(r,z)\}^n \, f_z(z) \, dz \, dA(r) \tag{30}$$

As a practical measure $f_z(z)$ can be taken as Gaussian. In this, the wind tunnel experiments yield the parameters of Δp required.

7.0 CONCLUSIONS

The paper has shown that the interior pressures in buildings are amenable to more detailed analysis than is conventionally given to them and that useful information on them can be easily derived from the wind tunnel data on external pressures. The uncertainties can be conveniently expressed in parallel statistical terms. The importance of fluctuating pressures are related to the area of the opening and interior volume and a simple criterion indicates when these are likely to be important.

Reference is made to the importance of calculating the internal pressures in cases where buildings are in close proximity to one another and internal pressures will be biased downward by the wakes of these structures. Finally, the related problem of infiltration is discussed. This question is controlled by the internal pressure regime but can be straightforwardly estimated using the experimental information from wind tunnel studies.

8.0 ACKNOWLEDGEMENTS

The assistance received in the preparation of the experimental material in this paper from Messrs. D. Djakovich, H.Y.L Hui and W. Mallais are gratefully acknowledged.

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PAPER 2

WIND PRESSURE DATA REQUIREMENTS FOR PREDICTING VENTILATION

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SUMMARY

The need for wind pressure data is illustrated by examples which show the sensitivity of predicted ventilation rates and the conditions under which the sensitivity occurs.

The problems of producing generalised pressure data which arise from the specific requirements of prediction methods are discussed.

WIND PRESSURE DATA REQUIREMENTS FOR PREDICTING VENTILATION

1. INTRODUCTION

Most ventilation prediction methods require the pressures generated by the wind on the external surfaces of buildings to be specified as input data. A convenient way of doing this is to use pressure coefficients from wind tunnel tests. This paper is concerned with the nature of this data as specifically required by the prediction methods.

The need for wind pressure data for design purposes and for validating prediction methods is well recognised (see for example Refs.1&2), yet the amount which is available is still very small in relation to the wide range of building shapes and arrangements which are of common interest. The lack of a suitable data compilation is in fact acknowledged in the ventilation design code for the UK (Ref.3), where it is stated that it is necessary to resort to wind tunnel tests to obtain detailed pressure distributions for most buildings. (Pressure data obtained for structural studies may be more widely available, but this tends to be biased towards isolated or tall buildings). It is therefore an opportune time to consider the special requirements of ventilation prediction methods.

Emphasis is placed on generalised pressure data suitable for design guides, rather than on data obtained from a wind tunnel model of a particular site. This is an important distinction, because the requirements of prediction methods lead to greater problems in the former case. The aim of the paper is to discuss these problems from the viewpoint of a user of prediction methods.

In the following, the pressure coefficient $\overline{Cp}$ at a point on the external surface is defined by

$$\overline{Cp} = \frac{\overline{P - Pr}}{\frac{1}{2}\rho Ur^2}$$

where $\overline{P - Pr}$ is the difference between the surface pressure and a reference pressure, Ur is a reference wind speed and ρ is air density. (The reference wind direction will be denoted by Ør). The overbars show that the pressure coefficient is derived from time-averaged measurements, since it is this which is invariably required by the methods.

2. IDEAL REQUIREMENTS

Wind pressure data for ventilation prediction would ideally satisfy the following requirements:

(i) The surface distribution of pressures would be specified in detail such that $\overline{Cp}$ is known for all points where there are ventilation openings.

(ii) The surface distributions would be specified over the 360° range of wind directions.

(iii) The reference wind speed and direction would be measured in the wind tunnel at the corresponding point where the full-scale values are measured.

The second of these requirements presents no measurement problems (with modern wind tunnel equipment), but it does raise the question of how much data can be incorporated in design guides. More complex issues are raised by the first and third requirements since it is generally not possible to satisfy them completely.

The extent to which they should be satisfied depends on the size of errors introduced when they are relaxed. An indication of the errors involved can be obtained by determining the sensitivity of predicted ventilation rates to the pressure data. This is done in the next section, but it must be remembered that a sensitivity analysis does not necessarily show true errors, because the prediction method will contain assumptions which are themselves sources of error. A distinction will be made between single-cell prediction methods and multi-cell methods.

3 SENSITIVITY OF PREDICTIONS TO PRESSURE DATA

3.1 Single-Cell Methods

The main aim of single-cell methods is to predict whole-house ventilation rate Q_H. The following results have been obtained with the British Gas method VENT 2 (Ref.4).

Figure 1 (which is Figure 14 of Ref.5) shows how the nondimensional ventilation rate of a simple terraced house varies with the two nondimensional parameters $\Delta Cp/Ar^2$ and C_{D_∞}/R_{E_L}. The first parameter is the ratio between the two driving forces of ventilation (wind and buoyancy). ΔCp is the difference between the two surface pressure coefficients Cp_1 and Cp_2 and Ar is the Archimedes number. Full definitions of the terms are given in Appendix 1 for completeness, but this is not all essential information because here we will consider a given house with constant temperatures. Under these conditions the parameter C_{D_∞}/R_{E_L} is constant and the parameter $\Delta Cp/Ar^2$ is equal to a constant multiplied by Δp, the difference between the actual surface pressures. Thus the variation of Q_H with Δp is shown by just one of the curves in Fig. 1, as indicated by the symbols in square brackets.

It is clear that the sensitivity of Q_H to Δp varies considerably. When the wind generated pressures are small in relation to pressures arising from buoyancy (i.e. $\Delta Cp/Ar^2 < 2$) the ventilation rate is very insensitive. When the wind pressures dominate however, ($\Delta Cp/Ar^2 > 2$) the sensitivity is large. For the example shown in Fig. 1, a 25% error in Δp leads to a 20% error in Q_H. For dwellings in the UK one can expect both types of situation to be encountered (see Table 1 of Ref. 5 for typical values of $\Delta Cp/Ar^2$). In some instances therefore, errors in Δp will be of no consequence, whereas in other instances they will be significant.

The errors in Δp can arise from several sources, but ultimately the value of Δp will be obtained by multiplying a pressure coefficient by the square of a wind speed, e.g. for the dwelling in Fig. 1

$$p = \tfrac{1}{2}\rho\, Ur^2 . \,\Delta Cp$$
$$= \tfrac{1}{2}\rho\, Ur^2\, (Cp_1 - Cp_2).$$

In many cases the required wind speed will be obtained by empirical estimation from the wind tunnel reference speed (see Section 5). Since Δp depends on the square of the speed and only on the difference of the pressure coefficients, the wind speed estimation procedure will tend to be a larger source of error than the pressure coefficients.

3.2 Multi-Cell Methods

The primary aim of a multi-cell method is to predict room ventilation rates, and this requires that the distribution of openings in the surfaces be specified. It follows that the distribution of surface pressures should be specified to the same detail. We are thus interested in the sensitivity of a room ventilation rate to a change in a part of the pressure distribution.

This is a more complex problem than that for single-cell methods. Experience with our own method VENT 1 (Ref.1) suggests that the sensitivity of room ventilation rates is similar in magnitude to whole-house rates, but the dependence on wind and temperature conditions is more complicated. This can in fact be seen in the results described in Reference 5. Although obtained with a single-cell method, the flow rates through the individual openings can be treated as room ventilation rates. Figure 2 shows an example (Figure 9 of Ref.5) and it can be seen that the flow rate through opening number 2 is in fact more sensitive to Δp than the whole-house rate for $\Delta Cp/Ar^2 < 2$.

It thus appears that prediction of room ventilation rates can place greater demands on the accuracy of pressure data than prediction of whole-house rates. This is not surprising because a small percentage error in Q_H could imply a much larger error in one of the room ventilation rates.

This leads on to a related question concerning the specification of the pressure distribution on buildings. It is common for single-cell methods to assume that the pressure does not vary over a given surface. This is an assumption which requires careful consideration.

4. SURFACE PRESSURE DISTRIBUTIONS

The main advantage of assuming a uniform pressure distribution on each surface of a building is that it simplifies the data input to the prediction method. It is however a questionable assumption, because the results in References 6 and 7 exhibit large non-uniformities, particularly on the windward faces of exposed buildings, and even of buildings in fairly dense group.

The prediction errors arising from this source will depend on the distribution of the openings. If the method assumes that the opening distribution is uniform, it is at least consistent to make the same assumption about the pressures. However, a uniform opening distribution is itself questionable, particularly when there are air vents in the walls. Before a proper judgement can be made about the acceptability of either assumption it is desirable that a sensitivity analysis be carried out.

For multi-cell models the assumption of uniform pressures is much less tenable and one should look for a more realistic representation of pressure distributions. One possibility is a two-parameter description (ie. the mid-height $\overline{Cp}$, and the rate of change of $\overline{Cp}$ with height). The data in Ref.8 indicate that this might be an acceptable approach. It would retain the simplicity required for single-cell models and it would be consistent with the overall approach desired for the presentation of wind pressure data (see Section 6).

5. REFERENCE WIND CONDITIONS

The user of a prediction method will have access to full-scale values of speed and direction (U_F and $\emptyset_F$, say), which have been obtained in one or more of the following ways:-

(a) from an on-site anemometer,

(b) from an anemometer at a local Meteorological Office weather station,

(c) from published data on "gradient wind speed" (the speed at the top of the atmospheric boundary layer).

Ideally the wind tunnel measurements (U_r and $\emptyset_r$) should allow the pressure coefficients to be based on wind conditions for all of the above cases. One way of achieving this would be to measure wind conditions at the points in the wind tunnel which correspond to the full-scale anemometer sites. This is not always feasible.

For case (a), one is faced with the problem that there is no generally accepted position for an on-site anemometer, and this problem is often confounded by the aerodynamic influence of nearly buildings (Ref 9). For this case therefore the best option is to build a model of the actual site, rather than make use of a generalised model,although problems with building proximity can still arise (eg. Ref.10).

For case (b), the problem is that the weather station site can not generally be simulated on the wind tunnel model, because it may be many kilometres from the building under investigation. In this case one has to rely on empirical relationships between reference wind conditions in the tunnel and those at the weather station. This could give rise to a significant source of error in the wind speed used for evaluating wind pressures (see Section 3.1). Improvements in this procedure are therefore just as desirable as improved pressure coefficients.

For case (c), there is no real problem about measuring gradient wind speed in the tunnel (or estimating it from boundary layer profile measurements). It is therefore a good choice as the primary reference wind speed, provided it is supported by profile measurements which allow pressure coefficients based on wind speeds (a) and (b) to be evaluated. The main problem with gradient wind speed is that the available full-scale data is nowhere near as detailed as the data for cases (a) and (b), so that the user of a prediction method will often rely on the latter.

6. SCOPE OF DATA REQUIRED

There are many factors affecting the pressure distribution on buildings. In Ref.7 they are classified into two groups i.e. factors related to building form and factors related to the properties of the wind.

If one just considers the first of these groups one is immediately faced with the problem of which building configurations should be tested. Obviously common building shapes and configurations should be covered by design data, but can these be represented by a reasonable number of wind tunnel models? One way of resolving this question might be to carry out tests on simple models and to systematically vary the building form in order to identify the major parameters which affect the pressure distribution (as in Ref.7).

Another problem which will be encountered is that of presenting the data in a compact manner. A prerequisite for this is a knowledge of what the important parameters are. Furthermore the most compact presentation will be obtained by expressing the parameters in non-dimensional form.

Both of these problems relate to keeping the amount of data to manageable proportions, whilst satisfying the requirements of the prediction methods. This emphasises the need to know fairly precisely these requirements, particularly regarding surface pressure distributions (Section 4).

7. TURBULENT PRESSURE FLUCTUATIONS

In the preceding discussion, consideration has only been given to the mean pressure coefficient $\overline{Cp}$. There is however substantial evidence that ventilation associated with turbulent pressure fluctuations can be significant and the two versions of the prediction method VENT (Ref.4) make an allowance for it. It is thus desirable that wind tunnel studies should also supply data about these fluctuations.

There is no straightforward answer to the question of the form this data should take, because the prediction of this type of ventilation is very empirical (Ref.9). It is suggested however that the coefficient of the root-mean-square of the surface pressure fluctuations is a suitable parameter, partly because it is used by VENT and partly because it is not particularly difficult to measure.

8. CONCLUSIONS

There is a need for generalised wind pressure data suitable for design purposes, because ventilation rate predictions are often sensitive to wind pressures.

The underlying problem is to restrict the data to manageable proportions, whilst satisfying the accuracy requirements of the prediction methods. This will require a systematic investigation of the important factors which determine surface pressures on buildings and a compact means of presenting the data. It will also require a careful study of the requirements of the methods, particularly concerning the individual surface pressure distributions. Multi-cell methods certainly require this information, although the position is less clear for single-cell methods.

The data should include a measure of the surface pressure fluctuations.

The possibility of improving procedures for utilising full-scale wind data from sites not modelled in the wind tunnel needs investigation.

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DW/LS
wp

APPENDIX 1

Definition of Terms

It should be noted that the terminology relates to a building with N identical openings.

a, b	Coefficients in the flow equation of each opening $\Delta p = aQ^2 + bQ$
A	Area of opening based on its physical dimensions
A_T	Total area of openings, $A_T = N.A$
A_r	Archimedes number, $A_r = U_B/U_r$
$C_{D\infty}$	Discharge coefficient of opening at high flow rate i.e. $C_{D\infty} . A = \sqrt{\rho/2a}$
$\overline{Cp}$	Pressure coefficient, defined in Section 1
g	Acceleration due to gravity
h	Reference height of building
R_{EL}	Leakage Reynolds number, $R_{EL} = \rho U_B/bA$
U_B	Effective air speed due to buoyancy $U_B = \sqrt{\Delta\rho gh/\rho}$
U_r	Reference air speed
ρ	Air density reference
$\Delta\rho$	Difference between internal and external densities
Δp	Pressure difference across opening or across building

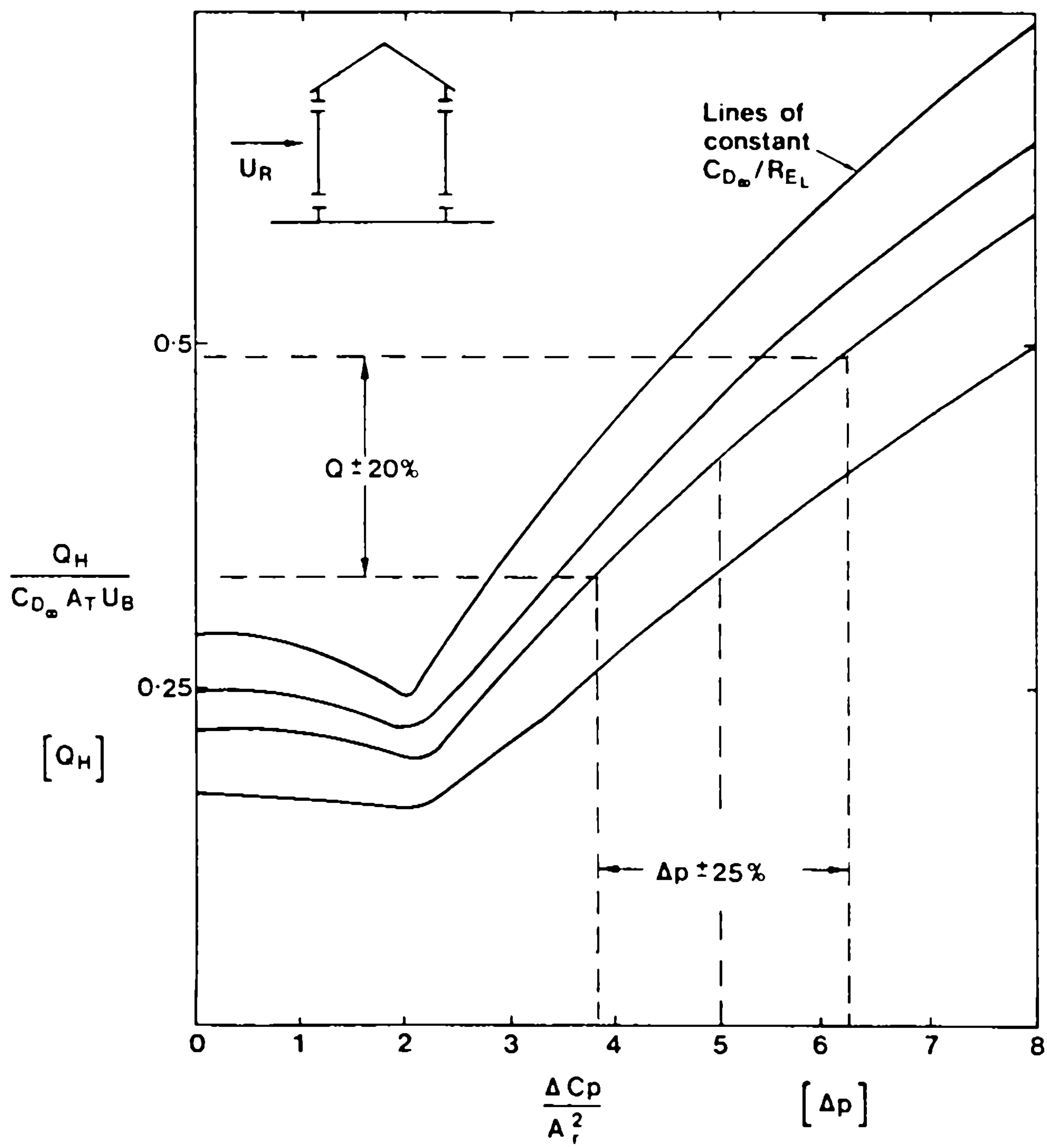

Fig. 1 EXAMPLE OF SENSITIVITY OF VENTILATION RATE Q_H TO PRESSURE DIFFERENCE Δp

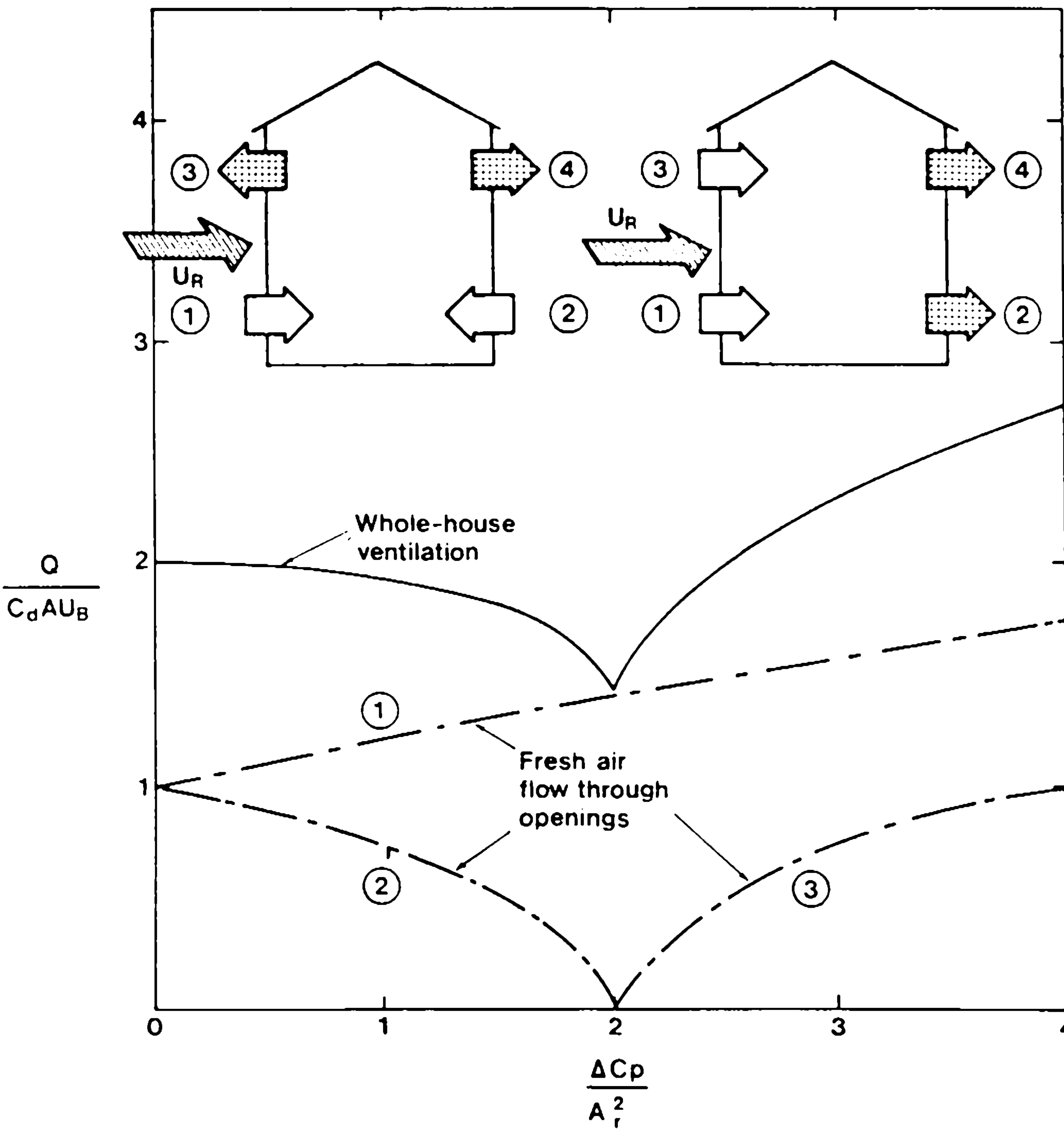

Fig. 2 SENSITIVITIES OF FLOWS THROUGH OPENINGS

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PAPER 3

FULL-SCALE WIND PRESSURE MEASUREMENTS ON LOW-RISE BUILDINGS

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FULL-SCALE WIND PRESSURE MEASUREMENTS ON LOW-RISE BUILDINGS

SUMMARY

In this paper some results of full-scale pressure measurements on three test-houses are presented. The measurement programme has hitherto given examples of pressure distributions caused by wind and temperature and has shown their importance in the study of air infiltration.

1 INTRODUCTION

Several models for the calculation of air leakage through a building surface area have been developed, but there is still a lack of full-scale data on pressure distribution and permeability characteristics of different building structures. From an energy point of view the combined effect of temperature and low wind speeds is of special interest.

Three single-family houses have up to now been equipped with measuring instruments and mean wind pressures and permeability characteristics have been studied. The test objects have been selected in order to reflect different surface roughness conditions. Some results of the investigations have been presented, [1],[2].

Earlier full-scale measurements for two test-objects have illustrated the pressure distribution at 24 measuring points, [1]. The first object (A) was of older construction, poorly insulated and surrounded by low-rise buildings. The other house (B) was newly-built, well insulated, mechanically ventilated and located in open-site conditions. For the third test-house (C), which was newly-built, the measurement programme was enlarged, especially with regard to the number of measuring points.

In this paper some of the results from field measurements are presented. The influences of different input parameters, such as leakage characteristics and pressure distribution, on the rate of air infiltration are discussed by employing a simple iterative calculation model.

2 DESCRIPTION OF THE TEST-HOUSE

The test house "C" is a 1½-storey prefabricated timber house. Ventilation is effected by means of an exhaust air system complemented by supply air terminal devices in the windows. The cross-section of the building shows a well-thought-out construction system with regard to air-tightness and degree of insulation.

The air-tightness obtained from pressurization tests amounted to 3.7 air changes per hour at a mean pressure of 50 Pascal. This exceeds the maximum rate of infiltration, 3.0 air changes, presented by the Swedish Code of Practice.

3 INSTRUMENTATION OF THE TEST-HOUSE

For test-house "C" the differences between external and internal pressure were determined at 100 measurement points at the same time, according to figure 1. Plastic tubes, of the same length, were connected from wood panels to a fluid multimanometer (open type). The panels are an integral part of the cover boarding.

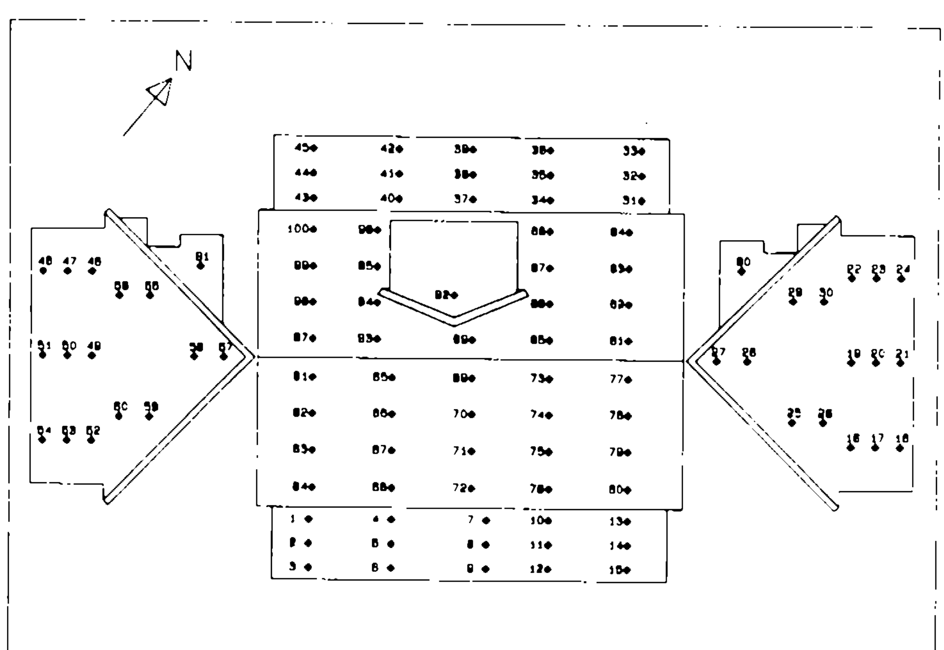


Figure 1 Measurement points

The equipment is simple and gives an instantaneous view of differential pressures for all measurement points. The pressures can be obtained as mean values at various periods or at individual moments.

The pressure coefficients C_p are defined from the following relationship

$$C_p = \frac{(p_{ext} - p_{int}) - (p_{st,ref} - p_{int})}{\frac{1}{2} \rho V^2}$$

where

p_{ext} = external pressure

p_{int} = internal pressure

$p_{st,ref}$ = reference static pressure at the roof ridge level

V = free stream wind velocity at the roof ridge level

ρ = air density

The full-scale measurements are characterized by a simultaneous registration of pressure distribution on the building, rates of air change measured using tracer gas, temperatures, and amplitude and direction of wind velocities.

Gauges for measuring the wind were installed at different heights (3, 7.5 and 10 metres) on a 10-metre mast. Pressurization tests were carried out, in accordance with the Swedish standards, in order to determine the degree of air-tightness. For the tracer gas measurements N_2O has been used.

4 EVALUATION OF PRESSURE DISTRIBUTION

The wind pressure on a house is usually given by means of pressure coefficients. The pressure coefficients, C_p-factors, recommended in the Swedish code of practice, are shown in figure 2. These values are normally inadequate for air infiltration studies.

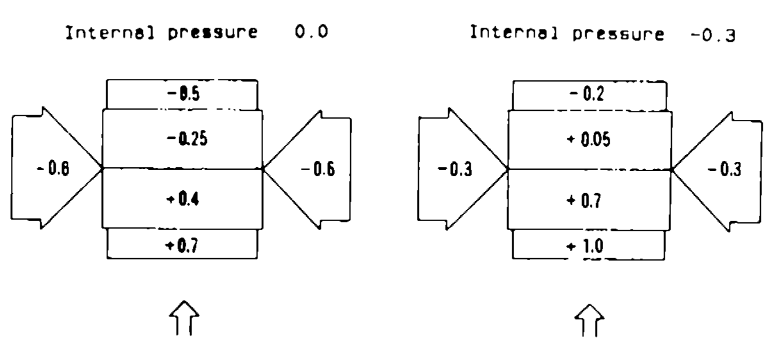


Figure 2 Pressure coefficients from the code of practice

The results from [1] show that the measured distribution for the first two test-objects differ from these standard values, see figure 3.

For the latest test-house "C", the pressure distributions were registered with normal ventilation, with forced ventilation and with the mechanical ventilation system switched off. The supply air terminal devices were both either closed or open. The different cases of natural and forced ventilation occurred alternately in order to reduce the effect of variations in climatic conditions. Climate data were registered during each measuring period.

One of the main difficulties in connection with full-scale measurements is to relate the measuring installation to a well-defined static reference pressure. Tests of different types of gauges, both in a wind tunnel and in full scale, show the problems with orientation tolerance, among other things.

The principle of measurement is based on the fact that all registered pressures are differences, and can therefore be applied with good accuracy to air infiltration calculations. The following figures give some examples of the distribution on the house. The values are obtained by averaging 25-35 recordings.

Pressure distributions for natural ventilation are illustrated in figures 4 and 5. For this wind direction, the combined store and garage on the eastern gable of the house does not influence the distribution. The dormer window on the north side gives a distinct reduction of pressure differences on some parts of the roof.

The work has shown that wind velocity as well as static and dynamic reference pressures vary considerably with height and wind direction. This variation is probably caused by vegetation and surroundings with low hills on one side of the house. Furthermore, it is rather difficult to register low wind velocities. The C_p-factors can for these reasons be more unreliable than the corresponding pressure differences.

These sources of error were accentuated for the wind direction WNW. The distribution for this direction is visualized in terms of pressure differences related to a static reference pressure at the roof ridge level, see figures 6 and 7.

When the wind comes from WNW, an area of suction is formed around the dormer window. The negative pressures over the gables vary.

The mechanical system does not influence the internal pressure and the total flow as expected. There is only a slight change in the pressures on the windward side and on the leeward side there is hardly any change. The rates of air flow measured by the tracer gas method show that the actual exhaust air is approximately 0.3 changes per hour, through the ventilation system, and 0.05 to 0.1 changes by uncontrollable air flow. This may be attributed to the fact that the mechanical system is

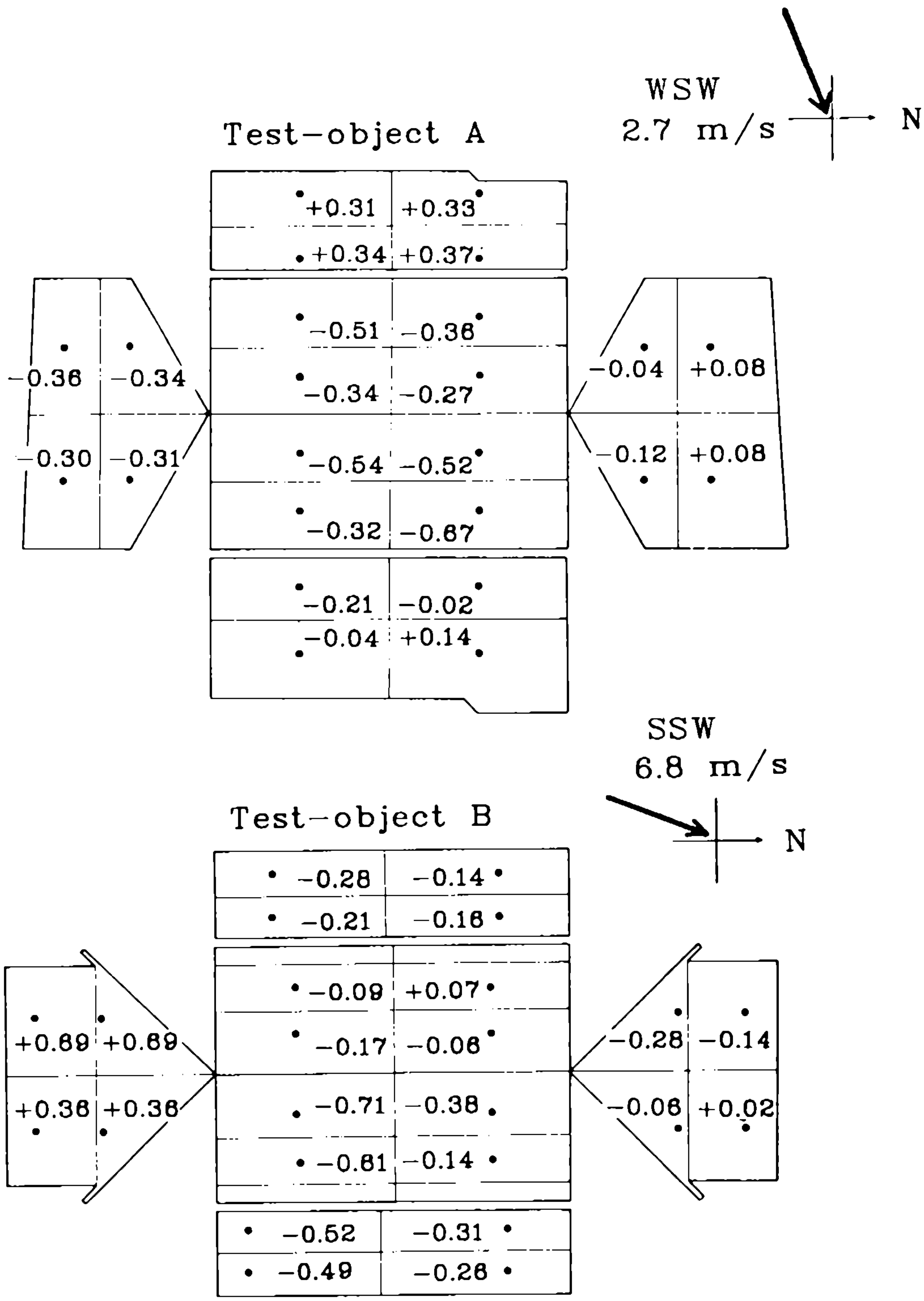
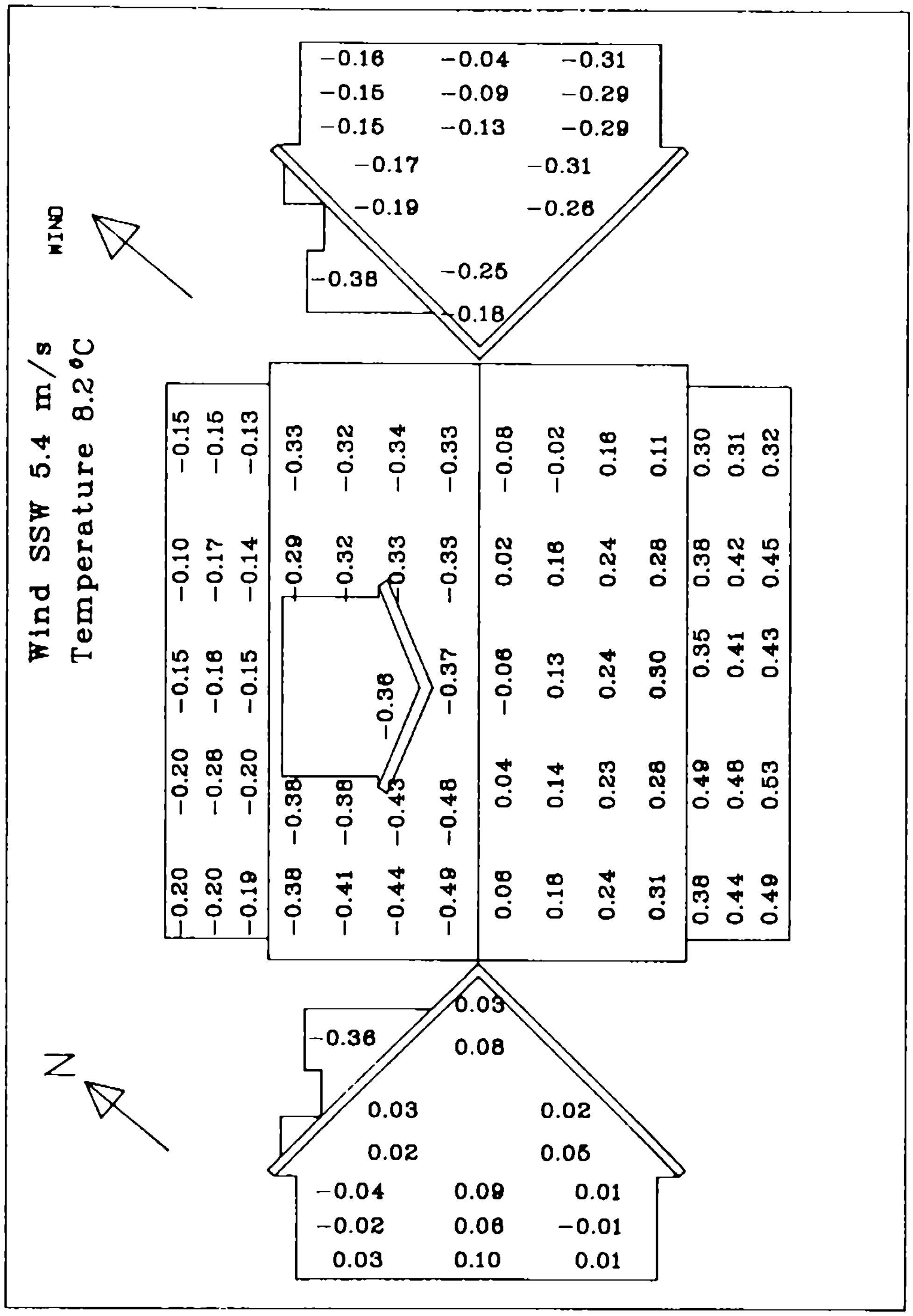
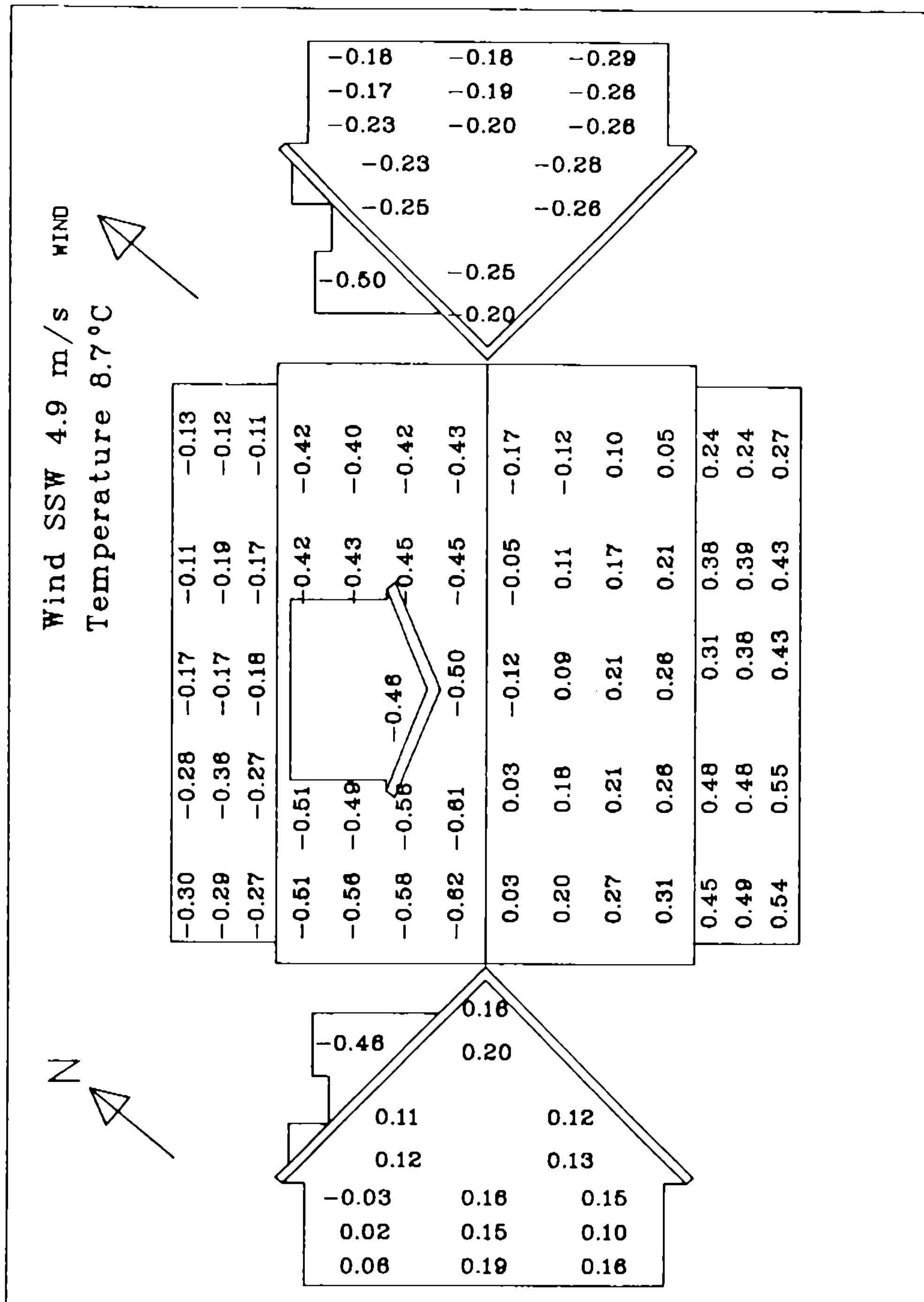


Figure 3   Pressure coefficients, measured values, [1]



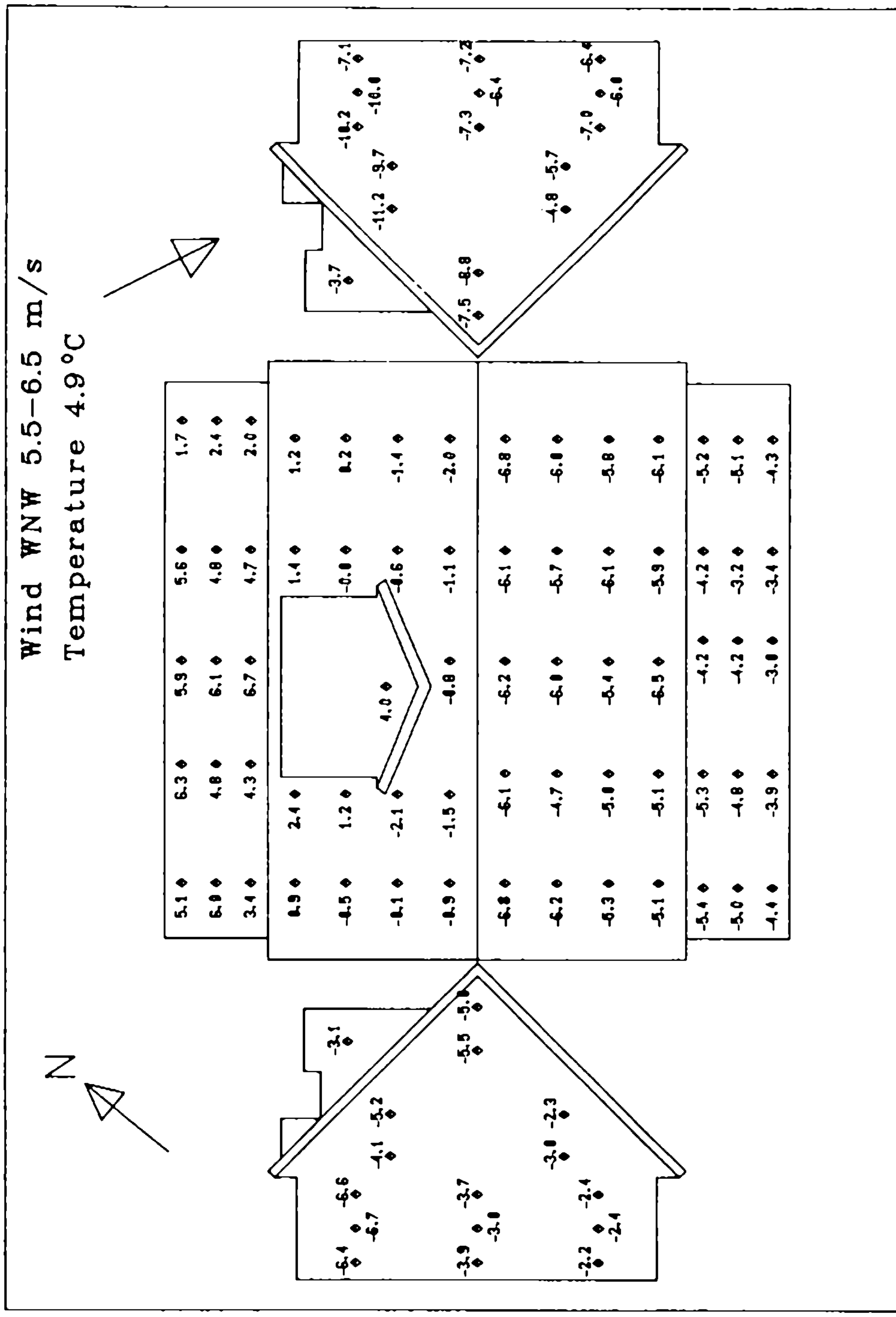
Pressure coefficients, C_p-factors

Figure 4 *Pressure distribution. Natural ventilation with closed openings in the windows. Wind from SSW.*



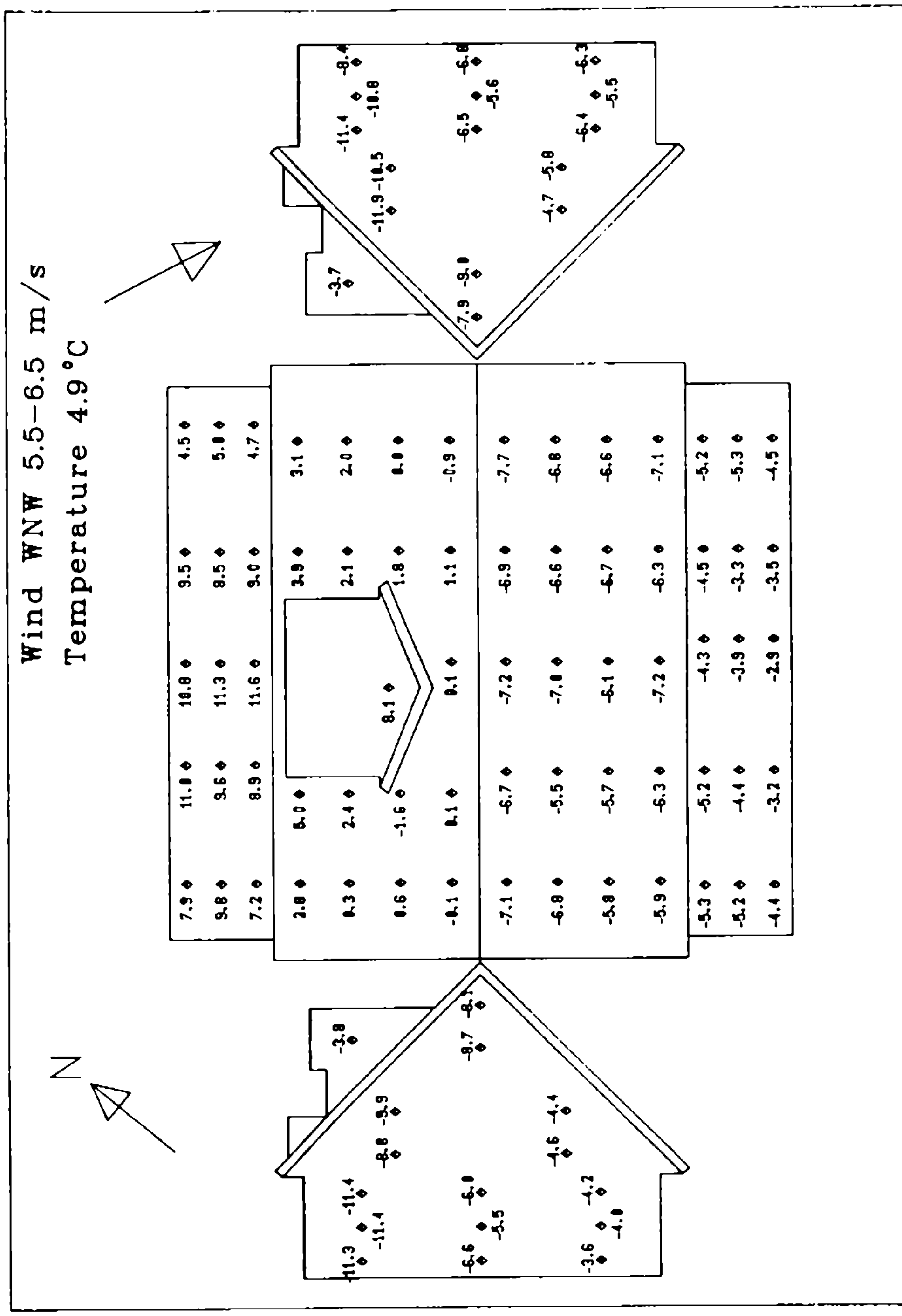
Pressure coefficients, C_p*-factors*

Figure 5 *Pressure distribution. Natural ventilation with openings in the windows open. Wind from SSW.*



Pressure differences (Pascal)

Figure 6 *Pressure distribution. Natural ventilation with closed openings in the windows. Wind from WNW.*



Pressure differences (Pascal)

Figure 7 *Pressure distribution. Normal mechanical ventilation with closed openings in the windows. Wind from WNW.*

working below the designed capacity of 0.5 changes per hour, which does not fulfil the requirements specified by the Swedish Standard, SBN 80.

The effect of openings in the windows varies with the rate of air changes and wind direction.

The wind pressure distribution can be illustrated graphically as in figure 8 for the windward wall and roof. For this wind direction the distribution is more uniform on the wall than on the roof. The total number and distribution of measuring points strongly influences the results. Even with 100 measuring points it is possible to miss out local areas of suction.

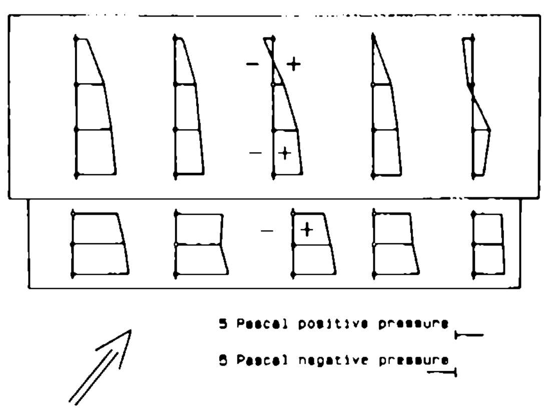


Figure 8 Pressure distribution on the windward wall and roof

5 ESTIMATION OF AIR EXCHANGE RATE

Calculations of air infiltration are based on pressure data and knowledge about the leakage characteristics of a building. A simple model for describing the pressure distribution due to wind and temperature differences over an element is as follows:

$$\Delta P_i = \Delta P_{W,i} + \Delta P_{T,i} \tag{1}$$

where

ΔP_i = total pressure distribution over element "i" (Pa)

$\Delta P_{W,i}$ = wind pressure difference

$\Delta P_{T,i}$ = temperature pressure difference

The air flow through an area A_i can be written approximately as:

$$q_i = K_i \cdot A_i \cdot \Delta P_i |\Delta P_i|^{\beta-1} \tag{2}$$

where

K_i = discharge factor per unit area for element "i" (m/s Pa^{β})

β = exponent depending on the flow characteristics ($0.5 \leq \beta \leq 1.0$)

In order to get the right dimensions in the equation above, β must be 0.5. It is also realistic to assume that the flow through most of the leakages is turbulent.

Based on results from pressurization tests, in the pressure-interval from 10 to 50 Pa, the discharge factors K_i, representing the permeability characteristics, can be derived from the equation

$$\mu = K_i \cdot A_i \cdot \Delta^{\beta} \tag{3}$$

where μ is the rate of air flow and Δ the applied pressure.

The total inflow q_T and outflow q_F from the house are

$$q_T = q_{TM} + \sum_i q_i \quad \text{for positive } \Delta P_i \tag{4}$$

$$q_F = q_{FM} + \sum_i q_i \quad \text{for negative } \Delta P_i \tag{5}$$

where q_{TM} and q_{FM} correspond to forced inflow and outflow respectively due to mechanical ventilation.

The total in- and outflow must be balanced, in an iterative process whereby the internal pressure is adjusted. It becomes necessary to introduce a correction term as given in the equation below. The need for this parameter arises from the fact that the actual permeability characteristics and the reference static pressures cannot be measured accurately. This gives the final expression:

$$q_T \cdot T_i = q_F \cdot T_o + \varepsilon \tag{6}$$

where

T_i = inside temperature (^{0}K)

T_o = outside temperature (^{0}K)

Air infiltration calculations based on the application of the code of practice are, of course, far in excess of those with C_p-factors obtained from full-scale measurements. This can be illustrated for a number of different measuring circumstances, see figure 9. The different cases of natural and forced ventilation are compiled in table 1. For some of the measurements there have been simultaneous tracer gas measurements.

Table 1 Different combinations of natural and mechanical ventilation studied during the measurements

ventilation system	position of supply air terminal devices	
	closed	open
ventilation system switched off	1	2
normal ventilation	3	4
forced ventilation	5	6

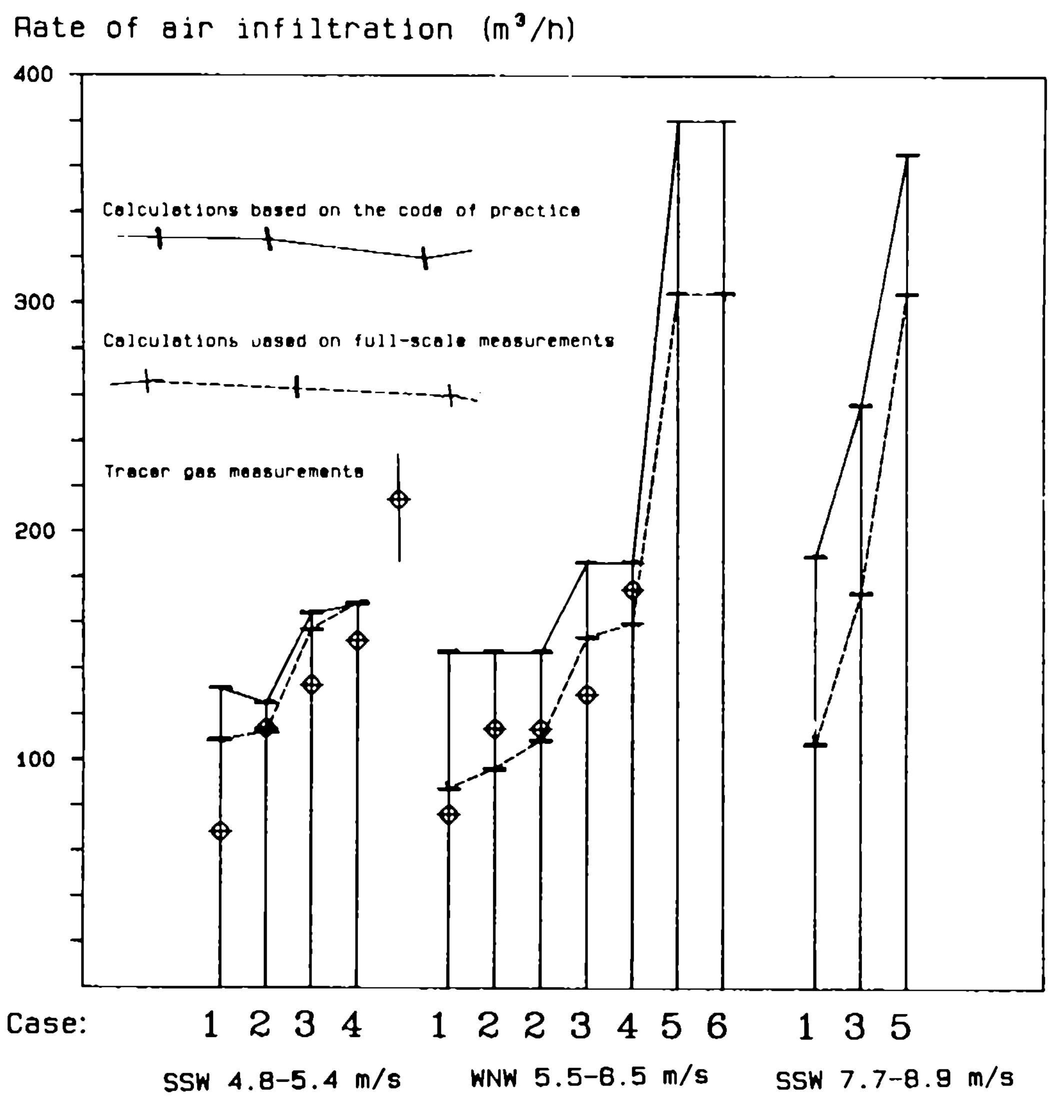


Figure 9 Calculations based on different types of C_p-factor

The climatic conditions were different for the three days of measurement. This seems in the first place to have had an effect on pressure distributions for natural ventilation. The results from the tracer gas studies are comparatively stationary. The divergence between calculations and measurements is most significant for a switched-off system with closed openings in windows.

6 DISCUSSION

The paper has shown some of the difficulties in performing climatic studies which can be applicable to ventilation studies. In spite of a comparatively large supply of measured data, it is hard to estimate correctly the rate of air flow. There is still a need for basic data during periods with low wind speeds. The fluctuations of wind-pressures and pressure drops through different constructions ought to be the subject for future research. The real driving force for air infiltration through a building construction is probably less than the measured pressure difference. The cavity behind the cover boarding has a neutralizing effect. Furthermore, simultaneous tracer gas measurements with better accuracy than the ones presented in this paper are required for comparison with calculations based on full-scale pressure measurements.

7 ACKNOWLEDGEMENTS

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PAPER 4

FULL SCALE MEASUREMENTS OF WIND LOADS ON FARM BUILDINGS

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Full scale measurements of wind loads on farm buildings

Summary

Efficient design of buildings requires a detailed knowledge of the loads the building will be subjected to in the course of its life. These loads consist of those induced by external meteorological conditions, such as wind and snow, together with building usage loads and service loads. This paper is concerned with wind load for agricultural buildings.

Full-scale measurements heve been made of wind loads on agricultural buildings and show the procedures of British Standard Institution CP3:Chapter V:Part 2 to be appropriate. However, the detailed information in the Code of Practice is shown to be in need of revision and augmentation by the incorporation of wind loads for additional building geometric parameters. Full-scale measurements have shown that pressure distributions are significantly non-uniform over a building surface and should therefore be taken into consideration in the design of buildings, especially for cladding and its fixings. The detailed pressure measurements also have direct application to ventilation design for buildings with permeable surfaces. External projections, such as inlet covers, have been found to influence the external pressure distribution and the measurements are of limited application in these cases.

1. Introduction

Many aspects of farm building design are currently being revised in accordance with the new British Standard Code of Practice for the design of buildings and structures for agriculture (BS 5502: 1978)[1]; which replaces the previous specification for general purpose farm buildings of framed construction (BS 2053: 1972)[2]. BS 5502 requires that Farm Buildings be designed in accordance with the British Standard Code of Practice, CP3:Chapter V:Part 2[3] which means the building's geometry is taken into consideration when assessing wind loads.

The procedure for assessing wind loads as set out in CP3:Chapter V:Part 2 have been criticised recently [4,5,6] and a fundamental review[7] has been carried out to examine the procedure and to consider proposed alternatives. This review is outlined in this paper together with an indication of the way a future revision of the British Standard can be made.

2 CP3:Chapter V:Part 2

The code of basic data for the design of buildings, CP3:Chapter V: 1952 was last revised in 1972 and a further revision is now in preparation. The code of practice is enforced through Building Regulations[8] and is therefore used for all industrial and domestic building. Farm Buildings are generally exempt from Building Regulations and are not required to comply with the Code. Although CP3:Chapter V:Part 2 is a National Standard it does not conform with other National standards in approach or in the calculation of wind load. By way of example two other National standards, USA[9] and Australia[10], are compared with the UK code for a calculation of overall lift and drag forces for a typical farm building. The nett pressure coefficients have been integrated to give the resultant loads in terms of coefficient of lift for the building and the coefficient of drag or force coefficient. The coefficient of lift (C_L) is defined as the total vertical force on the building (positive in the downward direction) divided by the wind dynamic pressure and building plan area. Similarly the coefficient of drag (C_D) is defined as the total horizontal force (positive in the direction of flow) divided by the wind dynamic pressure and the building frontal area.

Values of C_L and C_D from codes and full-scale measurements[7] are presented in Table 1. The USA and Australian codes show gross over-estimates of both lift and drag as compared to full-scale measurements, whereas the UK code gives closer agreement.

Code	C_L Coefficient of lift	C_D Coefficient of drag
UK	-0.30	+0.39
USA	-1.00	+0.59
Australia	-0.80	+0.68
Full-scale measurements	-0.35	+0.25

Table 1. Resultant loads

3. Full-scale measurements

To explore the validity of using the present code of practice and to provide further information, a range of full-scale buildings was instrumented. The measurements have covered all types of framed agricultural and horticultural buildings but have excluded measurements on circular bins and tower silos. Results have been published for measurements on glasshouses[11], film plastic greenhouses[12,13] and for framed farm buildings[14].

3.1 Experimental Method

The buildings on which measurements were made were all located on farms in England and were selected for their exposure. They were in open country with no obstruction within 100 m of those faces exposed to the prevailing wind. In all cases surface pressures were measured over the span of the building at mid length and in some cases surface pressures were also measured at intermediate points along the length of the building and on the end walls.

Two methods of sensing surface pressures were used. Where the building cladding was smooth, as on glasshouses, surface pressures were sensed by tapping holes. Where, however, the cladding was not smooth, as was the case with corrugated asbestos cement clad buildings, surface pressures were sensed by probes mounted normal to the surface. The probes[15] were insensitive to flow direction in the plane of the surface. They sensed the pressure 125 mm above the corrugations and were unaffected by them. Pressure signals from the sensors were transmitted by 6.7 mm internal diameter flexible tubing to a central measurement and recording station. Tube lengths of up to 30 m were used.

Wind total pressure was sensed by a directional pitot tube held into the flow by a vane. A sensor was mounted on a mast, at the same height above the ground as the ridge of the building, in the undisturbed upstream flow. Static pressure was sensed at the same location by a probe which was insensitive to variations in flow direction in the horizontal plane. The total and static pressures were transmitted by 6.7 mm internal diameter tubing to a differential pressure transducer at the central recording station. Tube lengths of up to 40 m were used. The static pressure was also used as a reference for the measurement of surface pressures. The angular position of the wind vane was sensed by a continuous rotation potentiometer housed in the base of the anemometer; this gave an electrical output proportional to wind direction.

Continuous recordings of the pressures at two points on the building and of wind dynamic pressure and direction were made simultaneously using a four-channel FM tape recorder. A control unit selected the surface pressures to be measured and switched pairs of pressure sensors in sequence, at 240 second intervals to differential micromanometers which provided analogue outputs to the tape recorder. Recordings were made when the mean wind speed exceeded 8 m/s at the standard meteorological height of 10 m. Conditions were then considered to be neutrally stable in the flow enveloping the building. The analogue records were later converted to digital samples for computer analysis; the digitisation rate was five data points per second.

The pressure coefficients given in this report are based on the wind dynamic pressure (q) at building ridge height and they are consistent with the derivation of pressure coefficients for use in the British Standard Code of Practice[3] and other design guides used in the United Kingdom.

The pressure coefficient for a given tapping point was assumed to be a single-valued function of wind direction $Cp(\phi)$ and was derived from a comparison of the probability density function (PDF) of wind load with the PDF of $[Cp(\phi).q]$ such that the difference between the two PDFs was minimised by selection of $Cp(\phi)$. This method of deriving a pressure coefficient takes account of the fluctuations in flow in the horizontal plane. Details of the method of processing the data have been presented in reference 7.

The response of the instrumentation was limited by the use of long lengths (up to 40 m) of 6.7 mm internal diameter pressure transmission tubing. The natural frequency of a 40 m tube is 1.7 Hz with an amplitude gain of 1.4. To reduce this gain to unity a pneumatic filter, consisting of a flow restrictor (small bore stainless steel tube) and a volume, were installed between the transmission tube and transducer. The pneumatic filter had a calculated time constant of 0.08 seconds. Similar filters were used on 30 m tube lengths to give an overall frequency response of 0 - 2.0 Hz (3 db down). This response was found to be adequate as there is little energy in the wind above 2 Hz and the response of structural building elements was found[7] to be attenuated above 0.3 Hz. The response of the wind direction indicator to changes in direction was 0 - 2.0 Hz (3 db down) for wind speeds in excess of 6 m/s.

3.2 Results

A limited sample of full-scale measurements is presented in this report for closed (completely clad) single-span farm buildings with a roof angle of 15 degrees. This is a popular roof angle for farm buildings and is chosen here to show the influence of height and span on the measured wind load. The results are for measurements made at building mid length for wind direction transverse to the line of the ridge. The measured external pressure coefficients (C_{pe}) for 5 farm buildings are shown for the windward roof slope in Fig. 1 and for the leeward roof slope in Fig. 2.

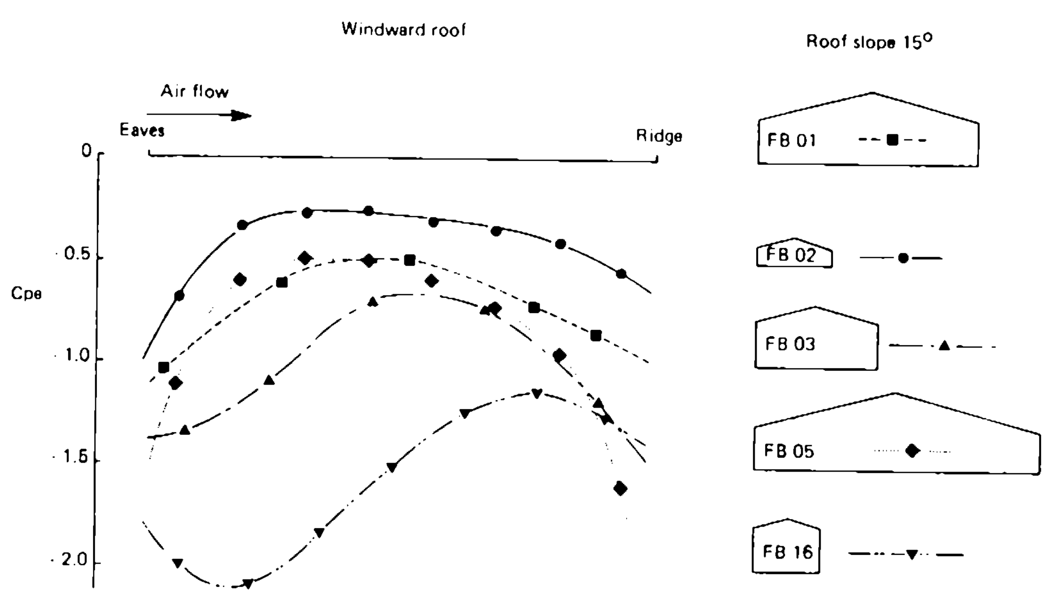

Fig. 1. Pressure distribution on the windward roof for a selection of buildings with a 15° roof slope

3.3 Discussion

On the windward roof slope (Fig. 1) the effect of varying span is clearly marked by comparing the pressure distributions for buildings FB05, span 28.0 m, building FB01 span 21.5 m, building FB03, span 11.9 m and building FB16, span 6.7 m. All these buildings have an eaves height of between 4 and 4.6 m and this limited variations in eaves height will only have a small effect on the pressure distribution.The effect of varying height is shown in Fig. 1 for one building only, FB02 where the height is 1.8 m. This building shows the same presssure pattern but the magnitude of the surface pressure is considerably reduced compared to FB16 which is of similar span.

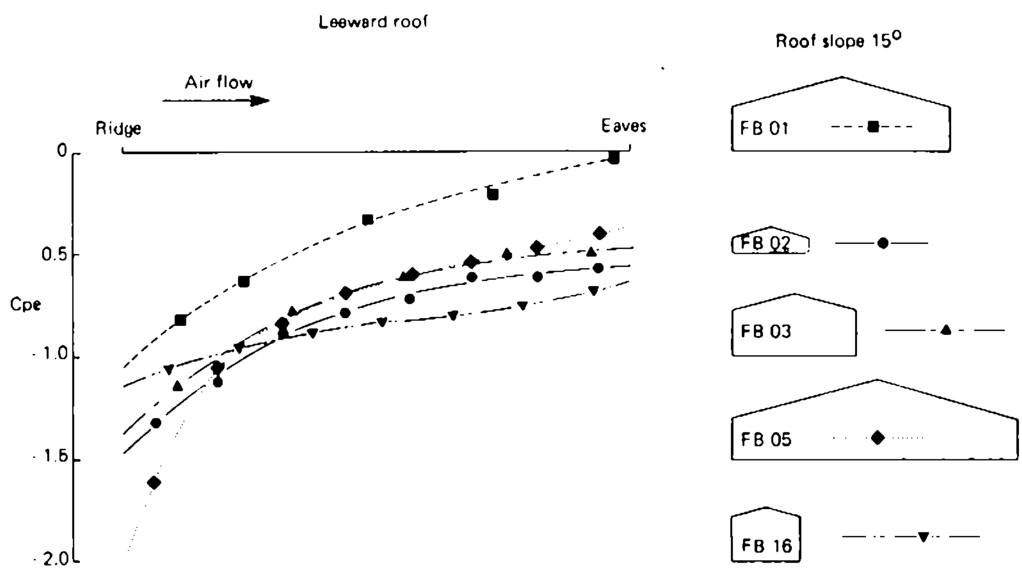

Fig. 2. Pressure distribution on the leeward roof for a selection of buildings with a 15° roof slope

Fig. 2 shows a similar distribution and magnitude of the load on the leeward roof for four of the buildings but for unexplained reasons building FB01 is significantly different. Additional measurements have been made on a building similar in shape to FB01 and these pressure measurements have confirmed the distribution shown in Fig. 2 and they are therefore considered to be a result of the building's geometry. Further measurements[14] have shown that pressure distribution is also influenced by roof pitch, scale and building length.

4. Deficiencies of the existing British Standard Code of Practice CP3:Chapter V:Part 2

There has been recent criticism[4,5,6] of the procedures used in CP3:Chapter V:Part 2. Although there are grounds for these criticisms it has been found from full-scale experiments[7] that the procedures are appropriate for the design of framed buildings and the measurements have shown that it is not the procedures of CP3:Chapter V:Part 2 that restrict its application but the detailed information contained within the standard on pressure coefficients that make it unsuitable for the design of many farm buildings.

This is illustrated in Fig. 1. CP3:Chapter V:Part2 limits the geometric parameters that influence the wind load to roof slope and height span ratio but as can be seen in Fig. 1, that with near constant roof slope and height, there is a significant change in wind load associated with span. For the case of farm buildings, where structural design is based on loadings with a safety factor of near unity, these differences are highly significant and simplifying the geometric parameter set to merely roof slope and height span ratio will make efficient design impossible. Figs. 1 and 2 also show that to assume the wind load is uniformly distributed is an imprecise assumption. Fig. 2 shows that a reduction in wind load between the ridge and the eaves can exceed a ratio of 3 to 1.

The lack of agreement between national standards is also a cause for concern. Firstly it demonstrates a lack of understanding and failure to agree on what should be establishable fact and secondly, and parochial to farm buildings, national standards other than the UK national standard can be used for designing farm buildings to satisfy the requirements of grant aid. Although in the example presented in Table 1 the UK code gave lower overall wind loads than the USA and Australian codes this was fortuitous and other national standards can be found which will give lower loadings than the UK code.

5. Concluding remarks

The pressure distributions presented in this report are for measurements made on full-scale closed farm buildings under natural wind conditions. The measurements made on pitched roof buildings show that the geometric parameters of length, eaves height, span and roof pitch all influence the wind load. The existing British Standard Code of Practice CP3:Chapter V:Part 2 simplifies wind load to the geometric parameters of roof slope and height span ratio. For farm building design, where the safety factors are of the order of unity, this in an unacceptable simplification.

The assumption in CP3 that for structural loading the wind load can be considered as uniformly distributed is also excessively simplistic.

In a future revision of CP3 these two deficiencies of the existing procedure should be resolved.

These two deficiencies also limit the use of CP3 in the design of ventilation systems. The enhanced geometric parameter set is necessary to predict the external pressure distribution for vetilation design and the non-uniform pressure distribution is of particular importance in conjunction with the permeablility to predict ventilation characteristics.

At present there is insufficient information to predict the wind loads on low rise buildings. Further measurements are being made on closed buildings to provide additional information of the effect of building geometry on wind load and this will assist in the development of a rationalised standard for use in structural and vetilation design.

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PAPER 5

AERODYNAMIC INTERFERENCE BETWEEN TALL BUILDINGS - WIND TUNNEL INVESTIGATIONS

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Schweizerische Bauzeitung 36 (11), 16 March 1978
(Dedicated to Jakob Ackeret on his 80th birthday)

The aerodynamic processes which influence the lower layers of the atmosphere in the human living space in the form of winds, storms and hurricanes are called non-stationary boundary layer phenomena which, in addition to their spatial structure, also have a time-dependent structure. The latter can be calculated only statistically. Within the spatial movement of air two characteristic properties stand out:

- The intensity (flow rate) increases with increasing distance from the ground while, in general, the degree of turbulence decreases.

- In the immediate vicinity of the ground their nature is decisively influenced by the spatial structure of the surroundings and the consequent pressure distribution (the latter is known as the wind load).

In recent years, as a consequence of the development in high-rise architecture, the cross-sectional dimensions as well as the height of the individual buildings have increased substantially along with the population density. The human living space, particularly in towns, has therefore increased to the extent that greater attention must be paid to aerodynamics, especially when the quality of the biosphere is considered in addition to the safety of buildings. Increased problems have already arisen in this field. The complexity of the movement structure of the air prevents a precise mathematical treatment, whence no generally valid solution has been found to permit a precise prediction of the aerodynamic processes, and therefore of the wind load. In this situation it is obvious that the solutions must be sought by means of experiments on reduced models.

Most nationally established wind pressure standards, which do not show complete agreement, are the result of experimental research. They mostly contain a time average and make it possible to estimate the aerodynamic forces to be expected. Specially to be mentioned are the DIN Standard 1055 and the Standard SIA 160. The latter is very detailed: evidence of its reliability is *inter alia* that it was taken into account in planning the vertical assembly building at Cape Kennedy.

In respect of interference, i.e. the mutual effect of adjacent buildings, the standards give no data.

1. Model Experiments

With the help of the model experiments described below, it is intended to cover the 3-dimensional flow round whole building formations over a wide angular range. Initial work on this theme has been published by Ackeret[1,2]; Egli[2]; Wise, Sexton and Lillywhite[3]; Davenport[4]; and Newberry, Eaton and Mayne[5]. The problem field studied is of great importance for airconditioning or at least for forced ventilation of high buildings. The pressure and consequent velocity distribution round a building complex affect the openings of the air shafts and thus the function of the airconditioning, the heat economy of the building, the dispersion of smoke and, not least, the air movement in the immediate neighbourhood of the buildings and their entrances and thus pedestrian areas and playgrounds. It must not be forgotten that damage to the buildings may also occur as the result of transient local pressure distributions, as has been shown by Thomann[6].

The validation of aerodynamic model research in wind tunnels will not be treated here in detail, but only the work of Truckenbrodt[7]; Haddon[8]; Ackaret and Egli[2]; and Krönke[9]. It was shown in these works that such studies on model scales of 1:250 and even less are quite reliable if great precision is not needed. If one needs greater precision than 5 to 10% and ignores the analogy of the Reynolds number, which is possible with acute angled objects, even smaller free-flow wind tunnels can be used. Thus, under stationary conditions, the velocity and pressure conditions, while not covering all aerodynamic processes, give valuable information for the architect and town planner on, for example, the suitability of building material for light building or on the principle arrangement of buildings in a complex.

The free-flow wind tunnel used in these studies has a rectangular cross-section of 350 x 450 mm which produces the constant and turbulent velocity distribution shown in Figure 1.

The mean, undisturbed air velocity was

$$\bar{v}_\infty = 27.0 \text{ m/s}$$

or about 100 km/h. It is used as a reference for the pressure coefficient C_p.

$$c_p = \frac{p - p_o}{q} = \frac{\Delta p}{q} = \frac{\Delta p}{\frac{\rho}{2} \bar{v}_\infty^2}$$

where p = locally measured static pressure
p_o = atmosphere reference pressure
ρ = air density corresponding to the air condition

To cover the diversity of building calculation, the model which covered a square plate of M x M (M = 62 mm) built of cubic modules could be changed by simple sticking. The unused field was carefully covered. The maximum model height is 3 times the module height, i.e. 186 mm. The Reynolds number for this height is by definition

$$Re_H = \frac{\bar{v}_\infty}{\nu} \cdot H = 360000 \qquad H = 3M$$

where ν = the kinematic viscosity of the air.

The static pressure was measured on each module side at 25 points distributed over height and width (5 x 5) with a precision multi-manometer.

The values of the calculated pressure coefficients C_p are presented 3-dimensionally so that the pressure distribution on a house wall in its projection can always be considered from outside.

2. Basics of Flow Around Bodies

Figure 2a shows qualitatively the stationary flow around two typical forms for high building through a real, i.e. frictional, flow parallel to the ground. The same figure can also be regarded as a short time record of an instantaneous flow. The local flow velocities and pressures in the accelerated influx region, which are related to one another in the energy equation, depend on the displacement intensity of the individual object. The properties of the flow comprise mainly the already defined Reynolds number which gives the ratio of the inertia to the friction forces. If the air conditions and the object remain unchanged, the Reynolds number is proportional to the change of velocity. Although the kinematics in both cases (angular and round columns) appear very similar at first sight, when considered aerodynamically there is a substantial difference. A comparison of the sections Q-Q and R-R in Figure 2b shows that, with a prismatic column, the separation occurs along a sharp edge, whereas with a cylindrical body it occurs along defined envelope lines. The separation point at sharp edges remains essentially independent of the magnitude of the velocity at any point. On the contrary, with rounded envelope surfaces it moves downstream with increasing velocity. The separation point has a decisive effect on the pressure distribution over the surfaces of the body (see Figure 2c) as well as on the vortex structure in the so-called wake. These two factors determine the stationary and time varying resistance of any body immersed in a flow. The constancy of the resistance coefficient c_W with changing Re number for a building with corners is as well accounted for by the unvarying site of the flow separation as the variation of the c_W value for rounded buildings (see Figure 2d).

These considerations show that high buildings which have sharp corners and large flat faces are easier to study aerodynamically with models than those which basically have a more favourable aerodynamic form. Eiffel[10], and Ackeret and Egli[1,2] have shown that, with angled building forms, the Reynolds conditions of the model law

Re model = Re design

for the estimation of stationary loads can be varied over a wide range - a condition which substantially simplifies and reduces the cost of model studies.

3. Pressure Distribution on an Isolated Building with Flow Over the Whole Angular Range

Figure 3 shows the pressure distribution over the roof and outer walls of an isolated tall building of square ground plan with undisturbed horizontal flow in the direction normal to a face. One should note the strong 3-dimensional curvature of the pressure distribution on the input side as well as the upward increasing negative pressure in the wake region. This pressure distribution confirms the mean value recommended by the SIA standard, i.e. $c_p = +0.9$ for the windward face and -0.8 for the roof, namely constant coefficients valid for the entire surfaces. From the pressure distribution it can be seen that the air in the immediate neighbourhood of the building must undergo a change of direction vertically upwards.

Figure 4 shows the undisturbed flow at $\phi = 45^o$ to the side face normal, i.e. in the direction of the long edge. Behind these edges are marked over-pressures of $c_p = +0.8$ which decrease over the two building faces to the downstream corners almost linearly to the undisturbed ambient pressure. Behind these edges over the lee faces underpressures of about $c_p = -0.7$ are generated: the SIA standard recommends $c_p = -1.0$ and thus takes account of pressure variations due to turbulence. The pressure distribution over the roof is asymmetric and shows a turbulence system like the spread delta wing on the suction side. The asymmetry can be attributed to the turbulence distribution. Kramer and Gerhardt[11] treat this type of flow in detail.

When there is no predominant wind direction, local pressure measurements over the whole angular range can be used by the planner. By means of a polar diagram (see Figure 5), local extreme values can be estimated.

Such extreme values can be used for estimation of the strength and choice of insulating material for windows. The polar diagram in Figure 5 was recorded in fifths of the total model height (H = 186 mm). In the diagram, for the sake of clarity, only three curves are shown. The missing curves, right of centre, can be easily reproduced by reflection at the axis of symmetry 0^o-180^o.

4. Interference Between High Buildings of Unequal Height

For this series of experiments two models were used, indicated as building 1 and building 2. With the same square ground plan M x M, the corresponding heights were H_I = 3M and H_{II} = 2M. The distance between the parallel models was basically 'M', i.e. 1 module length.

The flow on both buildings was from behind in the direction of the face normals. The pressure distribution round both buildings shows on the side faces C and D a similar pattern to that of the individual building, but the shorter building experiences about 50% greater load than the taller. The pressure gradient at the side C is surprisingly high where there is a pressure coefficient of $c_p = -1.0$ at the front corner. This value is about 40% higher than that of the SIA standard for an isolated building and for one such is confirmed by Figure 3.

Of special interest for this configuration is the question of what influence a change in the building distance has on the pressure distribution. Figure 7 shows quantitatively the pressure amplitudes measured in three horizontal planes 1, 2 and 3 for five points at any given time for different d/b ratios. The diagram shows areas of local pressure fluctuation measured on the model. This could, without claim to great precision, simply show the danger of local oscillations due to wind forces with variation of the building distance. In interpreting the measurements, it must not be forgotten that non-stationary processes of this kind occur more rapidly in the model than with full scale buildings.

Figure 8 shows the pressure distribution round buildings I and II with free flow at $\alpha = 45^{0}$. The load on the roof F is surprisingly high which, for reasons of clarity, is shown rotated 90^{0} about its vertical axis. The highest measured local pressure coefficient on this surface is $c_p = -1.8$. The value is substantially greater than in Figure 4 for an isolated building. The particularly unfavourable alternating load on side C is attributable to the effect of the high edges between the faces E and D. They form the points of separation.

Figures 9 and 10 show the pressure distribution at buildings I and II in row formation, where the free flow occurs along the line of the buildings. This arrangement should help to clarify the effect of wind shadow on the pressure pattern.

In Figure 9 the shorter building is in the wind shadow of the taller and, as expected, exerts almost no effect on the pressure pattern of building I. Conversely, building II is subjected on all sides to underpressure. Face C is most heavily loaded; all other sides show appreciable deloading in comparison with an isolated building.

Figure 10 shows the reversed sequence of Figure 9. The shorter building II proves to be a source of disturbance in front of the taller building I. It can be described as a wind shadow effect only with reservation. The sign of alternating load on the adjacent sides C and D is the result of the damming effect of the side C in the upper region. As can be shown by smoke tests, the flow in this region is partly turned downwards whereby an eddy occurs near the ground between the two buildings. The result of this is that positive c_p values are found in the lower region of face D. The variable pressure distribution, which can have a psychological effect, does not exceed the values recommended in the SIA standard in any region.

5. Flow Patterns

Because the current theory of building aerodynamics as already indicated by Ackeret can only give a satisfactory quantitative prediction in exceptional circumstances, in future model experiments will have to be used more and more. Flow patterns give a precise picture of the processes which, in addition to identifying the problem, can often contribute to its solution. Above all, it must be assumed that they are recorded with adequately high Reynolds numbers and with suitable techniques for making the flow visible.

Figures 11 to 15 show boundary structures close to the ground which occur with various configurations of three tall buildings - the building complex. The flow of the buildings in all the figures is left to right, the light points mark the dead zones. Zones with reduced and increased flow velocities are easily seen as well as traces of eddies. The disturbed flows are surprisingly wide close to the ground compared with the dimensions of the buildings.

6. Summary

The experiments described are intended to give specialists in the building sector a deeper insight into all aerodynamic processes where lack of knowledge often leads to damage. In order briefly to achieve an aim, simple means are used. Since it was found from the start that not all details of the model could be transferred to full scale, initially the efficiency of better corresponding wind profile is omitted. The process is validated and, provided with proper signs, the magnitude of the wind load is given and specially endangered areas indicated, i.e. latent dangers are predicted and damage is avoided.

7. Conclusions

Building aerodynamics covers, as before, a field with many unsolved problems. Although the first scientific measurements by Eiffel[10] before the turn of the century are available and the objective of aerodynamics at that time was quite clear, in comparison with other branches of science in this area little was done. It seems to me apt at this point to remember how Ackeret indicated in 1965

- since there is almost no co-operative work, work is often duplicated.

- a centre for wind pressure research should be created, possibly in Europe.

- the badly neglected field of meteorological storm aerodynamics must be attended to and a damage inspectorate set up and mutual exchange of experience organised.

- further work will have to be mainly experimental.

In this connection special mention must be made of work done in Austria. In addition to the construction of a wind tunnel for building aerodynamic studies.

It is desirable that in the future, in addition to accident investigations, aimed and co-ordinated basic research and development of building aerodynamics in the widest sense should begin. To this category also belongs the problems of remote heating plant, heat-power stations, cooling towers, flue gas dispersion from waste burning plant, etc. Town planners, architects and building engineers require further consideration of the nature of the SIA standards. These should no longer be drawn up by established institutions but their aim is now another form of aerodynamics. It has been found that,not only from the scientific point of view, building aerodynamics is exciting but is no longer an ignorable constituent of environmentally correct and careful building. This seems completely justified when it is considered that wind damage to buildings is exceeded only by the fortunately rare floods and earthquakes.

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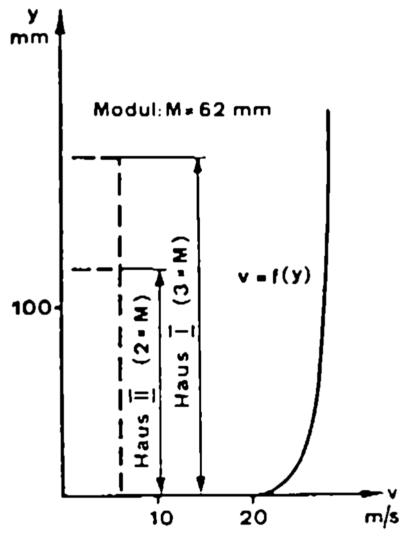

Fig.1 Velocity profile

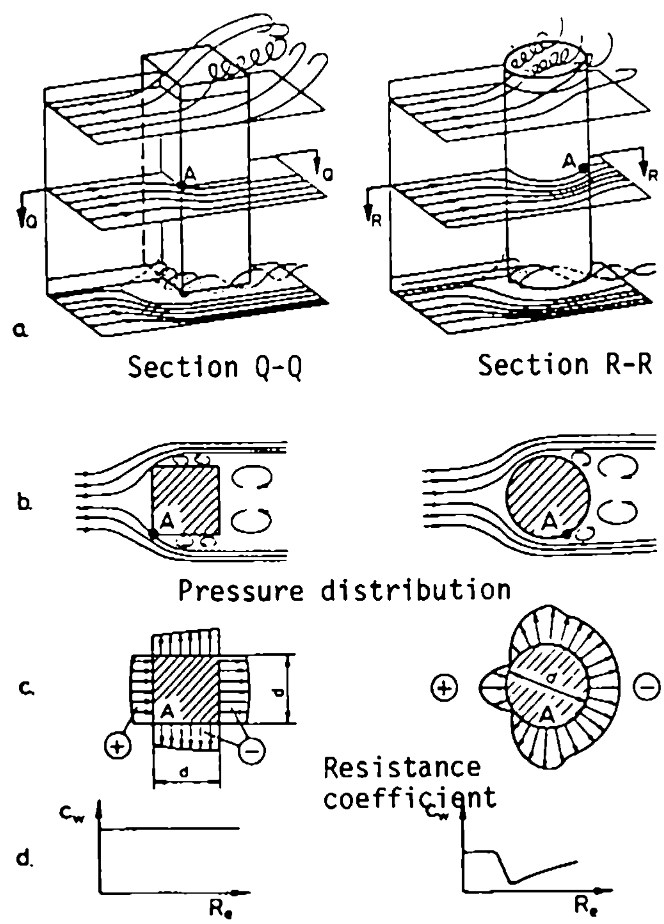

Fig.2 Flow around bodies

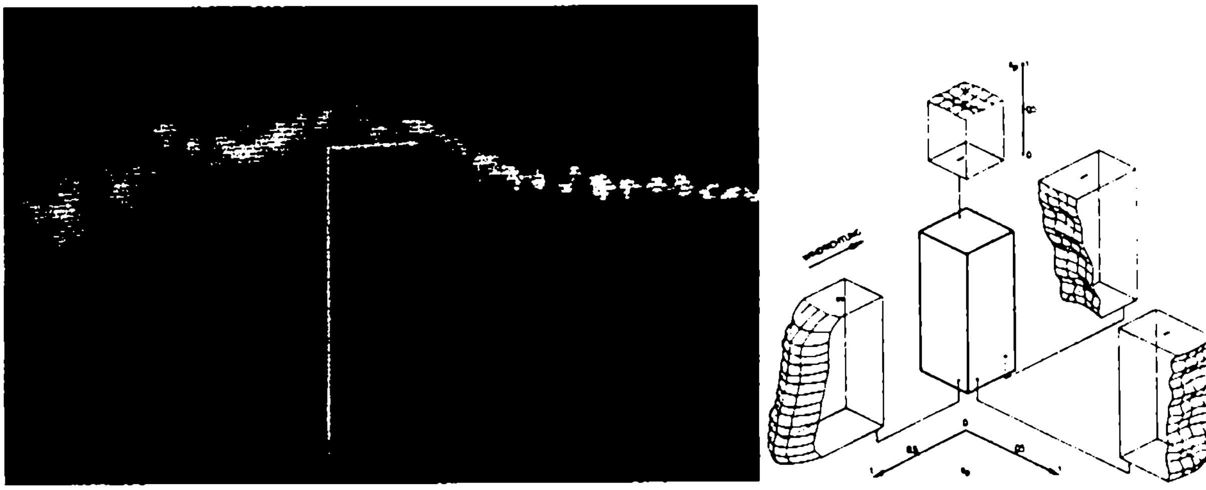

Fig.3 Isolated tall buildings - wind normal to face

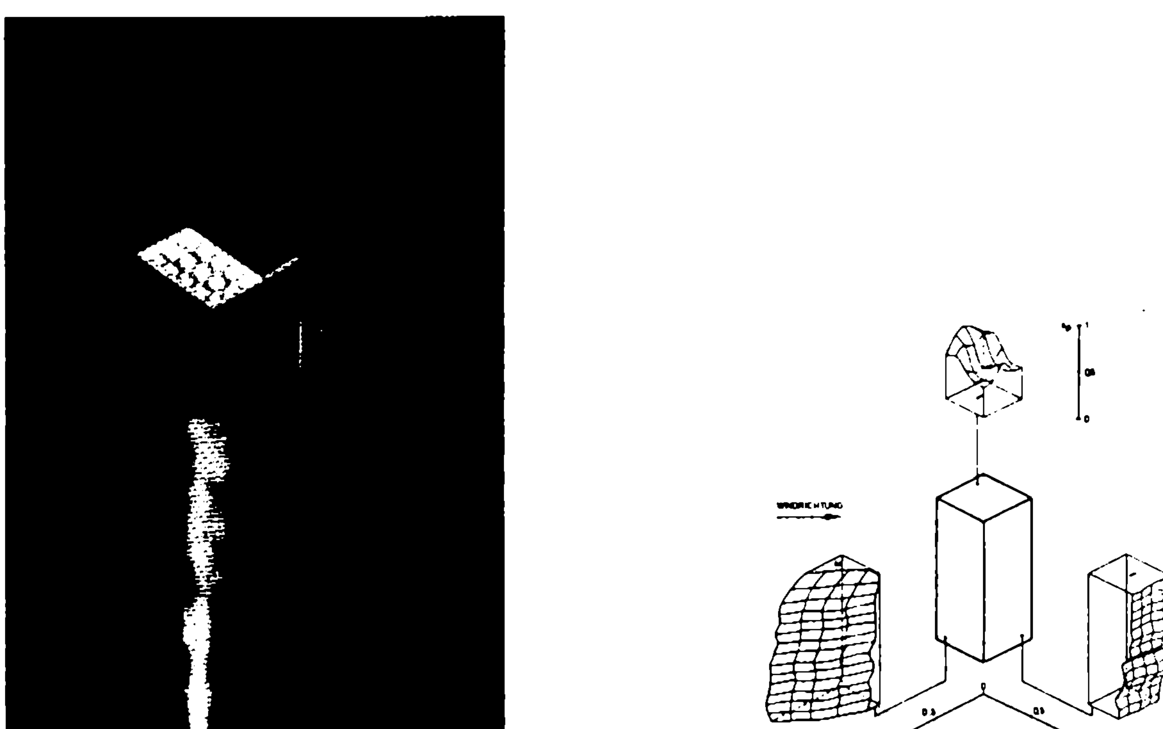

Fig.4 Isolated tall buildings - wind incident to corner

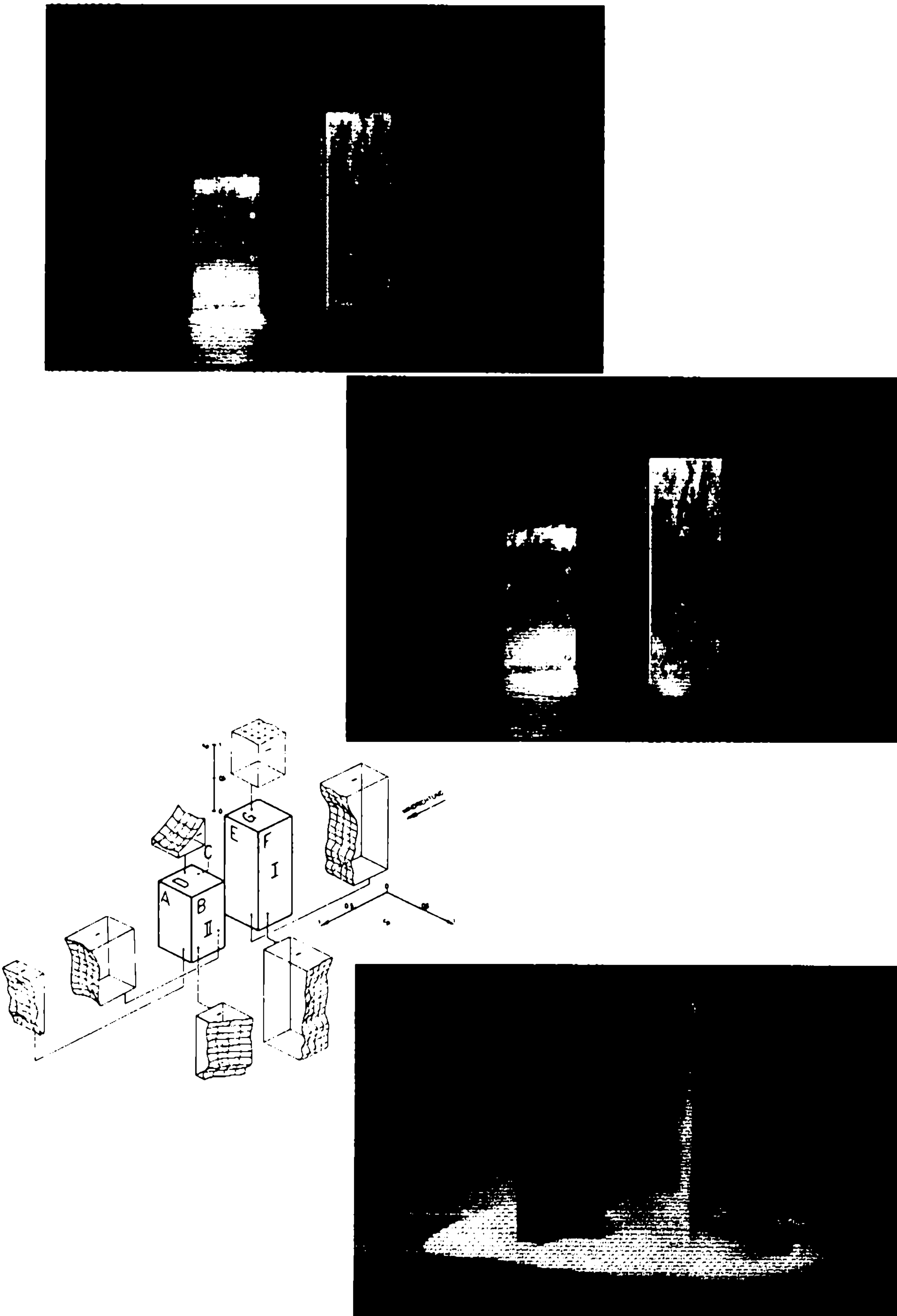

Fig. 9 Wind shelter effect of tall buildings in row formation - taller building upwind

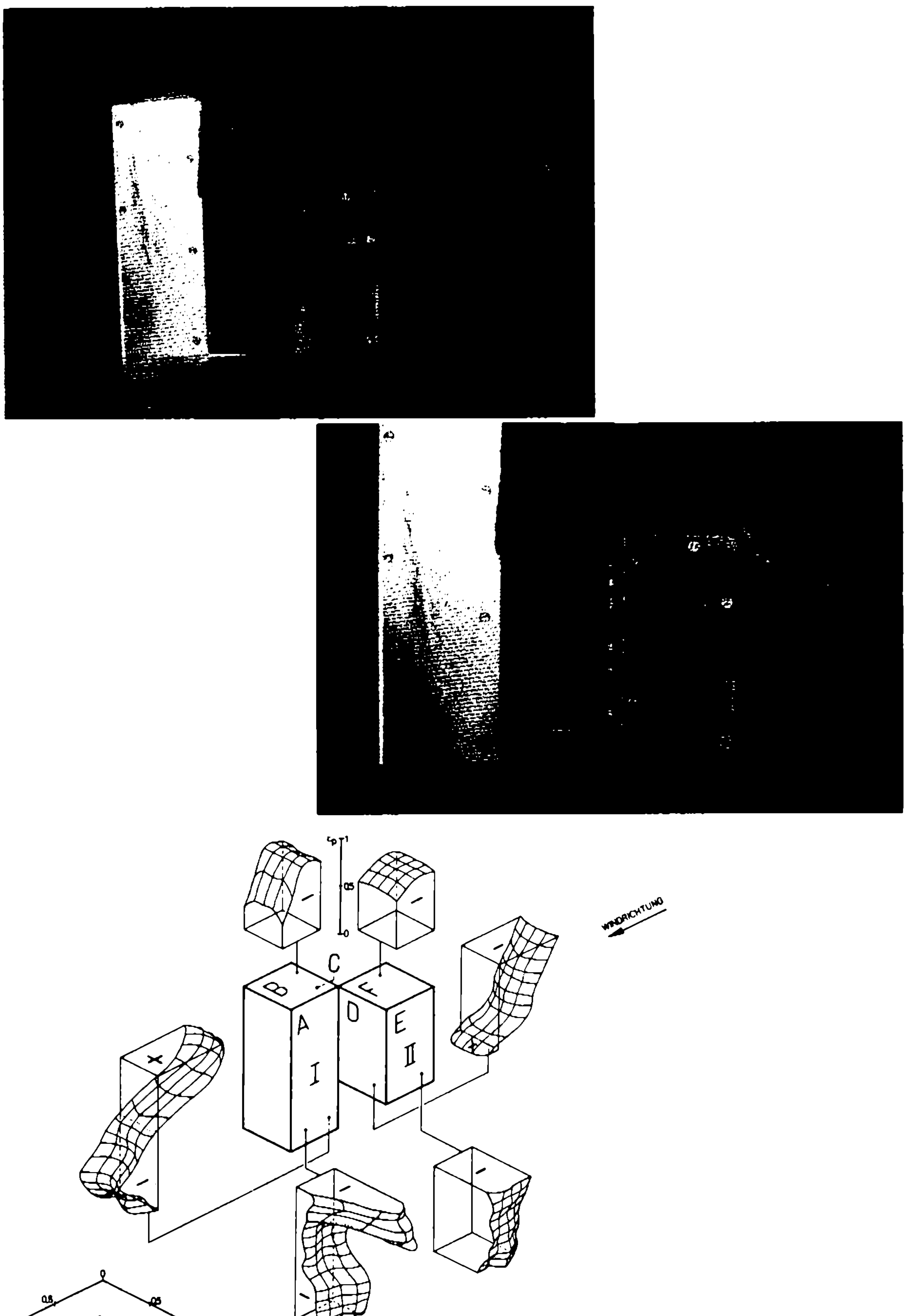

Fig. 10 Wind shelter effect of tall buildings in row formation - taller building downwind.

Fig. 11

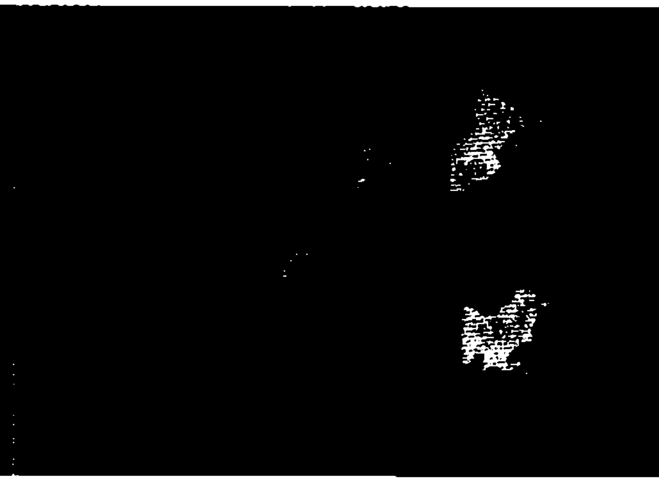

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Figs. 11 to 15 Structure of the boundary layer in the immediate vicinity of the ground for complex building arrays.

AIR INFILTRATION CENTRE - WIND PRESSURE WORKSHOP
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PAPER 6

WIND PRESSURE DISTRIBUTIONS AND VENTILATION LOSSES FOR A SINGLE-FAMILY HOUSE AS INFLUENCED BY SURROUNDING BUILDINGS - A WIND TUNNEL STUDY

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WIND-PRESSURE DISTRIBUTIONS AND VENTILATION LOSSES FOR A SINGLE-FAMILY HOUSE AS INFLUENCED BY SURROUNDING BUILDINGS - A WIND TUNNEL STUDY

SUMMARY

This paper describes a wind tunnel investigation of wind pressure distributions over a 1:100 scale model of a detached, 1½ storey single-family house surrounded by identical houses in various regular arrays. Time-mean pressures were measured at 122 locations on the walls and roof of the model at wind angles between 0° and 90°.

Pressure coefficients obtained from the tests have been used for the calculation of wind induced ventilation rates and associated heat losses from a full-scale house for a range of wind speeds, u, and indoor - outdoor temperature differences, ΔT. The air leakage area is assumed to be uniformly distributed over the building envelope.

To characterize a specific array of buildings with respect to its wind sheltering effect on the test house a heat-loss reduction factor is introduced which is shown to be a function of a densimetric Froude number based on u, ΔT and h_T, the height above ground of the neutral thermal level.

LIST OF SYMBOLS

A_l	area of leakage openings in test house surfaces	m^2
a, b	distance between buildings, def. in Fig 4.	m
c	specific heat of air	kJ/kgK
c_p	local time-mean pressure coefficient $c_p = (p - p_o)/q_o$	
$c_{p_{av}}$	mean-pressure coefficient, averaged over building surface	
f	frequency of longitudinal velocity fluctuations	Hz
Fr	densimetric Froude number, $Fr = u_o^2 \cdot T_e/g \cdot h_T \cdot \Delta T$	
g	acceleration of gravity	m/s^2
h	height of test house	m
h_T	reference height for Froude number, $h_T = 2\ z_T$	m
I	air infiltration rate	m^3/s
l	length of test house	m
n	air change rate, $n = 2.6 \cdot 10^3 \cdot I/V$	1/h
p	local static pressure on model surface	Pa
p_o	static free-stream pressure	Pa
q_o	dynamic free-stream pressure at height z = h	Pa
Q	heat loss due to natural ventilation (subscripts: e = exposed position, s = sheltered position)	kWh/day
ΔQ	reduction of heat loss, $\Delta Q = Q_e - Q_s$	kWh/day
r_Q	heat loss reduction factor, $r_Q = \Delta Q/Q_e$	
S(f)	power spectral density of longitudinal velocity fluctuations	m^2/s
T	air temperature (subscripts: e = external, i = internal)	K
ΔT	temperature difference, $\Delta T = T_i - T_e$	K
u_o	mean wind velocity at z = h	m/s
u'	longitudinal velocity fluctuations	m/s
V	internal volume of test house	m^3
z	height above ground	m

z_T	height of neutral thermal level	m
β	wind angle, def. in Fig 4	degrees
γ	exponent, def on p. 7	
δ	height of model boundary layer	m
ρ	density of air	kg/m^3

1. INTRODUCTION

In cold or temperate zones the heat loss resulting from natural ventilation is an important factor in the energy balance of buildings. As energy conservation becomes increasingly important, advanced calculation models for predicting the ventilation losses are being developed. For these calculations an accurate knowledge of the wind pressure distributions over the building surfaces is required. However, most of the available wind pressure data refer to isolated buildings fully exposed to wind from all directions which is a situation rarely encountered in practice. Wind sheltering effects on the pressure distribution over a building have been studied only for;

i) a two storey town house behind either a similar house, a fence or a tree belt, [1],

ii) a two-storey detached house behind single, double and triple rows of trees, [2], and

iii) a cuboid model located at the centre of an array of identical models, [3, 4].

The purpose of the wind tunnel study presented in this paper is to provide wind pressure data for a detached single-family house which is part of a group of similar houses. The house chosen for the tests is of a type that is becoming very common in Sweden. Although the patterns of the investigated building groups are of a schematic character they are typical for site plans in many recently developed areas.

The measured wind pressures have been used as input data in an analytical model for the calculation of air change rates and corresponding heat losses for a full scale house as influenced by the surrounding buildings. The calculation model is based in principle on the following relation between the infiltration rate, I, and the pressure difference, Δp, acting across any opening,

$$I = c \cdot \Delta p^{0.5}$$

The coefficient c, which is a measure of the effective leakage area, has been taken from results of field measurements on a large number of Swedish single-family houses.

It is hoped that the data obtained from this study will not only help to predict more accurately the ventilation losses from buildings situated within a group of similar buildings, but also to provide a basis for the planner's choice between alternative building groupings to minimize wind-related energy losses.

2. EXPERIMENTAL FACILITIES AND PROCEDURE

2.1 The wind tunnel

The wind tunnel used for the investigation is of the closed-return type with a total length of 28 m, a test section 3 m wide, 1.5 m high and 11 m long and a maximum wind speed of 23 m/s. The models were mounted on a 2.8 m dia turntable with its center located 8.5 m downstream of the entrance to the test section, see Fig 1.

An atmospheric boundary layer over flat, open terrain was simulated by means of spires at the upstream end of test section and a 7 m fetch of floor roughness, consisting of 40 mm and 70 mm cubes in a regular array with a density of 10%. The mean velocity and turbulence intensity profiles of the flow at the centre of the turntable are shown in Fig 2. The boundary layer height, δ, was 1.0 m .

2.2 The models

The building models were 1:100 scale models of a typical Swedish single-family house with dimensions as shown in Fig 3. The instrumented model was made of 3 mm plexiglass with 122 pressure taps (diameter 0.5 mm) distributed over the walls and the roof while the identical surrounding models were made of solid wood. To facilitate the calculation of wind-induced air flow rates into and out of the building, the locations of the pressure taps were chosen so that the measured pressure values could be taken to represent averages over equal-sized areas on each of the building surfaces, excepting the upper part of the gable walls.

The model configurations investigated are shown in Fig 4. They were chosen so as to allow an estimate of the total ventilation loss from all the buildings in a group by combining results for the test house in different building groupings.

2.3 Instrumentation and test procedure

The pressure taps in the model surface were connected by plastic tubes to a 48-port Scanivalve with a Druck PDCR 22 pressure transducer via pneumatically operated clamps and a manifold tube device which makes it possible to measure up to 400 pressures in one model set-up. A MINC-11 computer was used for the calculation of time-mean pressures and corresponding local c_p-values and also to control the opening and closing of the tube clamps as well as the rotation of the turntable between test runs.

The time-mean pressures were determined by averaging instantaneous pressure values sampled with a frequency of 10 Hz over a period of 15 seconds.

The dynamic pressure at roof top level was used as reference pressure for the pressure coefficients. It was measured at the location of the test model - with no models mounted on the turntable - and calibrated against the dynamic freestream pressure measured by a pitot-static tube placed 1.25 m above the centre of the turntable. This tube was also used for the measurement of the static (reference) freestream pressure.

3. TEST RESULTS

The results obtained from the pressure measurements are exemplified in this paper by:

a) horizontal and vertical c_p-distributions over the test house, and

b) average c_p-values for all the model surfaces as well as c_p-differences between the windward and leeward facade walls as functions of the wind angle.

The examples are chosen to illustrate the influence of one or two buildings located at various distances upwind of the test house and of the density and extension of a group of buildings surrounding the test house.

The effect of a single building at various upwind locations on the c_p-distribution over the test house is illustrated by Fig 5a, in which are included, for comparison, the c_p-distribution over an isolated house as well as the c_p-values given in the National Swedish Building Code, SBN 80. The influence of the upwind building decreases rapidly as the distance between the buildings increases.

The influence of two upwind buildings, placed side by side with a spacing b = 2 l, is small when the wind is blowing at right angles to the front face of the buildings but increases with increasing wind angle up to $\beta \approx 30^o$, as shown in Fig 5b-c. This effect becomes still more pronounced as the spacing between the upwind buildings is reduced.

In a group of buildings with the test house located at the centre of the group, the first row of surrounding buildings causes a considerable change in the magnitude and distribution of the wall pressures on the test house while the effect of adding one or more rows of buildings to the group is relatively small, except at wind angles about 30^o and 60^o. At these wind directions the additional rows block the air stream which would otherwise penetrate the upstream part of the building group.

For a group with a given number of building rows surrounding the test house the spacing between the buildings has a marked influence on the c_p-distribution, Fig 5e.

Some of the effects described above are further illustrated by Fig 6, which shows the influence of the wind angle β on the average c_p-values for the walls and roof of the test house, and by Fig 7, where the average pressure difference, $\Delta c_{p_{av}}$, between the windward and leeward facades is plotted against the wind angle.

The pressure coefficients obtained from the tests have been used for the calculation of wind induced ventilation rates and associated heat losses for a full scale house as influenced by surrounding buildings, wind speed, and external air temperature.

4. HEAT LOSSES DUE TO NATURAL VENTILATION

Pressure differences across the building envelope due to wind and internal-external temperature differences drive air through cracks and interstices in the building surfaces.

In buildings with self-draught ventilation this uncontrolled ventilation results in heat losses which in cold or temperate zones account for a large part of the total energy consumption. The ventilation rates are often considerably higher than needed to ensure safe levels of indoor air quality.

The pressure difference due to wind alone can be expressed as:

$$\Delta p_W = \frac{\rho\, u_o^2}{2} (c_{p_e} - c_{p_i})$$

where c_{p_e} and c_{p_i} denote external and internal pressure coefficients.

The thermal pressure difference caused by an internal-external temperature difference is given by:

$$\Delta p_T = - \rho \cdot g \cdot 273 \cdot (\frac{1}{T_e} - \frac{1}{T_i}) \cdot z$$

which can be approximated by:

$$\Delta p_T = - \rho \cdot g \cdot \frac{\Delta T}{T_i} \cdot z$$

where $\Delta T = T_i - T_e$

The air infiltration rate, I, induced by the total pressure difference over the building envelope can be expressed as:

$$I = f(Re) \cdot \alpha A \cdot \left[\frac{2}{\rho}(\Delta p_W + \Delta p_T)\right]^{0.5} \qquad (1)$$

where Re is an 'average' Reynolds number characterizing the air flow through the leakage openings, α is the relative leakage area and A is the wind-exposed area of the building envelope.

Compared with the equation

$$I = C \cdot \Delta p^{\gamma} \qquad (0.5 \leq \gamma \leq 1)$$

which is commonly used to fit house leakage data obtained from field measurements, Eq (1) has the advantage of being dimensionally homogeneous and it enables a dimensionless infiltration rate

$$I' = \frac{I}{u_o A}$$

to be derived, which is a function of Reynolds number, $Re = u_o h/\nu$, a densimetric Froude number, $Fr = u_o^2 T_e / g\, h_T \Delta T$, the relative leakage area, α, and the pressure coefficients c_{p_e} and c_{p_i}.

The analytical model used for the calculation of air change rates in a full scale house is based on Eq (1). A full description of the calculation model is given in [5].

The house has a floor area of 100 m^2 (ground floor) + 60 m^2 (second floor) and a living space volume of 400 m^3. It is assumed that the air leaks are uniformly distributed over the building envelope, having a relative area $\alpha = 4 \cdot 10^{-4}$, which corresponds to an air change rate of 0.5 h^{-1} at $\Delta T = 20^{\circ}C$ and $u_o = 3$ m/s when the house is situated in a fairly dense group of buildings. The α-value is an average of values obtained from pressurization tests in a number of Swedish single-family houses.

For the calculations it is further assumed that mean flow rates through air leak openings are determined by mean-pressure differences across the building envelope; this assumption is implied in the chosen relationship between flow rate and pressure difference which applies only to steady flow. Effects of external flow turbulence are therefore neglected, which could be a significant source of error in the calculation of air change rates. The simplification might, however, be justified when studying normalized heat loss reductions due to surrounding buildings, where turbulence effects on the building in wind exposed and sheltered position respectively are likely to be of the same order of magnitude.

The internal pressure coefficient, c_{pi}, has been determined by applying, in an iterative process, the equation of continuity on the air flows into and out of the building using 80 of the external c_p-values measured on the wind tunnel model: 42 local c_{pe}-values from the facade walls, 35 from the gable walls and 2 average c_p-values for the roof surfaces.

For comparison, calculations were also made with a simplified model using only 4 average c_p-values, 2 for the combined facade wall-roof surfaces and 2 for the gable walls. The maximum error introduced by this simplification was found to be ±15%. However, for the main part of the cases studied the error is about ±5%, as exemplified in Fig 8. The 4-cell model therefore seems to be accurate enough for practical applications.

The calculated air change rates have been used to determine:

- the resulting heat losses, Q_e and Q_s, from the house in wind-exposed and wind-sheltered positions respectively

$$Q = 6.7 \cdot 10^{-3} \cdot n \cdot V \cdot \rho \cdot c \cdot \Delta T \quad [\text{kWh/days}]$$

- the reduction of heat loss due to surrounding buildings

$$\Delta Q = Q_e - Q_s$$ and

- the normalized heat loss reduction

$$r_Q = \frac{\Delta Q}{Q_e}$$

It should be noted that r_Q is independent of the leakage area of the house, the same α-value being used for the calculation of both Q_e and Q_s.

Examples of heat loss reductions for the test house due to wind shelter from other buildings are given for two series of building groups, with either normal or staggered layout patterns, the spacing between the buildings being a = b = 2 l in both cases.

The order of magnitude of ΔQ, in kWh/day, for the test house in building groups with a normal layout pattern at $\beta = 0^o$ is shown by Fig 9. For this wind direction the reduction caused by the first inner row of surrounding buildings is not increased by the addition of another one or two building rows. At other wind directions the size of the building group has a certain influence on the heat loss reduction as shown in Fig 10a, where the normalized reduction, r_Q, is plotted against the Froude number. The maximum values, r_{Q_m}, occurring at high Fr-values and varying with the wind direction, lies between 0.1 and 0.2. For a denser group, like model conf. D13, the maximum r_Q-value can be as high as 0.4.

For a building group with a staggered layout pattern, r_Q shows a much stronger variation with the number of building rows, except at wind angles about 90^o, as could be expected, Fig 10b.

As evident from Fig 10, r_Q reaches a value close to its maximum value at Fr $\approx$ 5, which holds for all the building groups studied. This Fr-value corresponds to, for example, a wind speed of 3 m/s and an internal-external temperature difference of 11^oC, which represent conditions often met during heating season in temperate zones.

CONCLUDING REMARKS

The wind pressure coefficients needed for the prediction of wind induced air change rates and resulting energy losses are mostly taken from Building Codes, in which the buildings are assumed to be fully exposed to the wind. In practice, a building is often sheltered from the wind, for example by other buildings.

The study presented in this paper has shown:

- that the use of c_p-values which are valid for isolated buildings can lead to considerable overestimates of air change rates and heat losses due to natural ventilation of a house which is part of a group of similar houses.
- that average c_p-values for each one of the building surfaces are sufficient to ensure a fairly accurate prediction of air changes and ventilation losses, provided that the leakage openings can be considered to be uniformly distributed over the building envelope.
- that the density and layout pattern of a building group should be taken into consideration if wind-induced energy losses are to be minimized.

ACKNOWLEDGEMETS

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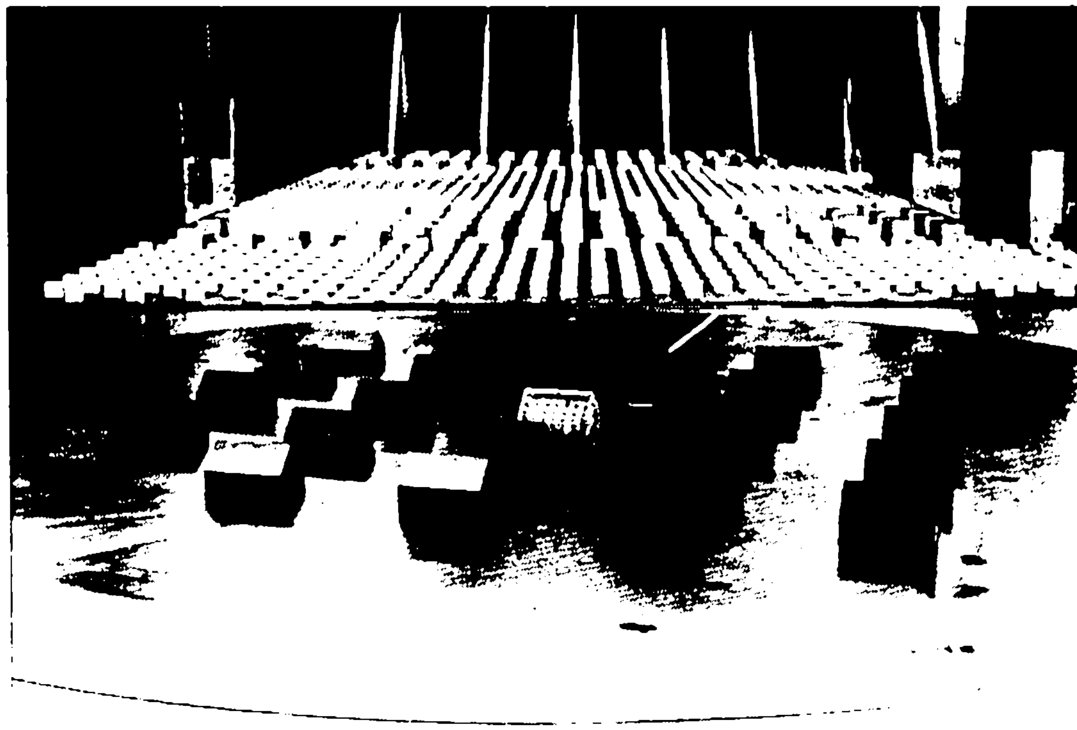


Fig. 1. Models installed in the wind tunnel

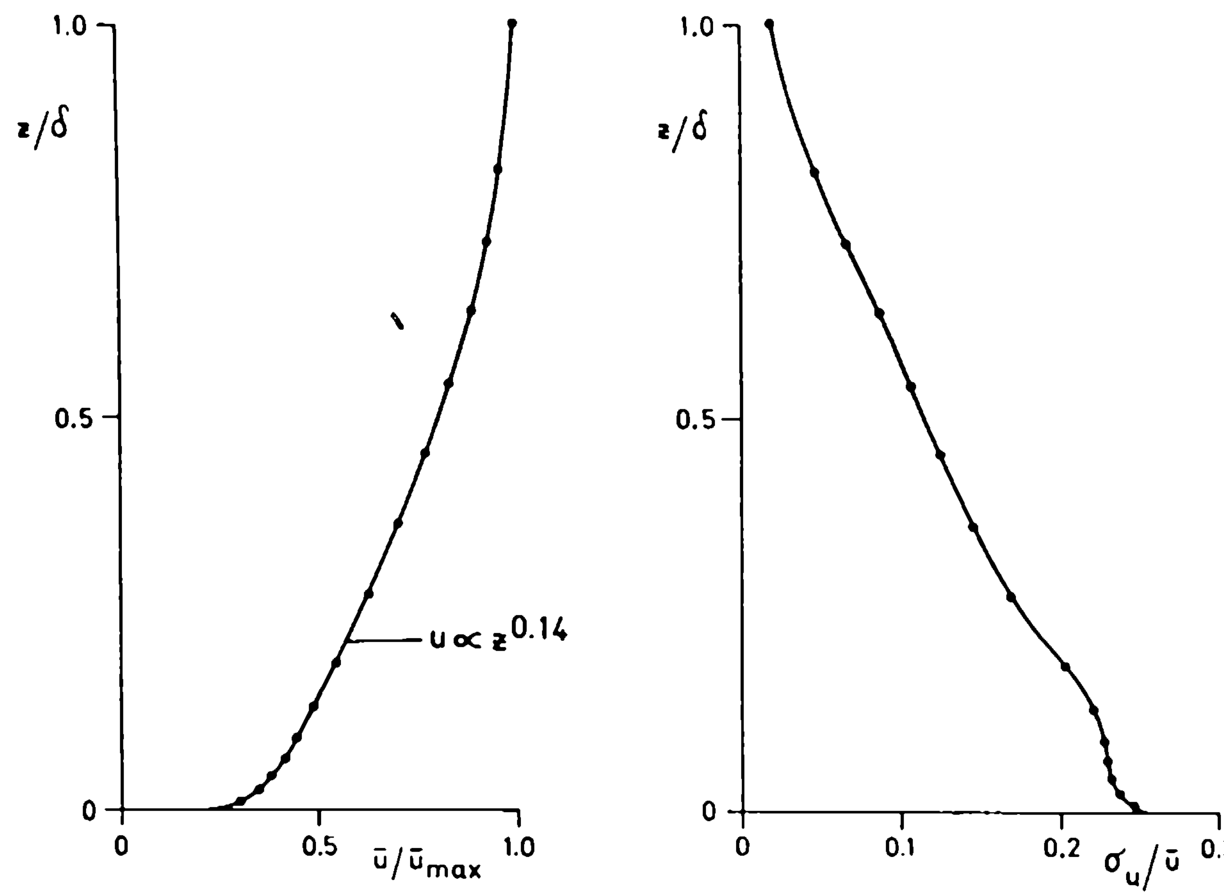
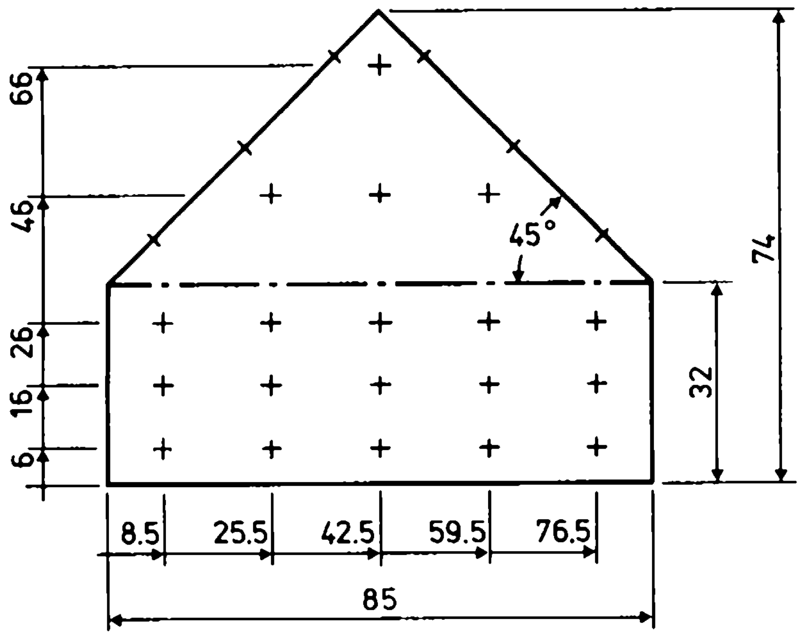


Fig. 2. Mean velocity and turbulence intensity profiles of the model boundary layer flow.



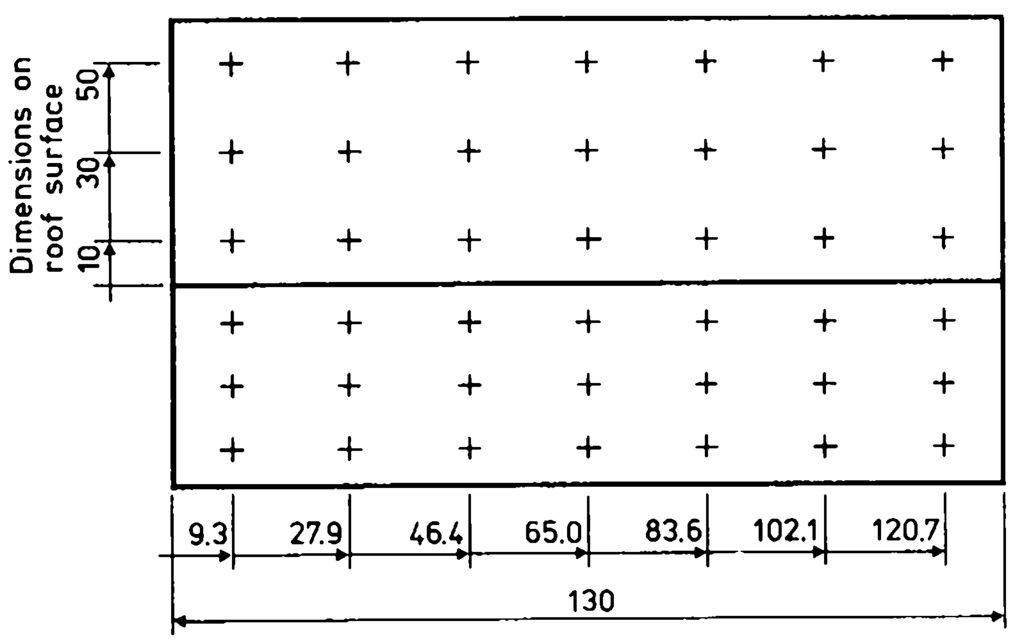


Fig.3 Position of pressure taps on the model

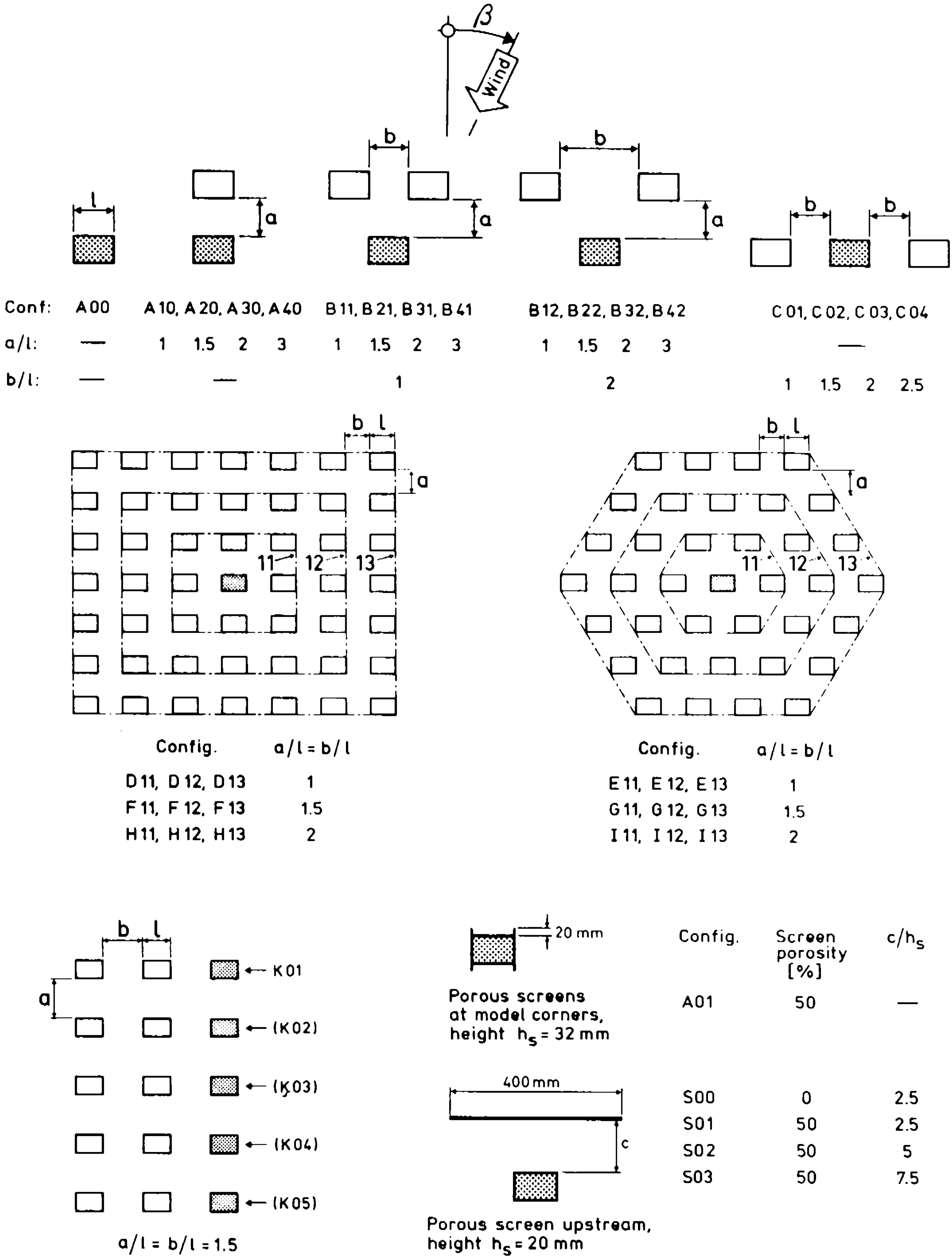
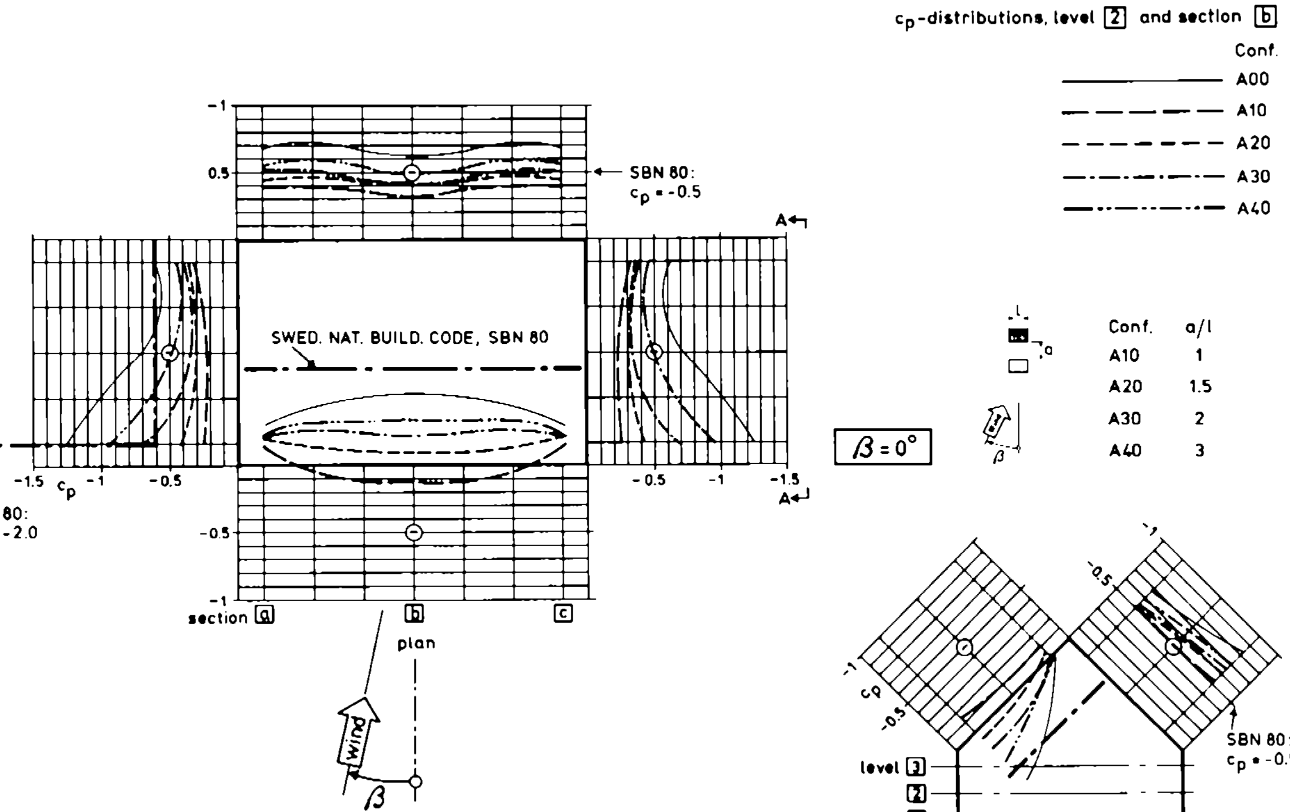
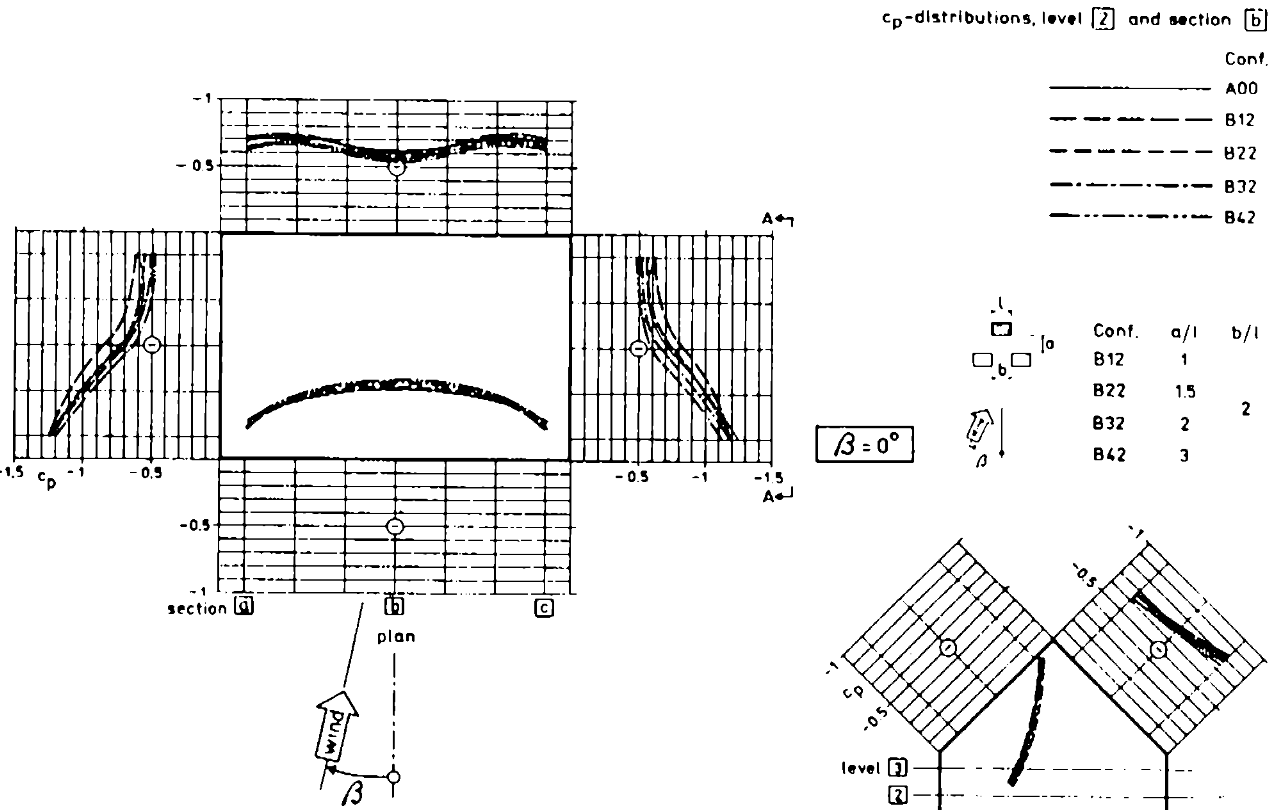


Fig.4 Model configurations investigated

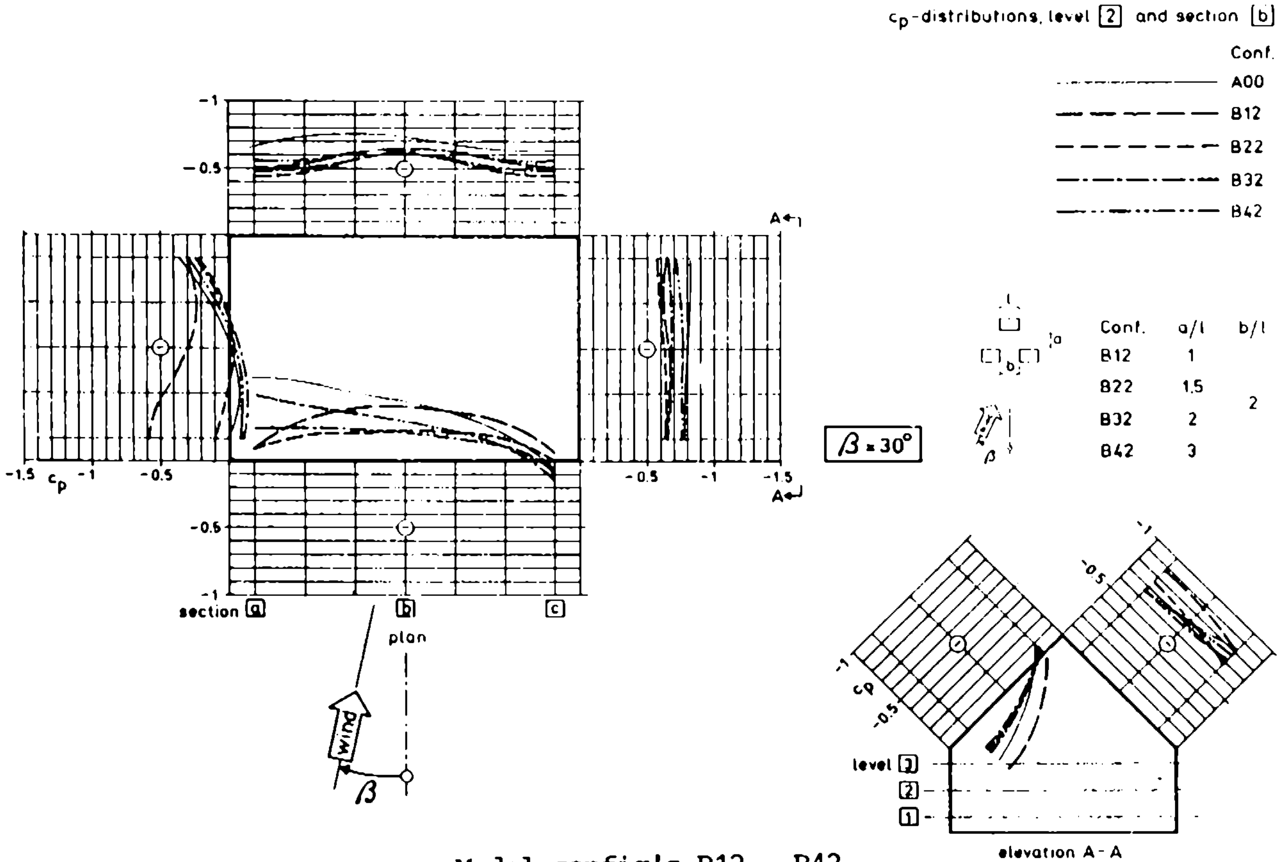


a. Model config's A10 - A40
Wind angle β = 0°

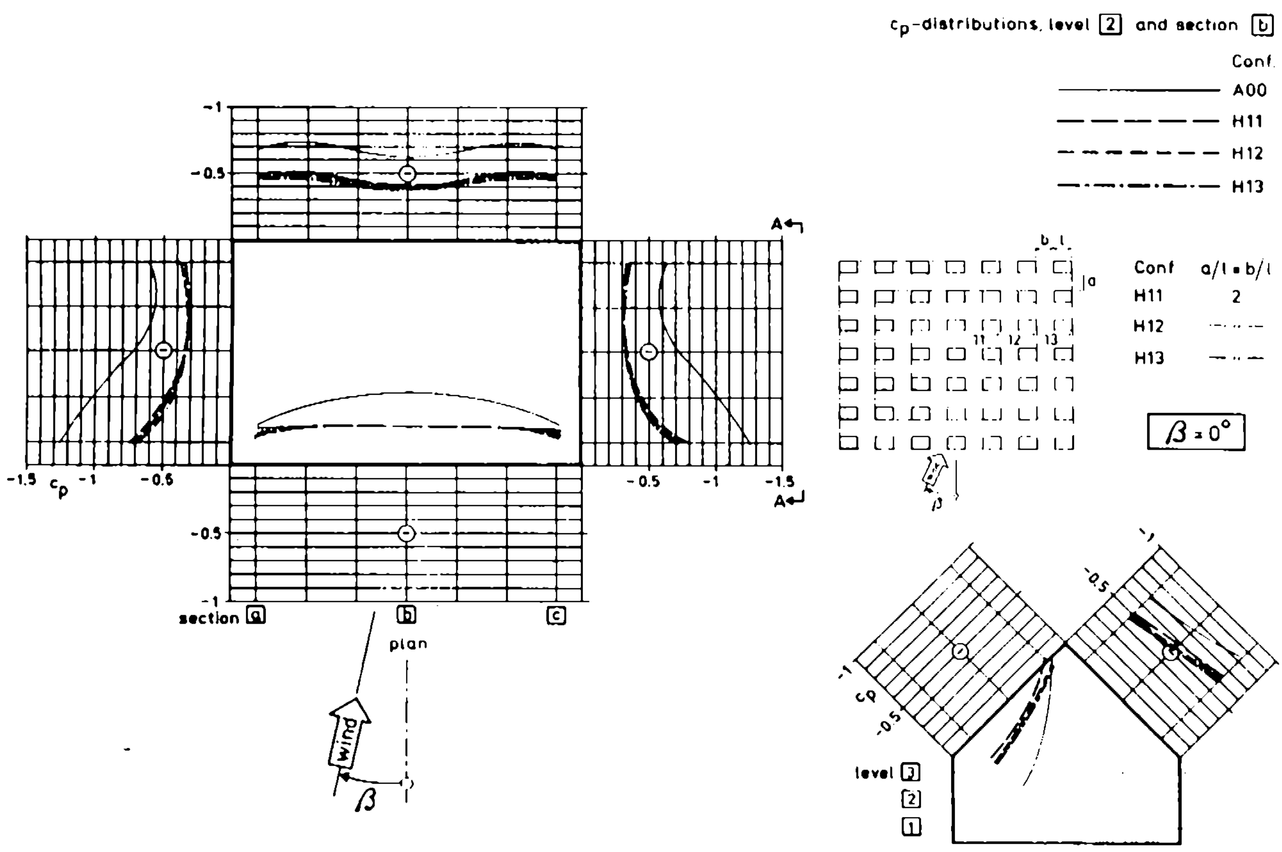


b. Model config's B12 - B42
Wind angle β = 0°

Fig. 5. Mean-pressure distributions over the test house.

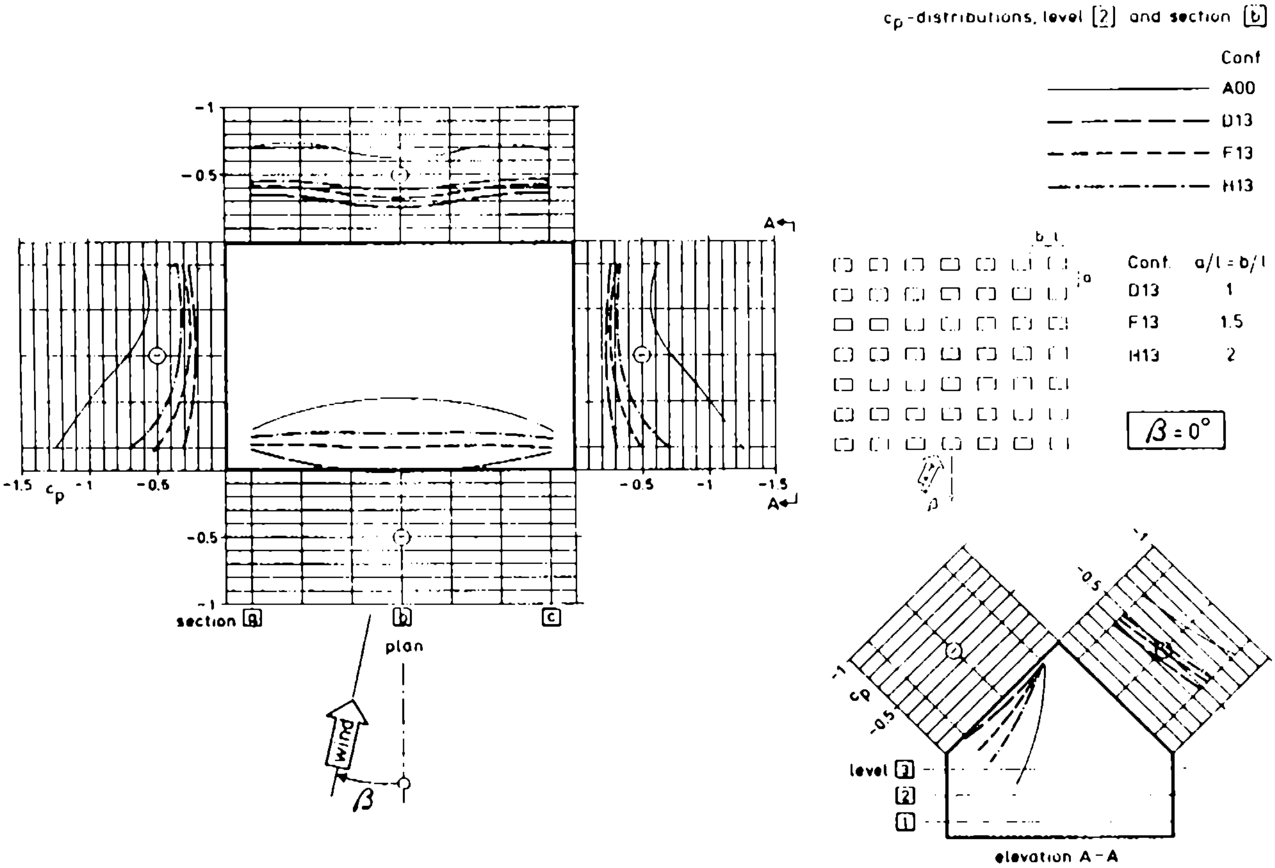


c. Model config's B12 - B42
Wind angle β = 30°



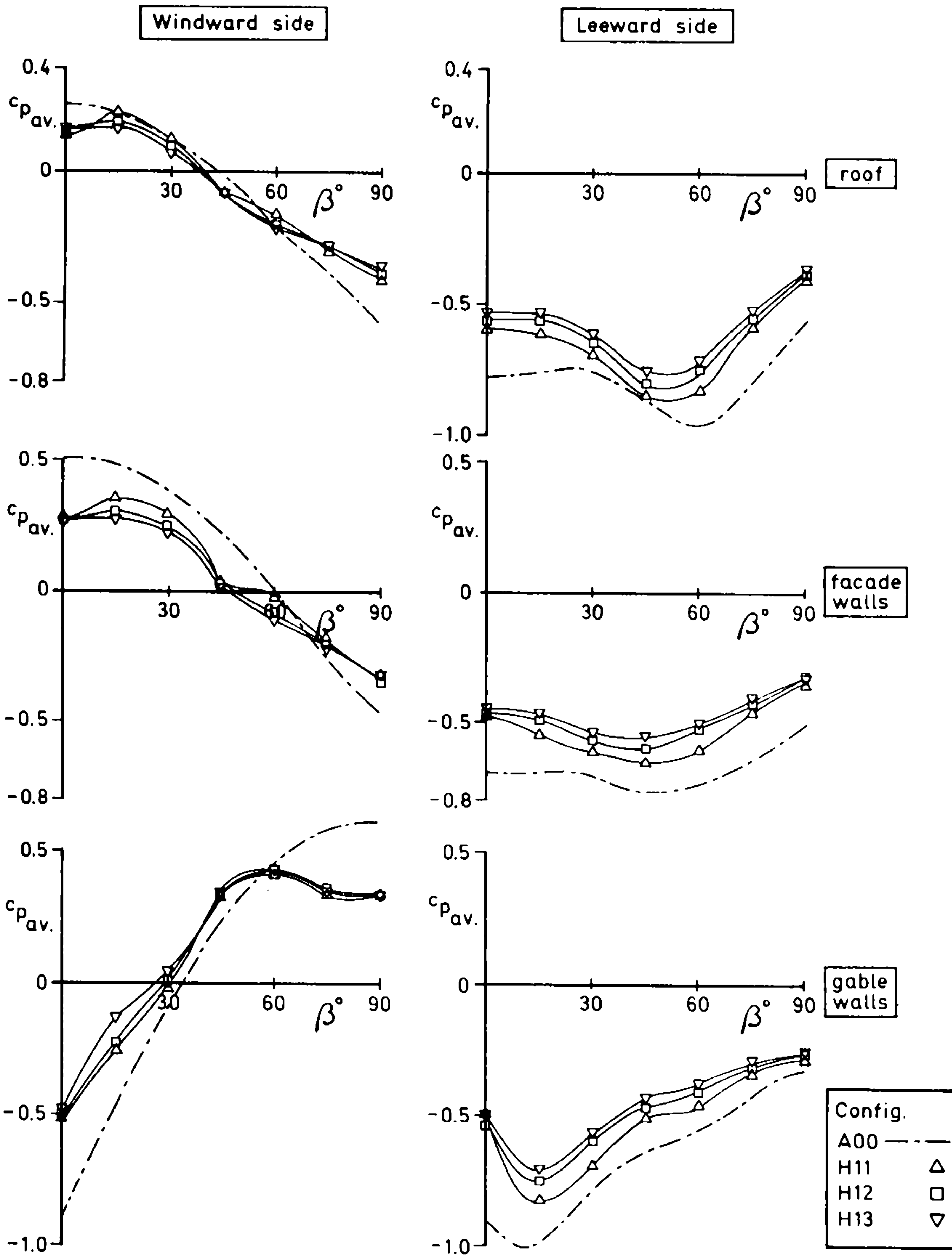
d. Model config's H11 - H13
Wind angle β = 0°

Fig. 5. Cont'd



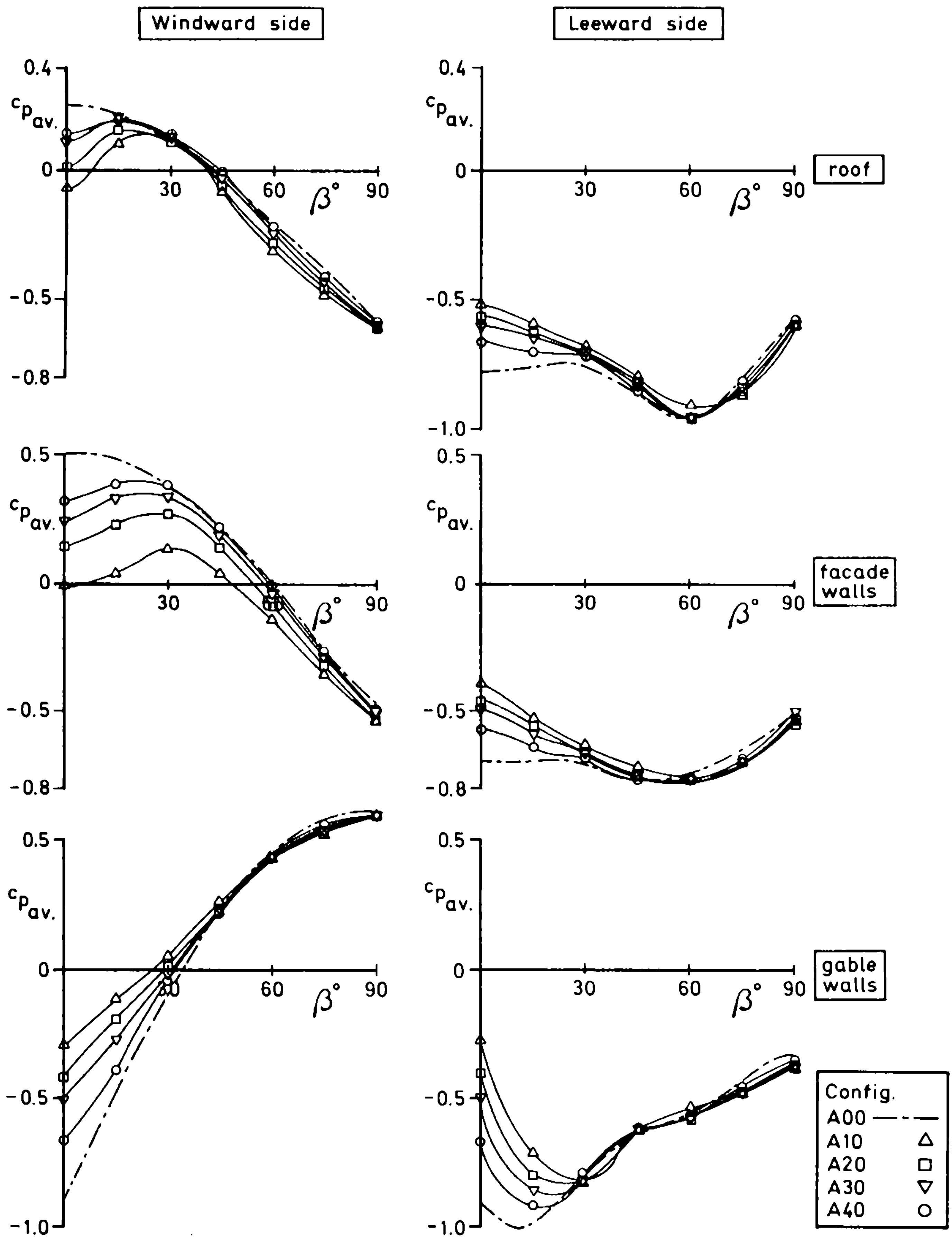
e. Model config's D13, F13 and H13
Wind angle $\beta = 0^{o}$

Fig. 5. Cont'd.



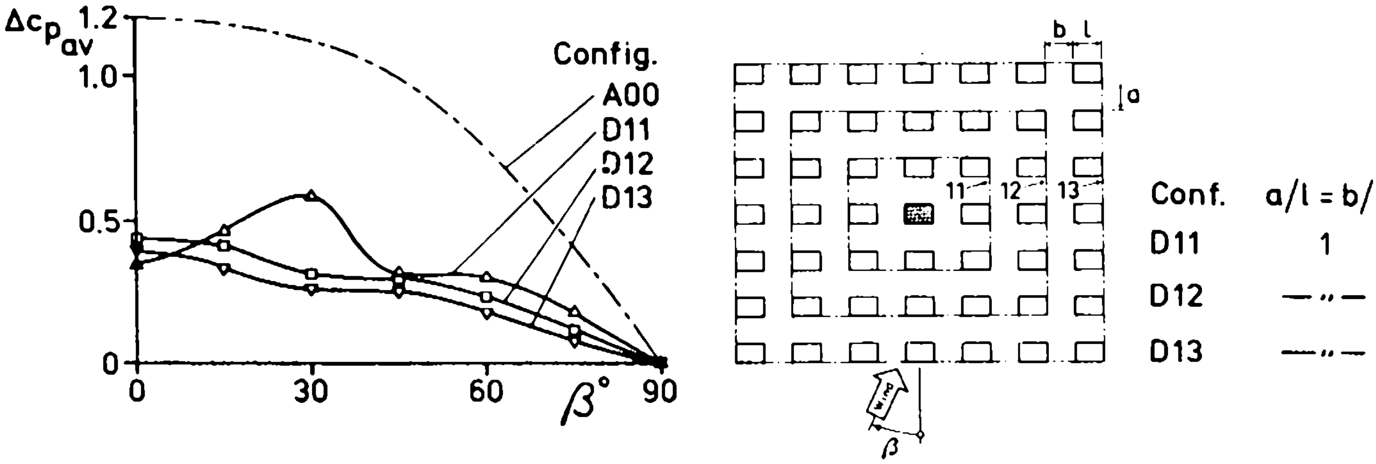
a. Model config's A10 - A40

Fig. 6. Average pressure coefficients for all model surfaces vs wind angle

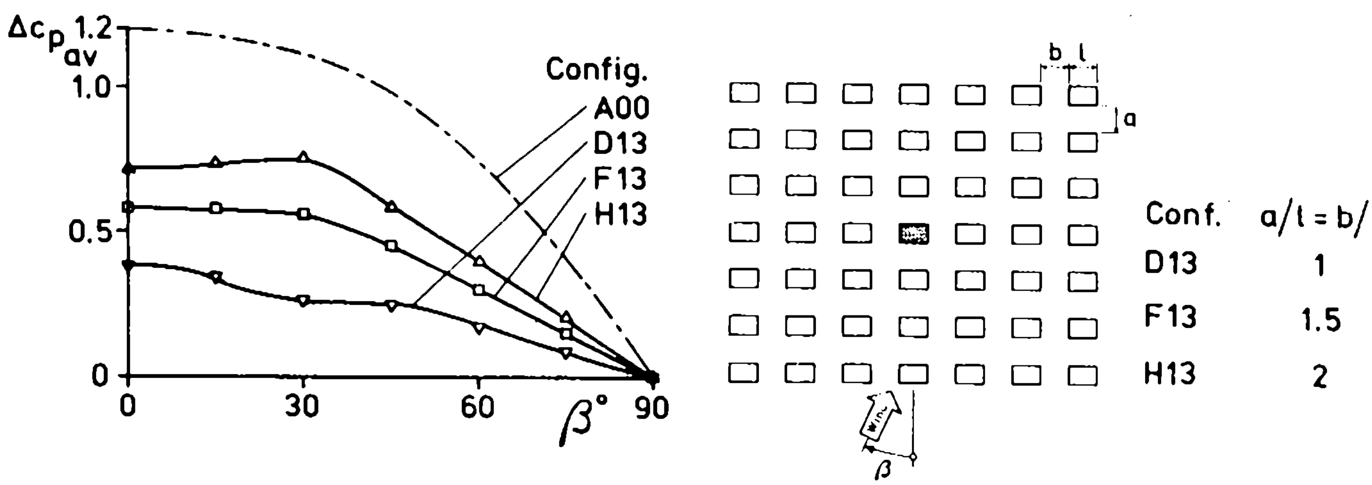


b. Model config's H11 - H13

Fig. 6. Cont'd

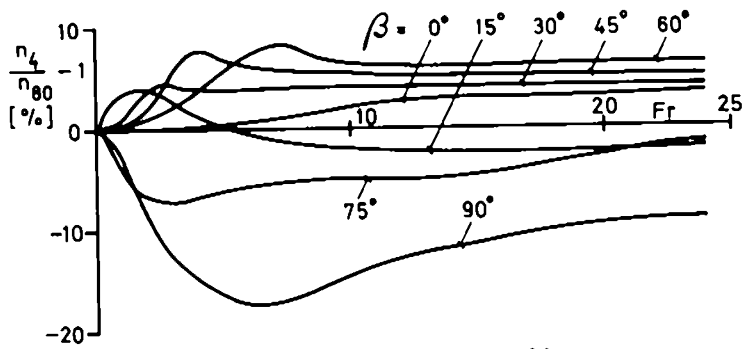


a. Config's D11,D12 and D13

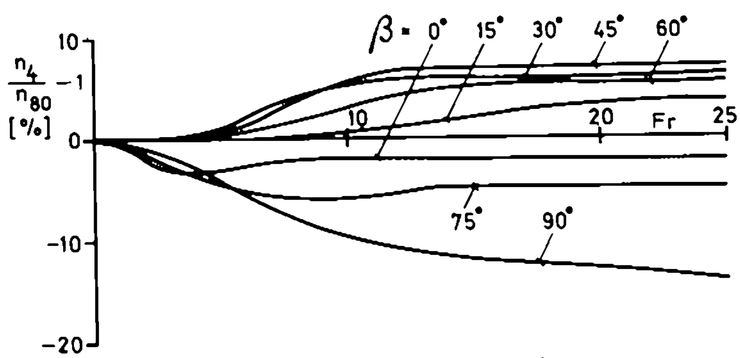


b. Config's D13,F13 and H13

Fig. 7. Influence of surrounding buildings and wind angle on the average pressure difference between windward and leeward facade walls



a. Model configuration A00



b. Model configuration D13

Fig. 8. Percentage error introduced by calculating air change rates with 4 average pressure values instead of 80 local values

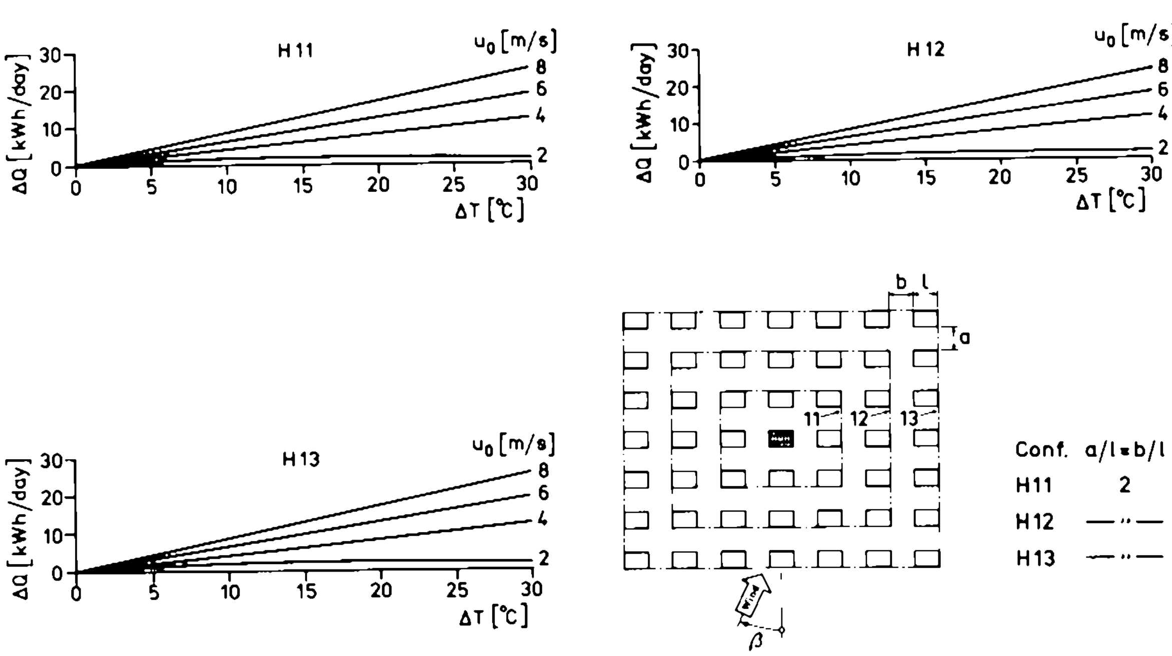
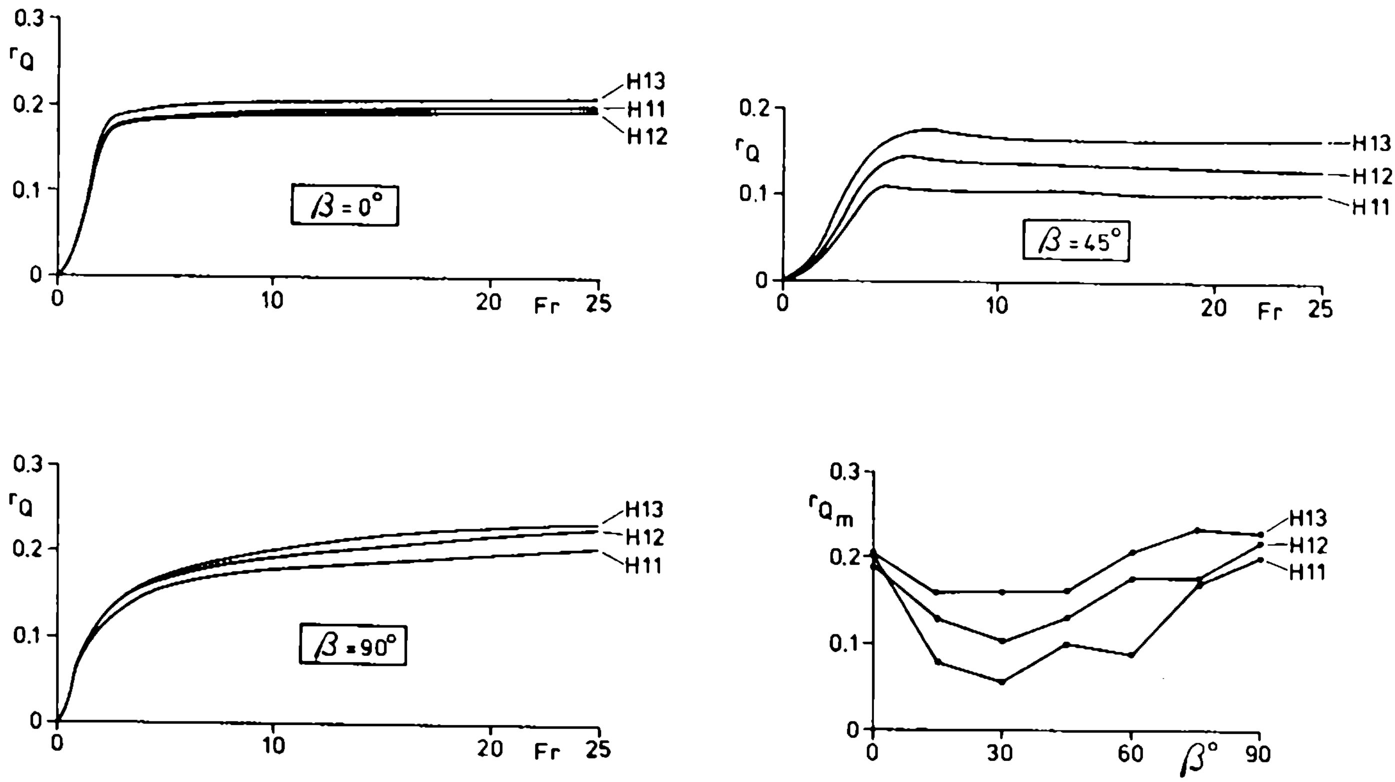
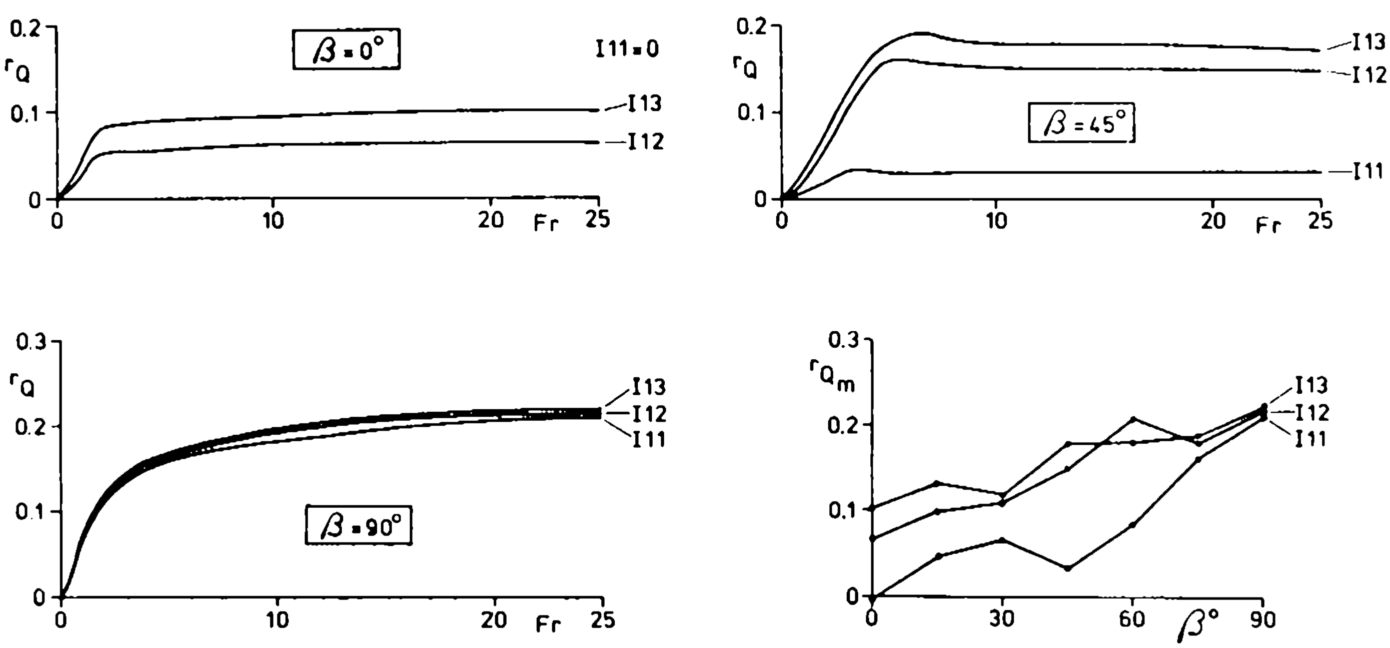


Fig. 9. Reduction of ventilation loss from test house due to surrounding buildings. Wind angle $\beta = 0^{o}$



a. Model config's H11 - H13



b. Model config's I11 - I13

Fig. 10. Normalized reduction of ventilation loss from test house vs Froude number and wind angle

APPENDIX

ON CRACK FLOW EQUATIONS

The analytical model used for the calculation of air change rates is based on the following equation for air flow through a leakage opening

$$u = \sqrt{\frac{d_h}{\ell} \; \frac{1}{\lambda} \; \frac{2\Delta p}{\rho}} \tag{1}$$

where

u	=	mean flow velocity	[m/s]
d_h	=	hydraulic diameter of crack	[m]
ℓ	=	crack length	[m]
λ	=	coefficient of frictional resistance, $\lambda = f(Re)$	-
Δp	=	pressure drop in the flow direction	[Pa]
ρ	=	density of air	[kg/m^3]
Re	=	Reynolds number, $Re = \frac{ud_h}{\upsilon}$	
υ	=	kinematic viscosity of air	[m^2/s]

The coefficient of resistance, λ, varies with the Reynolds number of the flow, and is also influenced by the surface roughness of the pipe (crack), as shown by Fig. 1.

For the different flow regimes, the following empirical relations have been established:

1. Laminar flow, $Re \lesssim 2000$ (Hagen)

$$\lambda = \frac{64}{Re}$$

On substituting the value of λ into eq. (1) we obtain

$$u = \frac{d_h^{\,2}}{32 \cdot \ell \cdot \rho \cdot \upsilon} \cdot \Delta p$$

or

$$q \propto \Delta p$$

2. <u>Critical flow (laminar - turbulent), 2000 $\lesssim$ Re $\lesssim$ 3500</u>

$$\lambda = \frac{3500 - Re}{1500} \cdot \frac{64}{Re} + \frac{Re - 2000}{1500} \cdot \frac{0.32}{R_e^{0.25}}$$

3. <u>Turbulent flow, smooth surface</u> (Blasius)

$$\lambda = \frac{0.32}{R_e^{0.25}}$$

$$u = \text{const} \cdot \frac{d_h^{0.63}}{(\ell \cdot \rho)^{0.5} \cdot \upsilon^{0.13}} \cdot \Delta p^{0.57}$$

$$q \propto \Delta p^{0.57}$$

4. <u>Turbulent flow, transition regime</u>, $k_s/d_h < (k_s/d_h)_{crit}$ (Selander)

$$\lambda = [1.9 \log (10/Re + 0.2\ k_s/d_h)]^{-2}$$

5. <u>Turbulent flow, rough surface</u>, $k_s/d_h > (k_s/d_h)_{crit}$ (Colebrook-White)

$$\frac{1}{\sqrt{\lambda}} = -2 \log \left(\frac{k_s/d_h}{3.71}\right)$$

$$q \propto \Delta p^{0.5}$$

To the frictional losses are added single losses at inlet, bends, and exit which, like the frictional loss in the turbulent, completely rough regime, are proportional to the square of the flow velocity.

Judging from the above, it may seem correct to describe the relation between volume flow rate and pressure difference by an equation of the form

$$q = k \cdot \Delta p^{\beta}, \qquad 0.5 \leq \beta \leq 1, \qquad (2)$$

which is commonly used to fit experimental data from pressurization tests over the whole Δp-interval. However, the value of β, and thus the dimension of k, will then vary with Δp which makes the equation dimensionally inhomogeneous and excludes the presentation of the volume flow rate in a dimensionless form.

In the present calculation of air infiltration rates the analytical model has therefore been based on eq. (1), which gives a leakage function of the form

$$q = f(Re) \cdot \alpha \cdot A \cdot \sqrt{\frac{2\Delta p}{\rho}} \tag{3}$$

where

A = area of building envelope

A_ℓ = effective area of leakage openings

α = leakage area ration, $\alpha = A_\ell/A$

This equation, unlike eq. (2), is physically correct and fits experimental data from pressurization tests if the nondimensional volume rate

$$q/A \cdot \sqrt{\frac{2\Delta p}{\rho}}$$

is plotted against $\sqrt{\frac{2\Delta p}{\rho}}$, as shown in Fig 2*).

If the leakage openings are assumed to be uniformly distributed over the building envelope the general expression for the total rate of volume flow may be written:

$$\dot{V} = f(Re) \int_A \left\{ \frac{2}{\rho}(Pe - 273\ \rho g z (\frac{1}{T_e} - \frac{1}{T_i}) - P_i) \right\}^{0.5} dA_\ell \tag{4}$$

---

*) From C.A. Boman and M.D. Lyberg: Analysis of Air Change Rates in Swedish Residential Buildings. Paper to be presented at the ASTM Symp. on Measured Air Leakage Performance of Buildings, Philadelphia, Pa. 2-3 April 1984.

where

A = area of that part of the wall over which the pressure difference, Δp, is positive

h = height above ground of level where $\Delta p = 0$

ℓ = characteristic length, $\ell = A/h$

Re = 'average' Reynolds number for flow through leakage openings

With

$$c_p = \text{pressure coefficient} = \frac{p - p_o}{\rho u_o^2/2}$$

(indices e = external, i = internal)

u_o = wind velocity at roof-top level

$$273 \cdot \left(\frac{1}{T_e} - \frac{1}{T_i}\right) \approx \frac{T_e - T_i}{T_i} = \frac{\Delta T}{T_i}$$

$$dA_\ell = \alpha \cdot dA = \alpha \cdot \ell \cdot dz = g(Re) \cdot \ell \cdot dz$$

eq. (4) becomes

$$\dot{V} = h(Re) \cdot \ell \int_o^h (c_{p_e} \cdot u_o^2 - 2\, gz \frac{\Delta T}{T_i} - c_{p_i} \cdot u_o^2)^{0.5} dz$$

$$= h(Re)\ \ell \cdot h \cdot u_o \cdot \frac{u_o^2}{3gh} \frac{T_i}{\Delta T} \left\{ (\Delta c_p^{1.5} - (\Delta c_p - \frac{2gh}{u_o^2} \cdot \frac{T}{T_i})^{1.5} \right\}$$

$$= h(Re)\ A \cdot u_o \cdot \frac{Fr}{3} \left\{ \Delta c_p^{1.5} - (\Delta c_p - \frac{2}{Fr})^{1.5} \right\}$$

$$(Fr = \frac{u_o^2}{g \cdot h \cdot \Delta T/T_i})$$

or, in dimensionless form

$$I = \frac{\dot{V}}{A \cdot u_o} = f(Re, Fr, \Delta c_p)$$

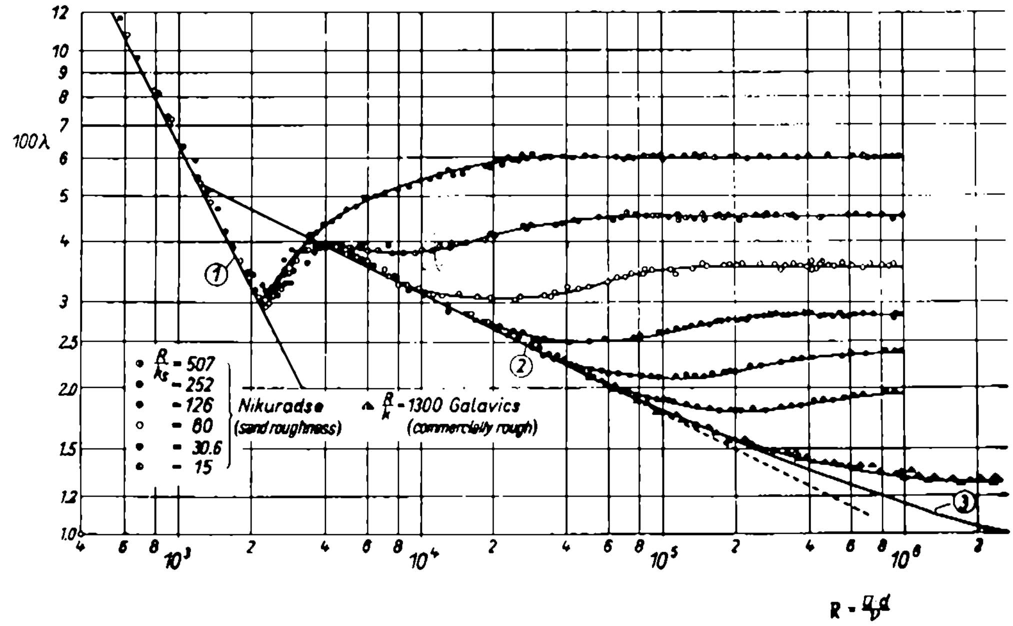


Fig. 1. Frictional resistance, rough pipes.
From H. Schlichting: Boundary Layer Theory, McGraw-Hill, N.Y., 1979.

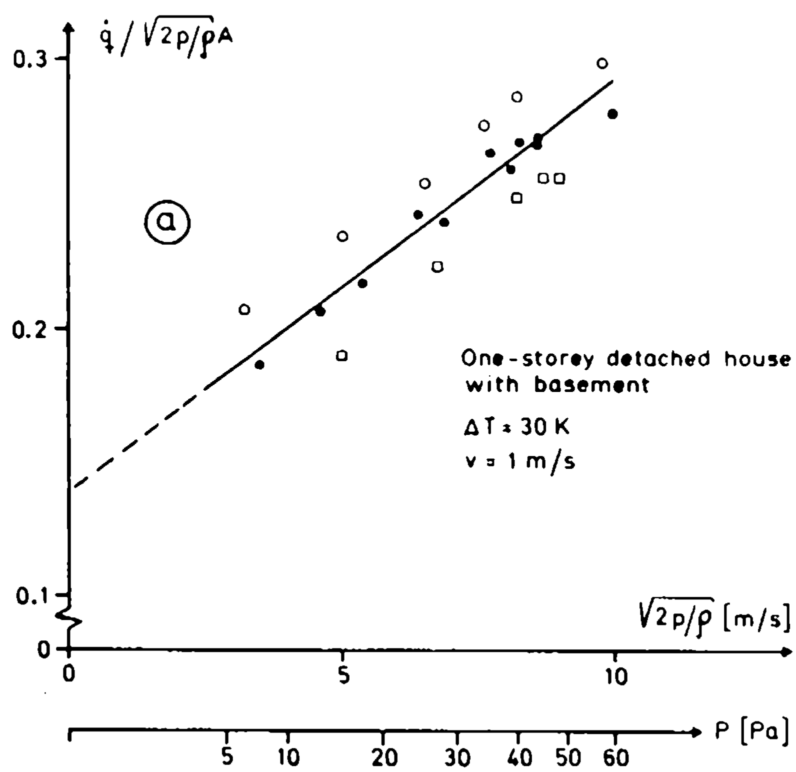


Fig. 2. Results from pressurization measurements, plotted in terms of Eq. (3).

AIR INFILTRATION CENTRE - WIND PRESSURE WORKSHOP
Brussels, Belgium
21-22 March 1984

PAPER 7

COMPUTER-FRIENDLY METHOD FOR THE REPRESENTATION OF SURFACE WIND PRESSURE DATA

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Until now, apart from a few isolated cases (e.g. Shaw [1]), little attempt has been made to present wind pressure results in analytical form, suitable for incorporation into an algorithm. This Chapter describes the author's application of Harmonic analysis to wind pressure coefficients from wind tunnel measurements on simple rectangular building models. These pressure coefficients were analysed as a function of wind angle, building shape and shelter. It is shown that, where wind tunnel results are mutually consistent, the equations derived from one or more data sets can be used to predict the pressure coefficient in other data sets to a level of accuracy acceptable for infiltration calculations.

1. Wind direction and Shelter - Harmonic Analysis

In general, for any point on any building, as the wind direction rotates through 360deg, the pressure coefficient associated with that point will describe a closed curve between $+\pi$ and $-\pi$. Formally this can be represented by a Fourier series of the form:

$$Cp(i) = a(0) + \Sigma\, a(i).\cos(i.\theta) + \Sigma\, b(i).\sin(i.\theta) \qquad (1)$$

(Stephenson [2])

This approach has been used by Shaw [1] to describe the pressure difference coefficients for full scale measurements on two schools. In principle the method can be applied to a building of any shape, and to any of the forms of pressure coefficient.
If the building is symmetrical, the mean value for a facade and the central line value can be represented by a Fourier cosine series.

This proposition was tested at the Air Infiltration Centre, using data extracted from Bowen [3] and Akins, Peterka, & Cermak [4]. The Bowen data consists of wind tunnel measurements on a rectangular test element of side ratio 3:2 and H/h = 1:1,2:1,4:1 & 6:1, where h is the height of the blocks in a staggered array surrounding the test block. This was the source data set for the NRC pressure coefficients.
(Shaw [5])
The data from Akins et.al [4] consists of mean pressure coefficients for each facade, averaged over aspect ratio (H/W) and boundary layer velocity distribution, for side ratios (L/W) of 1:1,2:1 & 4:1.
In both cases the data sets generated were a composite of measurements from equivalent points on the various faces of the test model, exploiting the symmetry of the experimental system to get the full range of wind directions.
A General Linear Interactive Model (GLIM) program was used to fit the Fourier series to the data sets. The results are shown in Figs. 1 to 6. (Baker and Nelder [6])
Data were analysed for pressure coefficients using a roof level reference wind (="roof level pressure coefficients"), and for "local pressure coefficients", referenced to the local wind profile. The "local mean pressure coefficient" refers to the area mean value of the local pressure coefficient for the facade.

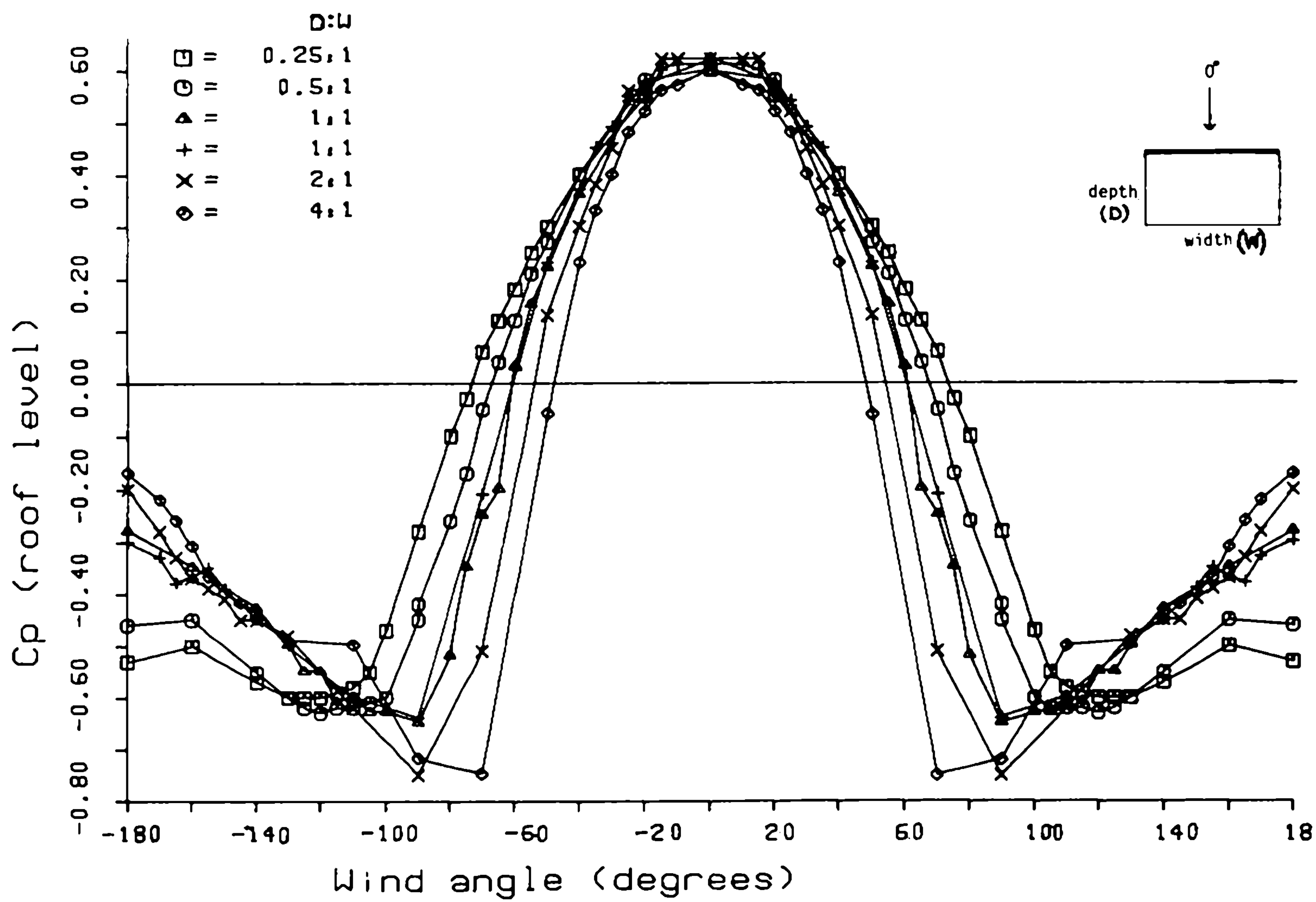


Fig. 1 Roof level, whole face pressure coefficients for simple rectangular blocks with various side ratios. (Akins.et.al. (4))

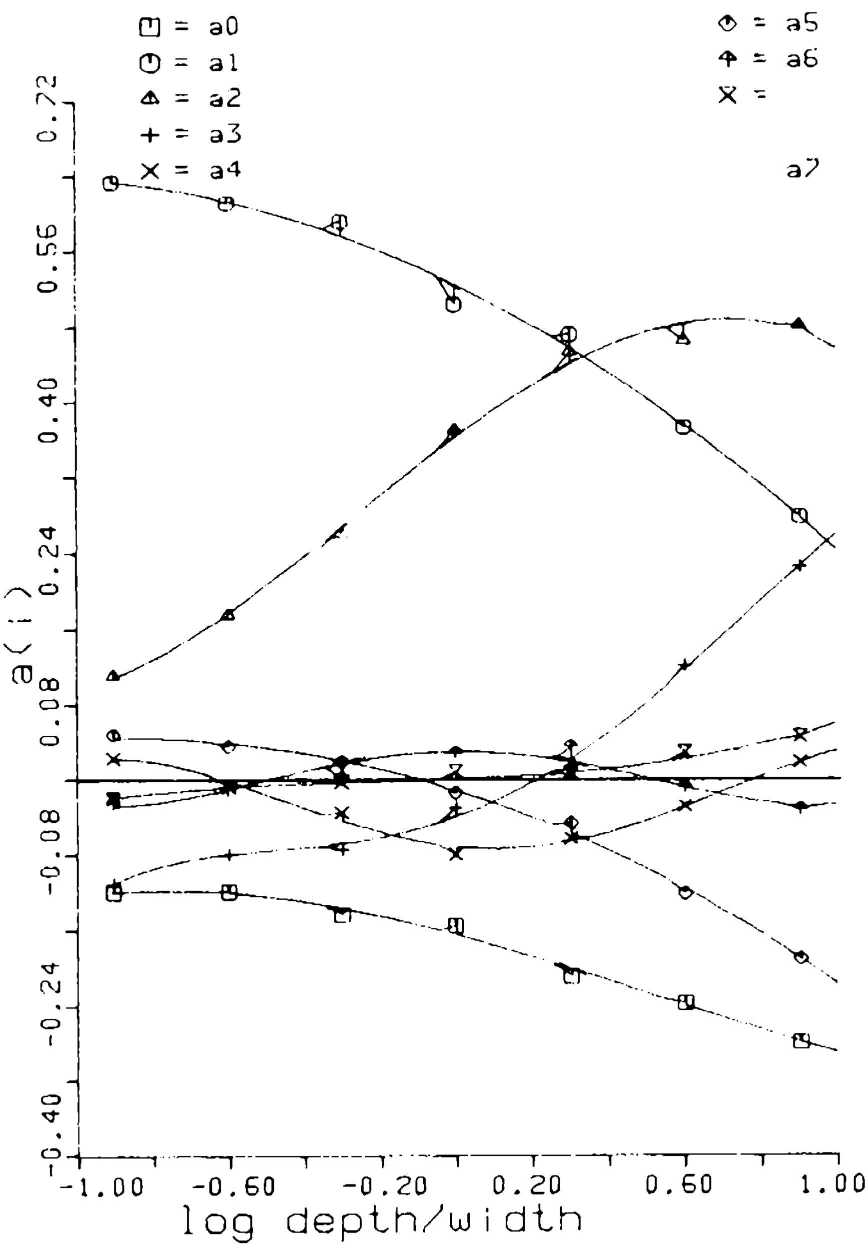


Fig. 2 Coefficients a(i) for roof level pressure coefficients.

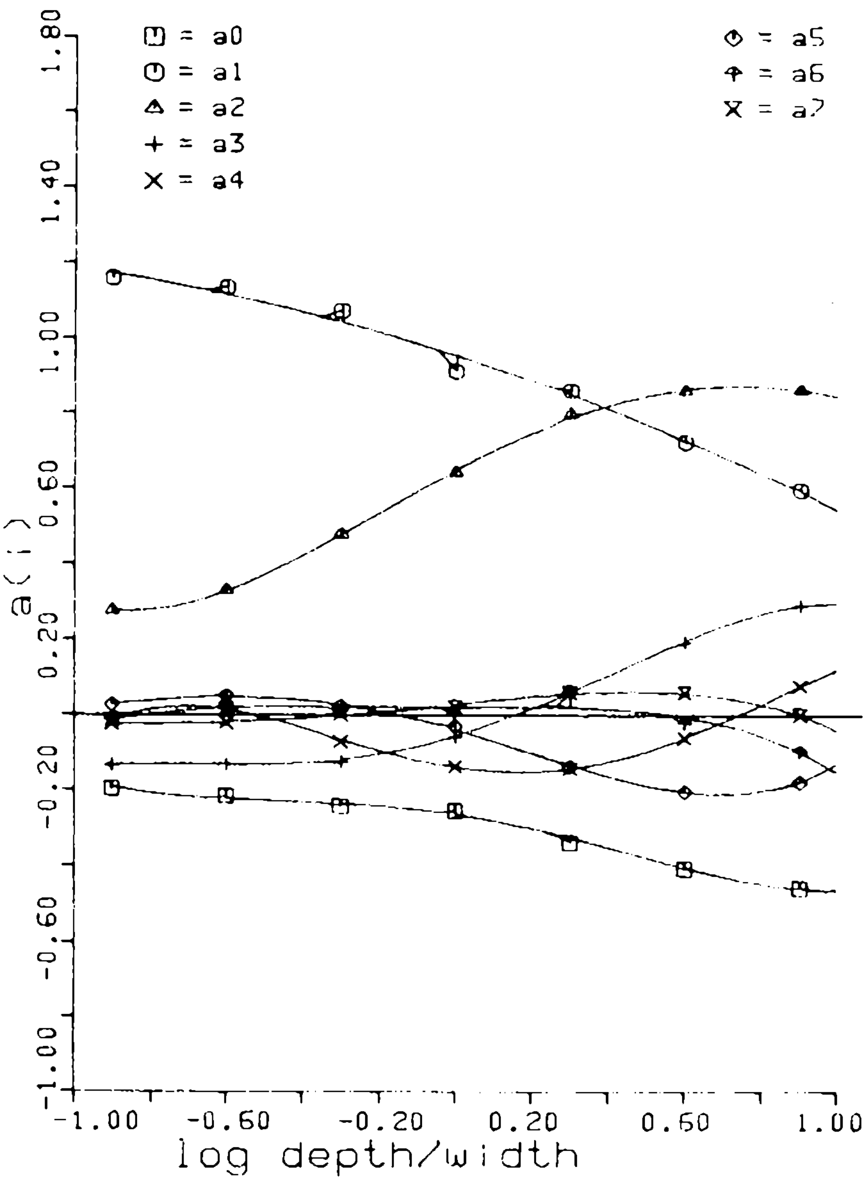


Fig. 3 Coefficients a(i) for local pressure coefficients.

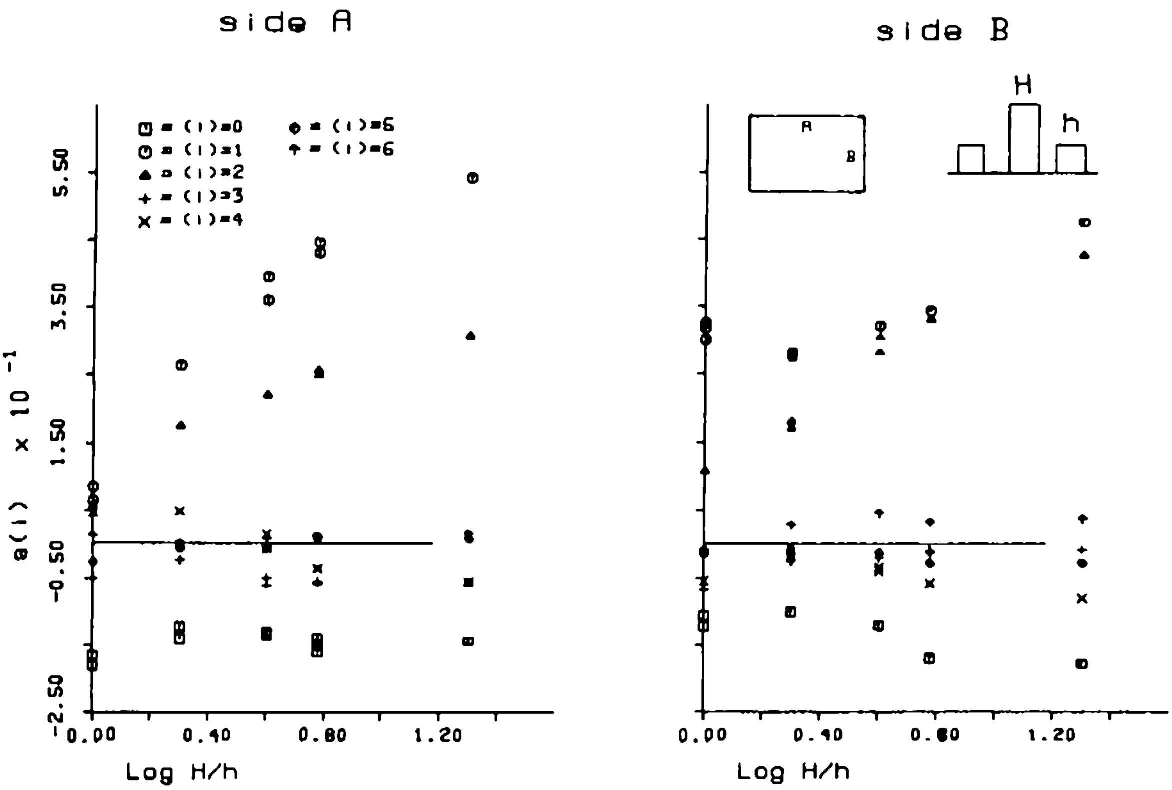


Fig. 4 Coefficients a(i) as a function of shelter (H/h).

The variation of the shapes of the curves with side ratio and shelter was investigated by plotting the coefficients of the best fit Fourier cosine series with side ratio for the Akins data, and with H/h for the Bowen data[3]. (see Fig.4).

Since $\cos(i.\theta)$ is always <1, any coefficient <0.1 cannot contribute more than 10% to the final figure. The results indicate that terms higher than the third are of marginal importance.

a(0) is seen to decrease steadily from -0.12 to -0.24 as the side ratio varies from 1/4 to 4 (side ratio S = D/W : W = width of facade containing the sampling point, D = length of side wall perpendicular to the sample wall). There appears to be little variation with H/h.

a(1) decreases with S from 0.61 to 0.4 and increases sharply as H/h increases from 1 to 6.

a(2) increases with S from 0.175 to 0.47 and increases with increasing H/h, but not as strongly as a(1).

a(3) and a(5) only make a significant contribution for S > 3. a(4) only features for 0.7< S < 3. These coefficients do not appear to vary significantly with H/h. They have little effect on the general shape of the curve, but do refine the fit around the extreme values.

The effect of displacement from the centre of the facade was investigated using a set of data from Bowen[3] corresponding to z/H = 0.85, H/h = 6, S = 2/3 for all wind angles. H is the height of the building model and z is the height of the pressure tap above the base. For each wind angle, the local pressure coefficient was fitted to a linear equation of the form:

$$Cp = A + B(X/W) \qquad (2)$$

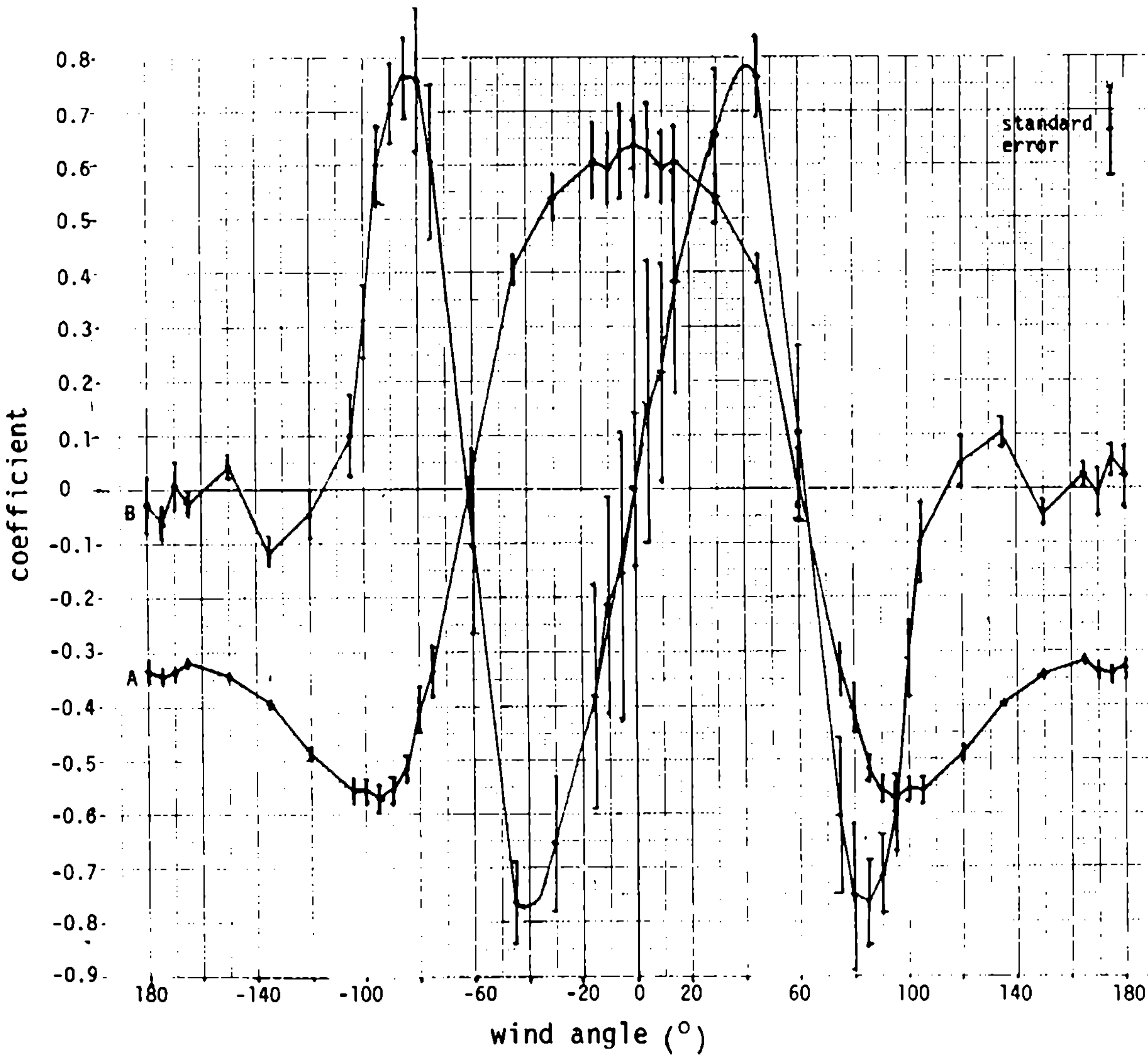


Fig. 5 Fourier analysis of the horizontal pressure distribution across a facade with wind angle. (see eqn. 2) (data from Bowen [3])

where X is the displacement from the centre line ($-0.5 < X < 0.5$). A and B were then analysed for dependence on wind angle (see Fig. 5). It became apparent that 'A' represents a cosine series with coefficients similar to those for the mean facade allowing for the variations with L/W and H/h. B was found to represent a sine series, dominated by b(3), and adequately represented by terms from b(2) to b(6). (see Table 3).
The mean pressure coefficients for the roof are illustrated in Fig. 6. It will be noted that these are the same for both the local and roof level pressure coefficients. It should be mentioned that this is the case only for a flat roofed building, since only then is the roof level velocity the same as the mean velocity for the roof surface.

A further set of data was used to look at the effect of departure from the rectangular block shape used in the original analysis.
This data is from "Wind Tunnel Investigation of CARE INC. Single Family Dwelling" , Tieleman H.W. and Gold R.R.[7].
The test building is illustrated in Fig. 7.

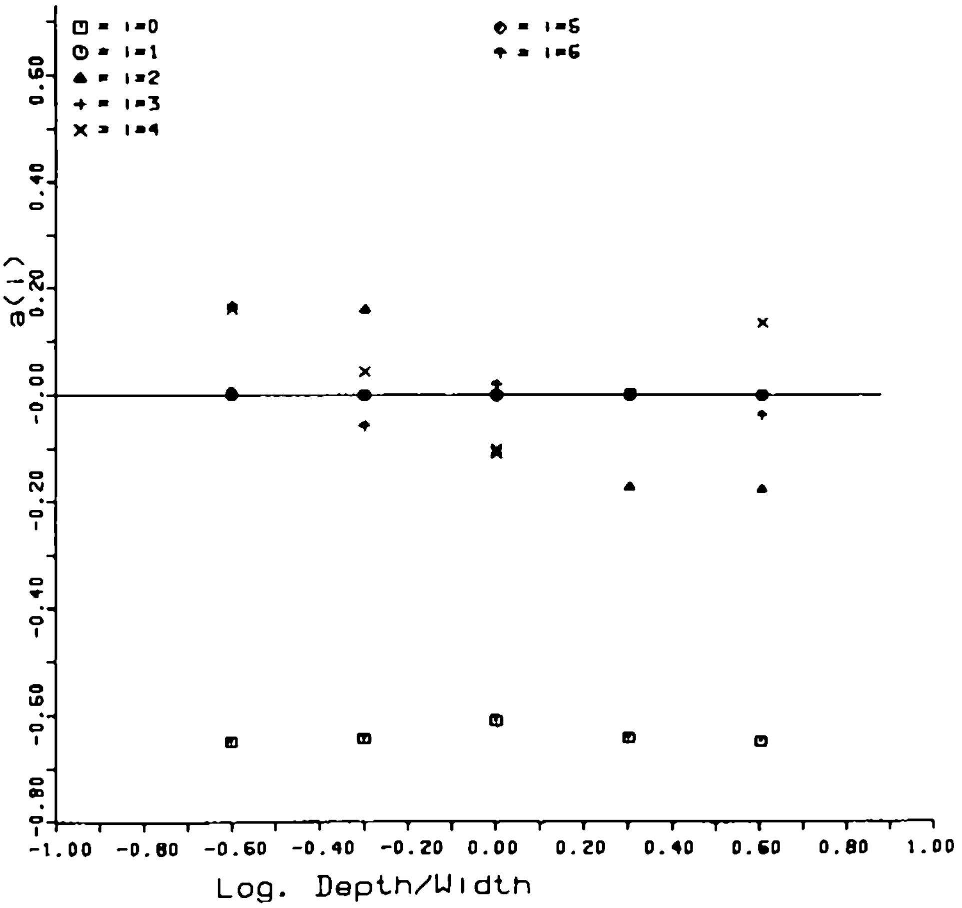
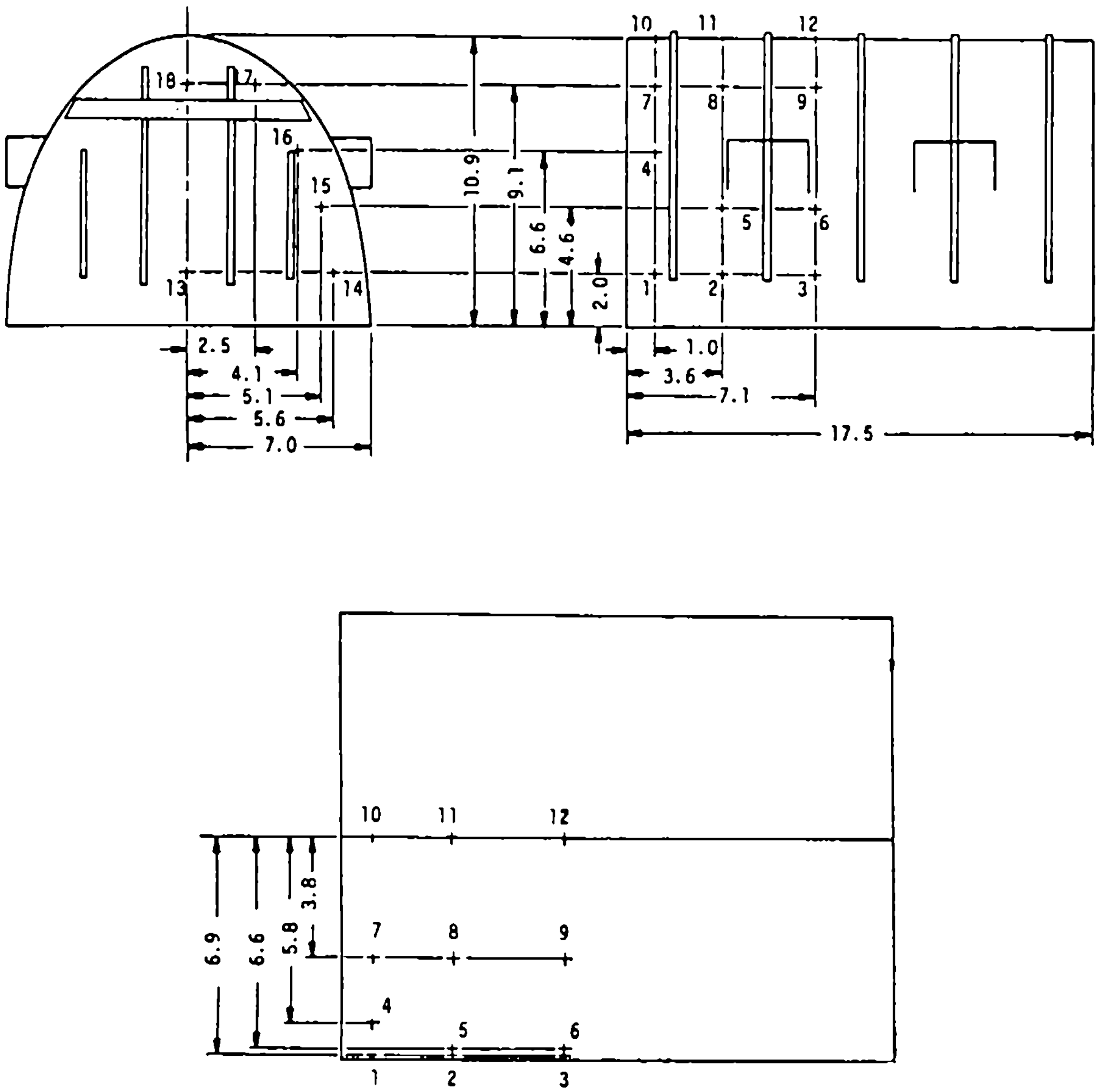


Fig. 6 Coefficients a(i) from eqn. 7.1 for the mean Cp of a flat roof. (same for both roof level and local reference winds)

Although the modelling was at 1/30th scale, it was felt that it would afford a chance to examine the gross effect of the shape variation. Two representative nodes were chosen, one on the centre line of the vertical end wall, and one as close to the centre line of the curved side wall as possible. The results were plotted in Figs. 8a and 8b . It can be seen that for the flat end, the mean pressure coefficient follows a similar pattern to that for a rectangular block building of almost the same ground plan, with reduced depth to width ratio. The response of the point on the curved side, however, is much more exaggerated.
A subsequent analysis of the data revealed that the a(0),a(1) and a(2) components of the cosine series were consistent with those of a building of much reduced depth. This is particularly the case for the a(1) component. The cosine curve corresponding to a depth to width ratio of 0.25:1 is plotted for comparison. The true ratio at ground level being 0.8:1, and at the height of the node, 0.755:1.
This reflects the difference in the shape of the wake, and the importance of salient edges in determining the response of the pressure distribution to wind angle.
This would suggest a possible direction for future work.



Note: All Dimensions in cm.

Fig. 7 Care Inc. Single Family Dwelling. Location of pressure taps. (Reproduced by kind permission of the authors: Tieleman and Gold[39])

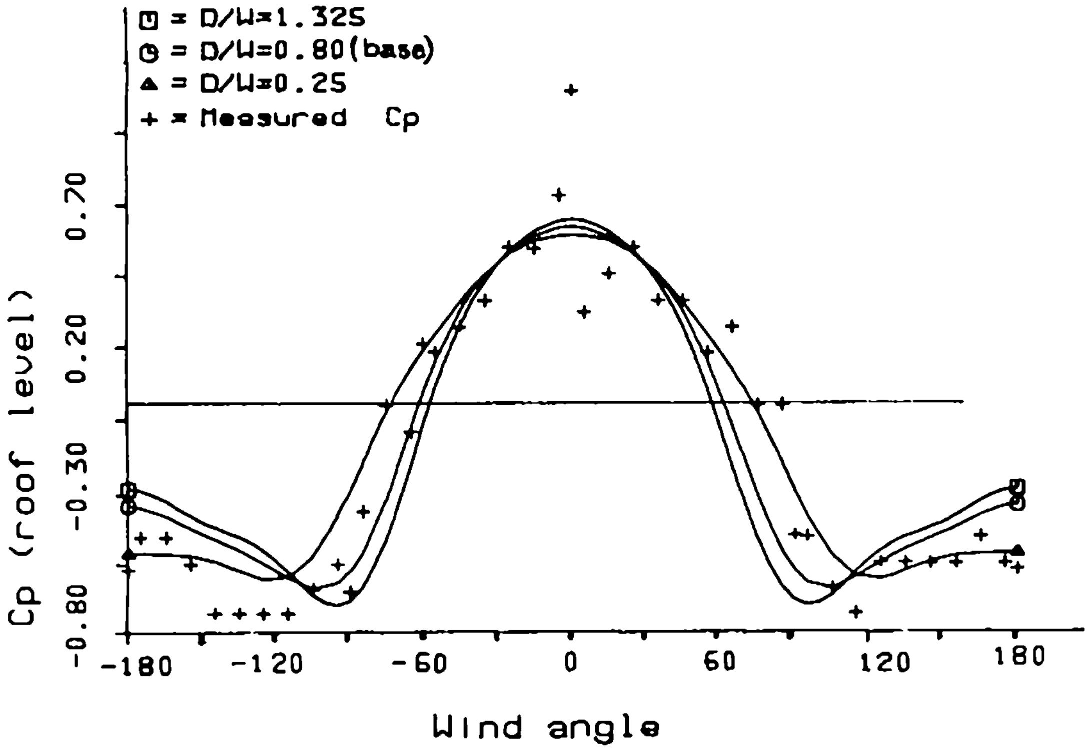


Fig. 8a Measured and calculated pressure coefficients plotted against wind angle for position 6 (side wall).

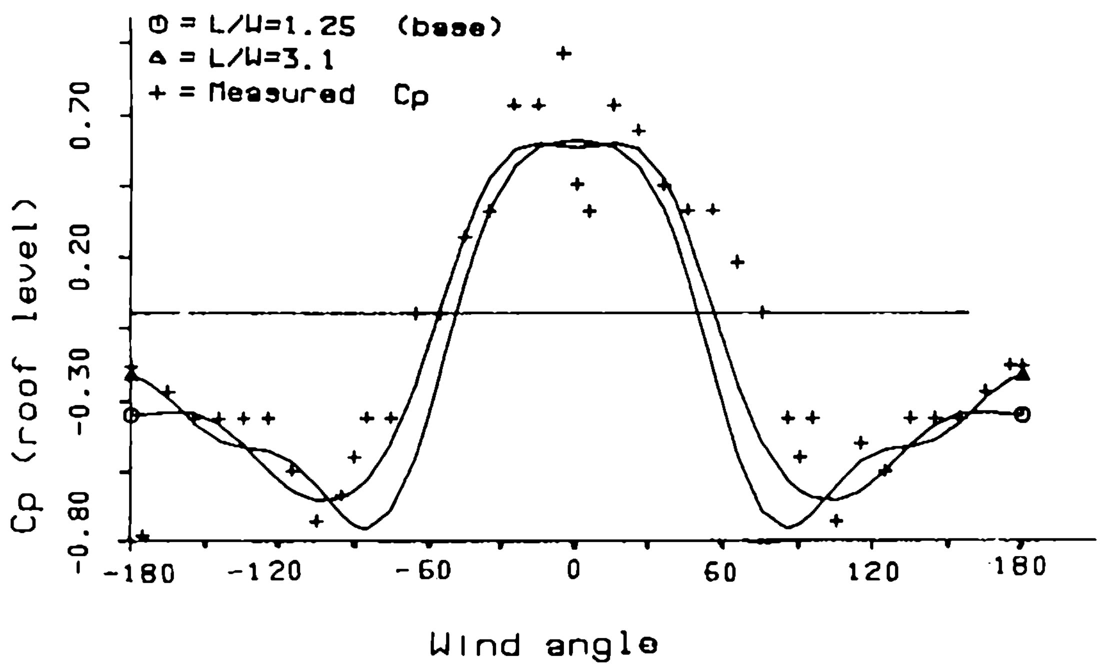


Fig. 8b Measured and calculated pressure coefficients plotted against wind angle for position 18 (end wall).

2. Numerical representation of pressure coefficients

Further application of the GLIM program showed that it is possible to represent the coefficients a(i) of equation (7.1) by a logarithmic series of the form:-

$$a(i) = c(0)+c(1)\ln(S)+c(2)(\ln(S))^2+ \quad +c(j)(\ln(S))^j \qquad (7.3)$$

Where S = depth/width.

The values of the c coefficients are given in Table (7.1) for the local pressure coefficients and Table (7.2) for the roof level pressure coefficients.

Table 1 Coefficients of the log series representation of a(i) values - Mean local pressure coefficients.

j= / i=	c0	c1	c2	c3	c4
0	-0.2649	-0.06472	-0.03495	+0.0000	+0.004874
1	+0.9554	-0.1405	-0.01655	+0.0000	+0.0000
2	+0.6491	+0.2348	-0.03344	-0.02185	+0.003512
3	-0.05675	+0.1316	+0.05825	-0.006923	-0.006154
4	-0.1390	-0.06426	+0.07754	+0.01994	-0.008779
5	-0.03753	-0.1242	-0.03128	+0.01735	+0.005251
6	+0.02109	+0.0000	+0.0000	-0.004720	-0.004081
7	+0.0264	+0.04633	+0.0000	-0.009425	-0.002029

Table 2 Coefficients of the log series representation of a(i) values - Mean roof-level pressure coefficients.

j= / i=	c0	c1	c2	c3	c4
0	-0.1650	-0.04703	-0.08028	+0.002002	+0.0000
1	+0.5246	-0.08610	-0.01593	+0.0000	+0.0000
2	+0.3620	+0.1285	-0.01645	-0.009425	+0.0000
3	-0.04080	+0.06241	+0.03675	+0.004254	-0.003265
4	-0.07162	-0.01711	+0.03561	+0.003753	-0.003331
5	-0.01152	-0.05663	-0.01400	+0.0000	+0.0000
6	+0.01969	+0.0000	-0.02574	+0.0000	+0.002839
7	+0.0000	+0.006109	+0.003154	+0.002335	+0.0000

These coefficients closely reproduce the data in Figs. 3 and 2.

The values for the a(i) and b(i) coefficients are given in Table 3. for H/h = 6, S = 2/3, z/H = 0.85.
This is the level corresponding approximately to the maximum positive pressure on the windward face, and thus for which the amplitude of the distortions caused by displacement from the centre line is also a maximum.

The procedure was to fit the values for various X/W to a straight line for each angle:-

$$Cp_{(\theta)} = (A + B(X/W)_{(\theta)} \qquad (4)$$

Where:-

$$A = a(0) + \Sigma\, a(i).\cos(i.\theta) \qquad (5)$$

$$B = \Sigma\, b(i).\sin(i.\theta) \qquad (6)$$

For comparison, the table also includes the corresponding coefficients for the whole face mean Cp and the local mean Cp for z/H = 0.850.
The effects of sheltering blocks can be expressed in the form :-

$$D = (Cp(0)-Cp(\text{sheltered}))$$

$$= f(T,T^2,T^3,S.T,S.T^2,S^2.T) \qquad (7)$$

Where S is the depth to width ratio as before and T is given by:-

$$T = \tanh\left(\frac{h}{(C.H)}\right) \qquad (8)$$

The deficit can be expressed by such a series for each of the Fourier coefficients a(i). The coefficients for equation 7 for i= 0 to 7 are given in Table 4.

The local pressure coefficients for zero wind angle for various S are plotted against z/H (Fig. 10). For $z/H > 0.1$, the curves collapse almost to a straight line. The best straight line fit is :-

$$Cp(0) = 1.617 - 0.8552(z/H) \qquad (9)$$

The mean roof reference pressure coefficients and the corresponding centre line values from Bowen[3] (depth/width = 2/3) have been plotted for shelter conditions from H/h = 1 to H/h = 6. (Fig. 9). The results all lie approximately on a straight line.

Table 3 a(i) and b(i) coefficients for z/H=0.85, S=2/3.

i/j	0	1	2	3	4	5	6	7
a(i)	-0.1055	+0.5029	+0.3379	-0.01625	-0.09895	-0.02349	0.0	+0.01509
b(j)	0.0	0.0	+0.2370	+0.4761	+0.2029	-0.1679	-0.1316	0.0
a(i)r (all)	-0.1505	+0.4480	+0.255	-0.055	-0.037	+0.013	0.0	0.0
a(i)r (loc)	-0.0896	+0.5262	+0.3469	-0.01467	-0.09058	-0.008457	+0.01833	0.0

Key:- a(i)r (all) = coefficients for the whole facade mean Cp.
a(i)r (loc) = local mean Cp fpr z/H=0.850

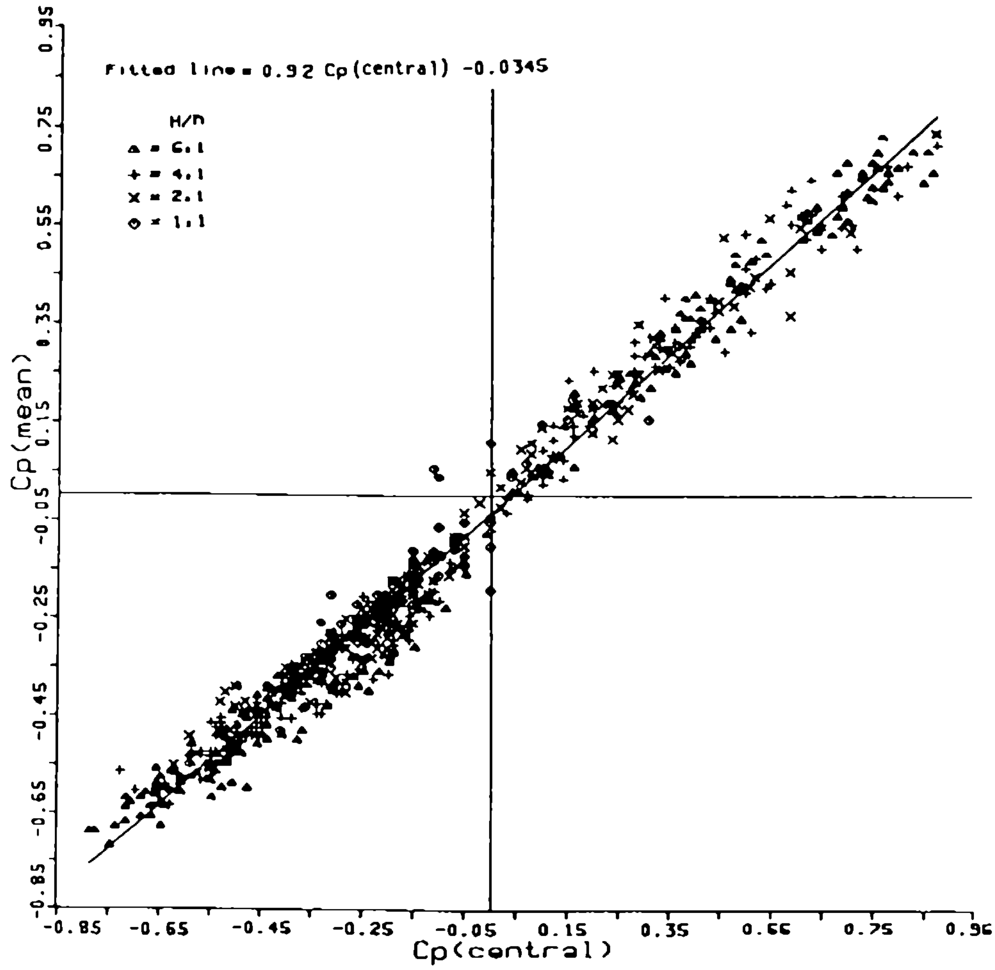


Fig. 9 Plot of mean Cp against centre line Cp for various z/H, H/h and wind angle for face A.(see Fig. 4) (data from Bowen[3])

Table 4 Coefficients of the tanh series representation of D values.

i	C	T	T^2	T^3	S.T	$S.T^2$	$S^2.T$
0	0.364	0.3126	-0.9310	0.7249	0.0	-0.1137	0.0
1	0.955	0.5993	0.0	0.5177	0.2157	-0.8841	0.0
2	100.(as)	0.0	1973.0	0.0	44.06	-3596.0	0.0
3	3.80	0.0	-3.391	11.72	0.0	0.0	0.1459
4	0.640	0.0	-0.6743	0.5268	0.0	0.1067	0.0
5	1.050	0.0725	0.0	0.04232	-0.07704	0.0	0.0
6	10.0	0.5564	0.0	-87.23	-0.6760	11.98	0.0
7	1.0	0.0	0.0	0.0	0.0	0.0	0.0

(as) = asymptote solution.

These coefficients match the data in Fig. 9 to within 10%, and mostly within 5%.

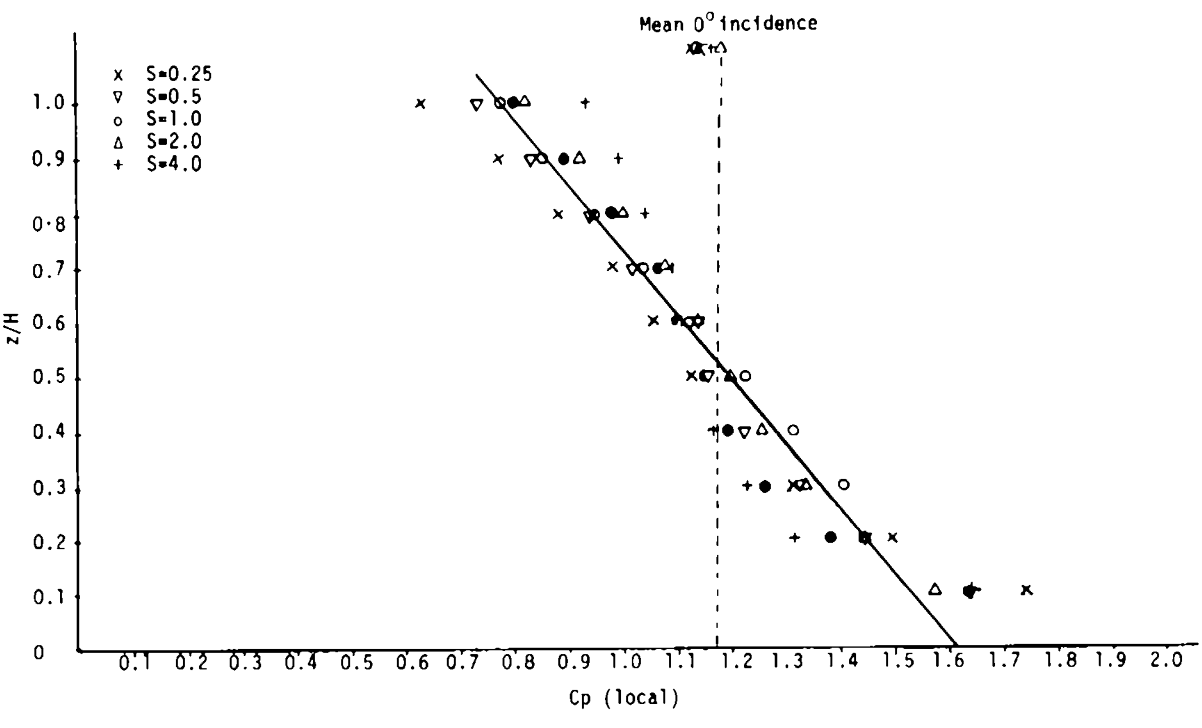


Fig. 10 Local pressure coefficients for zero wind angle and various S plotted against z/H.

Equation 4 can be used for any wind direction for which the wind is incident on the facade, i.e. -90 to +90 degrees and represents a scaling factor taking into account the variation of wind speed with height. This is due to the fact that the centre line pressures vary little with wind angle over the central part of this range where the scaling factor is important.

A similar exercise could be carried out for Cp(90) and Cp(180). For this range of wind directions, however, the flow pattern is dominated by the building and is largely independent of the oncoming wind profile, and a scaling factor may be therefore unnecessary.

for S = 2/3: $Cp(mean) \cong 0.92\ Cp(central) - 0.03$ (10)

for S = 3/2: $Cp(mean) \simeq 0.97\ Cp(central)$ (11)

for the flat roof:

$$Cp(mean) = -0.3612 + 0.4141\ Cp(central) \quad (12)$$

3. Case studies

3.1 Aylesbury test house

Wind pressure data has been gathered by Eaton and Mayne[8] of the Building Research Establishment (England) for a test building near Aylesbury. The mean roof level Cp has been calculated for the Aylesbury Test House data for points near the centre line of the East and West facades. (3EW3,5EW3,3WW3,5WW3). (see Fig. 11).

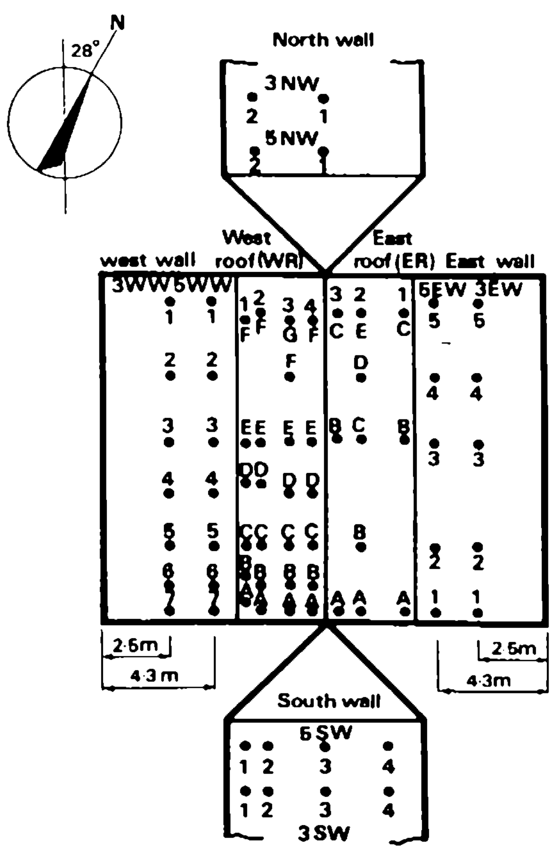


Fig. 11 Aylesbury Test House - location of pressure taps
(From Eaton and Mayne [8] reproduced by permission of the Controller, HMSO Crown Copyright)

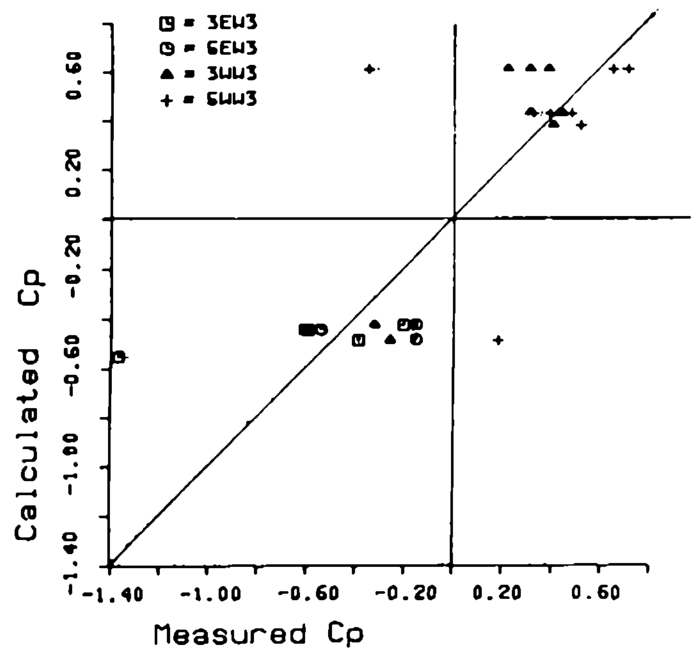


Fig. 12a Measured vs. calculated pressure coefficients for the Aylesbury test house.

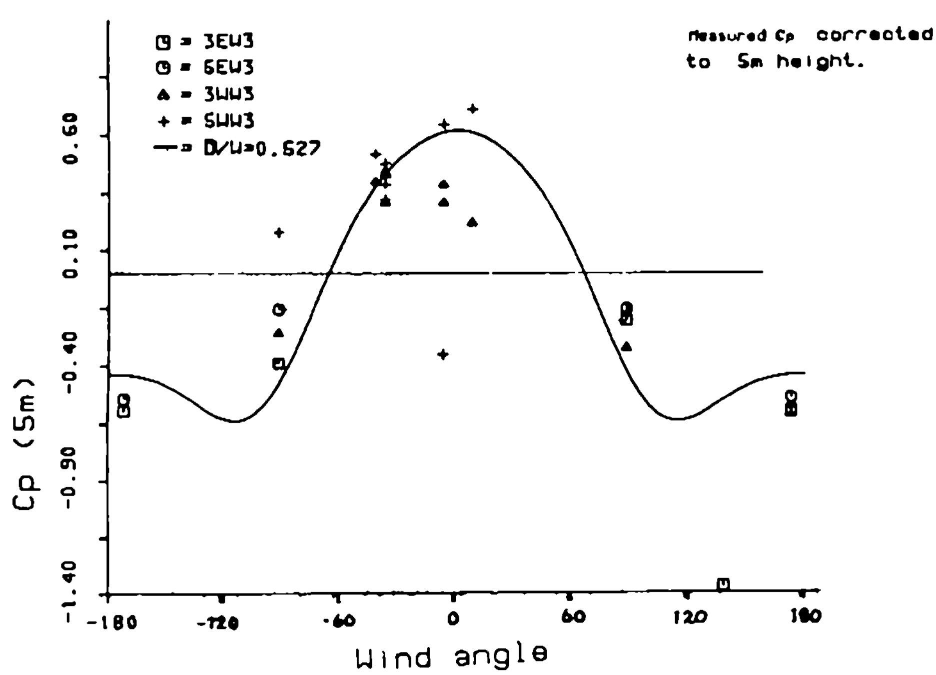


Fig. 12b Measured and calculated pressure coefficients plotted against wind angle for the Aylesbury test house.

The calculated values, using the coefficients derived from Table 2, are plotted with the data in Fig. 12a against each other and both against relative wind angle in Fig. 12b.

It can be seen that there is a considerable scatter of the data points. This is a result of the unsteady nature of the real wind under the strong wind conditions when the field measurements were made.

3.2 CAARC tall building model

The method has been tested against the CAARC data from Melbourne[9]. Here the local pressure coefficients were used. The data to be matched was the roof level Cp on the centre line for $z/H = 2/3$.

The data for the building is:-

H = 183m (600'), L = 45.72m (150'), W = 30.48m (100')

$6 < H/h < 15.25$ for the 6 wind tunnel investigations, h = roughness block height.

S = 2/3 for the centre line of the wider face.

The power law exponent for the velocity gradient is given as 0.26. Therefore:-

$$V(z)/V(H) = (z/H)^{0.26} \tag{13}$$

$$Cp(r)\ 2/3 = \left(\frac{V(z)}{V(H)}\right)^2 . \frac{[Cp(\ell)[2H/3]] . \langle Cp(\ell)\rangle}{\langle Cp(\ell)_o \rangle}$$

$$= (2/3)^{0.52} . (1.047/1.110) . \langle Cp(\ell)\rangle \tag{14}$$

(From equations 9 and 13 and Table 1 for the case of 0^o wind angle).

$$= 0.7639 \langle Cp(\ell) \rangle \tag{15}$$

The coefficients a(i), calculated using the coefficients from Table 1 are displayed in Table 5.

Table 5

	Mean local Cp's (= Cp( ))	Roof level Cp's (H/h=6)
a(0)=	-0.244	-0.159
a(1)=	+1.010	+0.557
a(2)=	+0.550	+0.308
a(3)=	-0.100	-0.060
a(4)=	-0.102	-0.059
a(5)=	+0.007	+0.009
a(6)=	+0.021	+0.016
a(7)=	+0.008	-0.002
b(i)=	0.0	0.0

The results are plotted against the CAARC data in Fig. 13. It can be seen that for the regions where equation 9 applies (-90 to +90 degrees), the fit is excellent.

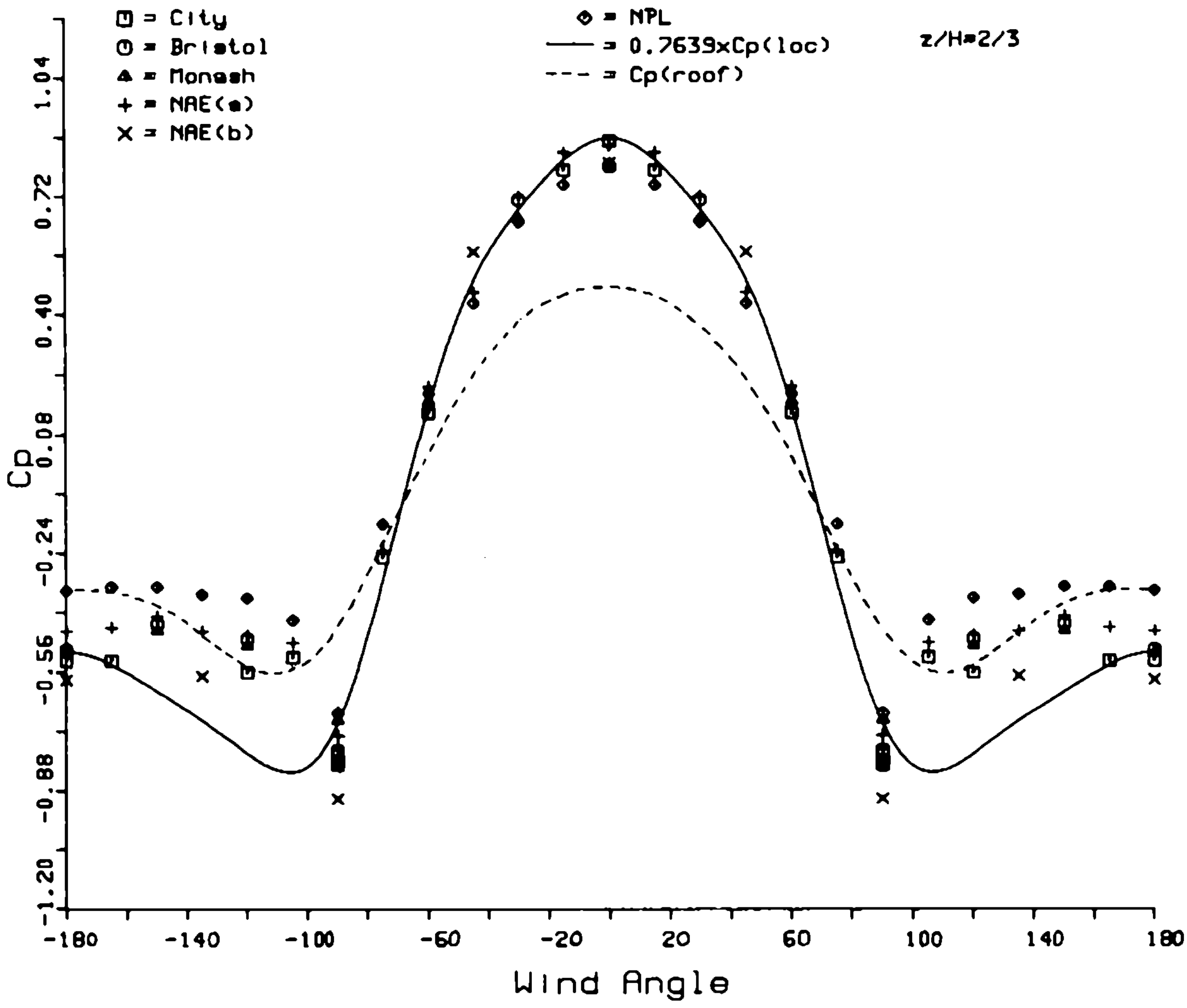


Fig. 13 Measured and calculated pressure coefficients plotted against wind angle for the CAARC Standard Tall Building Model.

The mean roof level Cp for the wider facade is also plotted, using coefficients from Table 2. It can be seen that this gives a better fit for wind angles greater than 100 degrees.
It should be noted that the mean local $\langle Cp(\ell) \rangle$ used above contains no information about the distribution of pressure on the facade, and so cannot be expected to be accurate when the pressure gradient is changing most rapidly.

3.3 Comparison with full scale measurements on a high rise building

Results from full scale and model measurements reported by Dalgliesh[10] for a Toronto office building also resemble the Fourier series solution. The mean and rms about the mean values were plotted against wind angle for the building. A sample of his results is given in Fig.14. An interesting feature is that the principal maxima of the rms plot appear to coincide with angles where the mean pressure coefficient is changing most rapidly. This suggests a possibility of finding a prediction function for the rmsm based on the derivative of that for the mean Cp with respect to wind angle.

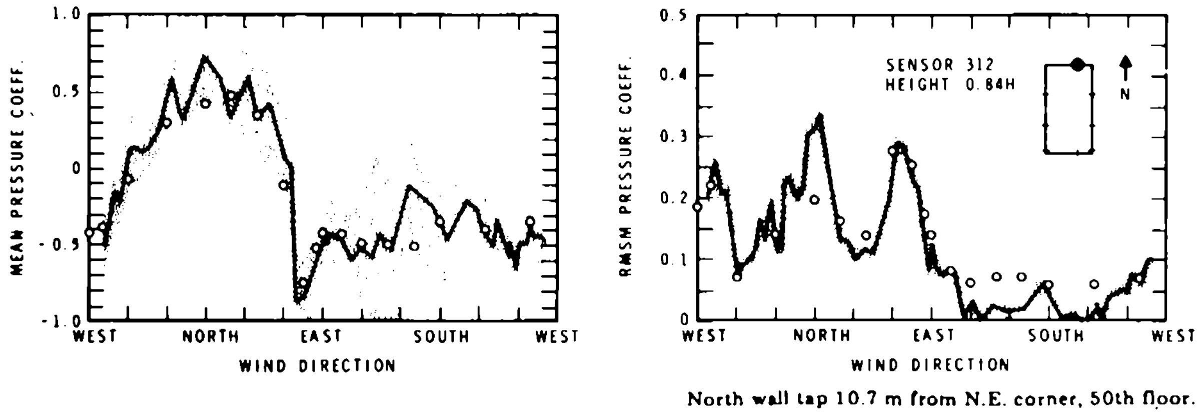


Fig. 14. Example of full scale measurements on a 57 storey office tower in Toronto. (from Dalgliesh[10])

4. Notes on the use of Fourier analysis

It should be noted that, when performing a harmonic analysis, the maximum order that can be derived is (k-2)/2 where k is the number of equally spaced data ordinates (y(i)). e.g. if the pressure coefficient is given for wind angles every 30 degrees, k = 12 and n(max)=5, if the interval is 15 degrees, k=24 and n(max)=11.

$$a(0) = (1/k) \sum_{m=0}^{k-1} y(m) \tag{16a}$$

$$a(i) = (2/k) \sum_{m=0}^{k-1} y(m).\cos(2.m.i.\pi/k) \tag{16b}$$

$$b(i) = (2/k) \sum_{m=0}^{k-1} y(m).\sin(2.m.i.\pi/k) \tag{16c}$$

Since the above study indicates coefficients of significant size up to n = 6 for a simple rectangular building, k must be at least 14, corresponding to an angular interval of 25.7 degrees. For more complex situations the solution may involve higher order terms and, thus, more closely spaced data points. If one attempts to fit higher order coefficients than is appropriate for the number of data points, aliasing can occur.

If the data points are not equally spaced, one can use the aforementioned GLIM method to obtain a rms best fit. The limit on the number of points required still holds.

7.5 Summary

The above examples demonstrate that the method of Harmonic Analysis can be applied successfully in the case of simple rectangular blocks and other simple shapes. The results of Shaw[68] show that it can be applied to real buildings of irregular form in the real environment (up to 3rd order, using 8 wind directions). The relationships derived in this chapter should be adequate for the calculation of whole facade mean pressure coefficients referenced to roof level or local winds, and should therefore be a useful tool for the prediction of wind induced air infiltration in buildings.

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AIR INFILTRATION CENTRE - WIND PRESSURE WORKSHOP
Brussels, Belgium
21-22 March 1984

PAPER 8

BASIC WIND PRESSURE DIFFERENCE COEFFICIENT DATA SET FOR PITCHED- OR FLAT-ROOF RECTANGULAR BUILDINGS

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BASIC WIND PRESSURE DIFFERENCE COEFFICIENT DATA SET

FOR PITCHED- OR FLAT-ROOF RECTANGULAR BUILDINGS

In many hot and humid climates cooling loads can be reduced or eliminated by using natural ventilation instead of mechanical cooling. The application of the natural ventilation cooling of buildings requires design guidelines for buildings to be cooled by the prevailing wind.

The U.S. Navy Shore Facilities in their Energy Conservation Program included the development of "Design Guidelines for Buildings Cooled by Natural Ventilation." The project covered five major areas: (1) Human Comfort Criteria; (2) Site Weather Analysis Building Aerodynamics; (3) Full Scale Testing to Measure Wind Pressures and Comfort Levels of Three Navy Buildings at Kaneohe Bay, HI; (4) Scale-Model Testing to Measure Wind Pressure Coefficients; and (5) The Development of a Computer Program Which Predicts the Effectiveness of Natural Ventilation on Human Comfort.

Scale models used in the (.98 x 1.64 m) NCEL boundary layer wind tunnel represented the three Navy buildings tested in Hawaii. The velocity profile modeled in the wind tunnel represented that of open country with scattered windbreaks.

Scale of models ranged from 1:46 to 1:80. Pressure and wind speed measurements were made using strain-gauge pressure transducers, hot-wire anemometers, and a 32-channel intelligent data logger. Pressure measured was the difference between instantaneous local pressure at a location on the model and the static pressure in the ambient flow over the model building. Mean pressure coefficients were averaged over the entire side of the model. The pressure coefficient used was defined by

$$\overline{C}_p = \frac{\overline{P - P_o}}{0.5\rho \overline{U}_R^{\,2}} \qquad (1)$$

where C_p is the nondimensional pressure coefficient

P_o is the local static pressure

P is the pressure at a location on the model

ρ density of air

$\overline{U}_R$ wind speed in the approach flow measured at the level of the roof of the model

Most of the models were tested in an isolated and sheltered environment with and without wall openings. One model was tested with adjacent structures present and another elevated and large window openings. Interior airspeeds and pressures were measured for nine wind directions for all models. Results of field and wind tunnel testing were plotted and compared. Comparison showed a good agreement between full-scale and model-scale measurements (Reference 1).

The air flow within the building was estimated using the following equation

$$Q = 0.61\, A_w\, \overline{U}_R\, (\Delta\overline{C}_p)^{\frac{1}{2}} \qquad (2)$$

where Q is the ventilation rate (m^3/hr)

A_w is the effective inlet/outlet opening area (m^2)

$\overline{U}_R$ is reference velocity at the site at roof level, m/hr, and

$\Delta\overline{C}_p$ is the pressure difference coefficient between opposite walls.

Basic data of wind pressure difference coefficient, , was developed by combining existing wind tunnel data and field test data. Since most Navy buildings have pitched-roof or flat-roofed rectangular building form, therefore the basic data set of pressure difference coefficients for these building types was developed, Figures 1a and 1b. More data is needed in order to validate and complete the curves (Reference 2). The curves reflect the pressure difference coefficient expected for a one-story building with a basic rectangular building form. Any deviation from the basic design will cause a change in pressure difference coefficient. Table 1 summarizes the expected changes in $\Delta\overline{C}_p$ due to architectural changes in the basic design. If the building under consideration is a two-story building, the basic $\Delta\overline{C}_p$ obtained from the graphs should be increased by 40%.

In summary, the initiated data-base of wind pressure difference coefficients can be used as input data to equation (2) for fast hand calculations or as input data to the NCEL computer program which estimates the thermal acceptability of the indoor environment and the usefulness of natural ventilation for the case being tested.

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Table 1 Effect of Architectural Characteristics on Pressure Difference Coefficients[a]

Architectural Characteristics	$\Delta\overline{C_p}$ (% increase)
1. Basic Design (one story)	0
2. Two or More Stories	40
3. Single Story Elevated Above Ground	30
4. Single Story with Extended Eaves and End Walls	25
5. Single Story Elevated Above Ground with Extended Verandas and End Walls	50
6. Single Story with Windward Wall Projections or Insets	25

[a]If two or more architectural characteristics are combined, the average of the % increase is taken with a maximum of 50% increase total. These corrections should be used only for the calculation of natural ventilation.

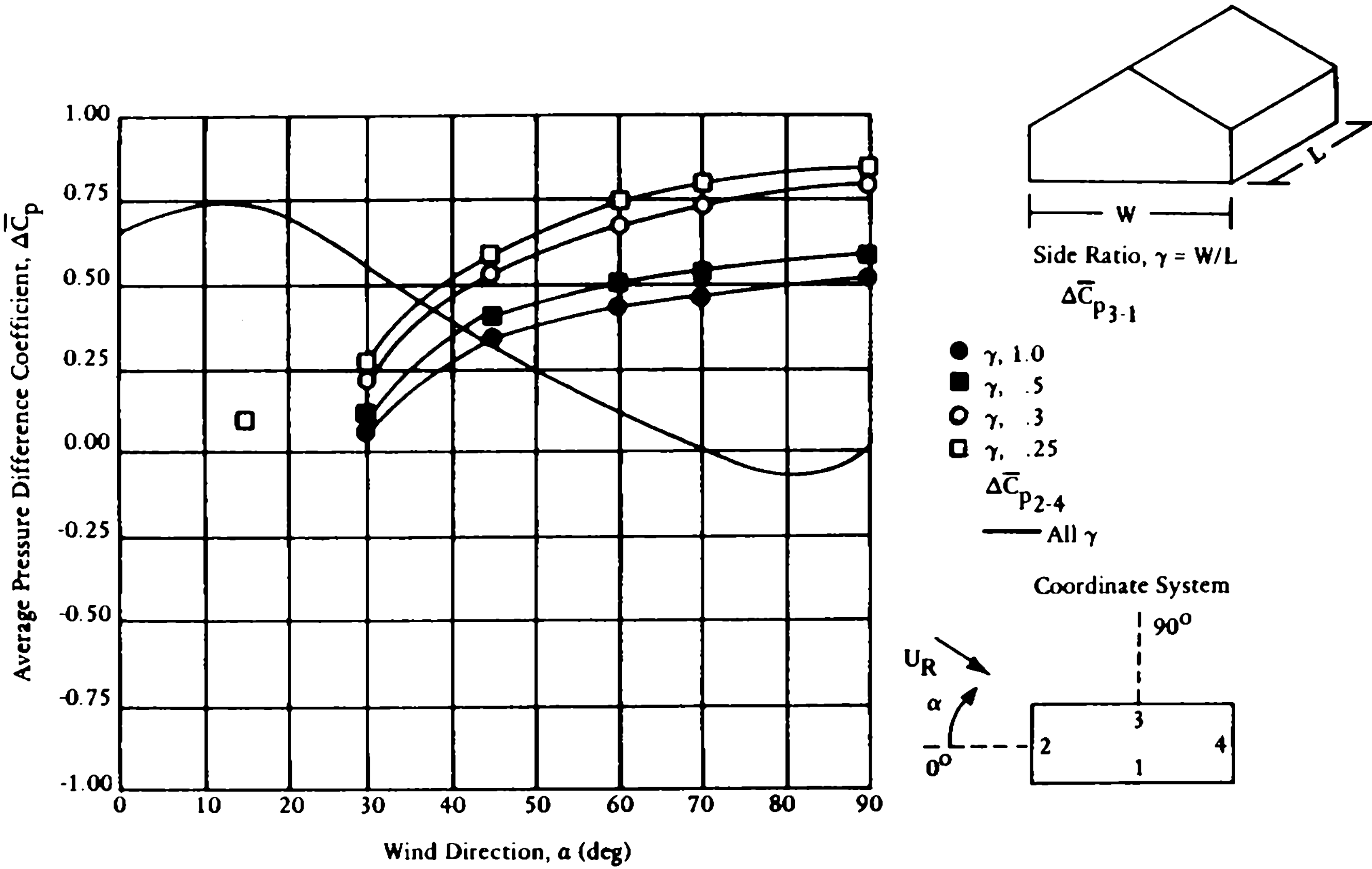

Figure 1(a) Average pressure difference coefficient for a single-story, on-grade, pitched-roof rectangular building. $\Delta\overline{C}_{p_{3-1}}$ and $\Delta\overline{C}_{p_{2-4}}$ is the pressure difference coefficient between long and short walls of the building.

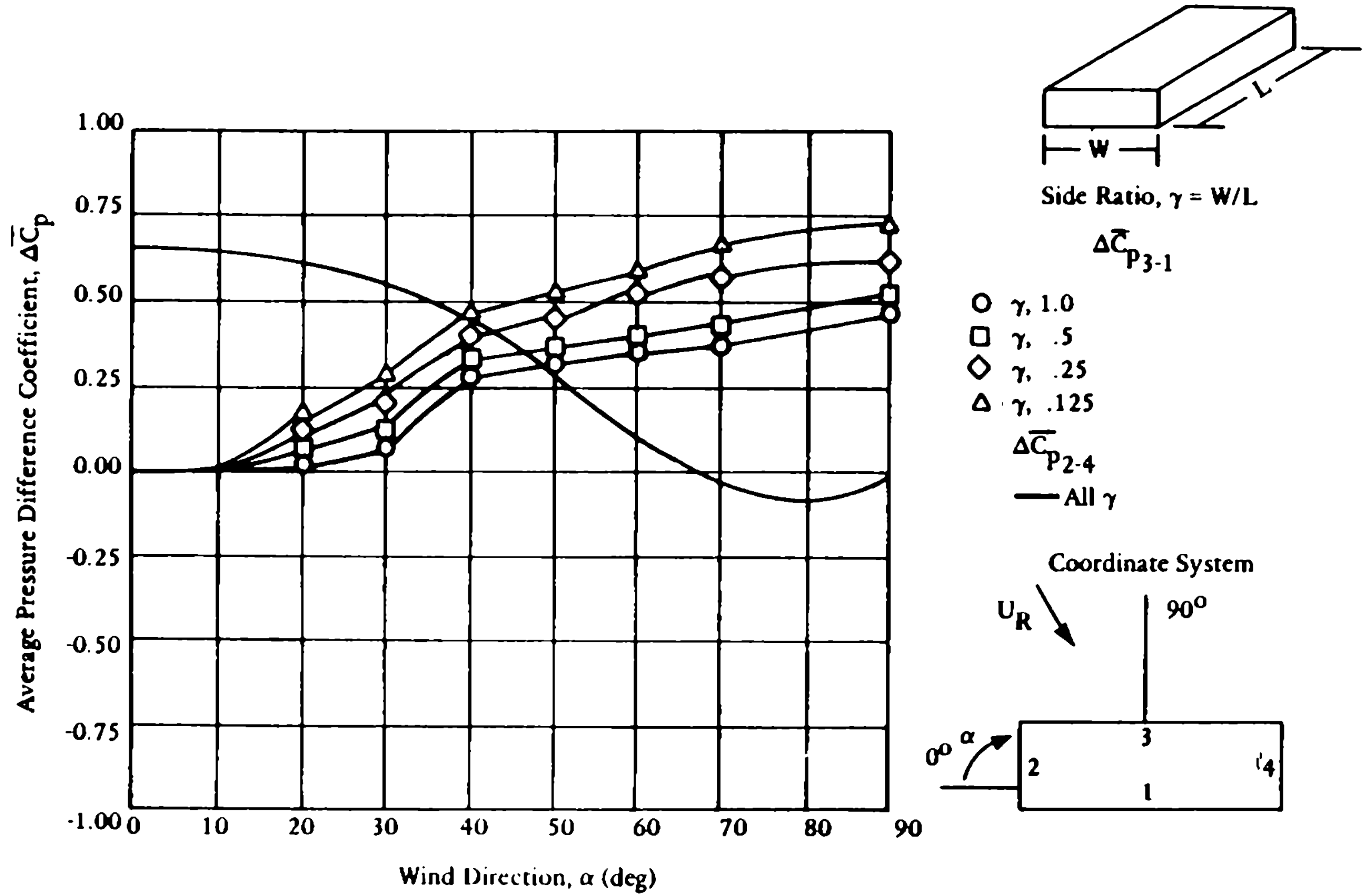

Figure 1(b) Average pressure difference coefficient for a single-story, on-grade, flat-roof rectangular building. $\Delta\bar{C}_{p_{2-1}}$ and $\Delta\bar{C}_{p_{2-4}}$ is the pressure difference coefficient between long and short walls of the building.

AIR INFILTRATION CENTRE - WIND PRESSURE WORKSHOP
Brussels, Belgium
21-22 March 1984

PAPER 9

FULL SCALE MEASUREMENTS OF WIND PRESSURES ON NAVY BUILDINGS
Summary of Remarks

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Summary of Remarks on

FULL-SCALE MEASUREMENTS OF WIND PRESSURES ON NAVY BUILDINGS

as presented by

Max Sherman

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During the summer of 1981 the Energy Performance of Buildings group made a set of full-scale measurements on three buildings at the Kaneohe Marine Corps Air Station (KMCAS) on the island of Oahu, Hawaii. The purpose of this study was to investigate the possible use of natural ventilation for cooling in the warm humid climate of Hawaii; this site is considered ideal for the investigation of natural ventilation because of the presence of the strong (i.e. 6 m/s average), steady, unidirectional trade-winds which blow all summer.

Three different types of buildings were measured for a period of approximately one week each. The weather (i.e. outside temperature, humidity, wind speed and direction) was measured at each site, as was the inside temperature and humidity. Furthermore, the interior and exterior surface pressures were measured relative to the static pressure in the wind. For each story of the building one interior and eight exterior pressure taps used: three windward, three leeward and one on each side; all three buildings were approximately oriented to take maximum advantage of the prevailing wind.

The first site was a two story, multi-purpose building (VEQ) with an approximate side ratio of 10:1. It had a very large amount of glazed area, half of which was openable horizontal louvers; it had overhangs and wing walls that were very efficient at trapping the wind. The second site was a side-by-side duplex that had very little openable area; the aspect ratio of this building was approximately 1:1 and it has overhangs but no wing walls. The third site was a side-by-side, up-and-down fourplex that had an aspect ratio of approximately 2:1. An interesting architectural feature of this site is that each apartment had an integral lanai (screen porch) in a leeward corner; this feature led to some ambiguity in the definition of the building envelope.

The results of this study will be published shortly by the Navy and will include a comparison to wind tunnel measurements of this site as reported by Sophia Ashley of the Navel Civil Engineering Laboratory. I can, however, make some preliminary observations from the full-scale data. 1) We measured pressure coefficients from -1.0 to 1.5. The value above unity are probably due to the inescapable fact that in a field measurement situation, one cannot always measure the exact same wind with the weather tower that is hitting the building. We believe that for some angles the tops of palm trees were shielding the weather tower and yielding a slightly smaller value of the wind speed (and hence maximum dynamic pressure) than would have been measured otherwise. We also tended to notice that for many of these buildings the leeward pressure coefficient was close to zero, even though the windward-leeward pressure coefficient difference had the expected value. 2) Over the octant of prevailing wind direction the pressure coefficients did not change significantly. 3) Infiltration predictions made with the LBL model agreed reasonably well with infiltration predictions made using the open area and measured wind pressures.

Once the study has been published by the Navy the data will be available for other researchers to use in their studies.

AIR INFILTRATION CENTRE - WIND PRESSURE WORKSHOP
Brussels, Belgium
21-22 March 1984

PAPER 10

USE OF WIND PRESSURE COEFFICIENTS IN THE LBL INFILTRATION MODEL

Summary of Presentation

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Summary of Presentation on

USE OF WIND PRESSURE COEFFICIENTS IN THE LBL INFILTRATION MODEL

as presented by

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The LBL model is a simple, physical, single-zone infiltration model. Since the description, derivation, and comparison of the model has been done elsewhere (AIC TN 11; Sherman & Grimsrud, Proc. 1st AIC Conf, 1980; Sherman & Modera, Proc. ASTM Conf on Infiltration Measurement, April, 1984), I will assume that the reader has some familiarity with it and I will discuss only the features relevant to wind pressure coefficients.

In the LBL model the stack and wind effects are calculated separately and then recombined; for the wind effect there is a parameter that contains in it all of the properties of the building and its immediate surroundings. The wind parameter is defined as follows:

$$f_W = C' \ (1-R)^{1/3} \ f_T \tag{1}$$

where:

C' is the generalized shielding coefficient

R is the fraction of leakage in the floor and ceiling

f_T is the terrain factor

The terrain factor is the means to correct the wind speed as measured at a weather tower to the site; the factor containing R adjusts the size of the wind effect relative to the amount of leakage that is in the walls relative to the floor and ceiling. Neither of these two factors will be discussed further.

The generalized shielding coefficient, C', reduces the effective dynamic pressure for the effects of local shielding in the immediate vicinity of the house. It can be calculated from the known exterior pressure coefficient at the site. In the LBL model there are five shielding classes and the value of the coefficient is determined from a table once the users has chosen the appropriate shielding class. The values for shielding class I (full exposed condition) were calculated from the wind-tunnel data collected by Cermak et al. at Colorado State University.

In order to make such a simple model of the wind effect several limitation had to be placed on the model; specifically, it includes no method for incorporating angular dependence as would be the case for unevenly distributed leakage, prevailing wind direction, or highly directional shielding (as might be the case for terraced housing), nor does it include a way to compensate for different side ratios. Thus, if any of the conditions are prevalent at a particular site, the LBL model could produce erroneous results for wind-dominated infiltration.

One straightforward method for solving this problem it to expand the definition of the generalized shielding coefficient to include some angular dependency. Depending on the level of accuracy desired, there are several procedures that could be used to accomplish this result. For example, if all the exterior pressure coefficients were known for a particular site as a function of angle, a generalized shielding coefficient could be calculated (once and on a computer) as a function of angle and then used, henceforth, in place of the tabular values, when calculating infiltration using the LBL model. Another procedure, which we have used, is to back calculate the shielding coefficient from measure wind, temperature and infiltration from full-scale measurements. This method has the advantage of being usable with the normally measured data that is available from full-scale test, while the former method is appropriate if scale-model testing is done.

AIR INFILTRATION CENTRE - WIND PRESSURE WORKSHOP
Brussels, Belgium
21-22 March 1984

PAPER 11

WIND PRESSURES ON ROOF VENTS

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WIND TUNNEL PRESSURES ON ROOF VENTS

Wind tunnel investigation of wind pressures on natural ventilation stacks have shown that it is important to take into account not only the shape, height and position of the stack on the roof, but also the local wind environment. This is espcially true when there are tall buildings whose descending wake can cause flow reversal.

These results were used in the Dutch Model Building Code NEN 1078 and in the Dutch Standard for Ventilation of Dwellings NEN 1087.

AIR INFILTRATION CENTRE - WIND PRESSURE WORKSHOP

Brussels, Belgium

21-22 March 1984

PAPER 12

WIND TUNNEL STUDIES ON THE EFFECTS OF LOCAL OBSTRUCTIONS ON WIND PRESSURES

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WIND TUNNEL STUDIES ON THE EFFECTS OF LOCAL OBSTRUCTIONS ON WIND PRESSURES

A wind tunnel study of wind pressures on the surface of building models was carried out at TNO. The effects of one building on the pressures experienced by another downwind were assessed. These were examined as a function of the height ratio of the two buildings and the separation between them. It was observed that the changes in the pressure on the side and downwind facades became insignificant for separations greater than about five times the height of the upstream building. The pressure on the upwind facade was significantly reduced at much greater separation.

AIR INFILTRATION CENTRE - WIND PRESSURE WORKSHOP
Brussels, Belgium
21-22 March 1984

PAPER 13

PRESSURE COEFFICIENT DATABASE FOR AIR INFILTRATION CALCULATIONS

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PRESSURE COEFFICIENT DATABASE FOR AIR INFILTRATION CALCULATIONS

Predicting air infiltration in buildings forms part of the Building Research Establishment's (BRE) programme of work on ventilation. The calculation models which are used to do this require as an essential input the surface pressure coefficients of the building being considered.

We have found that at present there is no comprehensive database that could be used satisfactorily for air infiltration calculations. This has been confirmed by the discussions that have taken place at this Workshop.

Work has started at BRE to develop such a database. Measurements are made in the BRE Environmental Wind Tunnel. This has an open working section which is enclosed in an air-tight operating chamber. The effective cross-sectional area of the working section is 2.00m wide by 1.25m high. The flow is produced by two parallel, aerofoil-bladed centrifugal fans and can be controlled to give any desired air speed of upto 23 m/s.

The airflow is artificially roughened by using various flow conditioning devices upstream of the model. By the correct choice of these devices, we can provide partial-depth simulation of turbulent atmospheric boundary layers formed over different terrains. Such simulations can provide us with a length scale of 1:200 between model and full scale. The models are mounted on a 1.75m diameter turntable which is rotated under computer control.

During our tests, we are considering the effect of the following parameters:

1. Building type

   - house

     detached

     semi-detached

     terraced

       in a 3-house row ... centre and end house

       in a 5-house row ... centre, off-centre and end house

   - Offices

2. Roof pitch

3. Roof height

4. Layout pattern of surrounding buildings

5. Density of surrounding buildings

6. Terrain

   rural

   suburban

   urban

7. Wind direction

Surface pressures on model buildings are measured through small copper tubes mounted flush with the surfaces. These are connected by short lengths of flexible tubing to a 48-way selector valve. Any pressure measuring port can then be selected by activating the valve from a PDP 11/35 minicomputer. The valve connects the tappings to a sensitive pressure transducer which converts the pressure fluctuations into corresponding linearised voltages. These signals are then fed into the front end of the computer for digitising and storage.

The resulting raw data is processed and at the end of each test, the final results are tabulated in the form of,

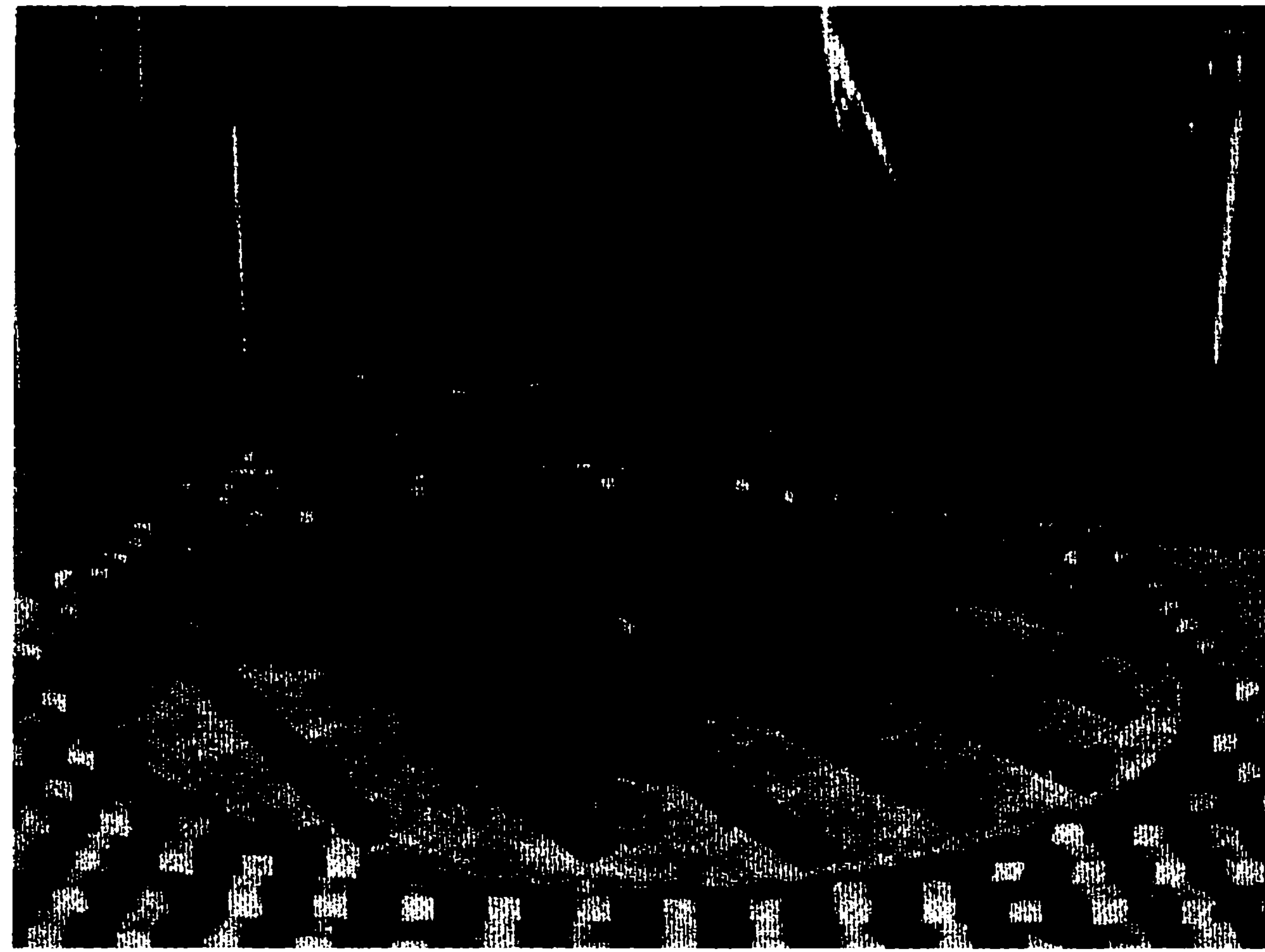
- port location
- mean pressure coefficient
- rms pressure coefficient
- skewness of the pressure fluctuations
- kurtosis of the pressure fluctuations
- pressure coefficient corresponding to the highest 5% of the fluctuations
- pressure coefficient corresponding to the lowest 5% of the fluctuations

The pressure coefficients are calculated by normalising the surface pressures with the reference dynamic pressure. The reference pressure is measured upstream of the building model and at a height corresponding to the roof eave of the model.

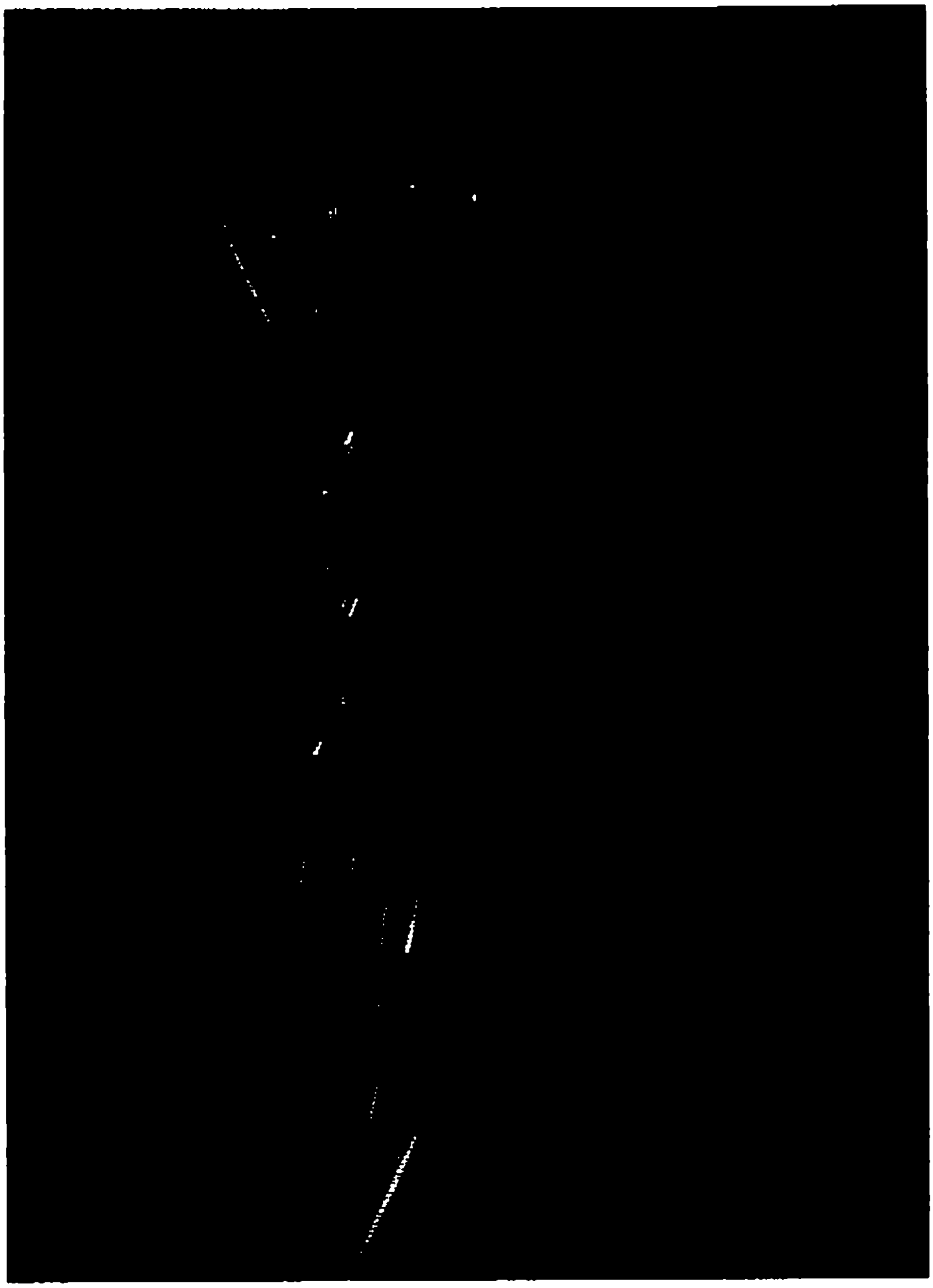
These are then archived onto storage discs together with headers corresponding to

- test identifier
- wind speed
- wind direction

The stored results can then be pulled out for subsequent use either as point pressures or can be further processed to give area-averaged pressures.



A view from inside the BRE Environmental Wind Tunnel,
looking upstream of the airflow.



A model of a house, pressure-tapped for wind tunnel testing.

AIR INFILTRATION CENTRE - WIND PRESSURE WORKSHOP
Brussels, Belgium
21-22 March 1984

PAPER 14

COMBINED EFFECT OF WIND, TEMPERATURE AND MECHANICAL VENTILATION ON PRESSURE DIFFERENTIALS FOR AIR INFILTRATION CALCULATION

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COMBINED EFFECT OF WIND, TEMPERATURE AND MECHANICAL VENTILATION ON PRESSURE DIFFERENTIALS FOR AIR INFILTRATION CALCULATION

The prediction of the energy requirement due to air infiltration and/or exfiltration through the building envelope is still difficult. A considerable discrepancy has been observed between the measured air leakage of multi-storey buildings and that calculated by the ASHRAE recommendation.

The air infiltration and exfiltration of a high-rise building is mainly due to the characteristics of the wind environment around the structure, the thermal gradient across the building envelope and mechanical ventilation. The first two causes are found to be predominant in a full scale observation of a twenty-storey apartment building [1].

Following the above mentioned full-scale measurement, the verification of both wind and thermal effects on the pressure differentials was attempted using a wind tunnel simulation for the former and a heated vertical duct for the latter [2,3].

The special problem of the combined effect or interaction of various causes on the total pressure was encountered during the data reduction. While it was assumed in the above analysis that the differential pressures caused by multiple reasons were given by a linear summation of the pressure caused by each individual action, this may not be true in reality. The case when the wind and mechanical ventilation acting together was extensively investigated and the non-linearity of both induced pressure differentials and air infiltration and exfiltration was discussed [4]. The combined action of stack effect and mechanical ventilation system operation is now under investigation.

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AIR INFILTRATION CENTRE - WIND PRESSURE WORKSHOP
Brussels, Belgium
21-22 March 1984

PAPER 15

EFFECT OF SURROUNDING TOPOGRAPHY ON PRESSURE DISTRIBUTION AT HUDAC TEST HOUSE

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EFFECT OF SURROUNDING TOPOGRAPHY ON PRESSURE DISTRIBUTION AT HUDAC TEST HOUSE

A 1:100 scaled model of a HUDAC test house was tested in a wind tunnel to measure the wind-induced pressure to calculate air infiltration rate (see Figures 1a and 1b).

The HUDAC test house was used for the simultaneous measurement of airtightness and air infiltration rate as well as the wind-induced pressure in a suburban area by DBR/NRCC as a part of Mark XI Energy Research Project [1,2]. Unfortunately the measurement of the wind-induced pressure difference across the building envelope at the site was rather limited and the important direct parameter to decide actual infiltration rate was missing.

The present study is to fill in this gap by carrying out the wind test for the measurement of the pressure distribution. The measurement made it possible to apply the previously measured airtightness coefficients for the calculation of air leakage rate at these houses for any given reference wind conditions, and consequently the comparison of these estimated values of air infiltration rate with the infiltration measurements.

The data shown at the Wind Pressure Workshop are a part of the results from the study, and attention is focussed on the effect of surrounding topography on pressure distribution. The wind tunnel test was repeated with and without proper proximity around the model building. It is self-explanatory that the effect of surroundings is clearly pronounced as a difference in pressure distribution. This is an interesting comparison because of the fact that the previously compared air infiltration rate on the same building by Shaw[2] was based on the pressure coefficients given by Bowen[3], which was the testing of an "isolated, tall building".

Figures 2a and 2b compare the calculated *vs* measured air infiltration rate for the test house using NRCC pressure coefficients on a "Tall Building Model" and pressure measured at the present study with proper proximity. The agreement is remarkably improved when properly measured pressure coefficients are applied.

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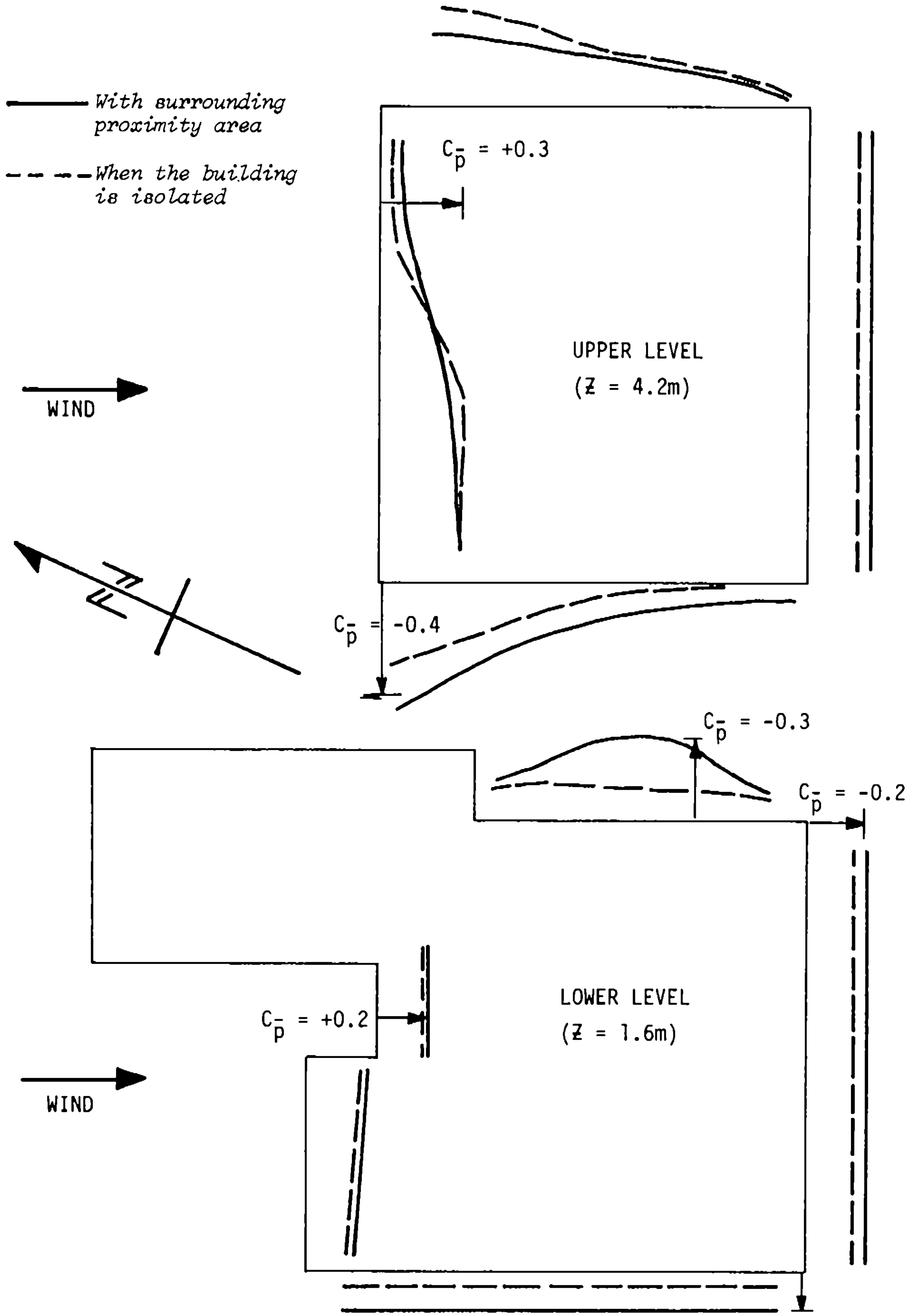
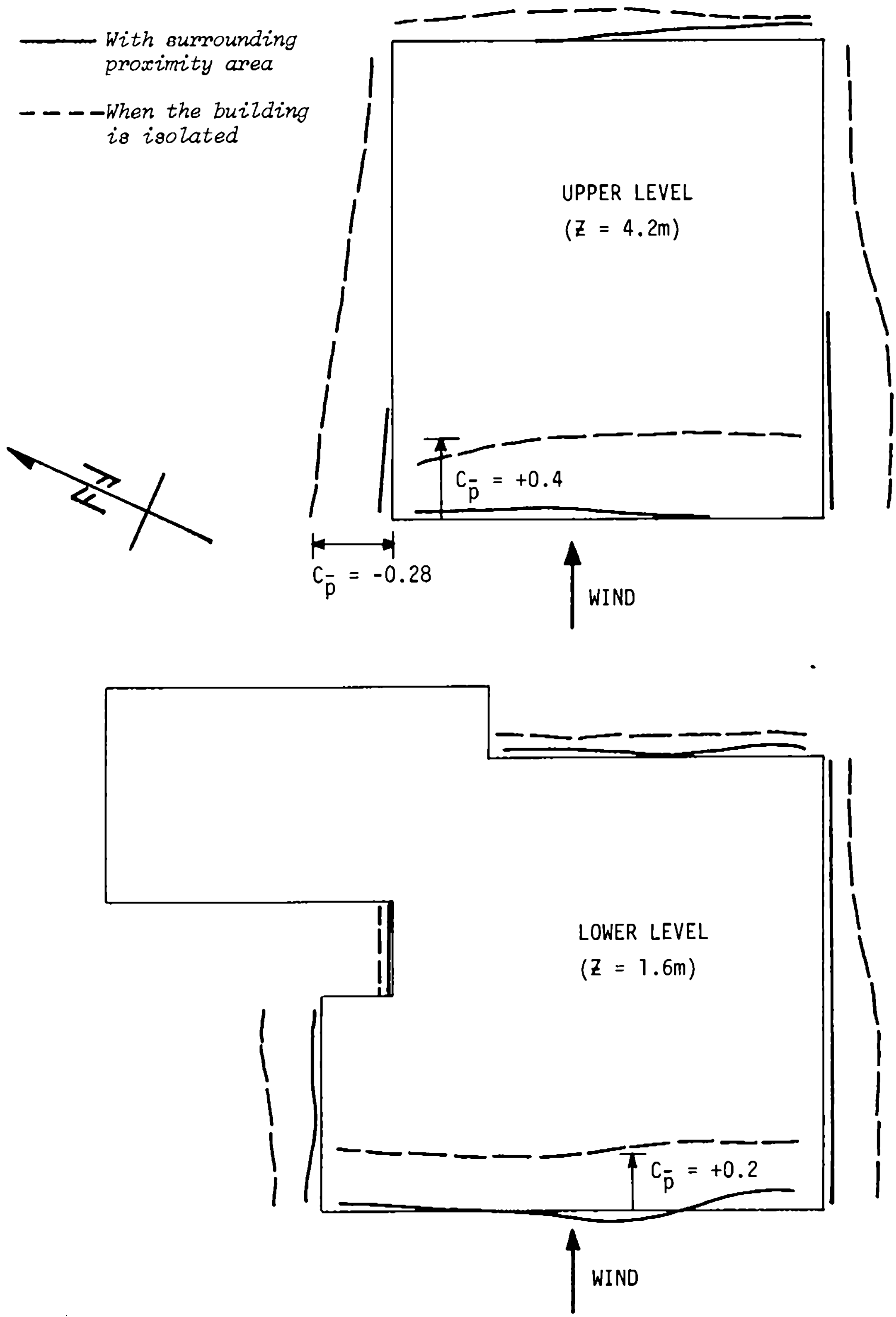
3. Bowen, A.J.
   LTR-LA-209, NAE/NRCC, 1976

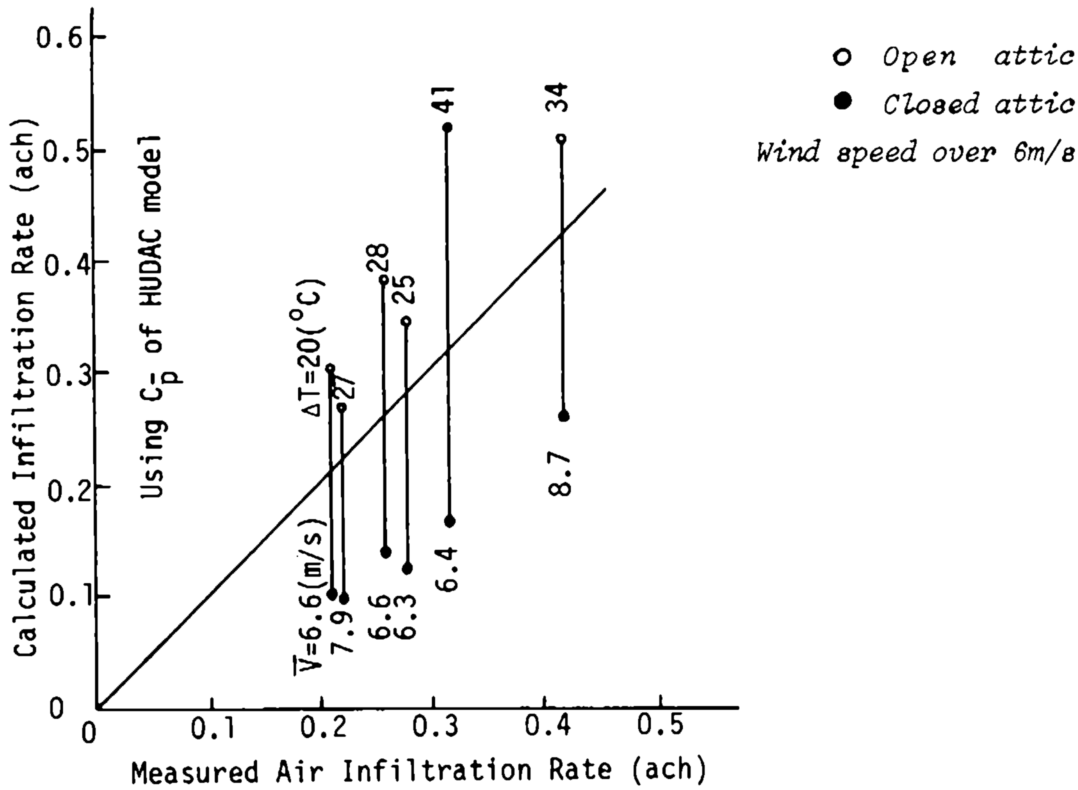
WIND-INDUCED PRESSURE ON "HUDAC" MODEL HOUSE - Figure 1a

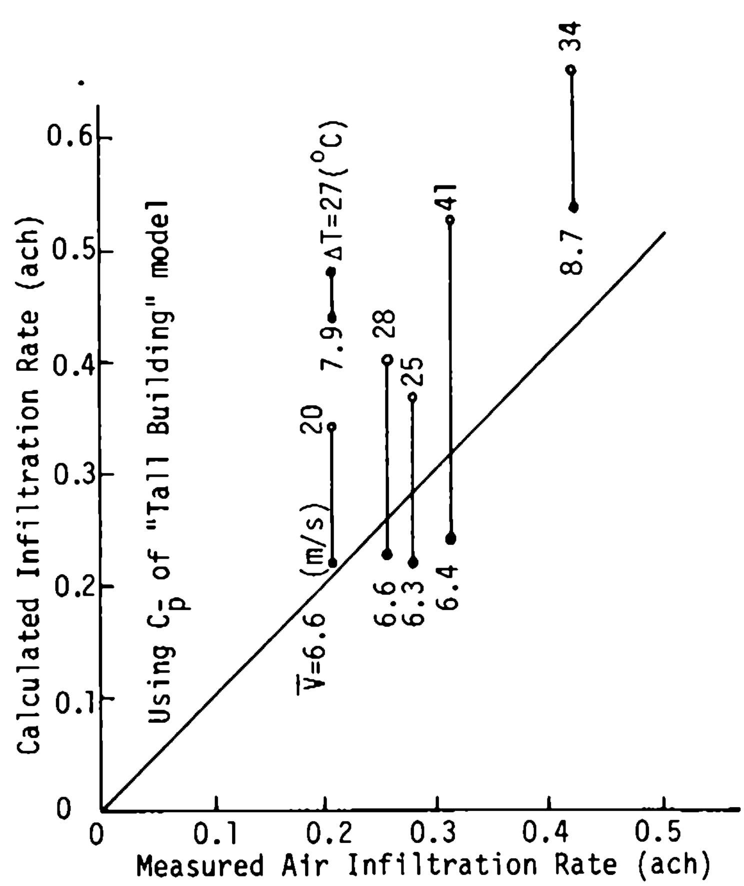


WIND-INDUCED PRESSURE ON "HUDAC" MODEL HOUSE - Figure 1b



CALCULATED vs MEASURED AIR INFILTRATION RATE FOR THE HUDAC "STANDARD" HOUSE (EFFECT OF $C_{\bar{p}}$) - Figures 2a and 2b





DISCUSSION

Presentation: Wind Pressure Data Requirements for Air Infiltration Characteristics (AIC Technical Note No.13) by C.M. Allen

K. Handa (Sweden)

1. The document presents an analytical review of the wind-induced loads and attempts to apply to ventilation problems. Such a review is unnecessary in 1983 as there are plenty of review papers dealing with the wind loading problems. What is lacking is suitable information for application to wind-induced ventilation. The document does not present any new advances in the field of air flow through buildings.

2. The review is based on the British code of practice CP3 and a book by Sachs which are irrelevant for air flow studies. For example, pages 11-14 of the document have no application today, as even the new Canadian code has omitted them. What is the point of including something old, when the new information is available ? Similarly, pages 9 and 10 are not applicable, as the gust factors are for extreme values of velocity and pressures for a given probability of occurrence. I am afraid that Chapters 2 and 3 are repetitions of phenomena well known to people working in the field of air flow through and around buildings. These chapters should be deleted completely or re-written with emphasis on air ventilation rather than on wind loads.

3. For wind-induced ventilation purposes, distribution of wind velocity and direction over the whole year are needed. The probability density function for the parent distribution may be expressed by Weibull or Rayleigh functions based on the data collected from meteorological stations. The averaging period should be 10 minutes as recommended by the World Meteorological Organisation (WMO). Methods for describing the yearly wind velocity and direction distribution for Denmark are presented in ref. A1. This type of information is needed for use in the evaluation of rate of air flow through buildings.

Now, the document does not deal at all with the annual wind velocity and direction distribution, which is the basic element needed in the assessment of the air exchange rate. What the document does is to give wind velocities based on extreme value analysis.

4. Clarification is needed for expression 4.2 on page 25.

$$q = \frac{\rho}{2} \left[\bar{U} + n\, u' \right]^2 \qquad (4.2)$$

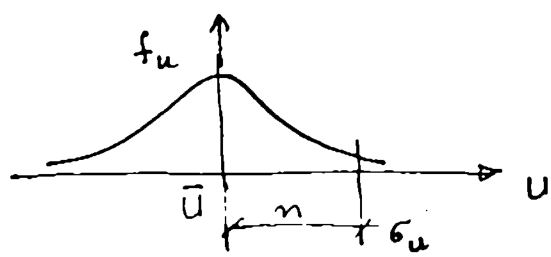
Expanding this expression, we get

$$q = \frac{\rho}{2} \left[\bar{U}^2 + \underbrace{2\, n\, u'\, \bar{U}}_{\text{linear}} + \underbrace{n^2\, u'^2}_{\text{non-linear}} \right] \qquad (4.2a)$$

Now, if we assume that the wind fluctuations u' are normally distributed, then the square of u' need not be normally distributed. I should like to know the physical significance of n and n^2.

In the wind loading problem, one generally uses the linearized version of equation 4.2a, written as

$$q = q_m + n\, \sigma_q = \frac{\rho}{2} \bar{U}^2 + \frac{n\rho}{2} \bar{U}^2 \cdot \frac{\sigma_u}{\bar{U}}$$



where σ_u and σ_q are the standard deviation of the velocity and pressure. n represents the distance between the mean values and the standard deviation. The statement on page 25, ".... that a value of n = 4 does the same for RMS coefficient .....", does not tie up with the physical processes and assumptions. Perhaps the authors have something else in mind which is not explained on page 25.

5. Another important question relates to the definition and values of the intensity of turbulence. The fluctuations may be grouped into three categories:

(i) those caused by the passage of air over large obstacles (hills, forests, semi-urban areas, etc.)

(ii) locally generated turbulence from the structure itself

(iii) convective turbulence

For wind loading problems, the fluctuations caused by large obstacles (type (i)) are the main contributing factor, as one is dealing with high wind velocities (V > 20 m/sec).

For ventilation purposes, low wind velocities are of interest (2 < V < 8 m/sec), and the convective turbulence can be an important contributing factor. The turbulence generated by the house is another factor which influences the flow through small openings, cavities, cracks, etc. Hence the type of turbulence encountered in wind-induced ventilation need not follow the same pattern as for high winds. The authors of the document have not elaborated on this point and have repeated what is already written in many other review papers.

6. One of the most important parameters is the internal pressure. Scanning through the documents, one finds that nothing specific is mentioned. The location and size of openings influence the internal pressure. A designer of natural ventilation systems needs to know the influence of openings located in areas of local high suction (corners, edges, etc.) on the efficiency of the system. In my opinion the document should address those problems for which there is not enough information available and should suggest some guidelines for analysis. The document should not concentrate on the pressure coefficients based on CP3 or from the book by Sachs, as their validity for ventilation purposes is in doubt.

7. In Chapter 7, Fourier series analysis is presented. The method is illustrated with the help of wind tunnel models.

The models tested in the wind tunnel are for assessing the pressure distribution for wind loading purposes. The influence of locally-generated turbulence from the building, internal pressure variation and convective turbulence is not included. For wind loading models, these tests are excellent. When extending to the wind-induced ventilation studies, the properties of the house become important. Various countries have different requirements for construction, materials, methods of design, type of ventilation system, etc. The air infiltration in a house is the result of interaction between wind, temperature and the structure. This is particularly true when dealing with low wind velocities, variable directions and large temperature differences. To fit the Fourier series to a limited number of data taken from the wind-loading models and suggest that they can be applied to air ventilation design is not recommendable.

Moreover, on page 40, the expression for C_p is

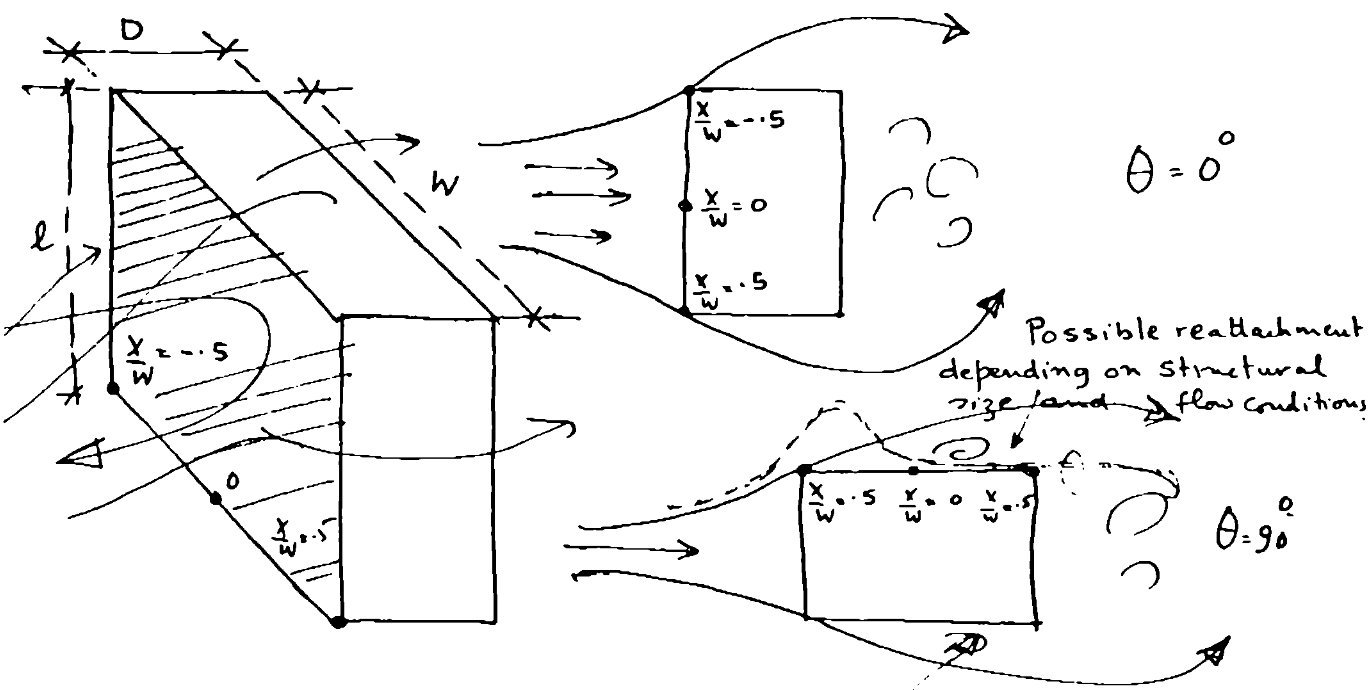
$$C_p = A + B \left(\frac{x}{w} \right)$$

On page 41, the limits for x are $(-0.5 < x \leq 0.5)$. Is x in metres ? Perhaps the authors mean that $\frac{x}{w}$ lies between -0.5 and 0.5.

Values of C_p are calculated based on the information given on pages 40 and 41 and are shown in the table below*.

θ	A	B	$C_p(x/w) = 0$	$C_p(x/w) = 0.5$	$C_p(x/w) = -0.5$
0	.65	0.0	0.65	0.65	0.65
20	.55	0.5	0.55	0.80	0.30
40	.45	0.8	0.45	0.85	0.05
60	0	0.1	0.05	0.05	-0.05
80	-0.4	-0.75	-0.4	-0.025	-0.775
90	-0.55	-0.7	-0.55	-0.20	-0.90
120	-0.5	+0.05	-0.5	-0.475	-0.525
180	-0.3	0	-0.3	-0.3	-0.3

* *Corrected values according to Dr Liddament*



Examination of the table shows that the pressure coefficient on the front face is constant independent of the size of the building, surface roughness characteristics and the level of turbulence present in the flow. For loading purposes, the use of evenly distributed pressure distribution may be an adequate model but for ventilation purposes, the location and size of the openings are important and hence a more systematic picture of pressure distribution is needed. I am afraid that the technique presented in this section is applicable to a particular example studies by the author and is not of general application.

However, the authors of the document have taken two sets of data from different experiments under different conditions by different authors (Aiken and Bowen, page 36) and then fitted Fourier series to obtain C_p factors. I would not personally place much faith in the values of C_p obtained in such a manner.

8. In our view, the problem of wind-induced ventilation should be tackled by studying the behaviour of wind at low speeds for different wind directions. Influence of locally-induced fluctuations and convective turbulence on the air infiltration should be examined. A study of the inter-dependence between the internal pressures and the location and size of openings is needed. Analytical expressions for the air flow through cracks, joints, etc. should be developed and the existing procedures for calculating the rate of air flow needs to be verified.

In Sweden, full-scale and wind tunnel measurements are being carried out for the purpose of studying wind-induced ventilation and this type of investigation should form the basis of the document for wind pressures. People actually working with the measurements realize the importance of various parameters needed in the evaluation of air exchange rate.

We suggest that a meeting of workers actually engaged in this field should be arranged in order to formulate a document. We should also like to emphasise that a document dealing with loading problems is not needed and the proposed document should not be published.

Reference A1: Erik Lundtaug Petterson, Ib Troen et al
Wind atlas for Denmark
RISO January 1981
RISO National Laboratory, Roskilde, Denmark.

C. Allen (U.K.)

Of the factors affecting air infiltration, the characterisation of the wind pressure distribution on the surface of the building and the estimation of the leakage distribution have proved the most difficult to establish. The review document AIC-Technical Note 13 and this report of the Wind Pressure Workshop constitute an effort to tackle the first of these weak points. The leakage problem is part of our future work program.

In both cases, however, the required end result is a workable data set for practical use by the architect or consulting engineer which will yield a value for the air infiltration of a building to the desired level of accuracy. This level of accuracy is somewhere in the region of ± 20-25%. The pursuit of perfection is the province of the academic.

The yardstick for judging the usefulness of existing data must be whether they can be used in a model and produce results with this sort of level of accuracy and, if so, under what sets of conditions. This problem was addressed in the Model Validation Report (AIC Technical Note 11).

Published pressure coefficient data has proved useful for modelling infiltration of exposed buildings, while wind tunnel studies such as that by Bowen, specifically commissioned for air infiltration purposes, have proved better for sheltered buildings. The more modern standards are mostly based on extreme value analyseus, are specifically aimed at wind loading and therefore cannot be used for air infiltration modelling. The older standards are based on maximum values of the mean pressure coefficient and therefore can be used, at least for the cruder purposes such as sizing heating systems.

With regard to the need for weather data, we are entirely in agreement. This material is, however, site specific and thus more suited to treatment elsewhere.

Section 4.1 reports on the reference winds which have been used by various workers in the definition of their pressure coefficients. The result queried was published by Corke and Nagib and therefore attention was drawn to it. For an explanation, it would be appropriate to discuss it with these authors. I would also like to draw your attention to a paper by T. Katayama in J.W.E.I.A. 15 (1983) pp27-38, in which is given a theoretical justification for an equation of the form:

$$\frac{P}{2}.C_p.(u^{-2}+\sigma^2)$$

The role of turbulence is admittedly of importance. At the time of writing Technical Note No.13 there was very little quantitative data. This precluded a more detailed treatment. The measurements by Dalgliesh were considered. A wind tunnel study by Kareem and Cermak (J.W.E.I.A. 16 (part 1)(1984) pp17-41) deals with the turbulence created by the building itself. The scant attention paid to turbulence was mainly due to the fact that very few models make provision for it and then only crudely.

The internal pressure is usually the unknown for which the equations of a model are solved rather than an input parameter. Internal parameters have been covered in many other reports and reviews, e.g. as referenced in AIC Technical Note No.8.

The method of Fourier analysis can be used on any function continuous in a closed interval. In AIC-TN-13, it was used at three levels:

1. Mean pressure coefficients for a whole facade,

2. Mean values at a given relative height (vertical distribution), and

3. Mean values for individual pressure taps (horizontal distribution).

The Bowen and Akins data were selected because of their completeness and the comparability of the conditions under which the experiments were carried out. The Bowen data was used successfully in infiltration modelling, so the primary function of the analysis was rather to find a way of systematically describing it for entry into a computer rather than shedding any further light on its validity.

The treatment of the horizontal variation of the pressure distribution was of type 3 above. The analysis was applied for a specific value of the relative height for a given side ratio. It was nowhere implied that the result was universally applicable. What was implied, however, was that valuable information could be extracted in the form of Fourier coefficients. I must apologise for a typographical error that crept through. The bracketed term should have read $(-0.5<x/w<0.5)$*, indicating that* w *referred to the whole width of the facade rather than the half width. With only seven pressure taps being used for the fit, one would not be justified in using anything more complex than a straight line. It should be pointed out that the points* ± 0.5 *lie outside the range of the measured values. Nevertheless, the skewed pattern of the pressure distribution is clearly shown (see also the paper by Palffy in this document). Greater attention on this point will have to await further development of model input procedures.*

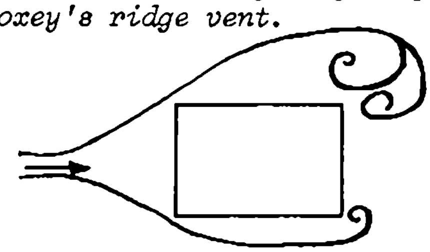
There are many features of importance including those you mentioned and also others such as internal temperature gradients, mixing and variation of wind direction as well as the wind speed, which might be taken into consideration in a model. One must ask, however, whether these would constitute unnecessary complication.

With regard to the development of analytical expressions for leakage, I am rather doubtful. Preliminary calculations using a simple duct/resistance network model loosely based on Johnny Kronvall's method have indicated that, at least for for smaller cracks, the calculated flow is very sensitive to the input parameters. A large change in flow was found to accompany changes in the input parameters which were an order of magnitude smaller than the measurement error for the field measurements on which the model calculation was based. This implies that such theoretical calculations would be difficult if not impossible to validate.

There is some room for improvement in the models, however, since there is a tendency to overestimate infiltration rates at high wind speeds and to underestimate them at low wind speeds. There is also room for adjusting the means by which mechanical ventilation is included (see paper by H. Tanaka in this document).

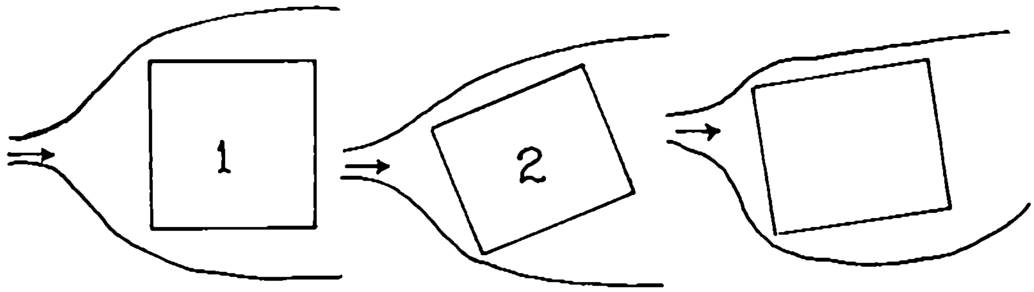
Presentation:	Full-Scale Wind Pressure Measurements on Low-Rise Buildings by J. Gusten
C. Allen (U.K.)	1. What was the frequency response of your manometer ?
	2. What reference wind was used for your pressure coefficients ?
	3. Where there any temperature effects on the measurements ?
J. Gusten (Sweden)	*1. About 3 seconds.*
	2. Roof ridge wind speed.
	3. The problem was avoided by not sampling on sunny days.

Presentation:	Computer-Friendly Method for the Representation of Surface Wind Pressure Data by C.M. Allen
E. Perera (U.K.)	You said that wake turbulence caused by the building itself will influence the base pressure, i.e. the leeward pressure. My thesis is that the base pressure coefficient is rather invariant and that this, a consequence of the turbulence of the approaching wind, dominates any other local effects. Could you comment on this ?
C. Allen (U.K.)	*I am not talking about the base pressure but that on the whole facade. Wake pressure appears to be dominated by the degree to which it is ventilated, either by ambient turbulence or where a large opening is present in the wake region which allows air to enter the wake by other pathways than around the building, e.g. Sophia Ashley's large windows, Roger Hoxey's ridge vent.*



The regions I referred to are on the side faces. Here, flow is dominated by the vortex shedding mode - the amplitude, frequency spread and reattachment point being modified by ambient turbulence (see paper by Kareem and Cermak, J.W.E.I.A., 16, pp17-42).

The r.m.s.m. should show the biggest amplitude for angled flow in the region of the transition between detached (figure 1) and attached (figure 2) flow when the flow is at its most unstable. This is borne out to some extent by the field observations of Dalgliesh.



H. Tanaka (Canada)

Regarding the effect of wind-induced C_p on air infiltration rate and application of A. Bowen's data:

Comparison has been made of measured Q at HUDAC house with calculated Q using Bowen's data and the measured C_p on the HUDAC house wind tunnel model. Major points are as follows (see paper 15 in this document):

1. Effect of immediate surroundings on C_p is pronounced.

2. Better estimate of Q achieved using properly measured C_p.

3. When the wind speed is not high ($\bar{V}$ < 7 m/s say), the effect of C_p was not significant because the stack effect was predominant.

Conclusion 3. above should not be understood that any crude set of C_p is applicable for the calculation of Q. It emphasises the importance of exact estimates of Q induced by stack effect.

Presentation: Use of Wind Pressure Coefficients in the LBL Infiltration Model by M. Sherman

D. Etheridge (U.K.)

1. Does the coefficient of C' in your model depend only on the external pressure coefficients C_p ?

2. Does your model predict that there is no effect of wind direction on the ventilation rate of terraced (row) houses ?

M. Sherman (USA)

1. *The quantity C' in the LBL model is calculated only from the exterior pressure coefficients. It is done once in a computer by determining the interior pressure coefficient that would make the wind-induced infiltration balance the exfiltration. The procedure has built-in assumptions about the isotropy of leakage and wind direction.*

   This procedure must be contrasted with the plot I showed at the workshop. The plot showed a measured value of C' as a function of angle. By measured, I mean that we measured the wind speed, temperature and infiltration and then back solved to find the C' that agrees with these measurements. In this sense, C' *depends on all of the house parameters, but does not use exterior pressure coefficients at all. This measurement procedure might be useful as a way of generalising the model for anisotropic cases.*

2. *In an orthodox version of the LBL model, there is no way to take account of anisotropy effects as would be the case for concentrated leakage sites or row housing. As Dr Liddament points out, however, these types of situations can be handled by assigning a different shielding class for each wind octant. A more general modification of the LBL model would be to use an empirical value for C' that would be a function of wind angle. This could be done by using a set of pressure coefficients from a wind tunnel or by making full-scale infiltration measurements and calculating C'.*

CONCLUDING REMARKS

M. Sherman (USA)

During the course of this workshop, I have heard some very technical issues discussed. They have included questions about the correct choice of stability for wind tunnel testing, the use of data intended for loading in infiltration work, the level of accuracy and precision needed, the format for the presentation of different types of data, etc. This discussion has centred primarily on exterior pressure coefficients, which may be appropriate if wind loading were our aim, but our purpose for this workshop is to find out what wind data is needed in order to calculate infiltration.

Even though exterior pressure coefficients may be used in various infiltration models, the calculation procedures always use sums of differences of pressure coefficients to determine one part of the total infiltration. Many errors that might be crucial in the determination of an individual pressure coefficient become completely insignificant in terms of the calculated infiltration. We must not, therefore, readily enter into debate on issues that to us are moot.

Although we must be careful to stay away from irrelevant issues, there are several issues we have touched on that are quite important. While researchers and model developers may be quite comfortable dealing with pressure coefficients, stability criteria and turbulence intensity, the practitioners who must use the models are unlikely to be. The outcome of our work must be in a form that is simple enough to use, but that retains the essential qualities. I assert that the traditional methods of expressing exterior pressure coefficients as a function of angle are not appropriate for the vast majority of the infiltration community, but rather a simplified method of presenting the data must be found.

The method I have suggested, of using the LBL model's generalized shielding coefficient as a function of angle, is one such method but whatever the choice there must be some method of presenting the digested results of the work of the research community. The existence of such digested wind pressure results would allow the user community to benefit from the work of the research community without undue intellectual burden. I would expect that a set of digested results for the dozen most common building types and a set of reduction factors for various sheltering conditions should be able to fit on a single page of paper.

To summarise my own impression of this workshop, I would hope that the wind engineering community would make its expertise and data available to the infiltration research community and that, between these two groups, a method for using wind data to generate usable infiltration results could be developed.

C. Allen
(U.K.)

Where do we go from here ? On the technical front, there are several avenues which may be pursued. There is a large quantity of wind tunnel data in existence but most of it is for individual, specific cases and, as such, difficult to analyse. The results of systematic studies could, however, be put to good use in finding a numerical representation of mean surface pressures which can easily be incorporated in models which use exterior pressure coefficients.

There is evidence from field measurements of air infiltration, that flow reversal is the rule rather than the exception. This indicates a need to pay attention to the role of fluctuating pressures, especially when calculating individual room ventilation rates. The development of a statistically-based approach may be of use, particularly for buildings in urban areas where the variation in wind speed and direction is large compared with the mean flow.

Effort should be made to achieve maximum simplicity of the presentation of results, compatible with acceptable accuracy, so that they can be used by the practising architect and consulting engineer with minimum difficulty. The wealth of information brought to the attention of the workshop will prove invaluable in furthering progress.

ADDITIONAL LITERATURE

The following additional papers on various aspects of wind pressure on buildings have been acquired by the Air Infiltration Centre since the Wind Pressure Workshop.

(1) Ashley S. Sherman M.
#NO 1359 The calculation of natural ventilation and comfort. Preprint ASHRAE Trans. 1984 vol.90 pt.1 19pp. 10 figs. 3 tabs. 13 refs. #DATE 01:01:1984 in English #AIC 873
ABSTRACT
Natural ventilation can be used to reduce cooling loads and increase human comforts in buildings in hot humid climates. Airflow rates are determined by the wind pressure on the faces of the building and the amount of open area. Describes wind pressure coefficient measurements made on 2 buildings at the Kaneohe Marine Corps Air Station on the island of Oahu, Hawaii during summer 1982. These full scale measurements will be compared to reduced-scale measurements made of the boundary-layer wind tunnel at the Naval Civil Engineering Laboratory. Estimates of the indoor comfort levels for different window conditions will be used as a basis for determining the acceptability of natural ventilation for cooling.
KEYWORDS
natural ventilation, wind, pressure coefficient, wind tunnel,

(2) Harrje D.T. Buckley C.E. Heisler G.M.
#NO 1206 Building energy reductions - windbreak optimization. ASCE International Convention and Exposition May 9-15 1981 NY = Journal of the Energy Division vol.108 no.EY3 November 1982 p.143-154 11 figs. 1 tab. 14 refs. #DATE 09:05:1981 in English #AIC 759
ABSTRACT
Uses wind tunnel model studies of houses to determine how best to reduce the surface pressure variations from wind and the associated air infiltration emphasizing the correct placement of suitably modelled coniferous trees. Finds that tree crowns convert the directed kinetic energy of approaching wind into random turbulent energy, which reduces pressure gradients on the windward walls, a prime region for air infiltration. The most cost and energy effective windbreaks are those that selectively protect against prevailing winter winds, use as few trees as possible, and are placed at least 2 tree heights upstream. Using an optimum planting pattern, an estimated 10 in energy for heating can be achieved.
KEYWORDS
windbreak, trees, modelling, wind tunnel, surface pressure,

(3) Holdo A.E. Houghton E.L. Bhinder F.S.
#NO 1282 Effects of permeability on wind loads on pitched roof buildings. Jnl of Wind Eng.Ind.Aerod. vol.12 1983 p.255-279 20 figs. 15 refs. #DATE 01:01:1983 in English #AIC 808

ABSTRACT
Studies the effects of permeability on the wind loading on a building. Compares experimental results from wind-tunnel tests with theoretical methods for estimating the mean and fluctuating internal pressures for various permeability. Observations show that the internal pressure can be estimated from known external conditions in terms of mean RMS and spectral values to a reasonable level of accuracy for the case where the permeability consists of circular apertures. Effects on the external pressure distribution due to permeability are found to be significant under certain circumstances
KEYWORDS
internal pressure, wind tunnel, permeabilty, wind pressure,

(4) Hoxey R.P. Moran P.
#NO 1387 A full-scale study of the geometric parameters that influence wind loads on low rise buildings. Jnl.Wind Eng.Ind.Aerod. vol.13 1983 p.277-288 6 figs. 9 refs. #DATE 01:12:1983 in English #AIC 891
ABSTRACT
Instruments full-scale agricultural and horticultural buildings with surface pressure sensors to measure wind loads under natural wind conditions. To show the effect of building geometry on wind loads, presents results of pressure coefficients on a selection of these buildings. The results in this report relate to transverse wind direction only. Shows that wind load does not reduce to a function of the geometric variables of height/span and roof pitch. Illustrates the effect of building eaves height, span, length and roof pitch by examples, but insufficient information is currently available to allow a generalised model to be proposed.
KEYWORDS
greenhouse, animal house, surface pressure, pressure coefficient, wind,

(5) Katayama T.
#NO 1329 A study of a probalistic model of wind induced ventilation. Jnl Wind Eng.Ind.Aerod. vol.15 1983 p.27-38 6 figs. 5 tabs. 6 refs. #DATE 01:12:1983 in English #AIC 846
ABSTRACT
There are several reports on studies of wind tunnel experiments and calculations on the response of air flow at an opening against the periodic variation of wind velocity and pressure. In these studies, the fluctuating components of natural wind velocity have been treated definitely. In this paper, theoretically derives the probability density function from a probabilistic model of wind velocity around the buildings, the consequent wind pressure, and the resulting ventilation rate and contamination concentration. Validates results using a model of an enclosure exposed to wind, with a nozzle as the inlet and an orifice as the outlet.
KEYWORDS
air flow, wind speed, wind pressure, wind tunnel, modelling, validation, air change rate, pollutant,

(6) Lee Y. Liang T.H. Tanaka H.
#NO 1331 Non linearity of pressure differentials induced by wind and mechanical ventilation. Jnl Wind Eng.Ind.Aerod. vol.15 1983 p.47-58 9 figs. 4 refs. #DATE 01:12:1983 in English #AIC 848
ABSTRACT
When wind and mechanical ventilation effects work together simultaneously, the combined effects of the two cannot be given by simple linear summation. Investigates this non-linearity of pressure differentials by the wind tunnel test of a model building, and verifies its effect on air infiltration.
KEYWORDS
mechanical ventilation, wind, wind tunnel, air infiltration, pressure,

(7) Sherman M H., Dickerhoff D J.
#NO 1440 Project Report. Field testing of wind cooling effects on Navy buildings. USA, University of California. Lawrence Berkeley Laboratory. Report No. LBL 14925, 1983, 37pp, 20 figs, 7 tabs, 10 refs. #DATE 01:05:1983, in English, #AICR US30.
ABSTRACT
Wind pressures on three Navy buildings at the Kanehoe Marine Corp Air Station, Hawaii were measured. Indoor and outdoor variables were also measured including temperature, dry bulb, wet bulb, relative humidity, wind speed, and wind direction. Pressure measurements were carried out using Validyne DP103 pressure transducers, and a static pressure probe. Natural ventilation is estimated 1. by combining window areas and pressure coefficients with wind speed and 2. using the LBL infiltration model.
KEYWORDS
ventilation, natural ventilation, buildings, wind pressure, wind direction, transducer, wind, pressure coefficient, probe, wind speed, open window

(8) Sherman M.H. Grimsrud D.T.
#NO 1369 Wind and infiltration interaction for small buildings. Annual meeting of ASCE,LA Oct.23-29 1982 = LBL-13949 20pp. 10 figs. 2 tabs. #DATE 01:10:1982 in English #AIC 881
ABSTRACT
Describes a model that predicts air infiltration from both wind and temperature influence to within 20 measured infiltration from a full-scale test structure, revealing an average discrepancy of less than 10 m3/hr (out of an average of approx 150 m3/hr). Presents direct measurements of the wind velocity and pressure coefficients induced by the wind on the full-scale test structure.
KEYWORDS
wind pressure, temperature, air infiltration, modelling, validation, test unit,

(9) Tamura G.T. Evans R.G.
#NO 1272 Evaluation of evacuated glass tubes for sampling of SF6/Air mixture for air exchange measurements. ASHRAE Jnl. vol.25 no.10 p.40-43 3 figs. 2 tabs. 4 refs. #DATE 01:10:1983 in English #AIC 802

ABSTRACT

Grab sampling of a tracer gas/air mixture in conjunction with the tracer gas decay technique is a convenient method for conducting a survey of air infiltration rates in homes. Examines such a method, using SF6 as the tracer gas and storing the concentration in evacuated glass tubes.

KEYWORDS

tracer gas, decay rate, measurement technique, sulphur hexafluoride,

(10) Vickery B.J. Baddour R.E. Karakatsanis C.A.
#NO 1289 A study of the external wind presure distributions and induced internal ventilation flow in low-rise industrial and domestic structures. Report BLWT-SS2-1983, University of Western Ontario 82pp. #DATE 01:01:1983 in English #AICR CA11

ABSTRACT

Uses model buildings to study external distribution of wind pressure and internal air flow. Compares air flow data with computed values derived from the pressure distribution data. Collects the pressure data obtained in a comprehensive study of wind loads on low-rise buildings and rearranges it in a form more suited to the computation of internal flows. Presents and discusses the methods emloyed in the reformulation and the results obtained. Briefly describes the development of design aids from which flow estimates could be made by simple hand calculations.

KEYWORDS

air flow, pressure distribution, modelling

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