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Wind pressure data requirements for air infiltration calculations

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Annex V Air Infiltration Centre

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Wind pressure data requirements for air infiltration calculations

Carolyn Allen

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 dissemmination 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.

Current participants in this task are Belgium, Canada, Denmark, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and United States of America.

1 Introduction

The development of computer programs for the modelling of energy flows in buildings was found to be inhibited by a lack of information on the ventilation heat loss due to air infiltration. This led to the setting up of the Air Infiltration Centre under the auspices of the International Energy Agency in order to gather, disseminate and analyse such information as is available. Part of the brief of the AIC was to validate computer models of air infiltration in buildings with a view to determining which parameters were important.

In such computer models, the driving pressures for the flow of air through a building envelope are a combination of:-

1) Wind pressure

2) Stack pressure, arising from temperature differences across the building envelope, and

3) Pressures due to mechanical ventilation systems,

of which the wind pressure proved to be the most difficult to specify.

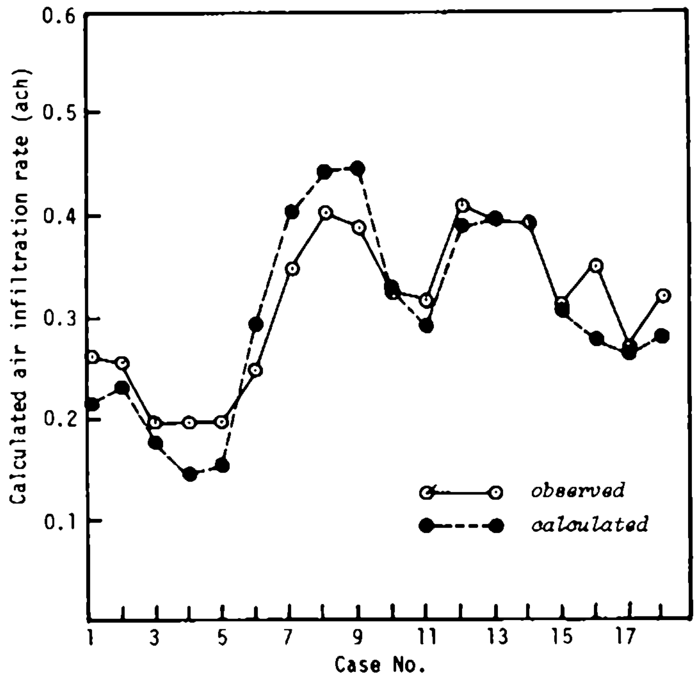
During the Air Infiltration Centres model validation exercise[1] , three houses were studied for which different methods of predicting the pressure distribution were used. The houses used were the Maugwil test house in Switzerland which had an exposed lie, one of the HUDAC Mk XI houses which were in an open suburban area and were partially sheltered (Canada), and a house in Runcorn (England) which was on a fully urban site, surrounded by buildings of approximately the same height.

Attempts were made to use full scale pressure differences measured in situ (Maugwil)(para.(1.1)), existing pressure coefficients (Cp) from wind loading tables together with a crude method of estimation for intermediate wind directions (Maugwil, HUDAC, Runcorn)(para.(1.2), and a set of wind tunnel results where the mean Cp was given as a function of relative height (z/H) for a range of shelter conditions (Maugwil, HUDAC, Runcorn)(para.(1.3)).

1.1 Full scale pressures

The attempts to employ full scale measurements pointed up several difficulties in their use. The averaging procedure can have a profound effect. The wind may, for instance, veer within an averaging period, without necessarily altering its mean speed, such that the pressure distribution changes. Unless there is a sufficient frequency of measurements to detect this change, there may ensue a switch of sign for the measured pressure, leading to a much reduced average pressure difference. Such a condition applied for case 5, and to a lesser degree, cases 4 and 10. (see Fig. (1.1a)) Thus, it is important in these cases to record a full set of local wind data on a continuous basis so that these situations can be identified.

a)



b)

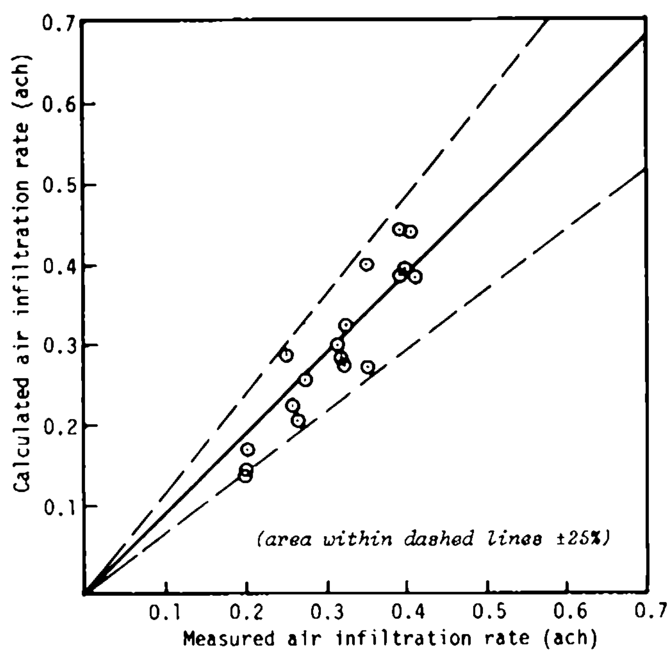


Fig.(1.1a) Case by case comparison of observed and calculated infiltration rates for the Maugwil House.

Fig.(1.1b) Comparison between calculated and measured air infiltration rates using "isolated building" pressure coefficients, for the Maugwil House.

1.2 Pressures from wind loading codes

The pressure coefficients from the British Code of Practice CP3 (Ch.V,Pt.2) have been used with a multi cell air infiltration model for the case of the Maugwil Test House. This is an isolated, detached single family dwelling in an exposed position. Windspeeds were high during the measurements. Agreement between the calculated and measured values is good. (see Fig (1.1b))

Attempts to use CP3 pressure coefficients with the HUDAC Mk XI House, which is partially sheltered proved much less satisfactory. (see Fig.(1.2))
Calculated and measured values for a house in Runcorn on a fully urban site bore little resemblance to one another when using CP3 coefficients. (see Fig (1.4))

1.3 Pressures from wind tunnel studies

This discovery of the inadequacy of the wind loading pressure coefficients to account for the effects of shelter led to the use of the aforementioned wind tunnel results from the Division of Building Research, NRC Canada. (Shaw[2]). These gave a much improved result for the two sheltered houses Figs.(1.3) and (1.5), but not for the exposed house (1.6).

In the case of wind loading pressures and wind tunnel results, the presentation of the data in the form of graphs and tables with only a limited number of wind directions was also found to be a handicap, since in the present application all values are required, not just those for which extreme conditions exist.

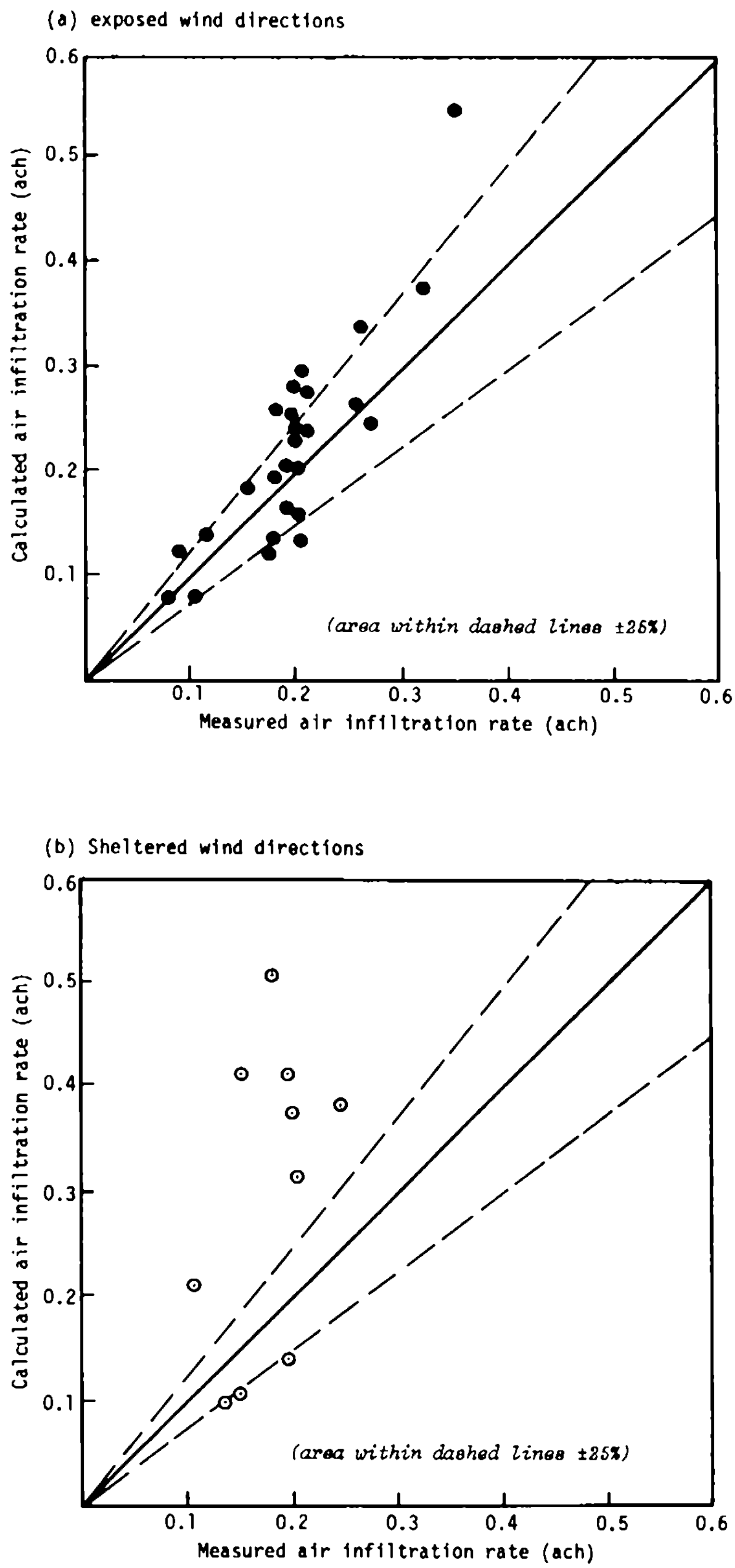


Fig.(1.2) Measured vs. calculated infiltration rates for the HUDAC Mk XI House.(using CP3 pressure coefficients)

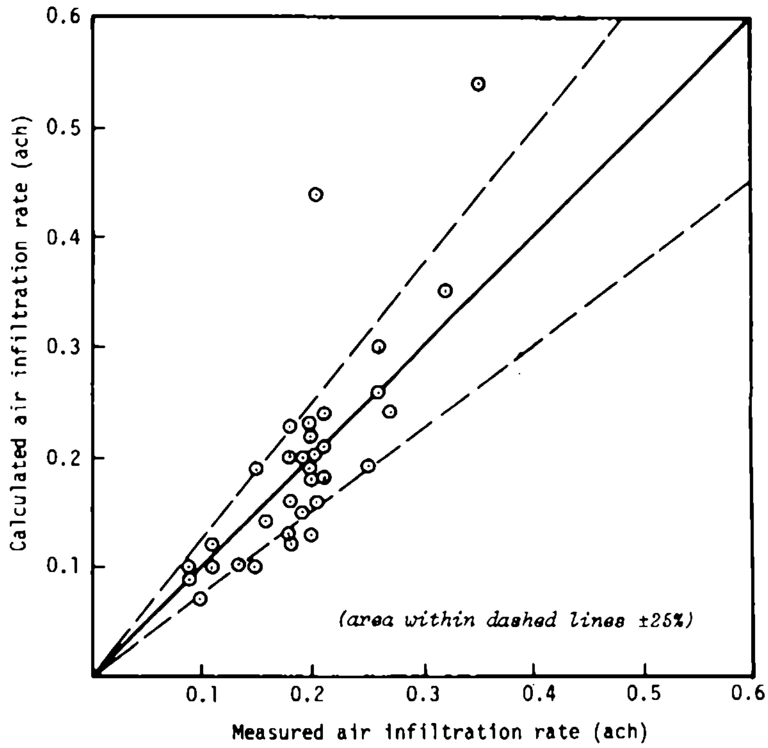


Fig.(1.3) Calculated vs.measured infiltration for the HUDAC Mk XI house using CP3 pressure coefficients. ('upgraded house')

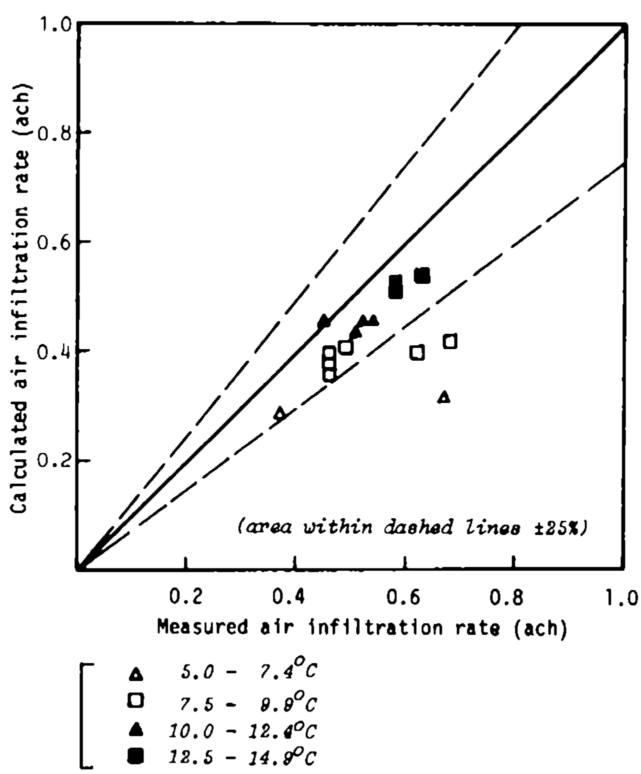


Fig.(1.4) Measured vs. calculated infiltration rates for the Runcorn House. (stack effect only)

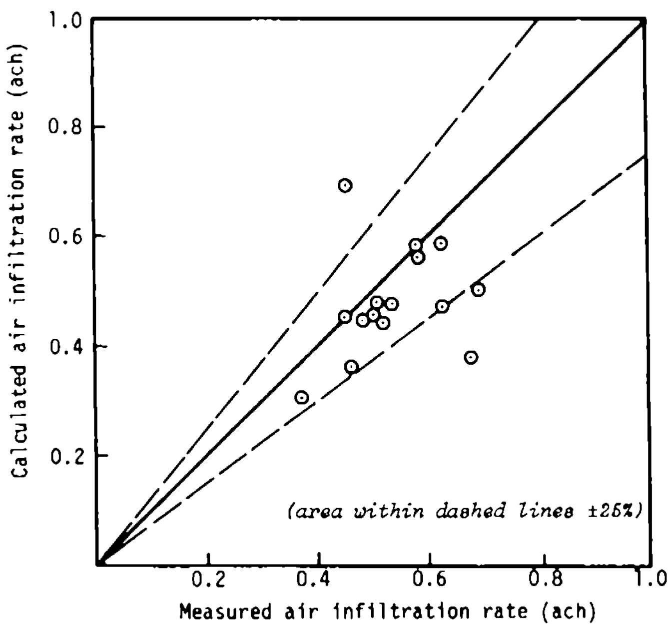


Fig.(1.5) Measured vs. calculated infiltration rates for the Runcorn House, using NRC pressure coefficients.

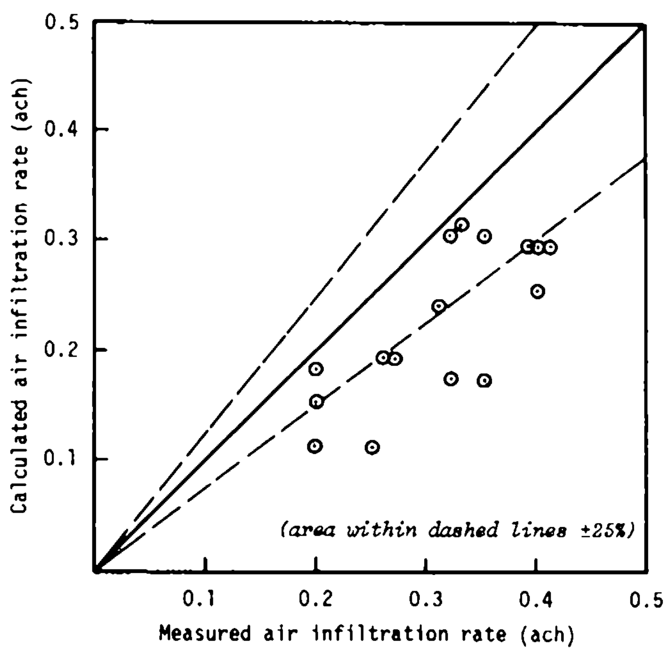


Fig.(1.6) Measured vs. calculated infiltration rates for the Maugwil House, using NRC pressure coefficients.

1.4 Summary of contents

This report contains a review of published information on the pressure distribution on buildings. It also presents a novel technique for presenting pressure coefficient data for use in the prediction of air infiltration rates.

More specifically, the report first includes a review of existing codes of practice on the prediction of wind pressures on buildings. Then the results of a survey of past research are discussed in relation to the requirements for the prediction of air infiltration rates. This research included measurements in wind tunnels and in the real wind, theoretical calculations of surface pressures, and some supplementary studies on flow around buildings, over topography, and around windbreaks. (These were included since they provide a means for estimating the local wind profile in more detail.)
The problem of flow reversal has been reviewed.

The evident inadequacies of the present data provided the incentive to develop a technique for more suitably presenting pressure coefficient data. This development, based on a detailed analysis of the results of some of the wind tunnel studies, is described in Chapter 7. The outcome is a technique which is both compact and "computer friendly".

Some further improvements in accounting for the effects of shelter have also been sought, particularly with respect to the urban setting.

The choice of reference wind or reference pressure for the calculation of pressure coefficients is also considered.
Finally, some of the gaps in our present knowledge which remain to be filled are summarised.

2 Existing codes of practice

There are several existing codes of practice which contain tables of pressure coefficients for buildings of various shapes. These include:-

(A) B.S.I. CP3. Ch V. Part 2[3].
Chapter I(C) of this document is now BS5925[4]. The pressure coefficients used in Ch.V. are used, omitting the extreme values, for the calculation of natural ventilation rates.

(B) National Building Code of Canada (1975), N.R.C. Ottawa, Canada[5]
This code made use of the pressure coefficients in the Swiss code of practice, which were based on the wind tunnel studies of J. Ackeret[6,7] (see Table (2.1))
More recently, the results of a wind tunnel study on models of low buildings, carried out at the University of Western Ontario, have been included. (Davenport[8,9])

(C) American National Standard A58.1 (1972)[10], - ANSI and the Southern Building Code of the US. both make use of the UWO data mentioned above.

(D) Australian Standard AS 1170 Part 2 (1975)[11]

An extensive summary of the contents of the above can be found in Sachs[12]

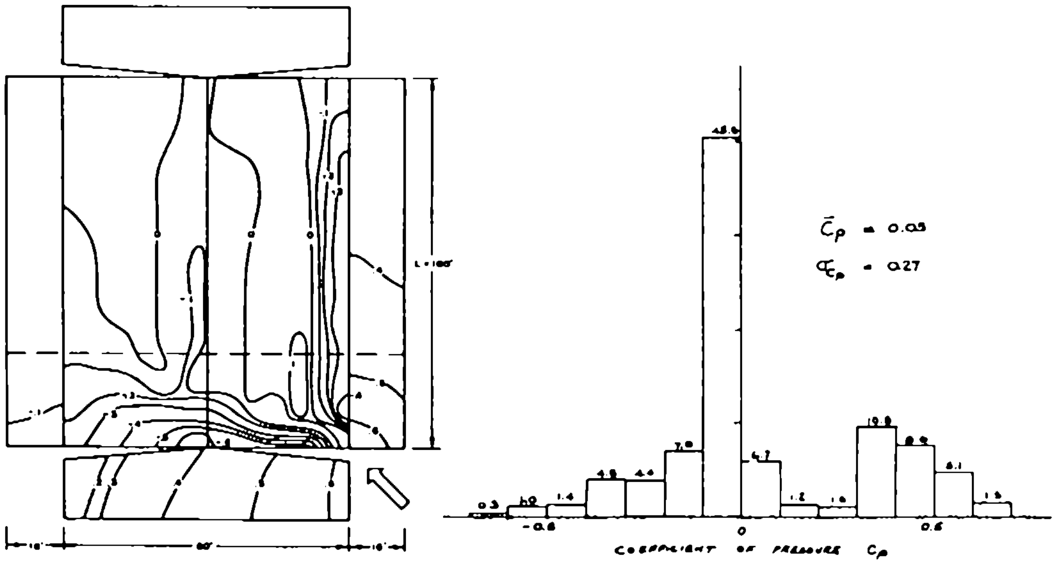
All of the pressure coefficients used in these codes of practice are primarily intended for wind loading applications. The wind equations with which they are used, and the original parametric studies used to produce them apply strictly only to strong wind conditions. Where such conditions do apply, it is reasonable to use these values.

It should be noted that the values quoted are the maximum values for the particular facade. Where the pressure coefficient is fairly uniform for the facade the approximation can be quite good. Where, however, the pressure distribution is non-uniform, the extreme values can differ widely from the mean value for the facade. In the case of the windward face this difference can be as much as 50%.

The proportions of the area of a model of a low rise building with different values of pressure coefficient, for a wind angle of 45 degrees, are shown in Fig.(2.1) (Davenport[9]). It can be seen that over half the surface area of the building has a pressure coefficient with an absolute value less than 0.1. This demonstrates, clearly, the need to use wind loading Cp's with extreme caution.

Davenport also remarked that each of the components used to calculate the wind pressure itself represents a statistical population with a mean, standard deviation and coefficient of variation.

Where an open country, standard, 10m reference wind is used, then:-



(a) (b)

Fig.(2.1) a) Pressure distribution on a low rise building for a wind angle of 45 degrees.
b) Distribution of surface area subject to different ranges of pressure value. (Davenport[9])

$$\begin{Bmatrix}\text{estimated}\\ \text{wind}\\ \text{pressure}\end{Bmatrix} = (q).\begin{Bmatrix}\text{exposure}\\ \text{height}\\ \text{factor}\end{Bmatrix}.\begin{Bmatrix}\text{shape}\\ \text{factor}\\ \text{Cp}\end{Bmatrix}.\begin{Bmatrix}\text{dynamic}\\ \text{gust}\\ \text{factor}\end{Bmatrix}.\begin{Bmatrix}\text{model}\\ \text{uncertainty}\\ \text{factor m}\end{Bmatrix} \qquad (2.1)$$

(1) (2) (3) (4) (5)

Where:-

(1) The reference pressure $q = 0.5.\rho v_{(ref)}^2$

For wind loading, this is related to the chosen return time and the dispersion of the values for the site. For ventilation calculations, one might use, for example, the hourly values for the site during a year, or any other time scale appropriate to that for the calculation being undertaken.

(2) The exposure height factor (Ce) allows for the conversion from open country terrain to the local terrain class. It is a function of the roughness length Zo. Davenport[9] gives the following relation for the mean values:-

$$Ce = 0.62 - 0.148.\ln Zo \qquad (2.2)$$

The coefficient of variation is of the order of 16%.

(3) The shape factor or pressure coefficient Cp is a strong function of wind direction and of the form of the building. Therefore one would require the distribution of wind speed and direction throughout the year for adequate modelling.

(4) The gust factor Cg multiplied by Cp gives the peak pressure coefficient. Its mean value can be taken as 1 for ventilation modelling purposes.
The combined coefficient of variation for Cp.Cg is of the order of 16%. This allows for the effect of turbulence.

(5) The "model uncertainty factor", m, is intended to allow for the scatter in the wind tunnel model results on which the pressure coefficients are based, and of the full scale pressure measurements with which they are compared.

If these elements are statistically independent, then the mean pressure can be represented by:-

$$\overline{P} = \overline{q}.\overline{Ce}.\overline{Cp}.\overline{Cg}.\overline{m} \qquad (2.3)$$

and the coefficient of variation V_p for the pressure (=st.dev./mean) is given by:-

$$(1+V_p{}^2) = (1+V_q{}^2).(1+V_{Ce}{}^2).(1+V_{Cp}{}^2).(1+V_{Cg}{}^2)(1+V_m{}^2) \qquad (2.4)$$

This statistical representation of wind loading pressures is rapidly becoming the accepted form forinternational and national standards.

Other standards which include tables of pressure coefficients are:-

The Swedish Building Code SBN-1980

The Norwegian Building Code

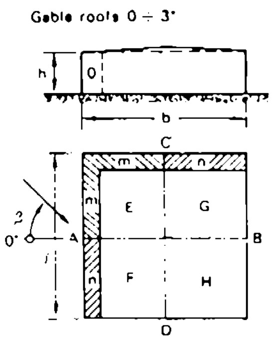
The French Building Code: Règles NV 65

German Standard DIN 1055 Pt.45[13]

Table (2.1) Pressure coefficient data for simple building shapes (after Ackeret[6,7], Sachs[12])

a) Simple square building.

1



External pressure coefficient $C_{p,a}$ for $h:b:l = 1:4:4$

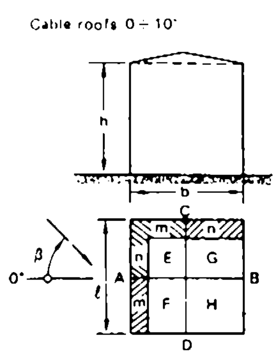
β	A	B	C	D	E	F	G	H
0°	+0·9	−0·3	−0·4	−0·4	−0·8	−0·8	−0·3	−0·3
15°	+0·8	−0·3	−0·1	−0·5	−0·7	−0·8	−0·2	−0·3
45°	+0·5	−0·4	+0·5	−0·4	−0·9	−0·6	−0·6	−0·3

Closed low square building

β	
15°	For section "0" (side C) $C^{*}_{p,a} = -0·8$
45°	For section "m" $C^{*}_{p,a} = -2·0$: "n" $C^{*}_{p,a} = -1·0$

Internal pressure coefficient $c_{p,i}$ for $\beta =$	0°	15°	45°
Openings uniformly distributed	±0·2	±0·2	±0·2
Openings on side A predominating	+0·8	+0·7	+0·4
Openings on side B predominating	−0·2	−0·3	−0·4
Openings on side C predominating	−0·3	−0·2	+0·4

2



Internal pressure coefficient $C_{p,a}$ for $h:b:l = 1:1:1$

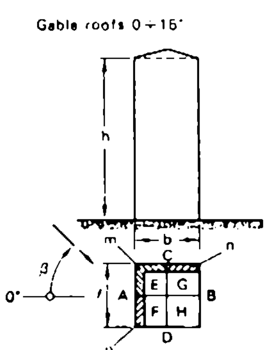
β	A	B	C	D	E	F	G	H
0°	+0·9	−0·5	−0·6	−0·6	−0·7	−0·7	−0·5	−0·5
15°	+0·8	−0·5	−0·7	−0·5	−0·7	−0·6	−0·5	−0·6
45°	+0·5	−0·5	+0·5	−0·5	−0·8	−0·5	−0·5	−0·4

Closed square building

β	
45°	For section "m" $C^{*}_{p,a} = -1·2$; "n" $C^{*}_{p,a} = -0·8$

Internal pressure coefficient $C_{p,i}$ for $\beta =$	0°	15°	45°
Openings uniformly distributed	±0·2	±0·2	±0·2
Openings on side A predominating	+0·8	+0·7	+0·4
Openings on side B predominating	−0·4	−0·4	−0·4
Openings on side C predominating	−0·5	−0·6	+0·4

3



External pressure coefficient $C_{p,a}$ for $h:b:l = 2·5:1:1$

β	A	B	C	D	E	F	G	H
0°	+0·9	−0·6	−0·7	−0·7	−0·8	−0·8	−0·8	−0·8
15°	+0·8	−0·5	−0·9	−0·6	−0·8	−0·8	−0·7	−0·7
45°	+0·5	−0·5	+0·5	−0·5	−0·8	−0·7	−0·7	−0·5

Closed high square building

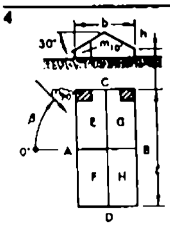
β	
45°	For section "m" $C^{*}_{p,a} = -1·0$; "n" $C^{*}_{p,a} = -0·8$

Internal pressure coefficient $C_{p,i}$ for $\beta =$	0°	15°	45°
Openings uniformly distributed	±0·2	±0·2	±0·2
Openings on side A predominating	+0·8	+0·7	+0·4
Openings on side B predominating	−0·5	−0·5	−0·4
Openings on side C predominating	−0·6	−0·8	+0·4

(C^{*}_{p} = maximum local pressure)

b) Rectangular building. Closed, saddle roof.

4



External pressure coefficient $C_{p,e}$ — $h:b:l = 1:8:16$

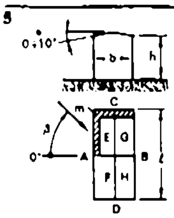
β	A	B	C	D	E	F	G	H
0°	+0·8	−0·5	−0·5	−0·5	+0·2	+0·2	−0·6	−0·6
45°	+0·5	−0·5	+0·4	−0·3	+0·1	−0·1	−0·8	−0·5
90°	−0·3	−0·3	+0·9	−0·3	−0·5	−0·1	−0·5	−0·1
10° 90°	For section "m" $C^*_{p,e} = -1·0$							

Internal pressure coefficient $C_{p,i}$

Wind direction β =	0°	45°	90°
Opening uniformly distributed	±0·2	±0·2	±0·2
Side A predominating	+0·7	+0·4	−0·2
Side B predominating	−0·4	−0·4	−0·2
Side C predominating	−0·4	+0·3	+0·8

Closed shed

5



External pressure coefficient $C_{p,e}$ — $h:b:l = 2·5:2:5$

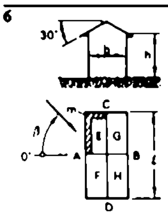
β	A	B	C	D	E	F	G	H
0°	+0·9	−0·5	−0·7	−0·7	−0·6	−0·6	−0·5	−0·5
45°	+0·6	−0·5	+0·4	−0·5	−0·9	−0·7	−0·6	−0·7
90°	−0·5	−0·5	+0·9	−0·4	−0·8	−0·2	−0·8	−0·2
45°	For section "m" $C^*_{p,e} = -1·5$							

Internal pressure coefficient $C_{p,i}$

Wind direction β =	0°	45°	90°
Opening uniformly distributed	±0·2	±0·2	±0·2
Side A predominating	+0·8	+0·5	−0·4
Side B predominating	−0·4	−0·4	−0·4
Side C predominating	−0·6	+0·3	+0·8

Closed house, nearly flat roof

6



External pressure coefficient $C_{p,e}$ — $h:b:l = 2·5:2:5$

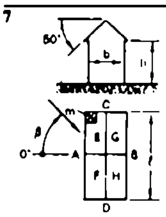
β	A	B	C	D	E	F	G	H
0°	+0·9	−0·5	−0·7	−0·7	−0·6	−0·6	−0·5	−0·5
45°	+0·6	−0·5	+0·4	−0·4	−0·4	−0·5	−0·6	−0·7
90°	−0·5	−0·5	+0·9	−0·4	−0·7	−0·2	−0·7	−0·2
45°	For section "m" $C^*_{p,e} = -1·2$							

Internal pressure coefficient $C_{p,i}$

Wind direction β =	0°	45°	90°
Opening uniformly distributed	±0·2	±0·2	±0·2
Side A predominating	+0·8	+0·5	−0·4
Side B predominating	−0·4	−0·4	−0·4
Side C predominating	−0·6	+0·3	+0·8

Closed house, medium roof

7



External pressure coefficient $C_{p,e}$ — $h:b:l = 2·5:2:5$

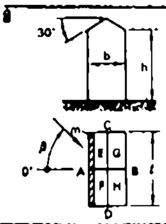
β	A	B	C	D	E	F	G	H
0°	+0·9	−0·5	−0·8	−0·8	+0·3	+0·3	−0·6	−0·6
45°	+0·6	−0·5	+0·4	−0·4	+0·3	−0·1	−0·5	−0·6
90°	−0·5	−0·5	+0·9	−0·4	−0·8	−0·2	−0·8	−0·2
75°	For section "m" $C^*_{p,e} = -1·2$							

Internal pressure coefficient $C_{p,i}$

Wind direction β =	0°	45°	90°
Opening uniformly distributed	±0·2	±0·2	±0·2
Side A predominating	+0·8	+0·5	−0·4
Side B predominating	−0·4	−0·4	−0·4
Side C predominating	−0·7	+0·3	+0·8

Closed house, steep roof

8



External pressure coefficient $C_{p,e}$ — $h:b:l = 2:1:2$

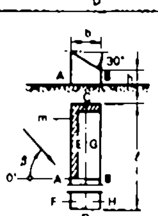
β	A	B	C	D	E	F	G	H
0°	+0·9	−0·5	−0·8	−0·8	−1·0	−1·0	−0·5	−0·5
45°	+0·6	−0·5	+0·4	−0·4	−0·3	−0·4	−0·5	−0·6
90°	−0·6	−0·6	+0·9	−0·4	−0·7	−0·5	−0·7	−0·5
0°	For section "m" $C^*_{p,e} = -1·2$							

Internal pressure coefficient $C_{p,i}$

Wind direction β =	0°	45°	90°
Opening uniformly distributed	±0·2	±0·2	±0·2
Side A predominating	+0·8	+0·5	−0·5
Side B predominating	−0·4	−0·4	−0·5
Side C predominating	−0·7	+0·3	+0·8

Closed high house

9



External pressure coefficient $C_{p,e}$ — $h:b:l = 1:2,4:12$

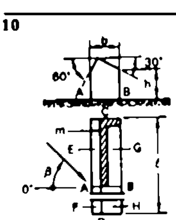
β	A	B	C	D	E	F	G	H
0°	+0·9	−0·5	−0·6	−0·6	−0·5	−0·5	−0·5	−0·5
45°	+0·5	−0·6	+0·4	−0·4	−1·2	−0·7	−1·1	−0·7
90°	−0·4	−0·3	+0·9	−0·2	−0·3	0	−0·3	0
180°	−0·4	+0·8	−0·7	−0·7	+0·1	+0·1	+0·2	+0·2
45°	Section "m" $C^*_{p,e} = -1·4$							

Internal pressure coefficient $C_{p,i}$

Wind direction β =	0°	45°	90°	180°
Opening uniformly distributed	±0·2	±0·2	±0·2	±0·2
Side A predominating	+0·8	+0·4	−0·2	−0·3
Side B predominating	−0·4	−0·5	−0·1	+0·7
Side C predominating	−0·5	+0·3	+0·8	−0·6
Roof EF predominating	−0·4	−0·8	0	0

Building with single slope roof

10



External pressure coefficient $C_{p,e}$ — $h:b:l = 1:1:5$

β	A	B	C	D	E	F	G	H
0°	+0·9	−0·5	−0·6	−0·6	+0·6	+0·6	−0·5	−0·5
45°	+0·5	−0·8	+0·4	−0·5	+0·2	−0·1	−1·0	−0·8
90°	−0·4	−0·4	+0·9	−0·3	−0·4	0	−0·4	0
180°	−0·5	+0·9	−0·6	−0·6	−0·5	−0·5	−0·1	−0·1
45°	Section "m" $C^*_{p,e} = -1·3$							

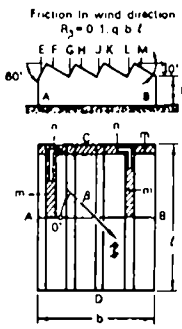
Internal pressure oefficient $C_{p,i}$

Wind direction β =	0°	45°	90°	180°
Opening uniformly distributed	±0·2	±0·2	±0·2	±0·2
Side A predominating	+0·8	+0·4	−0·1	−0·4
Side B predominating	−0·4	−0·7	−0·1	+0·8
Side C predominating	−0·5	+0·3	+0·8	−0·5
Roof EF predominating	+0·5	0	−0·1	−0·4

Building with shed roof

c) Other.

11 — Building with multiple shed roofs

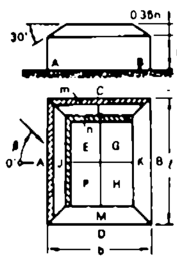


External pressure coefficient $C_{p,e}$ for $h:b:l = 1:4:5$

β	A	B	C	D	E	F	G	H	J	K	L	M
0°	+0·9	−0·3	−0·4	−0·4	+0·6	−0·6	−0·6	−0·5	−0·5	−0·4	−0·3	−0·3
45°	+0·5	−0·4	+0·5	−0·3	+0·2	−0·8	−0·5	−0·4	−0·2	−0·4	−0·2	−0·5
90°	−0·4	−0·4	+0·9	−0·3	−0·3	−0·4	−0·4	−0·4	−0·4	−0·4	−0·4	−0·3
180°	−0·3	+0·9	−0·3	−0·3	−0·2	−0·3	−0·3	−0·4	−0·4	−0·6	−0·6	−0·1
0° ÷ 180°	Section "m" $C^{*}_{p,e} = -1{\cdot}3$; section "n" $C^{*}_{p,e} = -2{\cdot}0$											

Internal pressure coefficient $C_{p,i}$ for wind direction $\beta =$	0°	45°	90°	180°
Opening uniformly distributed	±0·2	±0·2	±0·2	±0·2
Opening on side A predominating	+0·8	+0·4	−0·3	−0·2
Opening on side B predominating	−0·2	−0·3	−0·3	+0·8
Opening on side C predominating	−0·3	+0·4	+0·8	−0·2

12 — Clipped flat roof

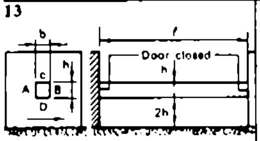


External pressure coefficient $C_{p,e}$ for $h:b:l = 1:3:4$

β	A	B	C	D	E	F	G	H	J	K	L	M
0°	+0·9	−0·5	−0·6	−0·6	−0·8	−0·8	−0·4	−0·4	−1·0	−0·4	−0·5	−0·5
45°	+0·5	−0·5	+0·5	−0·4	−0·6	−0·5	−0·5	−0·5	−0·5	−0·5	−0·5	−0·5
90°	−0·5	−0·5	+0·9	−0·4	−0·8	−0·4	−0·8	−0·4	−0·4	−0·4	−1·0	−0·4
0° + 90°	Section "m" $C^{*}_{p,e} = -1{\cdot}1$; section "n" $C^{*}_{p,e} = -1{\cdot}5$											

Internal pressure coefficient $C_{p,i}$ for wind direction $\beta =$	0°	45°	90°
Opening uniformly distributed	±0·2	±0·2	±0·2
Opening on side A predominating	+0·8	+0·4	−0·4
Opening on side B predominating	−0·4	−0·4	−0·4
Opening on side C predominating	−0·5	+0·4	+0·8

13 — Closed connecting passage-way

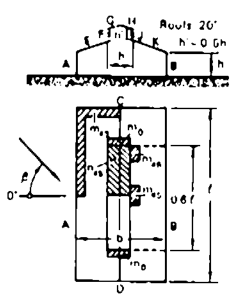


External pressure coefficient $C_{p,e}$ for objects $h:b:l = 1:1:10$ between large walls

β	A	B	C	D
0°	+0·8	−1·2	−1·4	−1·5

Internal pressure coefficient $C_{p,i}$ $\beta =$	0°
Opening uniformly distributed	−0·5
Opening on side A predominating	+0·7
Opening on side B predominating	−1·1
Opening on side C predominating	−1·3

14 — Closed building with roof vent



External pressure coefficient $c_{p,e}$ for $h:b:l = 1:4:8$

β	A	B	C	D	E	F	G	H	J	K
0°	+0·8	−0·5	−0·7	−0·7	−0·2	+0·6	−1·0	−0·6	−0·5	−0·6
45°	+0·4	−0·5	+0·4	−0·5	−0·3	+0·2	−1·3	−1·4	−1·0	−0·7
90°	−0·4	−0·4	+0·8	−0·3	−0·4	−0·2	−0·3	−0·3	−0·2	−0·4
0 ÷ 45°	Section "m" $C^{*}_{p,e} = -1{\cdot}2$; section "n" $C^{*}_{p,e} = -2{\cdot}4$									

Internal pressure coefficient $C_{p,i}$ for $\beta =$	0°	45°	90°
Vents at F and J closed	±0·2	±0·2	±0·2
Vents at F and J open	−0·2	−0·5	−0·3
Vents at F only open	+0·5	+0·1	−0·2
Vents at J only open	−0·4	−0·9	−0·2

3 Pressure distribution on a building

3.1 Derivation

The pressures experienced by a building are determined by its size, shape and local windfield.
It is not yet possible to give a complete description of flow around all types of structure, due to the complex nature of the interactions between the wind and the building, although it is possible to arrive at some general conclusions for relatively simple building shapes.
Ideally, full scale pressure measurements should be made. (see Chapter 5)
This is not always possible, - at the design stage the building does not yet exist, in which case a properly conducted model test is the next best alternative. (see Chapter 6)
Even this may not be a practical alternative. In the early stages of a project, or where the size of the development is large, or the situation is complex, the costs of running a detailed wind tunnel test for the determination of the air infiltration alone would be prohibitive. Making use of the results of a wind loading study is a possibility for most high rise buildings, although there have been doubts cast on the applicability of the pressure coefficients derived for the strong wind case to low windspeed conditions. This also applies to the pressure coefficients given in the various building standards which are intended for wind loading applications. (see Sachs[12])

For air infiltration calculations one can discard the extreme local values of pressure coefficients in the wind loading code. (see Chapter 2) These usually apply to areas which are small compared with, for example, the area of the facade corresponding to the wall of a room. Since the wind loading pressure coefficients represent time averaged, spacial maximum values, they go some way towards compensating for these local effects. This is the approach used in BS5925, in which the whole face pressure coefficients from CP3 are used for calculations of natural ventilation. The fluctuating component of the pressure is still required, however, to allow for the calculation of flow reversal in a crack.

3.2 A general description

As the wind blows over the building, the air approaching it is decelerated and a positive pressure appears. The air is deflected by the front face and the flow separates at the salient edges formed by the corners of the building and the edge of the roof. This gives rise to negative pressures, which may be large relative to atmospheric pressure. Negative pressures are also experienced on the rear facade of the building in the wake region.
The pressure distribution on the roof depends on its geometry. Handa[14] quotes a value of 30 degrees for the critical roof pitch, above which a wind blowing normal to the eaves will raise a positive pressure on the windward side of the roof. The full scale Aylesbury experiment (Eaton and Mayne[15,16]), where the roof pitch was varied between 5 degrees and 45 degrees indicates a critical value of 22.5 degrees.

The pressures experienced all vary with time due to the unsteady nature of the flow in the natural wind.

3.2.1 Effect of building geometry

General:-
For a simple isolated rectangular low rise building without projections or overhangs, with the wind blowing normal to the roof ridge, the maximum pressure occurs in the centre of the windward wall. The pressure drops off rapidly as the corners are approached. The largest negative excursions occur closest to the edges where flow separation takes place. Commonly, the flow on the front face below the stagnation point is downwards and away from the building at ground level. This forms the "horseshoe" vortex in which the air follows a spiral path until it spills around the sides of the building. The exact pressure distribution on the flank and lee faces of the building will depend on the building geometry. A tall building gives rise to more upward deflection of the flow and therefore greater suctions in the roof area. When a wall is long in the direction of flow, the flow which detached at the leading edge may reattach. This can alter both the magnitude and position of the regions of maximum suction. (see Figs. (3.1) to (3.3))

When the wind approaches the building at an angle, the pattern of flow is rather different (see Figs. (3.4), (3.5)). The building now presents two faces to the oncoming wind, which divides at the leading corner in proportions which depend on the angle of approach to the two faces. The pressures will be positive or negative accordingly. There is less upward flow than in the case of normal flow, so that roof suctions are generally lower in magnitude. When the roof pitch is less than about 10 degrees, very large negative pressures can be experienced (Handa[14]), near the leading corner, due to the formation of separation vortices. (see Figs. (3.6), (3.7))

3.2.2 Effect of overhangs and projecting walls

These have the effect of trapping the air on the windward face, thus smoothing the pressure distribution. The pressure experienced remains near the maximum value between the stagnation point and the projecting surface, e.g. as shown in the wind tunnel studies of Jensen and Frank[17]. See Fig (3.8)
There is a corresponding effect on the flank surface pressures. Since less of the flow is diverted over the roof, the suction experienced is much less intense.
Wall mullions and projecting balconies have a similar effect. The pressure distribution is exaggerated. On the windward face, positive pressures are more positive, and on the leeward faces, the negative pressures are either unchanged or more negative. As above the pressure gradients on the flanks are reduced.

In the case of a flat roof with a parapet, the edge where flow separation occurs is raised above the level of the roof. Most of the suction is experienced by the parapet structure itself. The wake eddy for the parapet thus ventilates that for the roof. The result

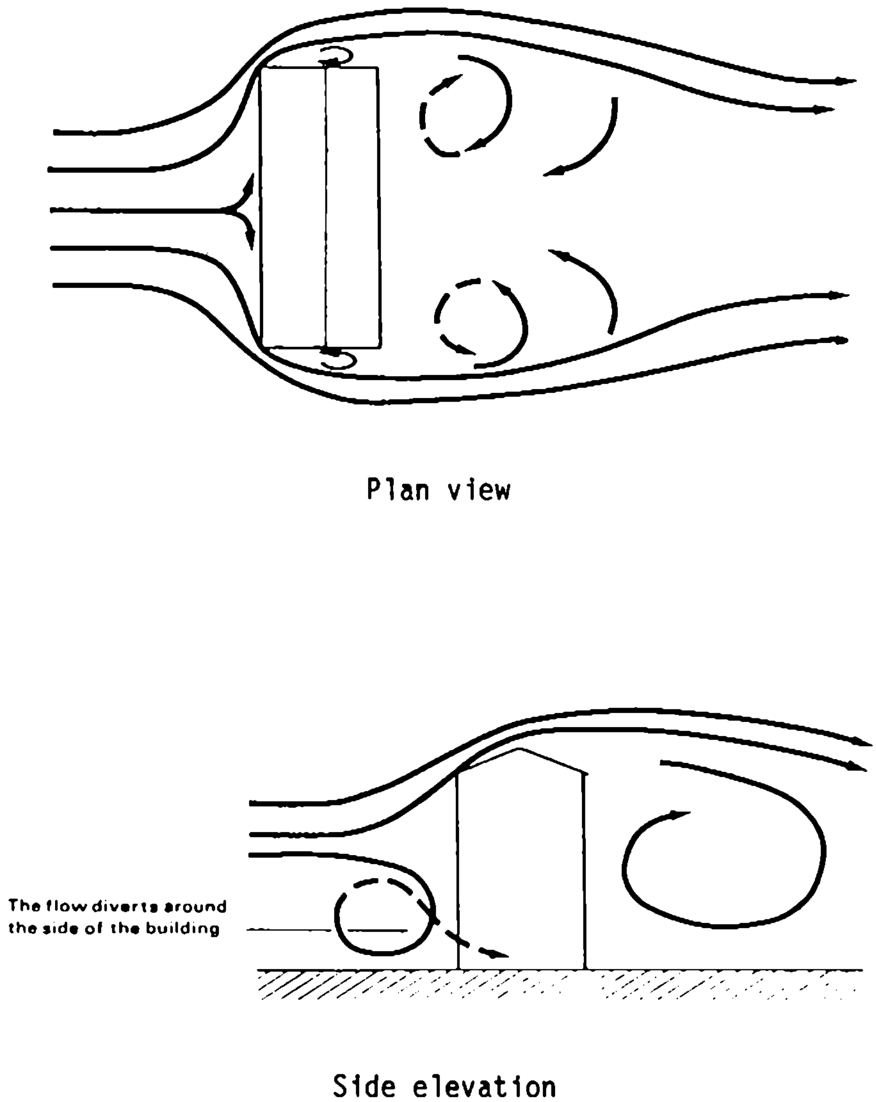
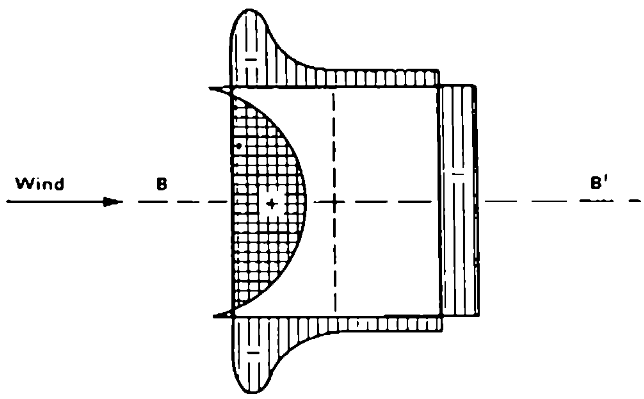
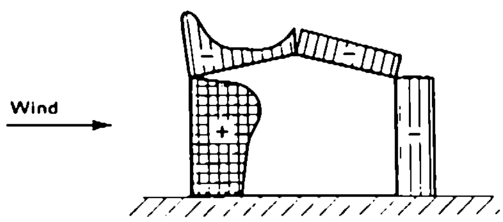


Fig.(3.1) Flow past a rectangular building with the wind direction normal to the long face.
(from Penwarden and Wise[18] reproduced by permission of the Controller, HMSO, Crown Copyright)(also Figs.3.2 to 3.5 and 3.9)

is that peak pressures and pressure gradients are reduced. As the size of a parapet increases with respect to the size of the building, so its share of the load due to flow separation increases also, so that its effectiveness is increased. (see Fig. (3.9))



Plan view



Side elevation

Fig.(3.2) Pressure distribution on a rectangular building with the wind direction normal to the long face.

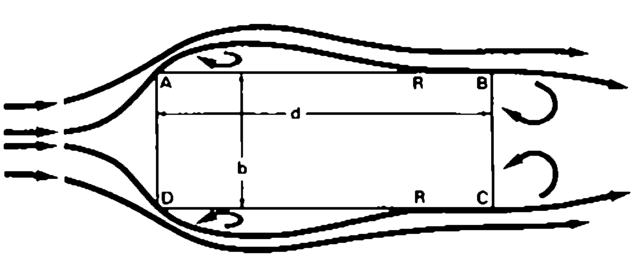


Fig.(3.3) Illustration of flow reattachment.

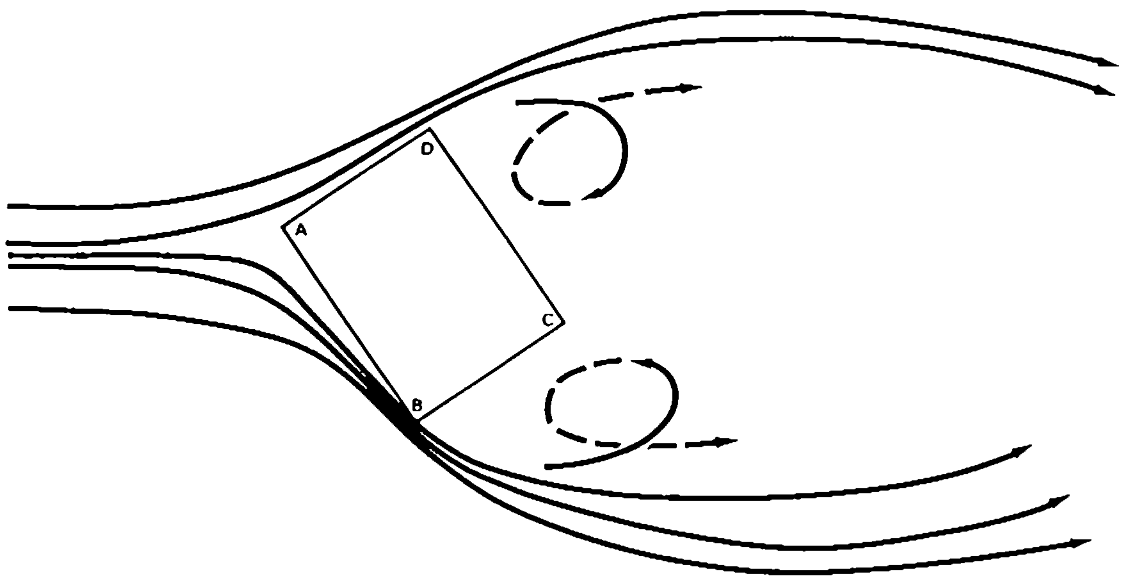


Fig.(3.4) Plan view of flow around a rectangular building with oblique wind incidence.

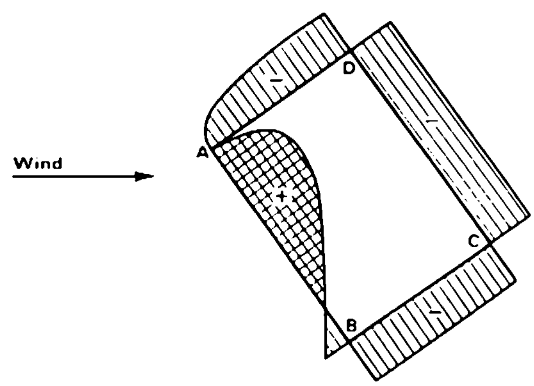


Fig.(3.5) Pressure distribution on the walls.

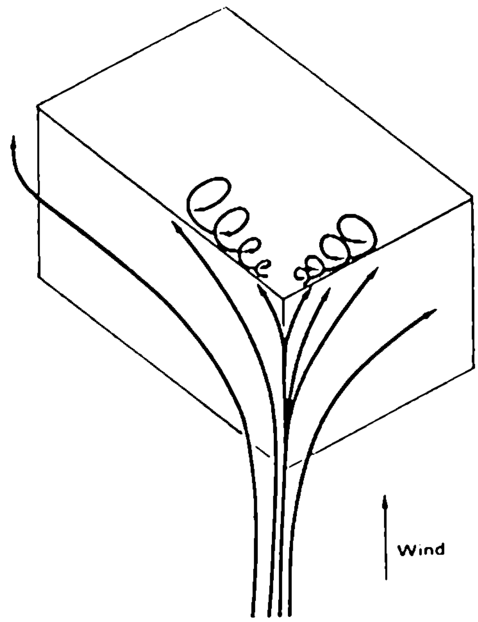


Fig.(3.6) Pattern of flow .

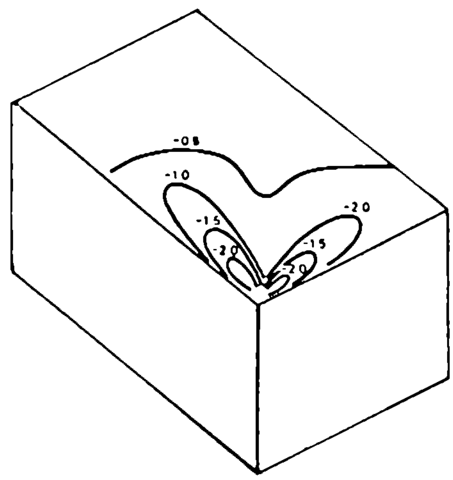


Fig.(3.7) Pressure distribution over the roof.

3.2.3 Effect of cladding

The presence of an open cavity e.g. behind cover boarding (Lindquist[19]), can exert a powerful influence on the pressure distribution experienced by the true wall of the structure. The capacitance and inertance of the cavity and the elasticity of the cladding leads to the damping out of spacial variations in pressure, and a reduction in the amplitude of pressure variations, particularly for the higher frequency components. This applies mainly to background leakages.

3.2.4 Effects of nearby buildings

In the event that a building lies close to another which is much larger, the flow experienced by the smaller building is dominated by that around the larger, especially when the larger building is upwind, to a degree dependent on the distance between them. (Phaff[20], van Dalen[21])
If the test building lies in the area of the descending wake, the flow may be nearly vertical, giving positive pressures on the roof and negative pressures elsewhere. This is a particularly important consideration when positioning flue outlets, in order to avoid the problem of flow reversal.

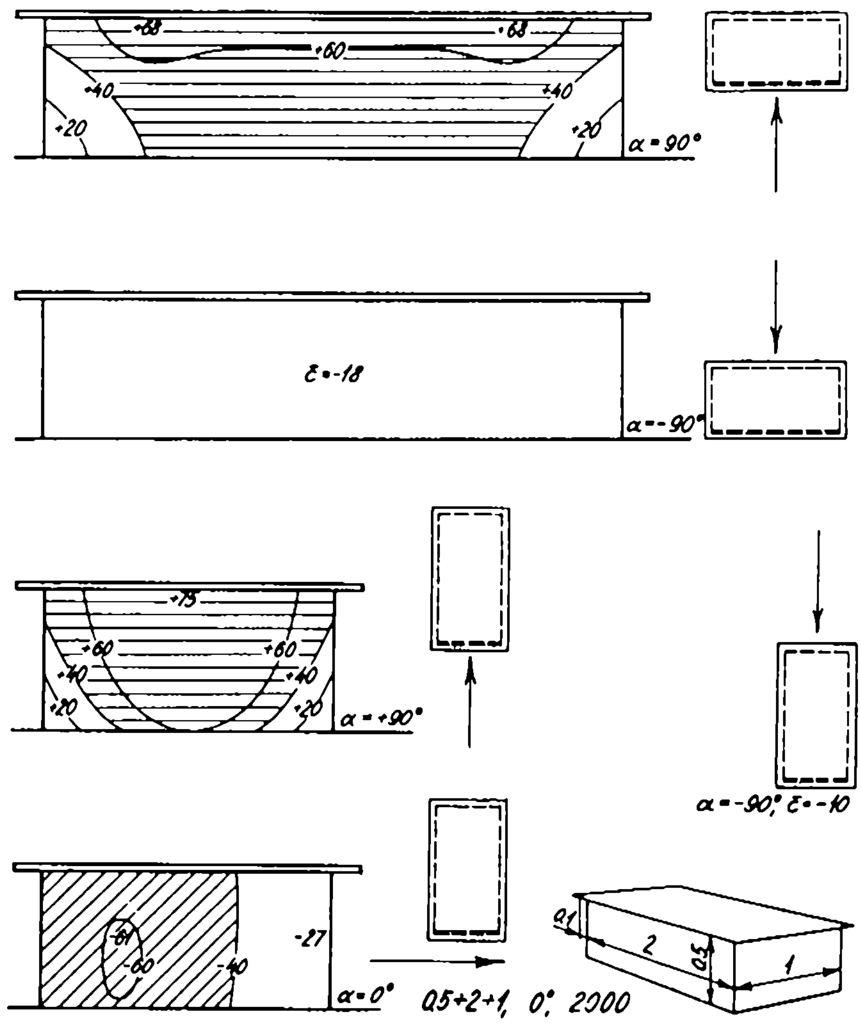


Fig.(3.8) Pressure distribution on a model building with overhanging eaves. (Jensen and Frank[17])

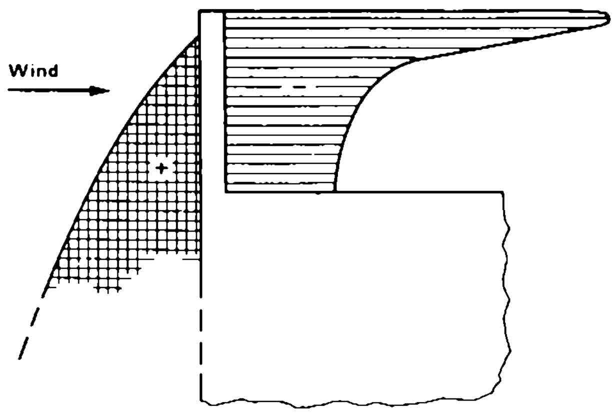


Fig.(3.9) Pressure distribution on a roof parapet (section).

3.2.5 Pressures on chimneys and flues

When modelling air infiltration and air movement in a building it is necessary to know the pressures at the mouth of any chimney or flue which may project through the walls or roof. This is a function of the position of the chimney on the roof, the roof pitch, and the height of the end of the flue above the surface of the roof. (Lugtenburg[22], van Dalen[21])

3.2.6 Effects of boundary layer structure on the pressure distribution

The main effect is due to the shape of the velocity profile. In a constant velocity field, the horseshoe vortex formed at the foot of the windward face of a bluff body is small and the stagnation point is relatively low down the front face. Fig (3.10). When there is boundary layer flow with the velocity decreasing as the ground is approached, the horseshoe vortex becomes much larger, and the stagnation point much higher on the windward face. The horseshoe vortex is still a notable feature when the wind blows onto a corner. (Corke, Nagib and Tan-atichat[23], Corke and Nagib[24], Hamilton[25]).

As yet, the effect on the general flow pattern of an accelerated flow near the ground has not been widely investigated. This occurs in the case of flow up a slope and in downslope flow caused by radiative cooling of the ground at night, and is therefore of interest in hilly terrain.
Another point of interest is that the flow down the face of a tall building mixes cold air from aloft into the layers near the ground. Thus, the value for the external temperature used in the calculation of the stack effect is, most appropriately, that near the top of the building.
As turbulence levels increase, the drag on the building is reduced, the intensity of the corner vortices is decreased, and there is a shift of energy into the lower frequency fluctuations (<1 Hz) from the intermediate ranges. (1 to 3 Hz). Corke et.al[23,24] draw attention to a strong tie between these low frequency, energy containing eddies and the pressure spectra. They also state that the wake Strouhal number also increases as turbulence increases, reflecting the modulation of the shear layers separating from the building by the upstream turbulence.

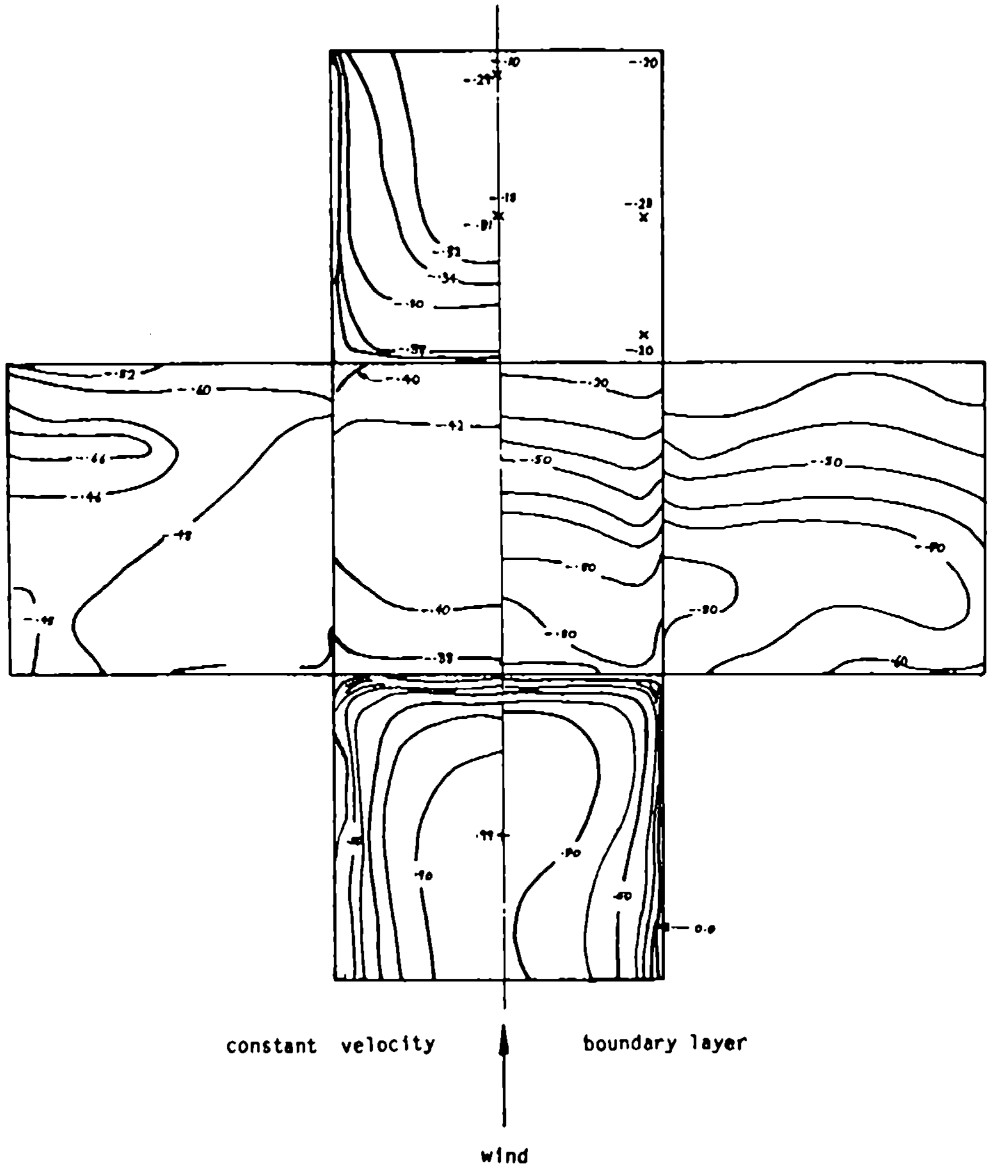


Fig.(3.10) Comparison of pressure coefficients on a cube for constant velocity and boundary layer flow. (after Hamilton[25])

4 Pressure coefficients

The general form of the pressure coefficient for a point on a building is defined by the equation (Lawson[26]:-

$$Cp = \frac{P-P(0)}{0.5.\rho.v^2} = f(L,H,WD,Re,M,St) \qquad (4.1)$$

Where:- L is a characteristic horizontal dimension,
H is a characteristic vertical dimension,
WD is the wind approach angle relative to the axis of the building,
Re is the Reynolds number,
M is the Mach Number (U/U(sound)) and
St is the Strouhal Number (n.L/v)

M only becomes significant for windspeeds in excess of 50 m/s, i.e. hurricanes, tornados and sonic booms, and can thus be safely ignored for the present application. The Strouhal Number, St, is used in two contexts. One for the wind approaching the building, where $L = {}^{x}L_{u}$ and v is the mean windspeed, yielding n, the frequency of the turbulence. For the building wake, L is the buildings effective width and n is the frequency of eddies shed by it.

Pressure coefficients may be defined for mean, peak and rms pressures. For the mean and peak pressure, P(0) is usually the static pressure of the free stream if the building were not there, or its nearest achievable equivalent in the case of full scale measurements. For rms pressures, if the mean pressure is used for P(0), we have the root mean square about the mean, (sometimes written rmsm).

The particular combination of pressure measurement and reference wind is determined by the purpose for which the data is required, and by the practical limits of the method used to acquire the data. One is inevitably faced with a compromise between the detail of the data required and the universality of the pressure coefficients so derived.

4.1 Reference Wind

The choice of reference wind has varied widely. Each method has its advantages and disadvantages. These are summarised below. (see Fig.(4.1))

1) Windspeed at 10 metres.

a) Simultaneous hourly mean wind.
This has the advantage of being a figure readily available as a standard meteorological measurement. It is independent of building form, but also takes no account of local shelter on its value. In an area where building heights are low, it can be quite useful.

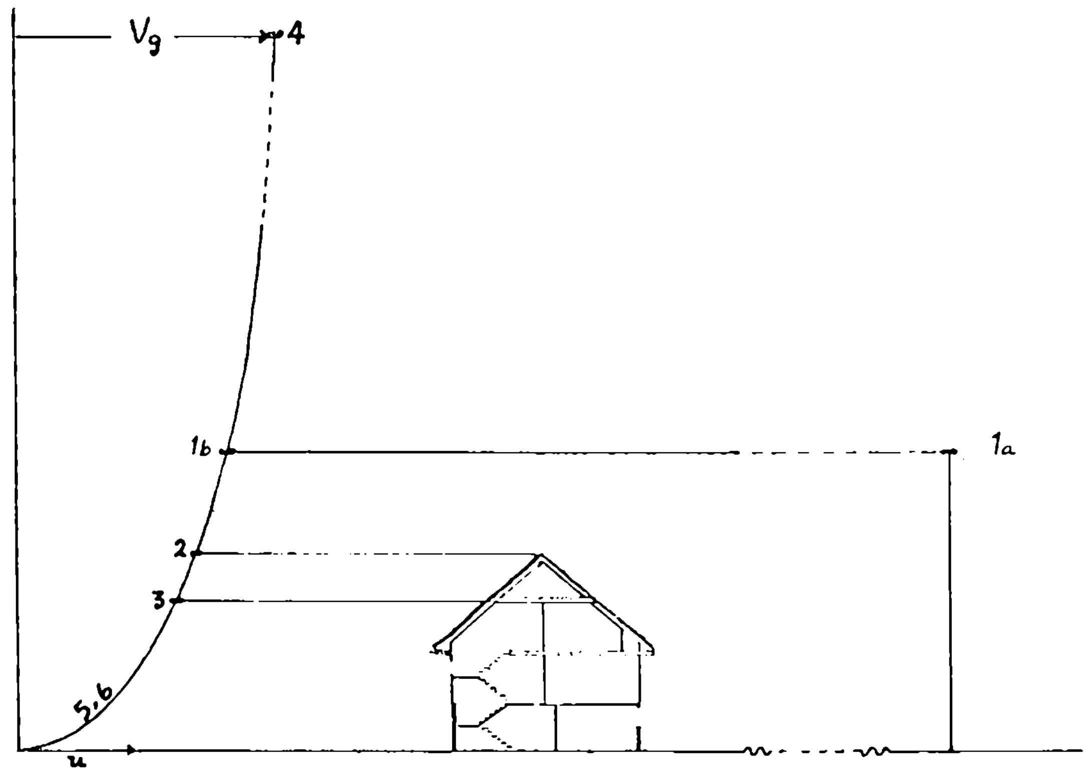


Fig.(4.1) Illustration of the choice of reference winds

1) 10m wind : a) Local, b) Remote or standard.
2) Roof ridge height.
3) Ceiling height.
4) Gradient height.
5) Local wind profile.
6) as 5 but with turbulence.

b) Meteorological standard windspeed for the site.
This is an hourly average windspeed which has a quoted probability of being exceeded in any one year, measured at 10m over open flat level ground in the vicinity of the buildings. Lawson[26]
This has the advantage of simplifying the statistical calculations for extreme wind analysis. The frequencies associated with peak winds and the hourly wind lie on either side of the spectral gap. Their probabilities of occurrence are, therefore, independent.
Coupled with a similar probability distribution for the wind direction this can be used when estimating the seasonal variation of energy loss using a very simple model, but not if any degree of detail is required.

2) Windspeed at roof ridge height upstream.
This has the advantage of being independent of building form.
This is the value used in BS5925 and CP3 and most of the published calculations for wind loading[3,4].

3) Wind at ceiling height
This is the reference level used by LBL, at the top of the heated space. This has the advantage of representing the top of the zone affected by stack action, and is independent of the external form of the building.

4) Gradient wind.
This is the value recommended by the group at Sheffield University. (Hussain, Lee, Soliman[27-34]) It has the advantage of being independent of terrain, and is equivalent to the free stream velocity in a wind tunnel. A reasonable estimate of the value of this windspeed can be arrived at in the field using published Meteorological data. The main disadvantage is one of scaling. To model this situation accurately, one has to reproduce the whole of the boundary layer in the wind tunnel rather than the lower part which is more frequently the case. This places severe limitations on the building scale which can be accommodated, and thus the detail of the pressure distribution which can be modelled.

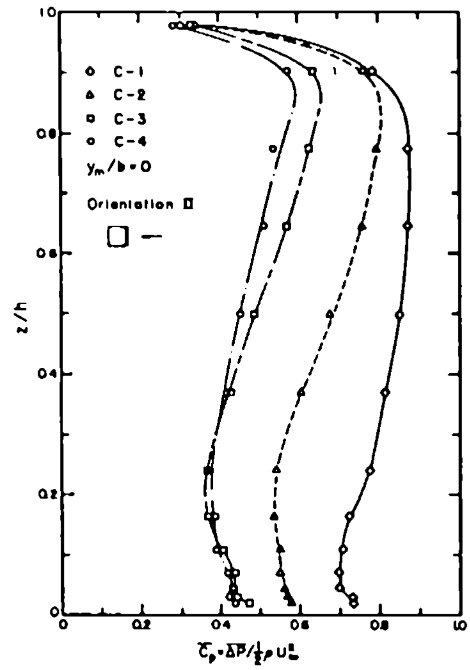
5) Local wind profile.
Where this can be determined it is useful, since then, local pressure coefficients can be used. These are then independent of local shelter and terrain. This considerably simplifies the wind tunnel modelling requirements. One needs to reproduce the turbulence structure and intensity, but can dispense with accurate modelling of local shelter, a distinct advantage since the accurate scaling of both at once is impossible. If one is using the mean local pressure coefficient for a facade, the corresponding reference wind is the mean wind acting on that facade, averaged over the area of the facade. It follows that the resulting coefficient may exceed 1.0 in places. This is the approach used at VPISU (Tieleman, Akins) and Colorado (Cermak, Peterka)[35-40].

A disadvantage common to the above is that the effects of the variation of turbulence for different boundary layer structures cannot be accommodated.

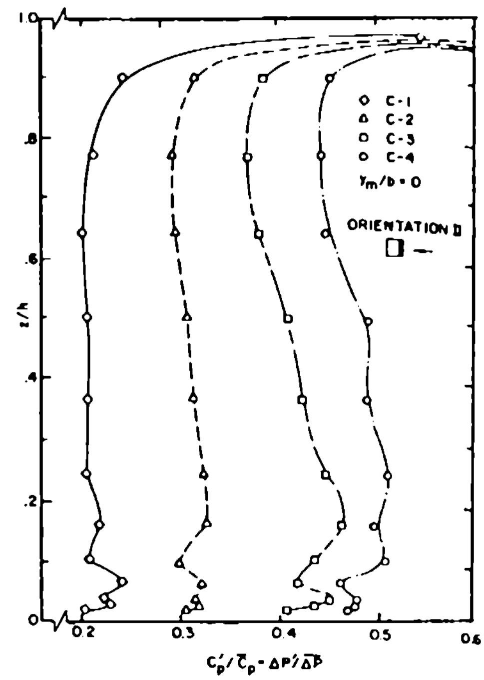
6) A modified local reference pressure of the form:-

$$q = \frac{\rho}{2} .(\overline{U} + n.u')^2 \qquad (4.2)$$

has been suggested by Corke et.al.[23,24]. The use of the combination of the mean and rms velocities for the present purpose is new, but has been used extensively in wind environment studies, relating to flow around buildings in urban areas for pedestrian comfort, and in the assessment of the effectiveness of windbreaks.
For the upwind face, a value of n=1 causes the vertical profiles of the mean pressure coefficients to collapse towards a single curve. A value of n=4 does the same for the RMS pressure coefficient. n=0 gives the best fit for the roof and surfaces other than the windward face in the case of wind blowing normal to one of the facades, otherwise the upwind values apply. (see Figs.(4.2), (4.3))

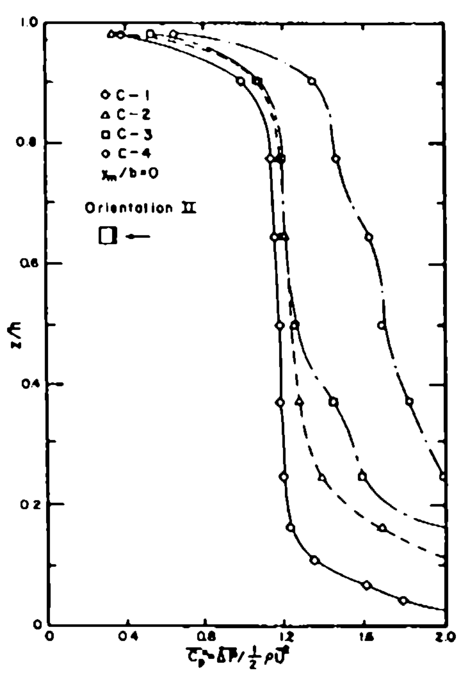


Vertical distribution of mean pressure coefficient along centerline of windward face of building for orientation II.



Vertical distribution of fluctuating pressure intensity along centerline of windward face of building for orientation II.

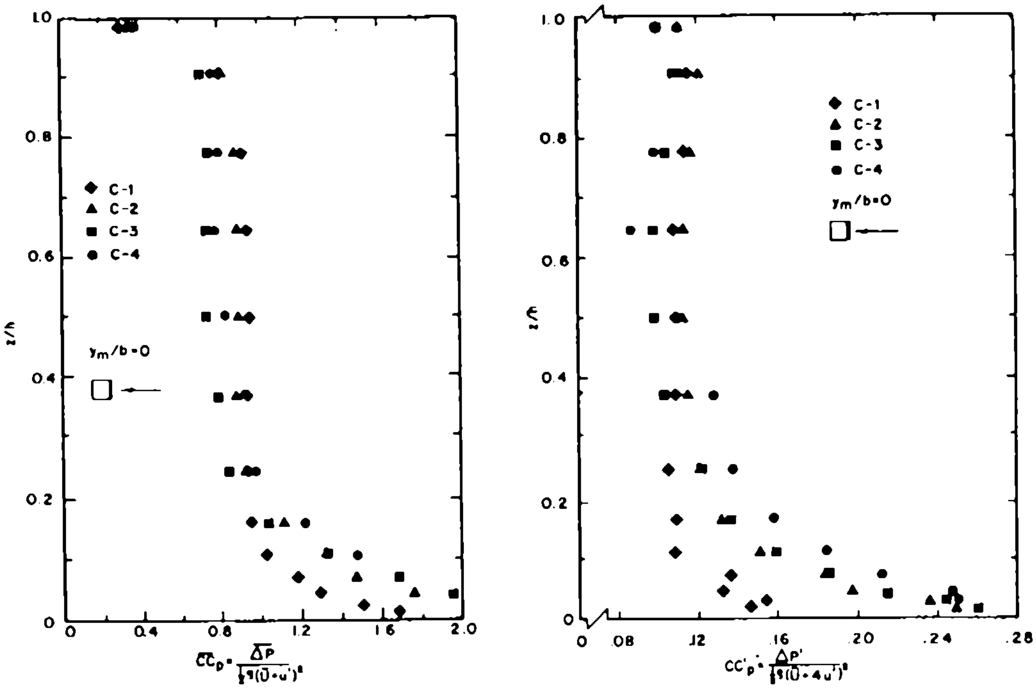
Fig.(4.2a) Free-stream pressure coefficients for a simple cubic building shape for four different boundary layer structures.



Vertical distribution of local mean pressure coefficient on windward face of building in orientation II.

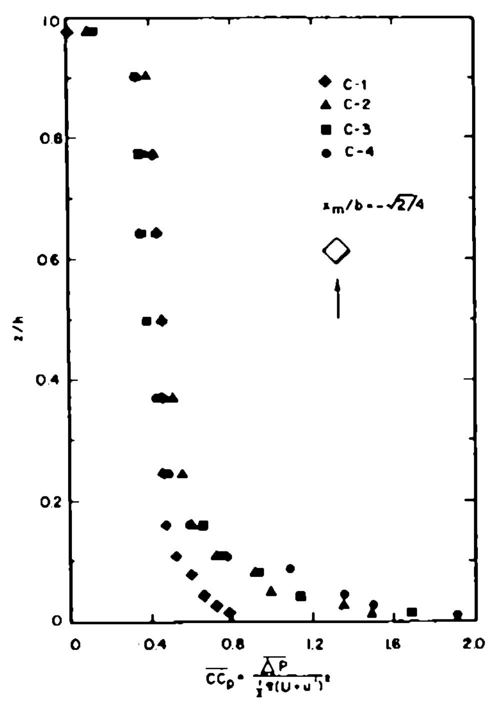
	Boundary layer			
	"C-1"	"C-2"	"C-3"	"C-4"
α	0.11	0.23	0.30	0.38
z_0 (in.)	0.00155	0.06	0.129	0.245
U_* (ft/s)	0.644	0.853	0.94	1.02

Fig.(4.2b) Local mean pressure coefficients. (Corke and Nagib[24])



Vertical distribution of corrected mean pressure coefficient ($n=1$) on windward face of building in orientation II.

Vertical distribution of corrected fluctuating pressure coefficient ($n=4$) on windward face of building in orientation II.



Vertical distribution of corrected mean pressure coefficient ($n=1$) on windward face of building in orientation I.

Fig.(4.3) Corrected mean pressure coefficients for a simple cubic building model in four different boundary layer structures. (after Corke and Nagib[24])

The degree of collapse for the Cp profiles for each facade varies somewhat, due to the differing degrees of influence of the upwind turbulence on the pressure fluctuations. In all cases, however, there was a considerable improvement over the case of uncorrected local pressure coefficients.
This system has the advantage of considerably simplifying the final form of the pressure coefficients, but has the disadvantage of requiring not only the local mean wind velocity profile but also the rms component or the turbulent intensity as input.

4.2 Fluctuating pressures

A number of workers in air infiltration have turned their attention to the contribution arising from fluctuating flow. (van der Held[41], Handa[14], Etheridge and Alexander[42], Potter[43])
The input requirements of an air infiltration model in this case include a knowledge of the rms. value of the pressure difference across the facade of the building for each leakage point, i.e. the local mean and rms. pressure coefficients and the internal pressure coefficient for the building at that position. Flow reversal can take place when the mean pressure difference is less than about 3 x (rms pressure difference). (Etheridge and Alexander[42])
In determining the overall flow of fresh air into a building, the combined effects of the non-steady contributions must be considered for all leakage points at any one epoch, since these will influence the variations of the instantaneous value of the internal pressure coefficient. It is important, therefore, to establish the degree of correlation between the fluctuating pressures at these loci. (Handa[14], Surry, Kitchen and Davenport[44]).
To that end one might also use the theory of acoustic circuits as used by Graham[45] and Card et.al.[46,47].

The time scale for the transmission of a pressure signal through a crack is small compared with that for the passage of the larger scale eddies in the wind which contain most of the energy. A reasonable analogy here is the pressure signal transmission through a 1.35mm diameter pvc tube described by Irwin, Cooper and Girard[48]. For a 10ft (3.05m) length, the delay time was about 10ms., the shorter the tube, the smaller the delay, whereas the turbulence time scale is between 5s and 5 min. The turbulence time scale is also long with respect to the time required for air to flow through most cracks, although where a cavity or shaft in a large building is involved, this may not be the case. Gumley[49,50] performed a similar set of calculations for tubes connected to a manifold, including the case of a fluctuating pressure signal superimposed on a steady signal. His calculations may well provide a basis for including fluctuating flow explicitly in air infiltration calculations.
These conditions imply that it should be possible to arrive at an answer based on the turbulent intensity of the wind and the geometry of the building. Preliminary model studies along these lines have been carried out by Holdø [51]and Corke et. al.[23,24] (see para.(4.1)). The latter propose including the rms component of velocity explicitly in the determination of the mean and rms local pressure coefficients.
The degree of correlation will depend on the relative scales of the energy containing turbulent eddies and of the building itself. In

general, the turbulence scale is usually much larger. One can therefore consider the building to be experiencing a wind field of near uniform structure but with varying strength. The pressure differences acting on the windward and leeward faces arising from eddies in the wind will therefore be well correlated. Those arising from the eddies generated by the building itself cannot be expected to be correlated, although it should be possible to estimate their frequency based on the appropriate Strouhal Number. (see para.(4.0))
Model studies of rms pressure coefficients are to be found in Table (A2.1), full scale measurements in Table (A1.1), and model studies of real buildings in Table (A2.2).(also see Chapter 6)

Until now it has been assumed by most workers that the fluctuations in the windfield, and of the pressure field have a Gaussian distribution. There is a growing body of evidence that this is not the case. Dalgliesh[52] and Peterka and Cermak[53] have described strong non-Gaussian behaviour in regions of separated flow and on the leeward walls in the case of high rise buildings. The pressures on the windward walls was observed as close to Gaussian.
In the case of low rise buildings, even the windward pressures show non-Gaussian characteristics. (Holmes[54])

Holmes found that for small values of the turbulent intensity (Iu), the distribution approached the Gaussian, but that for Iu of the order of 20% to 30% , the distribution is significantly skewed.
He gave a set of equations in terms of the turbulent intensity which can be used to estimate the proportion of the time for which the flow reversal condition is satisfied, and thus the non-steady part of the contribution to the infiltration.

It should not be forgotten that the wind varies not only in magnitude, but also in direction. This problem has been considered by Hoxey[55] who fitted a quadratic function to the angular variation of the pressure coefficient over a range +/- 20 degrees, using this to calculate a probability distribution for the mean pressure coefficient at a particular location on the surface of a greenhouse.

5 Survey of pressure measurements in the real wind

Full scale pressure measurements on buildings and measurements on model buildings in the real wind are listed in Tables (A1.1) and (A1.2) respectively. Field measurements of flow around windbreaks and buildings are listed in Table (A1.3). (see Appendix 1)
Much of the information was extracted from Ref.(56). All the information is presented in a similar format to that of Ref.(56). Entries are listed in order of building height. Information given includes the names of the investigators, the organisations to which they were affiliated at the time of the investigation, the location, type, size and exposure of the building, and details of the tests which were carried out.

6 Wind tunnel techniques

6.1 General

Wind tunnel studies are used when it is not practical to study a building at full scale, either because it is too difficult to instrument or because it does not yet exist. Some studies have been undertaken of models of existing buildings, usually relating to problems with cladding failure etc. but a few have been carried out for the specific purpose of comparing wind tunnel results with those from full scale measurements.
Such wind tunnel studies have several distinct advantages. In particular, the conditions for the tests are both consistent and readily reproducible when required,- a state of affairs rarely encountered in the real wind! Systematic investigations can be carried out and critical parameters identified.

The conditions which must be fulfilled for the wind tunnel flow to match the full scale atmospheric boundary layer are given in Table (6.1).
If all of these conditions could be met, then all features of the flow in the atmosphere could be matched. Unfortunately this is not possible. The appropriate choice of scale is very important. The requirements for optimum modelling of flow over gross terrain features differ greatly from those for modelling flow around an individual building. In the former case scales of the order of 1:1000 or greater are used. In the latter, for work involving fluctuating flows a scale of about 1:250 is more appropriate, while for flow around building detail, such as overhanging eaves, parapets, balconies, mullions, etc.,1:50 or less may be necessary to satisfy condition (7). This arises from the depth of the local boundary layer on the wind tunnel model being larger in proportion to the overall size of the model than that on the building in the real wind.
The longitudinal scale of turbulence is also difficult to match at model scale, being much larger relative to the size of the building in real life than can be reproduced readily in the wind tunnel.
Most wind tunnels are designed to simulate a neutrally stratified, adiabatic boundary layer, typical of high wind speeds. These conditions are best suited to the study of wind pressure on buildings from the viewpoint of wind loading. Wind pressures for ventilation span the full range of conditions from light variable winds to the extreme conditions which are usually studied.
Little work has been done which ventures into these lower speed regions. What there is, (Katsura[57],) suggests that the pressure coefficients are reduced at lower windspeeds. This indicates the need for further work to be done, specifically aimed at studying conditions more commonly encountered in nature. (see Appendix 2)

Some detailed parametric wind tunnel studies (A.Hunt[58], Akins[35]) offer some indications of the determining factors for the pressure distribution.
Studies comparing full scale and wind tunnel measurements (Tieleman, Akins, and Sparks[38], Holdø[51]) describe the conditions under which measurements at model and full scale agree.

Table (6.1) - Similarity requirements

Condition	Possibility of fulfilment
(1) Undistorted scaling of geometry	Yes: within limits of scale
(2) Equal Rossby No. $Ro=U/L\,\Omega$	No
(3) Equality of gross Richardson No. $Ri=(dT/T).(L/U^2)g$ If two or more layers are present with differing stratification, this quantity must be matched for each layer individually.	Yes, in a meteorological wind tunnel (MWT)
(4) Equal Reynolds No. $Re=U.L/\nu$	No, but not too serious since most features depend weakly on Re.
(5) Equal Prandtl No. $Pr=\nu/(k/\rho\,.Cp)$	Yes
(6) Equal Eckert No. $U^2/(Cp.dT)$	No, incompatible with matching Ri. Effect is small.
The following surface boundary conditions must be similar:-	
(7) Surface roughness distribution which exhibits aerodynamically rough behaviour must match.	Yes, within limit that the minimum roughness exceeds $10.\nu/U^*$
(8) Topographic relief	Yes
(9) Surface temperature distribution.	Yes, by using heating and cooling elements in the WT floor upstream.
These approach flow conditions must also be matched:-	
(10) The distribution of mean velocities.	Yes
(11) The distribution of turbulent velocities, including the energy spectra.	Yes for bottom 10-15% of WT Turbulence scale matching difficult.
(12) The mean temperature distribution.	Yes
(13) Fluctuating component of the temperature distribution.	Yes, in MWT.
(14) The longitudinal pressure gradient should be zero.	Yes
(15) If the flow is layered, e.g. an inversion is present, The relative thicknesses of the layers must be the same.	Not yet.

Key:

Given that L is the scale length, U is the scale velocity U^* the friction velocity = $\sqrt{(\tau/\rho)}$, is the shear stress. Ω is the angular velocity, T is the scale temperature, dT is the scale temperature difference, g is the acceleration due to gravity, ρ is the density, ν is the kinematic viscosity, Cp is the specific heat at constant pressure and k the thermal conductivity:-

6.2 Effects of building form on modelling requirements

The pressure pattern experienced is governed by the separation and reattachment of the boundary layer on the building surface. This is strongly determined by the form of the building. In the case of the basic rectangular block, and other shapes where the surfaces are bounded by sharp edges, flow separation is forced by the building geometry. (see Ch.2)

Provided that the linear and velocity scales are matched and the longitudinal turbulence scale, ${}^{x}L_{u}$, is sufficiently large, this class of building shapes is easily modelled.
Where reattachment takes place, the size of the reattachment bubble is dependent on the Reynolds Number. This can cause a distortion of the flow at model scale relative to that at full scale. (Macha, Sevier and Bertin [59])

Where the surface of a building is curved the position at which the boundary layer trips is determined by the surface roughness.

For the flow round the model counterpart of such a building to behave in the same way as its full scale prototype, it is necessary to roughen the surface of the model, the amplitude of the roughness elements being sufficient to penetrate the laminar boundary layer on its surface, a similar consideration to that applying when modelling small scale detail on the surface of a building such as balconies, mullions and parapets.

6.3 Effect of boundary layer structure

Wind tunnel tests cannot be used to simulate flows with a substantial component of rotation in the horizontal plane. It is not possible to model, for example, the variation of wind direction with height (Ekman spiral) by this method. This has been assumed to be of negligible effect but for the very tall structures now in existence, this may not be the case. For this, the answer may lie with rotating flow experiments such as those of Caldwell and van Atta [60,61], (see also Cermak [62])
Cases of extreme vorticity such as tornados also require this kind of approach.

Stratified flow around larger scale topographic features has been modelled by towing an inverted version of the structure through a water tank, the density variation being produced by doping with salt. Gross flow is well reproduced by this method, but turbulence is not well represented.
Flow over complex topography is also a field where future work is required. Some studies of polutant dispersal in a simple model valley in a turbulent boundary layer were reported by Fackrell and Robins of CEGB Marchwood Laboratories[63].
This problem has been tackled more often by numerical modelling than by actual physical modelling. (see Chapter 8, Table 8.1b and Chapter 9). Radiative exchange has not been considered as yet, although this will become necessary in order to understand conditions of valley flow.

The effects of latent heat release and precipitation do not lend themselves to physical modelling, other than for the extreme case of wind driven rain. Such studies have been undertaken at the Building Research Institute, Tokyo.

There are other non standard profiles which need investigating, e.g. the low level jet, often observed in areas of extensive plains, such as the Great Plains in the USA and the Great European Plain (north Germany). This field is characterised by high velocities, relatively low turbulence, occurring mainly at night. (Roth[64])

Wind tunnel studies of flow in the urban environment have largely concentrated on problems of pedestrian comfort and damage to nearby buildings. From the point of view of air infiltration studies, a more useful subject area would be the effects of a nearby large building on the pressures experienced by a smaller building lying in its wake. (Gerry and Harvey[65], Pfaff[20], van Dalen[21]) (see Table (A2.1e))
A list of studies on wind flow around buildings can be found in Table (A2.1g).

6.4 Comparison of Wind Tunnel Performance

The performance of wind tunnels in comparison with each other is described in Melbourne[66]. This paper describes a series of studies in which tests were carried out for a standard tall building model, the specification of which was prepared by Wardlaw and Moss[259] for the Commonwealth Advisory Aeronautical Research Council (CAARC).

Surface pressures and dynamic response were measured at 6 establishments:

1) University of Western Ontario (J.D.Holmes)

2) University of Bristol, England (T.V.Lawson)

3) Monash University, Australia (W.H.Melbourne)

4) National Physical Laboratory, England (D.E.Walshe, J.A.B.Wills, P.Jones)

5) National Aeronautical Establishment, Canada (K.R.Cooper, R.L.Wardlow)

6) City University, England (D.M.Sykes)

The following parameters were compared :-

1) boundary layer characteristics,
2) mean pressure coefficients,
3) standard deviation (RMS) pressure coefficients,
4) pressure spectra,
5) probability distributions of pressure measurements on the model surface,

6) displacement of the top of the model,
7) effect of structural damping, and
8) base overturning moment.

Small trends were observable in respect of pressure measurements, attributable to differences in longitudinal velocity spectrum and requirement for blockage correction. There were no obvious trends in the dynamic response measurements where most of the data compared to within 15%.

6.5 A Survey of Wind Tunnel studies

(see Appendix 2)
Wind tunnel studies of real buildings are listed in Table (A2.1). These include some model studies carried out for wind loading purposes prior to construction. In some cases full scale pressure measurements are available. In these cases the number of pressure taps at model and full scale is quoted.
Detailed studies of general forms, such as rectangular blocks, and of simple building shapes, are listed in Table (A2.2).

Data from the studies of Bowen[67], and Akins, Peterka and Cermak[36,37] (based on Akins[35]) on rectangular blocks have been analysed at the Air Infiltration Centre for their dependence on side ratio, wind angle and shelter in order to find a way of presenting the results of such studies in a more "computer-friendly" form. The results of this analysis are given in Chapter 7.

7 Analysis of wind tunnel results

Until now, apart from a few isolated cases (e.g. Shaw[68]), 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.

7.1 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:

$$Cp(i) = a(0) + \Sigma\, a(i).\cos(i.\theta) + \Sigma\, b(i).\sin(i.\theta) \qquad (7.1)$$

(Stephenson[69])

This approach has been used by Shaw [68] 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[67] and Akins, Peterka, & Cermak[37]. 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 used in Chapter 1. (Shaw[2])
The data from Akins et.al 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.(7.1) to (7.6). (Baker and Nelder[70])
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.

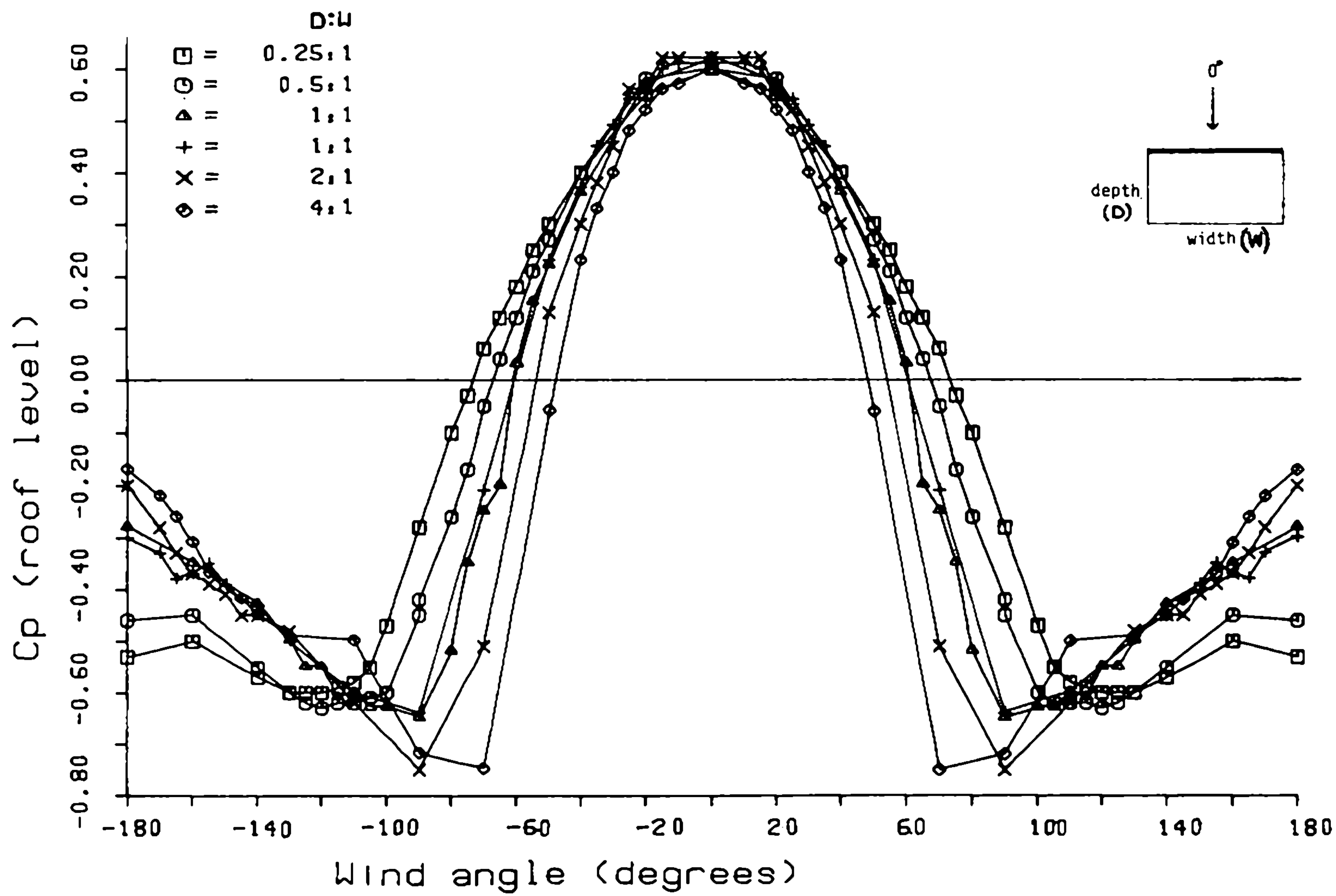


Fig.(7.1) Roof level, whole face pressure coefficients for simple rectangular blocks with various side ratios. (Akins.et.al. (4))

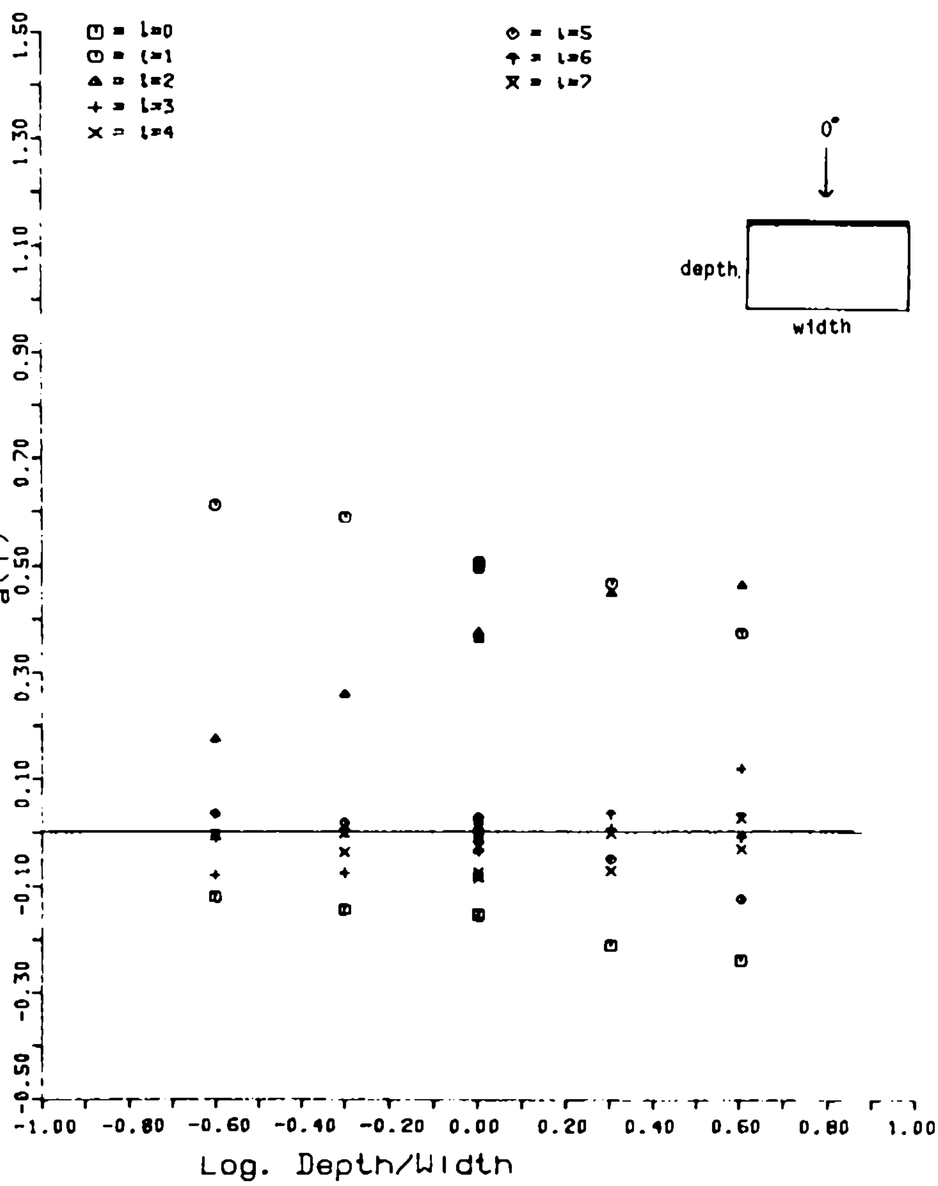


Fig.(7.2) Coefficients a(i) for roof level pressure coefficients.

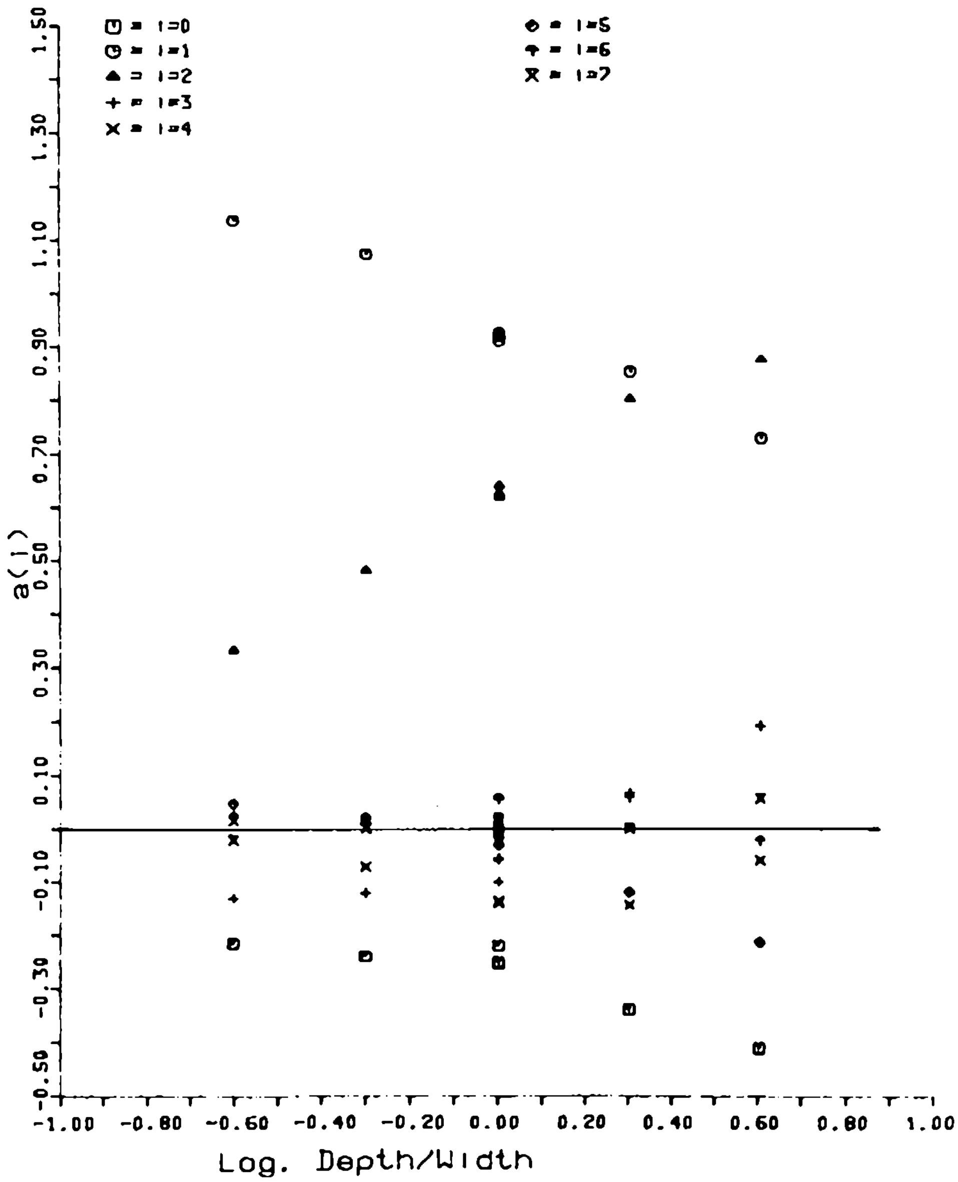


Fig.(7.3) Coefficients a(i) for local pressure coefficients.

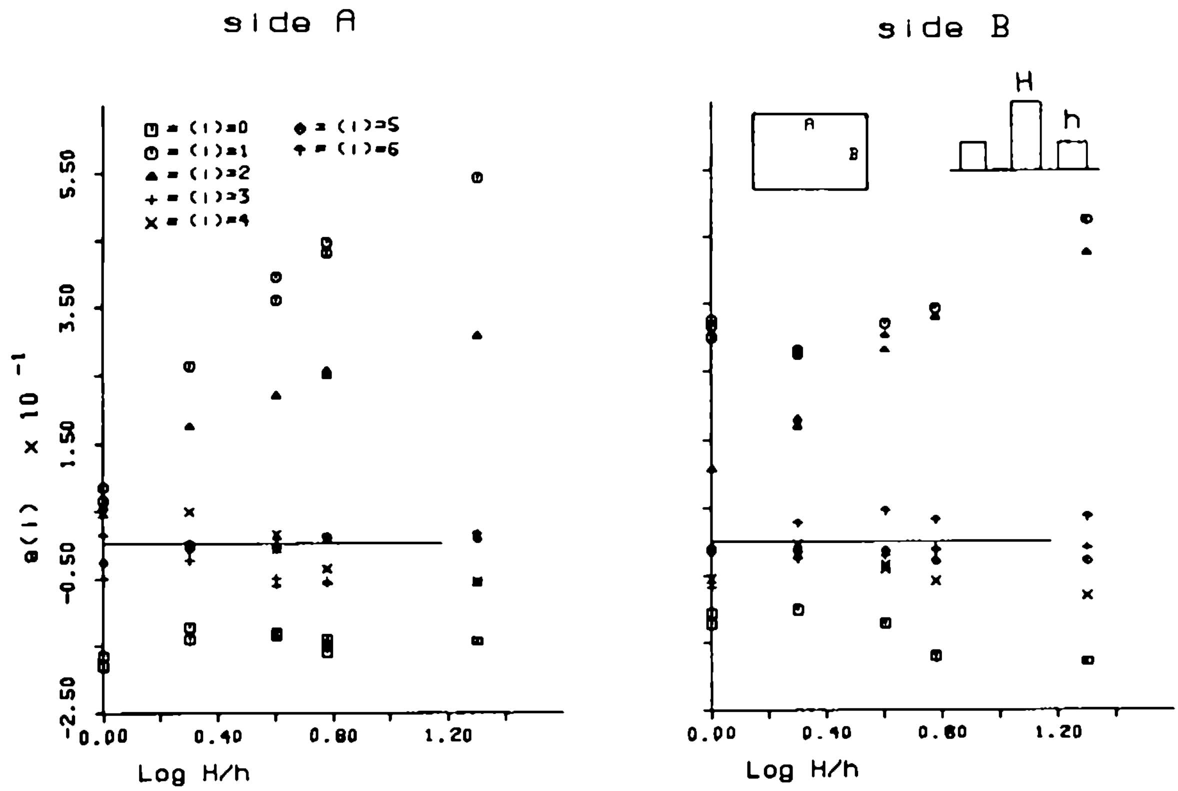


Fig.(7.4) Coefficients a(i) as a function of shelter (H/h).

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. (see Fig. (7.4)

Since cos(i.θ) 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 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:

$$Cp = A + B(X/W) \qquad (7.2)$$

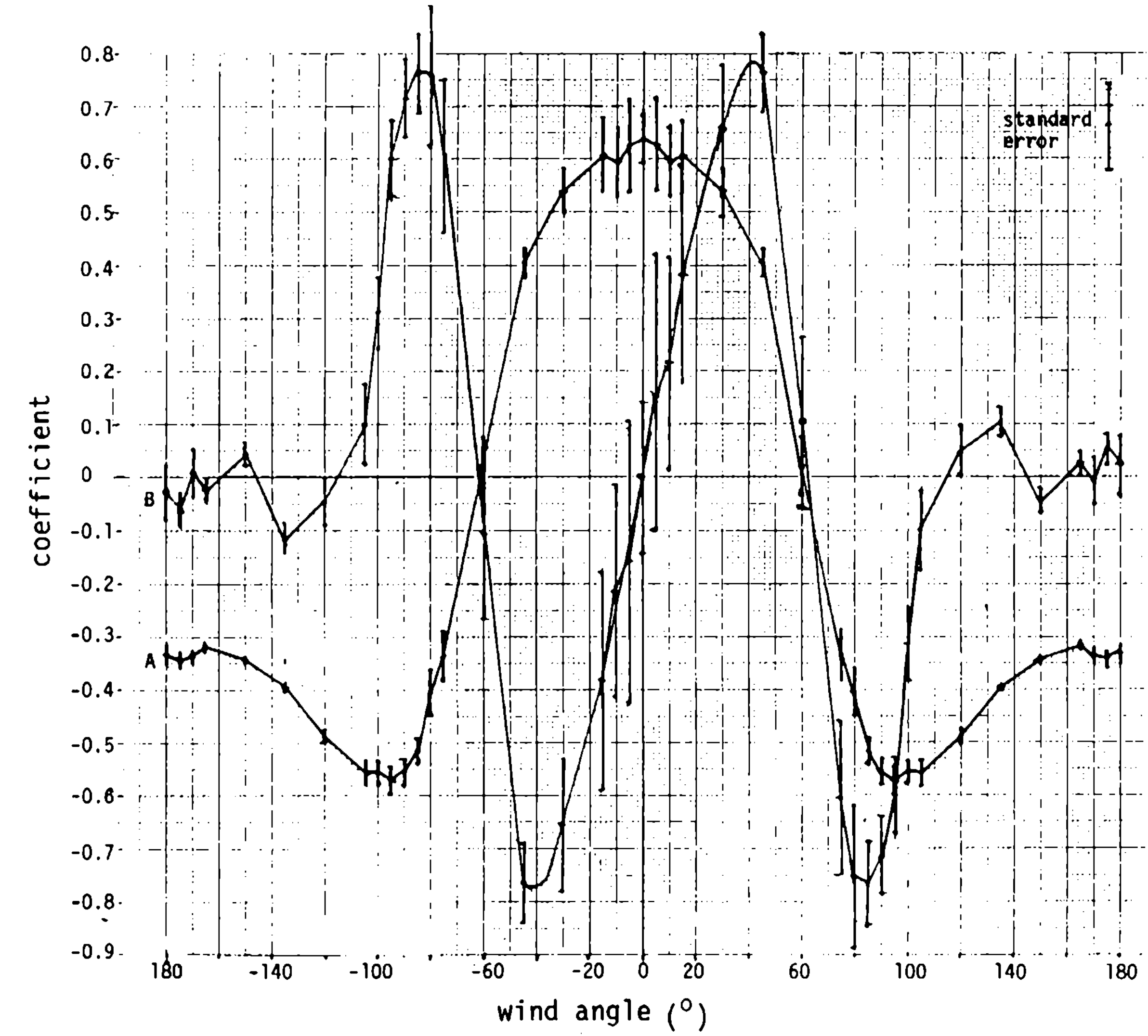


Fig.(7.5) Fourier analysis of the horizontal pressure distribution across a facade with wind angle. (see eqn. 7.2) (data from Bowen[67])

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. (7.5)
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 (7.3))
The mean pressure coefficients for the roof are illustrated in Fig (7.6). 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.[39]
The test building is illustrated in Fig. (7.7)

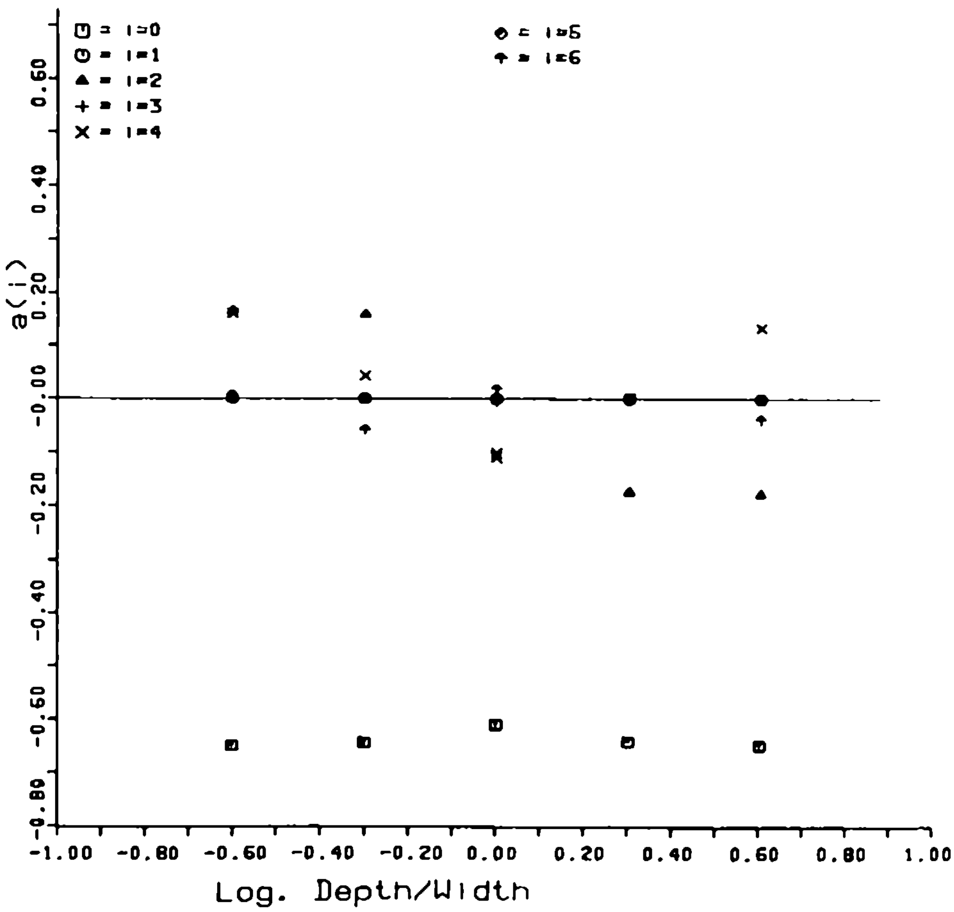


Fig.(7.6) Coefficients a(i) from eqn. 7.1 for the mean Cp of a flat roof. (same for both roof level and local reference winds)

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. (7.8a) and (7.8b). 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.

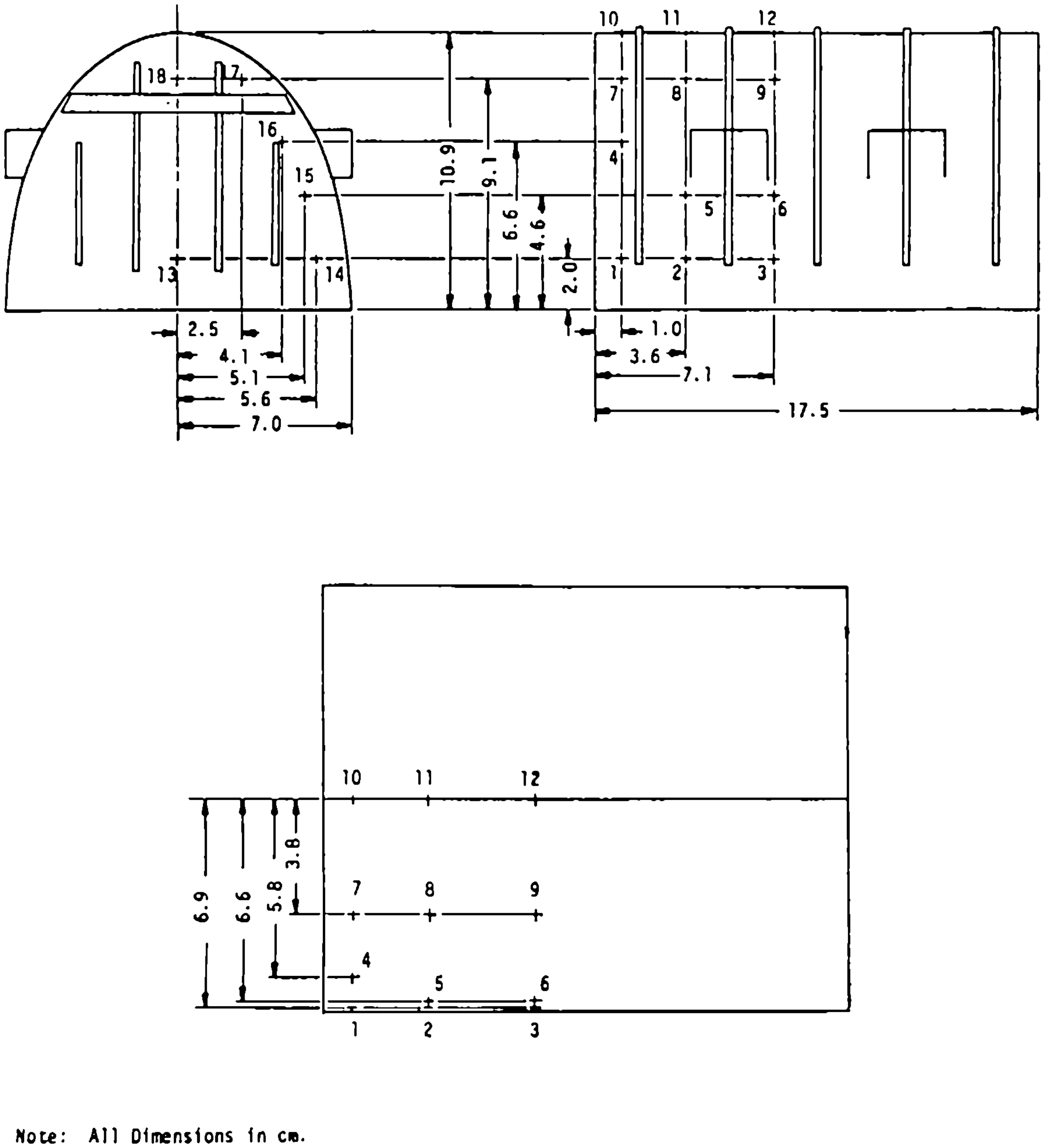


Fig.(7.7) Care Inc. Single Family Dwelling. Location of pressure taps. (Reproduced by kind permission of the authors: Tieleman and Gold[39])

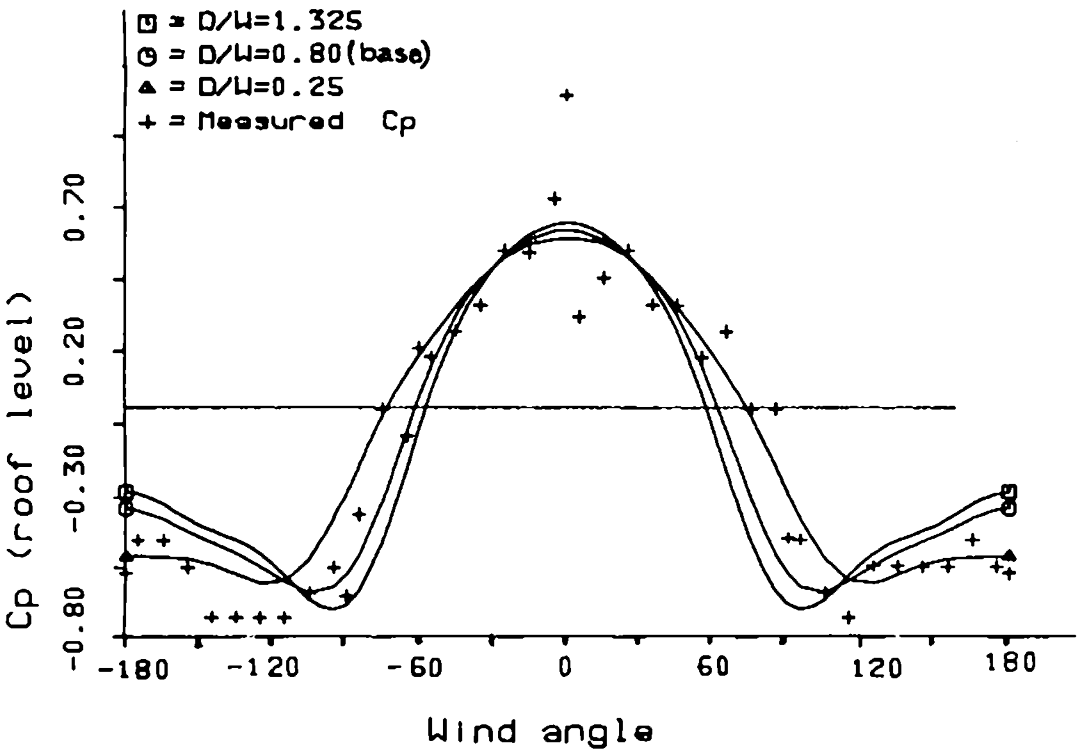


Fig.(7.8a) Measured and calculated pressure coefficients plotted against wind angle for position 6 (side wall).

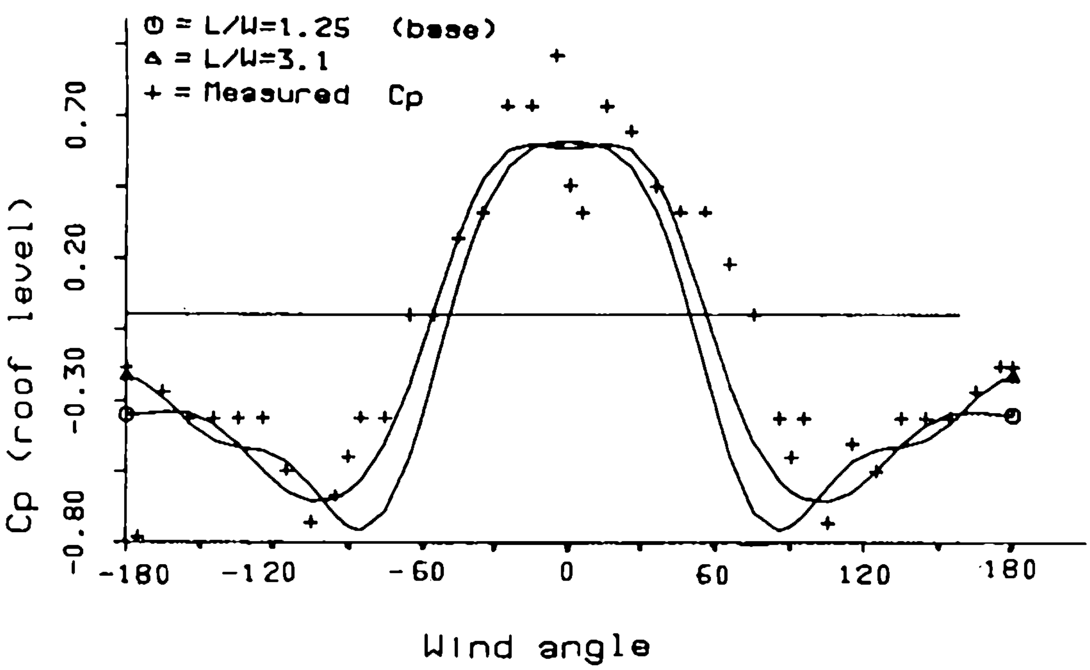


Fig.(7.8b) Measured and calculated pressure coefficients plotted against wind angle for position 18 (end wall).

7.2 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 (7.1) Coefficients of the log series representation of a(i) values - Mean local pressure coefficients.

a(i) j=	0	1	2	3	4	5	6
0	-0.2418	-0.07016	-0.1225	0.0	+0.0441	0.0	0.0
1	+0.9358	-0.1496	0.0	0.0	0.0	0.0	0.0
2	+0.6293	+0.2420	+0.03818	-0.02440	-0.02684	0.0	0.0
3	-0.06432	+0.1207	+0.05121	0.0	0.0	0.0	0.0
4	-0.1371	-0.0622	+0.06033	+0.01826	0.0	0.0	0.0
5	-0.01546	-0.09586	-0.08173	0.0	+0.02441	0.0	0.0
6	+0.05484	0.0	-0.05104	+0.0973	+0.01203	-0.05505	0.0
7	+0.01092	0.0	-0.0316	+0.0145	+0.01844	0.0	0.0

Table (7.2) Coefficients of the log series representation of a(i) values - Mean roof-level pressure coefficients.

a(i) j=	0	1	2	3	4	5	6
0	-0.1532	-0.04332	-0.05981	0.0	+0.02435	0.0	0.0
1	+0.5031	-0.08585	0.0	0.0	+0.1564	0.0	-0.08276
2	+0.3689	+0.1479	-0.02574	-0.02252	0.0	0.0	0.0
3	-0.03146	+0.05712	-0.01061	+0.007807	+0.01978	0.0	0.0
4	-0.07928	-0.03031	+0.05996	+0.01161	-0.01460	0.0	0.0
5	-0.08458	-0.04409	-0.01777	-0.00624	0.0	0.0	0.0
6	+0.02826	+0.03123	-0.01961	-0.01589	0.0	0.0	0.0
7	+0.007429	0.0	-0.02585	+0.006443	+0.01425	0.0	0.0

These coefficients closely reproduce the data in Figs.(7.3) and (7.2).

The values for the a(i) and b(i) coefficients are given in Table (7.3) 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:-

$$Cp_{(\theta)} = (A + B(X/W)_{(\theta)} \tag{7.4}$$

Where:-

$$A = a(0) + \Sigma\, a(i).\cos(i.\theta) \tag{7.5}$$

$$B = \Sigma\, b(i).\sin(i.\theta) \tag{7.6}$$

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 :-

$$D = (Cp(0)-Cp(sheltered))$$

$$= f(T,T^2,T^3,S.T,S.T^2,S^2.T) \tag{7.7}$$

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

$$T = \tanh\left(\frac{h}{(C.H)}\right) \tag{7.8}$$

The deficit can be expressed by such a series for each of the Fourier coefficients a(i). The coefficients for equation 7.7 for i= 0 to 7 are given in Table (7.4).

The local pressure coefficients for zero wind angle for various S are plotted against z/H (Fig. 7.10). For z/H > 0.1, the curves collapse almost to a straight line. The best straight line fit is :-

$$Cp(0) = 1.617 - 0.8552(z/H) \tag{7.9}$$

The mean roof reference pressure coefficients and the corresponding centre line values from Bowen[67] (depth/width = 2/3) have been plotted for shelter conditions from H/h = 1 to H/h = 6. (Fig (7.9)). The results all lie approximately on a straight line.

Table (7.3) 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

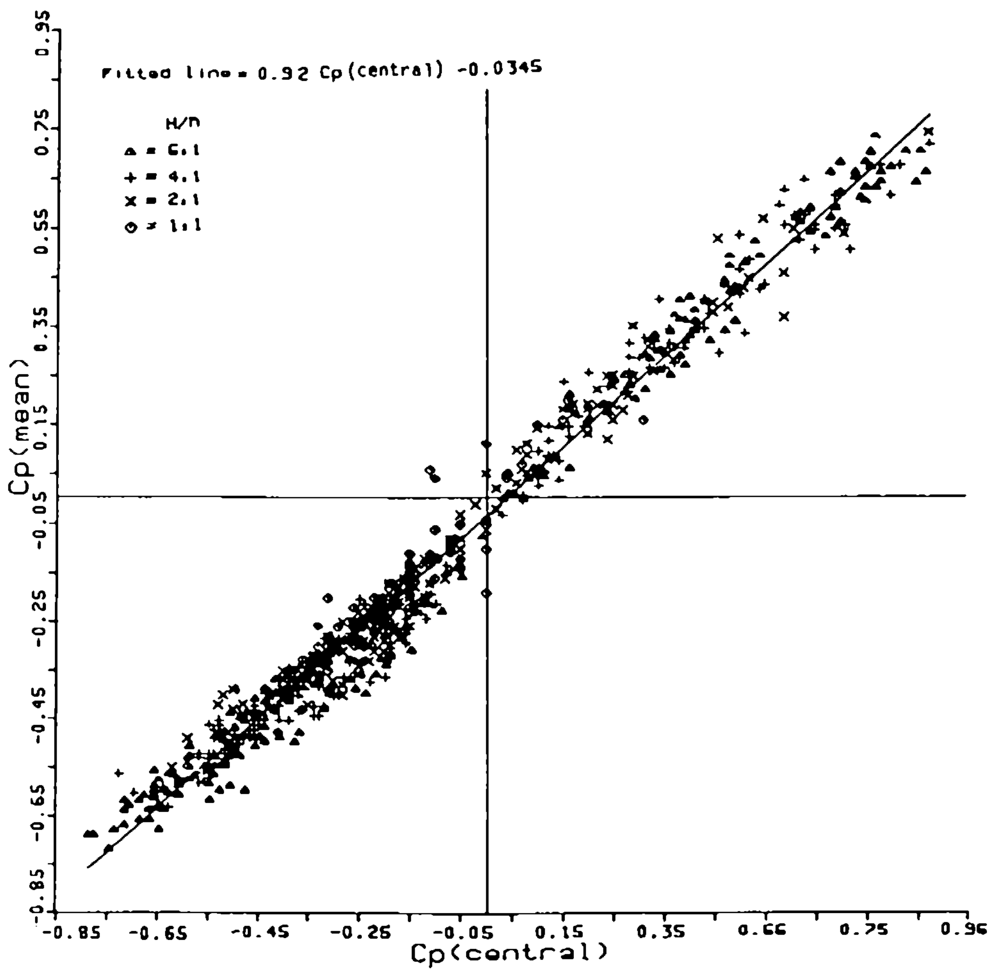


Fig.(7.9) Plot of mean Cp against centre line Cp for various z/H, H/h and wind angle for face A.(see Fig.(7.4)) (data from Bowen[67])

Table (7.4) 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.(7.9) to within 10%, and mostly within 5%.

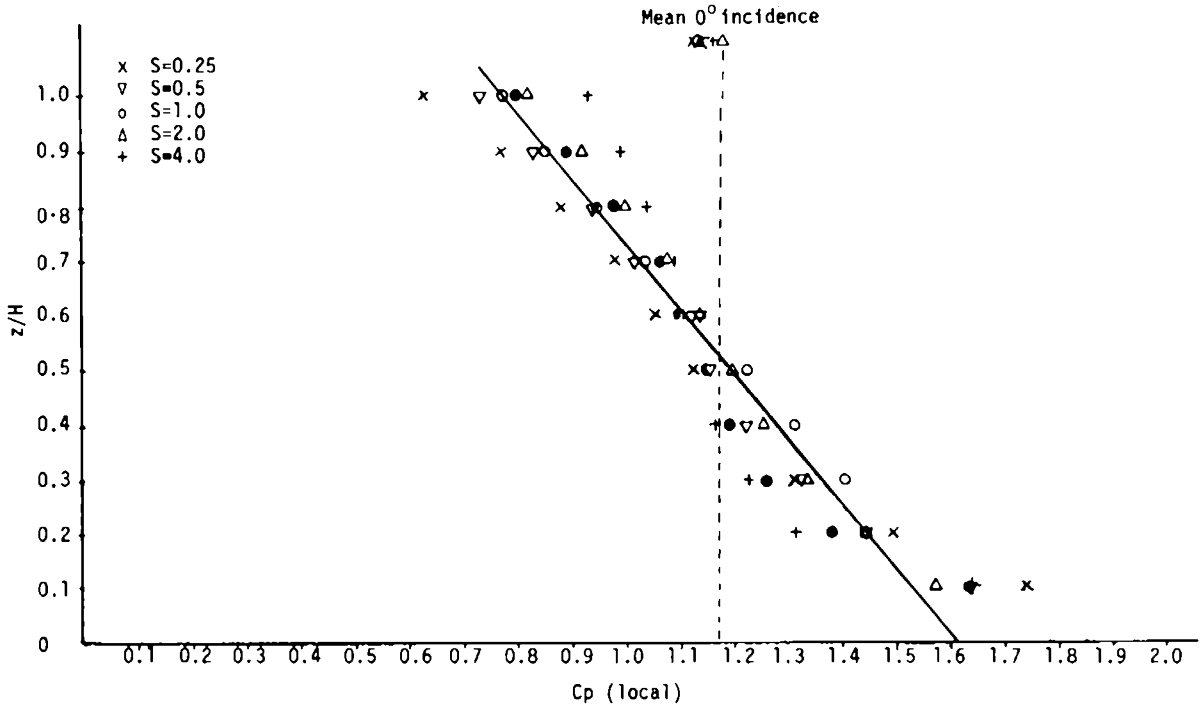


Fig.(7.10) Local pressure coefficients for zero wind angle and various S plotted against z/H.

Equation 7.4 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: $Cp(mean) \simeq 0.92\ Cp(central) - 0.03$ (7.10)

for S = 3/2: $Cp(mean) \simeq 0.97\ Cp(central)$ (7.11)

for the flat roof:

$$Cp(mean) = -0.3612 + 0.4141\ Cp(central) \quad (7.12)$$

7.3 Case studies

7.3.1 Aylesbury test house

Wind pressure data has been gathered by Eaton and Mayne[15] 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. (7.11))

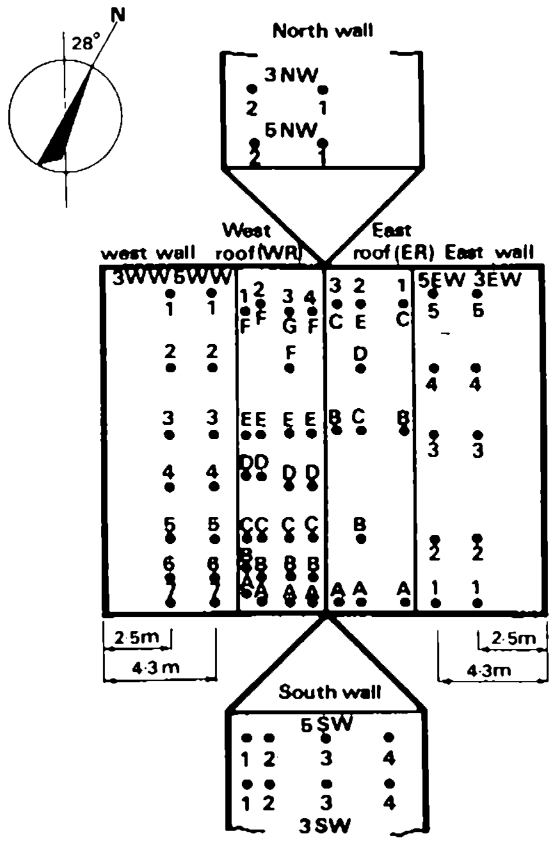


Fig.(7.11) Aylesbury Test House - location of pressure taps
(From Eaton and Mayne[15] reproduced by permission of the Controller, HMSO Crown Copyright)

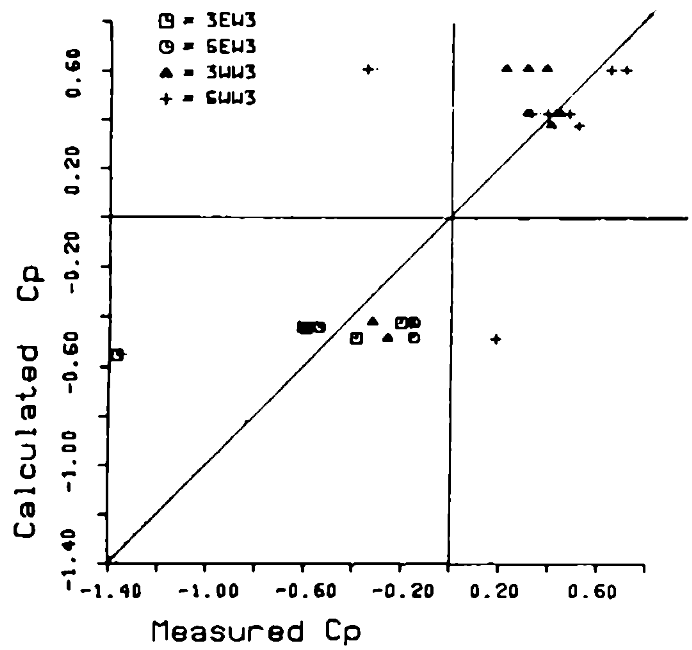


Fig.(7.12a) Measured vs. calculated pressure coefficients for the Aylesbury test house.

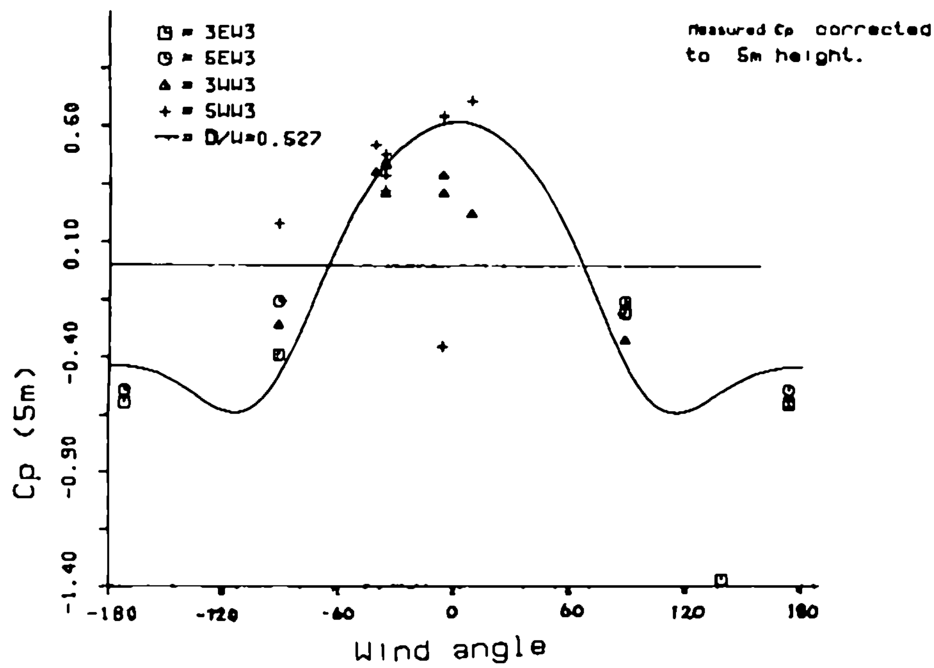


Fig.(7.12b) Measured and calculated pressure coefficients plotted against wind angle for the Aylesbury test house.

The calculated values, using the coefficients derived from Table (7.2), are plotted with the data in Fig.(7.12a) against each other and both against relative wind angle in Fig.(7.12b).

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.

7.3.2 CAARC tall building model

The method has been tested against the CAARC data from Melbourne[66]. 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:-

$$V(z)/V(H) = (z/H)^{0.26} \qquad (7.13)$$

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

$$= (2/3)^{0.52} . (1.047/1.110) . \langle Cp(\ell)\rangle \qquad (7.14)$$

(From equations (7.9) and (7.13) and Table (7.1) for the case of 0^o wind angle).

$$= 0.7639 \langle Cp(\ell)\rangle \qquad (7.15)$$

The coefficients a(i), calculated using the coefficients from Table (7.1) are displayed in Table (7.5).

Table (7.5)

	Mean local Cp's (=<Cp(ℓ)>)	Roof level Cp's (H/h=6)
a(0)=	-0.232	-0.1505
a(1)=	+0.996	+0.448
a(2)=	+0.538	+0.255
a(3)=	-0.105	-0.055
a(4)=	-0.103	-0.037
a(5)=	+0.0106	+0.013
a(6)=	+0.041	0.0
a(7)=	+0.005	0.0
b(i)=	0.0	0.0

The results are plotted against the CAARC data in Fig (7.13). It can be seen that for the regions where equation (7.9) applies (-90 to +90 degrees), the fit is excellent.

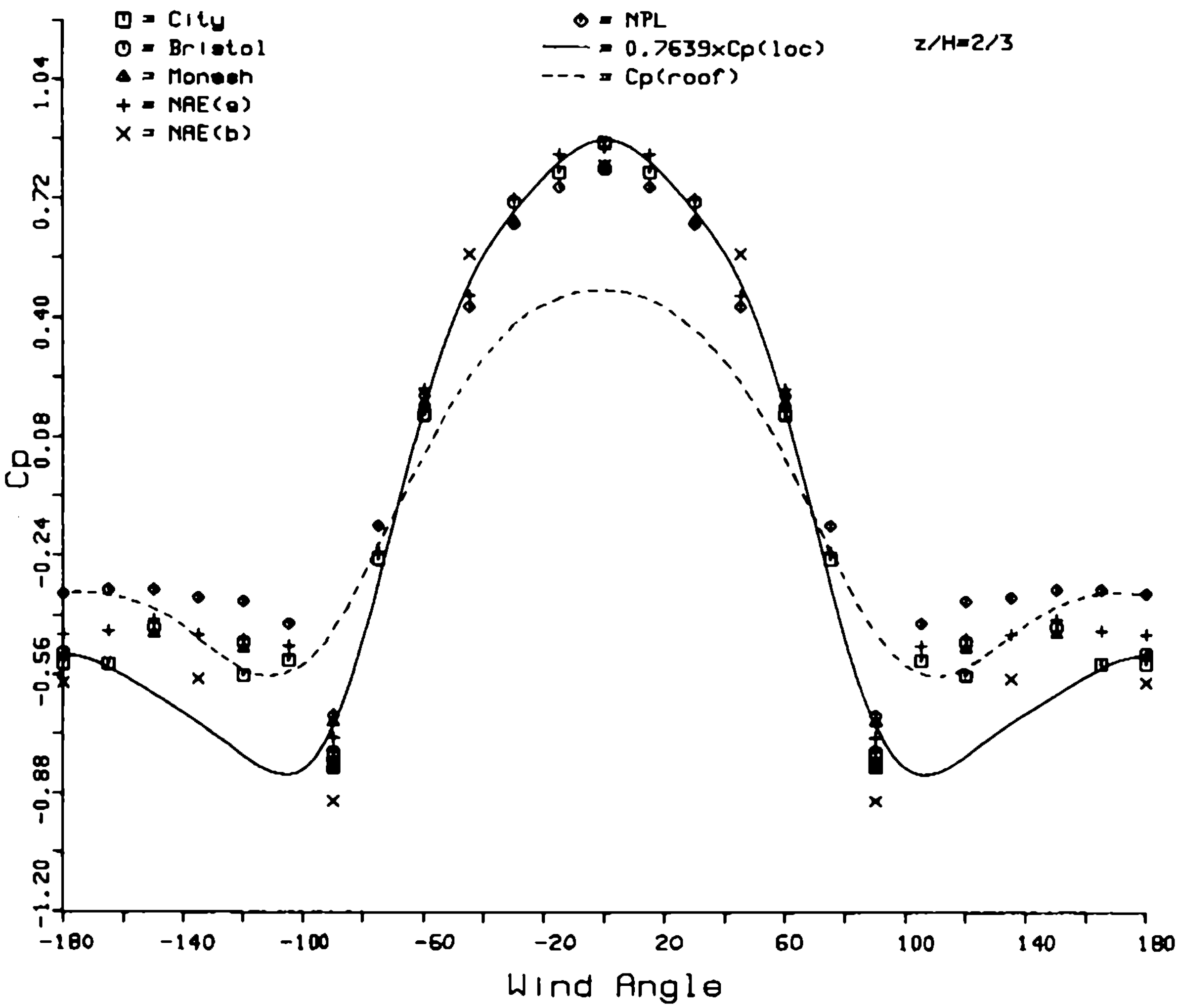


Fig.(7.13) Measured and calculated pressure coefficients plotted against wind angle for the CAARC Standard Tall Building Model.

The mean roof level Cp for the wider facade is also plotted, using coefficients from Table (7.2). 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 <Cp(ℓ)> 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.

7.3.3 Comparison with full scale measurements on a high rise building

Results from full scale and model measurements reported by Dalgliesh[52] 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. (7.14). 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.

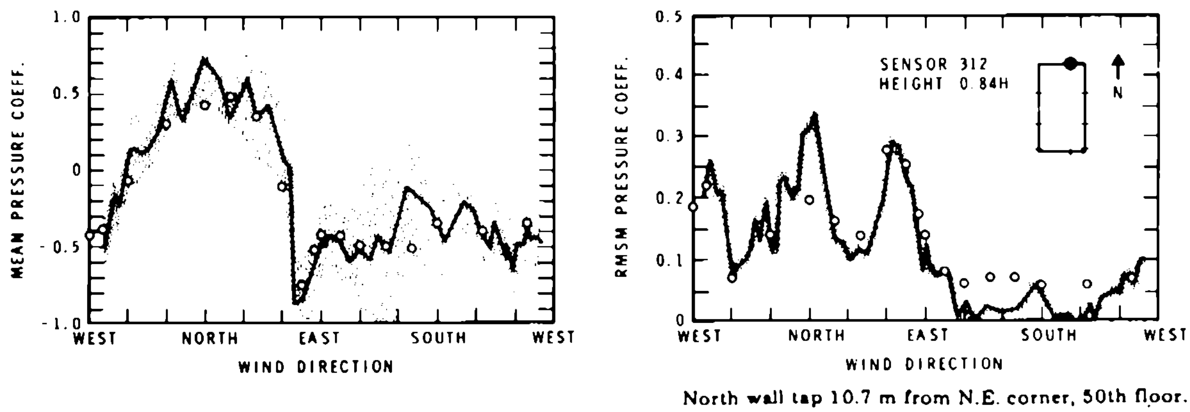


Fig.(7.14) Example of full scale measurements on a 57 storey office tower in Toronto. (from Dalgliesh[52])

7.4 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.

$$a(0) = (1/k) \sum_{m=0}^{k-1} y(m) \qquad (7.16a)$$

$$a(i) = (2/k) \sum_{m=0}^{k-1} y(m).\cos(2.m.i.\pi/k) \qquad (7.16b)$$

$$b(i) = (2/k) \sum_{m=0}^{k-1} y(m).\sin(2.m.i.\pi/k) \qquad (7.16c)$$

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.

8 Theoretical modelling

8.1 Modelling of the pressure distribution

Work in this area appears to be rather sparse. Such as there is, is listed in Table (8.1a).
Purely theoretical models have, up to now, been confined to consideration of the 2D case, which is susceptible to treatment by transformation techniques. (e.g. Yih[71], Parkinson and Jandali[72], Kobayashi[73]), or to numerical modelling. (Hunt[74])
All suffer from the disadvantage that they cannot cope with flow separation.
Empirical methods are described by Hoxey[55] who uses a quadratic function of wind angle (see Chapter 4), Shaw[68] and the author (see Chapter 7), using Fourier series.

8.2 Modelling of the wind profile

A selection of papers on numerical modelling of the atmospheric boundary layer over complex terrain are listed in Table (8.1b) (see Chapter 9)

Table (8.1)

a) Pressure distribution

Investigator(s)	Affiliation/ Organisation	Method Used	Case Studied
Hiemenz Homan (Yih 71)	----	2-D viscous, laminar stagnation flow.	Pressure distribution on the windward face. Solves for uniform approach flow and 2-D or axisymmetric bodies.
G.V.Parkinson T.Jandali (72)	----	Potential flow theory	2-D incompressible potential flow external to a symmetric bluff body and its wake. Requires the location of separation points on the bluff body and base pressures in the separated regions. Useful only for 2-D bodies since uses transformation methods for the solution.
Shoji Kobayashi (73)	Structural Mechanics Inst. of Construction Technology Kajima Constr. Co.Ltd. Japan	2-D potential theory	Pressure distribution on the windward faces of a 2-D rectangular cylinder in uniform flow. Used transformation methods to assess the variation across the facades for different wind angles.
J.C.R.Hunt (74)	Univ. of Cambridge	rapid distortion theory	Predicts flow around a 2-D body in uniform flow with isotropic turbulence. Predicts mean and fluctuating surface pressures for regions where there is no flow separation.
J.D.Holmes (75)	James Cook Univ. of N.Queensland Townsville Australia	Computer simulation model - damped Helmholz resonator (central difference) used simulated external pressure record as driving function.	Mean and r.m.s internal pressure coefficients (both are monotonic functions of the ratio of windward to leeward opening areas.) Considers inertia and response time effects for a step change in pressure, as in the case of window failure (or door opening).

b) Studies of the wind field - complex terrain

Investigator(s)	Affiliation/ Organisation	Method Used	Case Studied
D.M.Deaves (76)	Cranfield Inst. of Tech.	Numerical model	Neutrally stratified B-L passing over a 2-D hill or embankment. Looks at the speed up ratio. Compares with full scale measurments at Brent Knoll and Black Mountain (Canberra, Australia The model can be adapted to arbitrary shapes.
P.A.Taylor (77)	Atmos. Environ. Service. Downsview, Ontario Canada	Numerical modelling	Models flow over 2-D ridges with a cosine squared profile. Neutrally stratified A.B.L
P.J.Mason R.I.Sykes (78)	Met.Office Bracknell Berks. U.K.	Numerical modelling	Flow over ridges
P.S.Jackson J.C.R.Hunt (79)	Univ. of Cambridge	Numerical modelling	Flow over a low hill. Including turbulence.
T.Kubo I.Hayakawa Y.Isobe (80)	Kanazawa Inst. of Technology Tokyo Inst. of Technology Regnl.Planning Team.Inc. Japan	Interpolation method	Models wind field over complex terrain based on a small number of observations.
Y.Ohishi (81) K.Shiozawa S-I. Okamoto	Nippon Kokan K.K Waseda Univ. Industl.Polln. Control Assn. of Japan	Numerical modelling	Uses a modified potential flow model to predict the mean wind field over complex terrain.

Additional References

Yocke et.al (82)
Berman et al. (83)
Antonia and Luxton (84, 85)
Auer (86)
Glauert (87)
Hunt (88)

9 The Wind Field

In order to use the pressure coefficients to generate surface pressures, it is necessary to provide an adequate description of the local windfield. The degree of detail required will depend on the choice of reference wind. This part of the report includes some of the more commonly used descriptions of the planetary boundary layer, and discusses some of the factors which affect the velocity structure on a local scale.

There are two basic levels of information.

1) Single point reference winds, such as Vg, V(10m), roof level or ceiling level reference winds, and,

2) Multi-point reference winds, i.e. mean and r.m.s velocity profiles.

Single point reference winds may be derived by:-

a) direct measurement,

b) reference to standard data, e.g. from BS5925[4],

$$U(z)/Um = Kz^{a} \qquad (9.1)$$

where Um is the average 10m windspeed for open country in the region of the building.

c) reference to a nearby site, e.g. from Sherman and Grimsrud[89],

$$v = v'. \frac{[\alpha(H/10)^{\gamma}]}{[\alpha'(H'/10)^{\gamma'}]} \qquad (9.2)$$

where the primed quantities refer to the wind measurement point.

The above equations are of the "power law" type. These are simple to use but are not readily given a physical interpretation. Alternatively one may use a logarithmic law, as derived from the theory of boundary layer flow. This is a more cumbersome formulation to use, but can be assigned a physical meaning.

There are two commonly used forms of the "log-law" :-

i) $$U(z) = (U^*/k).\ln[(Z-d)/Zo] \qquad (9.3)$$

where d is the displacement height, Zo is the roughness length, U* is the friction velocity and k is von Karmans constant (= 0.4). (ESDU[90, 91]).

This form of the equation is confined to the constant stress layer (0-30m)

ii) The Rossby formula as used by Jensen and Frank[17]:-

$$(U(z)/U^*) = (1/k).\ln\left[(Z+Zo)/Zo\right] \quad (9.4)$$

or the extended version for the whole boundary layer used by Deaves[92,93]:-

$$\frac{U(z)}{U^*} = \frac{1}{k}.\ln\frac{Z+Zo}{Zo} + 5.75y - 1.875y^2 - 1.333y^3 + 0.25y^4 \quad (9.5)$$

This form of the equation has the advantage of avoiding the use of the displacement height which is not easy to determine.

The friction velocity can be estimated using :-

$$U^* = k.(V(z) - 0.01z)/\ln((z+Zo)/Zo) \quad (9.6)$$

where z is the height of the measurement, as long as y = z/Zg is small. (Lawson[26])

Multipoint reference winds are required when local pressure coefficients are used. One may require individual values of wind speed for the local pressure coefficient, or the average windspeed over the whole facade for the "whole face mean pressure coefficients" from eqn.7.1 and Fig.(7.3). The following calculations were made of the mean windspeed appropriate for use with the local mean pressure coefficients derived in Chapter 7.
In this case, the reference wind is given by :-

$$\overline{U} = \frac{\int_{z1}^{z2} U(z)\,dz}{\int_{z1}^{z2} dz} \quad (9.7)$$

where z1 and z2 represent the heights of the upper and lower bounds of the facade, thus for wall A, z1 = 0 and z2 = Ze, while for roof R, z1 = Ze and z2 = H (see Fig. 9.1).

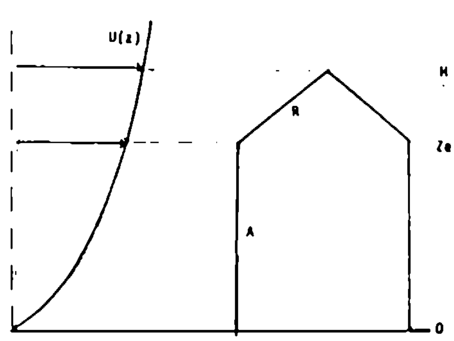


Fig. (9.1)

For a power law, the mean velocity is of the form:-

$$\bar{U} = \frac{k}{(a+1)} \cdot \frac{(z2^{(a+1)} - z1^{(a+1)})}{(z2-z1)} \qquad (9.8)$$

In the case of the Rossby formula:-

$$\bar{U} = \frac{\int_{z1}^{z2} U(z).dz}{(z2-z1)} \qquad (9.9)$$

$$= \frac{U*}{k} \cdot \left[\frac{(z2+Zo)\ln(z2+Zo)-(z1+Zo)\ln(z1+Zo)}{(z2-z1)} - (1+\ln Zo) + \right.$$

$$+(1/(y2-y1).(2.875(y2^2-y1^2) - 0.625(y2^3-y1^3)$$

$$\left. - 0.333(y2^4-y1^4) - 0.05(y2^5-y1^5)\right] \qquad (9.10)$$

The last group of terms reduces to (+0.0096((z2+z1)/2)) when (z2-z1)/h is small.

The equivalent form of this equation for eqn. (9.3) is:-

$$= \frac{U*}{k} \cdot \left[\frac{(z2-d)\ln(z2-d)-(z1-d)\ln(z1-d)}{(z2-z1)} - (1+\ln Zo) \right] \qquad (9.11)$$

Although this form of equation is more complex, it is generally compatible with the published expressions for the effects of terrain, shelter, roughness changes and stability.

Of these perturbing factors, sloping terrain tends to dominate. Even a slope as small as 1:50 can swamp the effects of a roughness change. (Panofsky and Petersen[94], Petersen and Taylor[95], Tieleman et.al.[38-40]). For a single point reference wind one may use a correction of the form used in CP3 and the French Code of Practice (Règles NV 65).

For multipoint reference winds, one of the numerical methods e.g. Deaves[76], or Jackson and Hunt[78] would be more appropriate. (see Table (8.1)).

Next in importance is the effect of shelter. For the effects of local shelter in the form of wind breaks and shelter belts, see Guyot[96], Perera[97], Raine and Stevenson[98]. For the effects of neighbouring buildings see Table (A2.2), Hussain and Lee[28-31], and Soliman[34].

For the nature of the flow around a building, see Fackrell and Pearce[99], Castro and Dianat[100], Corke, Nagib and Tan-atichat[23]. The results from these authors can be used to estimate the zone of influence of a building, and thus, to some extent, the effect of a large building on the smaller buildings in its wake.
In the case of an array of tall buildings, the mixing caused by the flow around them is sufficient to destroy the structure of the wind profile.

Changes of roughness have been dealt with in some detail by Blom and Wartena[101], Townsend[102,103], Shir[104], Wood[105] and Deaves[92,93]. That consideration of roughness changes is necessary can be seen upon examining the values of fetch required to establish a new boundary layer. (see Table (9.2)) The theory of Deaves[92,93] has now been incorporated into a new ESDU data item 82026 ([91], Lawson[106])

Weakest of the major perturbing factors on the wind profile on the scale of a building is that of stability. The effect of departure from neutral stability is largely on the turbulent component of the wind, affecting the scale and intensity of the eddies, and the distances over which they are propogated. This effect can become notable if one is using the reference wind corrected for turbulence of Corke et.al.[23,24]. (see Chapter 4).
The effects on the temperature gradient will not usually be significant, since the temperature drop over the height of the building is usually small compared with the internal-external temperature difference. Where this is not the case, Ti-To is itself small, and the stack contribution to infiltration not very significant. There may be rare exceptions, e.g. when there is strong radiative cooling at ground level.

Table (9.1) Fetch required to establish a new equilibrium boundary layer after a change in roughness. (Deaves[92,93], ESDU[91])

a) Smooth to rough

Zo (m)	0.5	0.2	0.1	0.05	0.02
F/Zg	52	68	84	105	139
Zg (m)	405	370	350	330	312
F (km)	21	25.2	29.4	34.6	43.4

b) Rough to smooth

Zo(u)/Zo	2.5	6.0	15	40	100
F/Zg	22	34	54	89	140
x 350 (km) (for Zo =0.1)	7.7	11.9	18.9	31.2	49

10 Targets for future research

The present calculations have shown how the variation of pressure coefficients with wind angle can be represented by a Fourier series. The dependence of the a(i) coefficients of the Fourier series on side ratio and shelter has been demonstrated. Further analysis of existing wind tunnel data on local pressure coefficients should yield more detailed information on the antisymmetric coefficients b(i). (Akins[35]) It would be useful to find other relationships such as eqn.(7.9), which relate local pressure coefficients to whole face pressure coefficients using the physical parameters of the building. (z/H, X/W, S)
Eventually, the results of Chapter 7 will be applied to the calculation of pressure coefficients for use with computer models and tested against the Air Infiltraton Centres model validation data sets .

The usefulness of the presently available data on wind pressures is still limited. The behaviour at lower windspeeds is not well known and should be investigated, particularly with respect to the fluctuating pressures arising from turbulence.
A study of the effect of adding a turbulent component to the reference velocity, after the manner of the comfort criterion used by those studying wind environment, (as proposed by Corke et.al[23,24]), offers promise for the unification of the pressure coefficient for different boundary layer structures, and thus achieving the desired result of making the pressure coefficient specific to the building alone.
The results of Dalgliesh[52] suggest that there is a strong contribution to the fluctuating pressure arising from flow separation on the building itself, superimposed on that from turbulence in the incoming flow. The frequency ranges for these two components of the fluctuating pressure are usually mutually exclusive. The simplified statistics associated with this property should allow the prediction of the fluctuating pressures on the building surface.
The probability distribution function (pdf) and cumulative distribution function (cdf) as described by Holmes[54] also indicate a need to explore non Gaussian effects in the separation regions. This would allow a better statistical treatment of the pressure differences to which the leakages in the structure are exposed, and thus of the infiltration over a wider range of conditions.

In order to incorporate such effects into a model we require a more explicit method relating flow through a crack to a fluctuating pressure signal. It may be possible to adapt the transfer function approach of Gumley[49,50] for flow in tubes connected to a manifold.
Future wind tunnel studies, in the light of the use of harmonic analysis techniques, should include the systematic investigation of other building shapes, e.g. those composed of combinations of simple block forms, those with pitched roofs, and those with curved surfaces.

The sheltering effect of neighbouring buildings on the pressure distribution also merits further investigation. This report gives some results, but for one type of array spacing only. The work carried out at Sheffield University (Hussain, Lee and Soliman[28-31] and Soliman[34]) offers some indications of the trends to be expected, but the results are not presented in a form which can be analysed as above.

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Appendix 1: Survey of pressure measurements in the real wind.

(Initial data from Appendix 2. from Symposium on Full Scale Measurements of Wind Effects on Buildings and Other Structures. University of Western Ontario June 23-29, 1974)[56]

Key

Analysis: M = mean, E = peak, P = probability, S = power spectrum, X = cross correlation

Type:- S = stone, St = steel, T = timber, C = concrete, R.C. = reinforced concrete, G = glass, Fb = fibre, Pl = plastic, comp. = composite, Pa = panel, Cst = cast.

Table (A1.1) Studies of full scale pressure measurements on real buildings

a) High rise buildings

Investigators	Affiliation/ Organisation	Building	Type (use)	Height metres (feet)	height breadth length	Exposure	Press. Ext.	Press. Int.	Wind V.	Wind Dir.	W/T tests	Analysis
R.A.Parmalee F.Khan	North Western Univ., U.S.A.	John Hancock Building Chicago, U.S.A.	Braced St.Fr.	337 (1107)	10: 2.4:1.5 (grnd) 1.4:0.9 (top)	Centre of Chicago tall bldg. near lake	48	3	6	6	Y	MEPSX
W.A.Dalgliesh W.von Tobel H.S.Ward	D.B.R./N.R.C Ottawa Canada	1 Commerce, Ct., Toronto Canada	St.Fr. (office)	239 (784)	10: 2.8: 1.4	City Centre with very tall bldgs. Near lakeshore	34	1	2	2	Y	MEPSX
F.Durgin R.Hansen et.al.	M.I.T., Boston U.S.A.	John Hancock Tower, Boston U.S.A.	Braced & Moment Res.Frame	224	10: 4.1: 1.5	City	50	-	1	1	Y	MEPSX
W.A.Dalgliesh W.von Tobel H.S.Ward	D.B.R./N.R.C Ottawa Canada	C.I.B.C.Bldg., Montreal, Canada	St.Fr. (office)	195 (640)	10: 2.2: 1.6	City Centre with bldgs. 10 storeys	12	0	1	1	Y	MEPSX
G.T.Tamura A.G.Wilson (107)	D.B.R. N.R.C. Canada		(offices) 44 storeys	185	10: 2.3: 1.65	city centre bldgs 10 storeys 700' hill to N.W.	8	(1)	1	1	N	M
C.W.Newberry K.J.Eaton J.R.Mayne (108,109)	B.R.E. U.K.	Post Office Tower, London, U.K.	R.C. (Comm. Tower)	168 (550)	10: 1.0: 1.0	Flat city centre + bldgs. of 100 ft	62	1	3	3	Y	MEPSX
W.H.Melbourne L.K.Stevens P.N.Joubert M.G.Lay P.Foden W.Fowler	Monash Univ. Univ.Melbourne " BHP Irwin Ltd. "	BHP House, Melbourne Australia	St.Fr. hullcore raft fdn. (office)	153 (500)	10: 2.5: 2.5	City centre near open sea area, terrain flat	82	0	6	6	Y	MEPSX

Investigators	Affiliation/ Organisation	Building	Type (use)	Height metres (feet)	height breadth length	Exposure	Press. Ext.	Int.	Wind V.	Dir.	W/T tests	Analysis
Ben Kato	Dept.of Arch. Univ.of Tokyo Japan	World Trade Centre of Japan Tokyo,Japan	St.Fr. Tube (office)	152 (500)	10: 3.4: 3.2	City centre with 2-9 storey bldgs on sea coast	12	0	1	1	Y	MESX
D.C.Perry	Georgia Inst. of Tech.,Ga., U.S.A.	Equitable Bldg., Atlanta,Ga., U.S.A.	St.Fr (office)	149 (490)	10: 3.4: 2.3	City centre	3	3	1	1	N	MEPS
S.Miyoshi Masahiko Ida T.Terayama (110)	Research Lab. of Asahi Glass Co.Ltd.,Japan	Kasumigaseki Bldg.,Tokyo, Japan	St.Fr (office)	147 (482)	10: 5.7: 2.0	surrounded by many bldgs.(not high)	6	6	2	2	Y	ESX
G.Hirsch H.Ruscheweyh	Tech.Univ. Aachen.,FRG	UNI Centre Cologne	R.C.	4 towers 135,118 100,88	....	Edge of city	6	2	1	1	Y	MEPSX
W.A.Dalgliesh W.Wright W.R.Schriever	D.B.R. N.R.C. Ottawa Canada	34 storey bldg. Montreal Canada	(offices)	134 (440)	10: 3.9: 2.7	10 storey buildings + one 600' building.	49d	(1) (ref)	1	1	Y	MRSX
W.A.Dalgliesh W.von Tobel H.S.Ward G.T.Tamura A.G.Wilson	D.B.R./N.R.C Ottawa Canada	C.I.L.House, Montreal, Canada	St.Fr. (office)	131 (430)	10: 4.0: 3.0	City Centre with bldgs. 10 storeys	12	0	1	1	Y	MESX
S.L.Bakos A.J.Burfitt L.Cridland	N.S.W. Inst. of Technology Australia	N.S.W.Inst. of Tech. Tower, Sydney, Australia	R.C	121 (392)	....	City	56	-	1	1	Y	MEPSX
T.Hisatoku H.Mukai S.Miyoshi	Takenaka Komuten Co. Research Lab. Asahi Glass Co.	Osaka Kokusai Bldg.,Osaka Japan	St.	120.51	....	lower bldgs.	12	0	1	1	Y	-

Investigators	Affiliation/ Organisation	Building	Type (use)	Height metres (feet)	height breadth length	Exposure	Press. Ext.	Int.	Wind V.	Dir.	W/T tests	Analysis
C.W.Newberry K.J.Eaton J.R.Mayne	B.R.E. U.K.	Vickers Tower Millbank, London,U.K.	St.Fr (office)	118 (287)	10: 2.5: 2.5	Flat city centre next to Thames R. bldgs. of 70 ft in S and W	9	0	1	1	N	MP
D.C.Perry	Georgia Inst. of Tech.,Ga., U.S.A.	Coastal States Life Ins.Bldg. Atlanta,Ga., U.S.A.	St.Fr	114 (375)	10: 3.3: 2.5	City centre	3	3	1	1	N	MEPS
Kunio Fujii M.Kobaya	Research Lab.of Shimizu Const. Co.Ltd.,Japan	Asahi Tokai Bldg.,Tokyo Japan	St. (office)	110 (361)	10: 3.0: 3.0	Urban Centre	72	6	2	2	Y	MEPSX
J.Blessmann	Escola de Engenharia da UFRGS, Porto Alegre, Brazil	Parque do Sol Bldg.,Brazil	R.C (apt.)	107.3 (353) tapered	10: 4.0: 1.7	Suburban area near city centre ?	42	2	1	1	Y	MEPS
H.Ishizaki Tatsuo Murota	Disaster Prevention Res.Inst.,Kyoto Univ.,Japan	Kobe Commerce Industry and Trade Centre Building Japan	St. (office)	107 (351)	10: 3.5: 3.5	City centre amongst tall bldgs. near Kobe harbour	44	0	0	0	-	MESX
D.C.Perry	Georgia Inst. of Tech.,Ga., U.S.A.	100 Colony Sq., Atlanta,Ga., U.S.A.	St.Fr.	88.5 (290)	10: 4.3: 4.3	Residential area with trees. Bldg. on slight ridge	80	4	2	2	Y	MEPSX
W.A.Snyckers	NBRI-CSIR South Africa	Sanlam Bldg., Heirengracht, Capetown,S.A.	R.C office bldg.	88	10: 8.0: 2.2*	Foreshore of city, unsheltered from sea	20/ 24	0	2	2	Y	MEP

Investigators	Affiliation/ Organisation	Building	Type (use)	Height metres (feet)	height breadth length	Exposure	Press. Ext.	Press. Int.	Wind V.	Wind Dir.	W/T tests	Analysis
M.Makino M.Nakahara T.Sato (111)	Kyushu Univ. Fukuoa B.R.I. Tokyo Japan	Hitachi Ltd. elevator test structure Mito City	St.Fr. +C.C. panels	81	81: 8.626: 8.246	low flat factory buildings suburbs	5	0	1	1	N	MEX
I.C.Ward S.Sharples	Dept.Building Science, Univ. of Sheffield England	Arts Tower Sheffield University	C.Fr + light- weight cladding 60% G. (admin.+ teaching)	78.0 (flat)	78: 45: 23	Urban exposed	10	2	1	1	N	M
Eiichi Kimura I.Matsushita Hisashi Hokugo	Architectural Inst.of Japan	Hitotsubashi Sogo Bldg. Tokyo,Japan	St.Fr	77.6 (287)	10: 7.0: 5.4	Urban area	12	-	-	-	N	EP
H.Ishizaki Tatsuo Murota	Disaster Prevention Res.Inst.,Kyoto Univ.,Japan	Plaza Hotel Osaka Japan	Comp. St./R	77 (286)	10: 10.5: 1.9	City area approx. 4km from sea and city centre	15	0	4	1	-	MESX
C.W.Newberry K.J.Eaton J.R.Mayne (112)	B.R.E. U.K.	Royex House, Barbican London,U.K.	R.C. (office)	67 (267)	10: 6.4: 2.7	Flat urban centre with tall bldg. in N & E	48	3	1	1	Y	MEPSX
J.R.Banister W.L.Holley	Sandia Lab. U.S.A	First National Bank Bldg. Albuquerque, New Mexico, U.S.A.	Fr.	62	....	Surrounded by low bldgs.	3	0	3	0	N	ME
Mario Takeuchi Gengo Matsui Satora Kazama K.Suda K.Higuchi Ryoichi Nagai (113)	Waseda Univ. Tokyo " " " Shibaura Inst. Tokyo Japan	No.51 Bldg. Waseda Univ., Tokyo,Japan	Comp. St/C (office)	59 (251)	10: 7.6: 3.3	surrounded by houses & 3/4 storey apartments near sea	20	5 (ref)	1	1	Y	MREPSX

Investigators	Affiliation/ Organisation	Building	Type (use)	Height metres (feet)	height breadth length	Exposure	Press. Ext.	Press. Int.	Wind V.	Wind Dir.	W/T tests	Analysis
Y.Lee H.Tanaka C.Y.Shaw (114)	Div.Mech.Eng. Div.Civ.Eng. Univ.Ottawa DBR.NRC Canada	Thompson Hall Univ.Ottawa (20 storeys)	R.C. Student Residence	56 (184) + 7m pnthse	10: 4.83: 3.93	city centre + 6 storey building to W. else lower bldgs.	44	16	1	1	N	M
P.N.Joubert L.K.Stevens M.C.Good E.R.Hoffman A.E.Perry (115)	Melbourne Univ. Australia	Barry building University of Melbourne Australia		47.5 (145)	10: 13.8: 2.9	lower bldgs. trees, fairly open	65d	---	12	(1)	N	ME
W.H.Melbourne	Monash Univ. Melbourne, Australia	School of Humanities Bldg. Monash Univ., Melbourne Australia	R.C. (Univ.)	44 (144)	10: 32: 3.0	Suburban area with 2-storey bldgs.	90	16	1	1	Y	MESX
E.Zeller	C.T.I.C.M., France	Grands Bureaux Florange France	Welded St.Fr (office)	42.4 (212)	10: 20: 3.0	open terrain with 1-3 storey houses	1	1	2	1	Y	MEP
C.W.Newberry (116)	BRE U.K.	State House	15 storey (offices) + 9 storey wing.	---	---	city	14d	---	(1)	(1)	N	MIE
S.Mackey	Hong Kong Univ.	Experimental buildings	---	---	---	---	126	1	24	24	Y	MEPSX
S.Mackey L.C.H.Lam	Hong Kong Univ.	Centre of high bldg research Cape d'Aguilar Hong Kong	St.exp'tl bldg.	30.48 (100)	10: 6: 3	open terrain	105	2	50	50	N	MEPSX
D.H.Freeston V.A.L.Chasteau	Univ. of Auckland N.Z.	School of Eng. Tower Block	....	(100) (approx)	....	....	10	1	1	1	N	MEPSX

Investigators	Affiliation/ Organisation	Building	Type (use)	Height metres (feet)	height breadth length	Exposure	Press. Ext.	Press. Int.	Wind V.	Wind Dir.	W/T tests	Analysis
J.P.A.Berhault P.O.A.L.Davies	ISVR,Univ.of Southampton, U.K.	Southampton Flats	R.C	....	....	Suburban and open water	1	1	3	3	N	MEPSX
Ph.J.Ham (117)	I.M.G. T.N.O. Delft Netherlands	Slotervaart Hospital Amsterdam	cruciform plan. 11 storeys	---	---	urban, flat terrain	---	---	(1)	(1)	Y	MI

b) Medium and low rise buildings

W.F.de Gids (118)	IMG-TNO Delft Netherlands	(1) flat Delft	(1) R.C. Resid- ential	1) 20m	----	flat terrain 15-20m bldgs. trees.	6	6	(1)	(1)	N	M
		(2) 2 mid- terrace houses near Rotterdam	Br.	2)4.9m 3)5.4m		2)&3) suburban v.flat terrain	8	8	(1)	(1)	N	M
J.E.Hill T.Kusuda (119)	N.B.S. Gaithersburg	Building 226 N.B.S.	(two rooms on 3rd floor)	15	15: 118: 32	open to N similar buildings parallel to S, gently rolling terrain	2d	---	1	1	N	S (study of fluctuating flow)
also R.D.Marshall G.Hsi (120)	Md. U.S.A.	Gaithersburg Md. U.S.A.	(walls and roof)				47	---	6	6	(Y)	MRSX(f)
H.Muehlebach P.Hartmann (121)	EMPA Duebendorf Switzerland	Maugwil test house Switzerland	bsmnt. C.C wlls.T.Fr	10m (roof) S&E 7.5m N&W	10: 9.11: 8.22	mountain S.facing slope 600m a.s.l exposed some shelter from slope in N.	4	1	2	2	N	M

Investigators	Affiliation/ Organisation	Building	Type (use)	Height metres (feet)	height breadth length	Exposure	Press. Ext.	Press. Int.	Wind V.	Wind Dir.	W/T tests	Analysis
W.F.De Gids L.L.M. van Schijndel J.A.Ton (122)	IMG-TNO	flat Kijkduin The Hague Netherlands	Resid-ential	8m approx. int.ht. 2.6m	irreg. plan	North Sea coast dunes 10m bldgs. S to E	5	1	(1)	(1)	Y	M
K.Eaton (15,16)	B.R.E., U.K.	Aylesbury Estate, U.K.	Resid-ential	7 (22)	....	Open country and suburban	116	2	4 (+5) (mobile)	1	Y	MEPSX
C.Y.Shaw (68)	D.B.R. N.R.C. Ottawa Canada	2 schools Ottawa Canada	teaching	1)4.0	irreg.	mature suburban (flat) 1)surrounded by houses and trees	7d	---	(1)	(1)	N	M
				2)3.8		2)exposed to East	7d	---	(1)	(1)	N	M
R.D.Marshall	N.B.S. U.S.A.	7 single-family dwellings, Philippines	Resid-ential	2.5 height to eaves	....	(1) Flat suburban to rural (2) Airport coastal exposure. (3) as (2)	5-10	1-2	1	1	Y	MEPSX
R.D.Marshall (123)	N.B.S. U.S.A.	2 dwellings, 1 single-family, 1 duplex, Great Falls, Montana, U.S.A.	Resid-ential	(1) 2.4 height to eaves (2) 3 height to eaves	....	Flat, clear	10	1	1	1	Y	MEPSX
G.T.Tamura	DBR.NRC Ottawa Canada	2 houses 1 storey occupd. Ottawa	T.Fr Resid-ential	---	---	suburban + woods	4	1	1	1	N	M
M.Guillaume	O.S.T.C. Belgium	houses at Saguies Belgium	prefab. concrete (dwellings)	5R 2.6E	L=14 W=11	flat terrain	7	1	1	1	N	M

Investigators	Affiliation/ Organisation	Building	Type (use)	Height metres (feet)	height breadth length	Exposure	Press. Ext.	Press. Int.	Wind V.	Wind Dir.	W/T tests	Analysis
D.A.Wells R.P.Hoxey (124)	Natl.Inst. of Agricultural Engineering Silsoe Beds. U.K.	5 glasshouses 1) 1 span 2) 2 spans 3) 6 spans 4) 7 spans 5) 8 spans	Met.Fr. +glass	1)2.4E 3.9R 2)3.4E 7.1R 3)2.4E 4.0R 4)2.4E 3.1R 5)2.8E 3.9R	21.3: 6.4 39.6: 25.6 79.6: 39.7 63.0: 22.4 88.8: 51.2	rural terrain other glass-houses	47 23 47 47 47	(1) (ref) (1) (1) (1) (1)	1 1 1 1 1	1 1 1 1 1	N	M
K.Handa J.Gusten (125)	Dept. Structl. Design, Chalmers Univ. of Technology Gothenburg Sweden	1) Partille hse 1.1/2 storey	stone with timber panel above. (residence) (occupied)	3.5 to 4.9 (29)	12.5: 9.5	semi-urban on the side of a ridge.	24	(1)	2	1	N	M(r)
		2)Kungsbacka 2 storey hse. Gothenburg Sweden	T.Fr. (residence) (occupied)	3.1E (45)	12.4: 7.7	2)open on slight N. facing slope	24	(1)	2	1		
M.Sherman (126)	L.B.L Berkeley Laboratory Univ. of California Ca. U.S.A.	Mobile Infiltrn. Test Unit.	(test structure)	3.0R	3: 5: 2.5	flat with isolated obstructions	76d	(1)	2	1	N	M

Additional References

Marshall (127), Kim and Mehta (128)

c) Flexible structures

Investigators	Affiliation/ Organisation	Building	Type (use)	Height metres (feet)	height breadth length	Exposure	Press. Ext.	Press. Int.	Wind V.	Wind Dir.	W/T tests	Analysis
R.P.Hoxey G.M.Richardson (129)	Natl. Inst. of Agricl. Engng. Silsoe Beds.	6 greenhouses 3 single span 2 x 4 spans 1 x 5 spans	film Pl.	1)2.9 2)3.1 3)3.4 4)3.7	W=7.2 W=6.2 W=6.2 W=26.3	open country exposed 1 metre bank at 3 metres.	1)43 2)43 3)43 4)43	(1) (1) (1) (1)	1(r) 1 1 1	1 1 1 1	N N N N	M(r)S M(r)S M(r)S M(r)S
				5)3.2 6)3.1 (approx.)	W=24.2 W=25.0	part of a group	5)65 6)43	(1) (1)	1 1	1 1	N N	M(r)S M(r)S
							direct measurement of dynamic wind pressure					

Table (A1.2): Studies of model buildings in the real wind.

Investigators	Affiliation/ Organisation	Building	Type (use)	Height metres (feet)	height breadth length	Exposure	Press. Ext.	Press. Int.	Wind V.	Wind Dir.	W/T tests	Analysis
M.Tachikawa (130)	Dept.Arch. Kagoshima University Japan	model bldgs. on a bldg. roof.	1)square prism 2)rectang. prism 3) box type structure	4 storey building	4:1:1 4:2:1 1:1:1	not given	50	0	1	1	N	MRES(X)
I.Kamei (131)	Dept. Arch. Engng. C.I.T. Nihon Univ. Narashino, Chiba Japan	model hse	box type structure	3.6	3: 1: 1	sea shore exposed.	112	(1) (ref)	7	1	Y	MI
M.Jensen N.Frank (17)	Technical Univ.of Denmark	Albertslund model hse 20km. W of Copenhagen	masonite on battens	1.63 (1:10)	1.63: 3.05: 1.50	open field	14	---	1	1	Y	M
H.W.Tieleman R.E.Akins P.R.Sparks (38)	VPI&SU Blacksburg Va.U.S.A Univ. of Western Ontario Canada	Price's Fork, Va. U.S.A. model test house	turntable mounted	2.4 (30)	2.4 4.9 4.1	complex terrain sloping site.	---	---	4	1	Y	MRE(1) M(r)
V.B.Torrance (132)	Heriot Watt University Edinburgh Scotland	single storey 1/2 scale model bldg. Edinburgh	rotating square with patio flat roof	(6)	L=18ft W=18ft central patio 6ftx6ft	suburban terrain fairly open	136	(1)	5	1	N	M(f)

Table (A1.3) Full scale studies of flow around windbreaks and buildings.

Investigators	Affiliation/ Organisation	Building	Type (use)	Height metres (feet)	h: b: l	Exposure	Press. Ext.	Press. Int.	Wind V.	Wind Dir.	W/T tests	Analysis
a) Studies of the flow around windbreaks												
W.H.Hogg (133)	Met.Office Bristol U.K.	Stockbridge House Exptl. Horticultural Station,Vale of York.	Shelter belt 7 rows of trees, mixed species	6m	---	open flat terrain	---	---	2	2	N	efficiency
b) Studies of the flow around buildings												
S.Murakami K.Uehara H.Komine (134)	Inst. Indl. Science Univ. of Tokyo Japan	High rise bldg. Mita 1 chome Minato ku Tokyo Japan	(offices) +windbreak	120	10: 0.31: 0.26	city 20 to 50m buildings	---	---	8	8	Y	V:MED

Table (A1.4) Some studies of the atmospheric boundary layer in the field:- Additional references.

Dalgliesh and Marshall (135), Newberry and Eaton (136)
Jensen (137), Petersen (138)
Jones, de Larrinaga and Wilson (139)
van der Hoven (140)

Appendix 2: Survey of Wind Tunnel Studies.

Key

E.W.T. = Environmental wind tunnel
M.W.T. = Meteorological wind tunnel
T.B.L.W.T. = Turbulent boundary layer wind tunnel
L.S.W.T. = low speed wind tunnel
I.A.W.T. = Industrial Aerodynamics Wind Tunnel
B.L.W.T. = Boundary layer wind tunnel
A.W.T.= Aeronautics wind tunnel
L.Sec = long section,
Sh.Sec = Short section
O.C. = open return
C.C.= closed circuit
v. = velocity
t.=time
Dimensions given in metres (feet)
f.s.e. = full scale equivalent
Pressure measurements:- d = pressure differences, S=spectra available
Analysis:- M = mean, R = r.m.s, E = peak values, X = cross spectra,
S = spectrum
reference points for Cp:- f = free stream, r = roof level, l = local

Table (A2.1) Wind tunnel studies on models of real buildings.

Investigators	Affiliation/ Organisation	Wind Tunnel Used	Scale	Name of Building	Pressure Measurements Full Scale Ext.	Int.	Model Scale Ext.	Int.	Analysis
a) High-rise buildings									
C.L.Harris (141)	Pennsylvania State Coll. Pa., U.S.A.	AWT C-V	1:250	Empire State Building + 2 neighbouring buildings. (640',895'9")	---	--- Looking at neighbouring building effects, wind angles 0,20,40,50 70 also angle +90,+180,+270 degs. results for v=40fps,60fps,80fps ref. free stream static pressure.	51	---	M
C.W.Newberry K.J.Eaton J.R.Mayne (112,142)	B.R.E. Garston England	B.R.E E.W.T	1:200	Royex House London H=66.0	48	1	---	---	MREXS
W.A.Dalgliesh W.A.Templin K.R.Cooper (143)	D.B.R-N.R.C Ottawa Canada	U.W.O T.B.L.W.T L.Sec	1:200 a=0.15(S) a=0.33 (N,E,W)	Commerce Court Tower Toronto H=239 57 storey	48	1	96d (32d f.s.e.)	---	MRES
W.A.Dalgliesh W.Wright W.R.Schriever	D.B.R-N.R.C. " Carleton U. Ottawa Canada	U.W.O. B.L.W.T.	1:400	34 storey office bldg. Montreal Canada	49	1	49 + additional taps	---	MRSX

Investigators	Affiliation/ Organisation	Wind Tunnel Used	Scale	Name of Building	Pressure Measurements Full Scale Ext.	Pressure Measurements Full Scale Int.	Pressure Measurements Model Scale Ext.	Pressure Measurements Model Scale Int.	Analysis
N.M.Standen W.A.Dalgliesh R.J.Templin (144)	D.B.R-N.R.C. Ottawa Canada	Sh.Sec A.W.T. N.R.C.	1:400	CIBC Building Montreal H=(600)	9	---	9	---	M(f)RXS
S.Miyoshi M.Ida T.Miura (110)	Asahi Glass Co. Ltd., Yokahama Japan	B.L.W.T. O.C. 1.5x1.5 test section	1:300	Kasumigaseki Building Tokyo Japan	6	6	---	---	M
Ph.J.Ham (117)	I.M.G. T.N.O. Delft Netherlands	O.C.Sh.Sec.	1:200	Slotervaart Hospital Amsterdam Netherlands	---	---	58d	---	M
J.E.Cermak (145)	Dept.Civ.Engng. Colorado State University Fort Collins Co. U.S.A.	E.W.T. and M.W.T.	1:98	Standard Oil Co.Ltd (Indiana) Bldg.	---	---	6	---	MR
			1:500	World Trade Centre Tower New York	---	---	4	---	MR
			1:200	Bank of America World H.Q. Building	---	---	2	---	MR

(Note: The actual number of pressure taps may be larger than stated)

Investigators	Affiliation/ Organisation	Wind Tunnel Used	Scale	Name of Building	Pressure Measurements Full Scale Ext.	Full Scale Int.	Model Scale Ext.	Model Scale Int.	Analysis
b) **Medium rise buildings**									
W.F.De Gids L.L.M.Van Schijndel J.A.Ton (122)	IMG-TNO Delft Netherlands	O.C. 1.1x1.1 tst.sect. TNO	----	3-storey block of flats Kijkduin The Hague Netherlands	5	1	4d	---	M
Z.Szalay (146)	Hungarian Inst. of Building Science	Cl.C. B.L.W.T. 1.6x1.2 tst.sect. Umax=22m/s	1)1:250 2)1:50	church with octagonal spire Sopron Hungary Terrain cl. II,III, moderately hilly	1)3 2)6	--- "	--- "	--- "	MRES(r) "
c) **Low rise buildings**									
H.W.Tieleman T.A.Reinhold (40)	VPI&SU Blacksburg Va. U.S.A	O.C. Sh.Sec 1.8x1.8 tst.sect.	1:70	Prototype Test house Quezon City Philippines	6	---	6	---	MREXS (roof)

Investigators	Affiliation/ Organisation	Wind Tunnel Used	Scale	Name of Building	Pressure Measurements Full Scale Ext.	Full Scale Int.	Model Scale Ext.	Model Scale Int.	Analysis
Aylesbury test house studies									
P.J.Vickery D.Surry (147)	Univ.of Western Ontario Canada	UWO B.L.W.T. 2.5x2.0 tst.sect. Umax=15m/s spires	1:100 v.=1:2 t.=1:50	Aylesbury Test House 22.5deg. roof pitch	72	1 1(ref)	72	--- data set	MRESX A32
L.Apperley D.Surry T.Stathopoulos A.G.Davenport (148)	Univ. of Western Ontario Canada	UWO B.L.W.T	1:500 v.3:10 t.1:150	Aylesbury test hse. reference v. at 10m.	72	1 1(ref.)	114	--- (tap not	M(f)RES positions are equivalent)
H.W.Tieleman T.A.Reinhold (40)	VPI&SU Blacksburg Va. U.S.A	O.C. Sh.Sec.	1:70	Aylesbury test hse. (roof)	8	1	6	---	MREXS
H.W.Tieleman R.E.Akins P.R.Sparks (38)	VPI&SU Blacksburg Va. U.S.A Univ. of Western Ontario Canada	VPI&SU O.C Sh.Sec. UWO B.L.W.T. L.Sec.	1:50 1:500	Aylesbury test hse. (2 wall/ 2 roof)	4	---	4	---	M(1)RE,M(r)
J.D.Holmes R.J.Best (149)	James Cook Univ. North Queensland Australia	O.C. B.L.W.T.	1:50 1:100	Aylesbury test hse.	72	1 1(ref.)	61 (31S)	---	MRE

Investigators	Affiliation/ Organisation	Wind Tunnel Used	Scale	Name of Building	Pressure Measurements Full Scale Ext.	Full Scale Int.	Model Scale Ext.	Model Scale Int.	Analysis
M.E.Greenway C.J.Wood (150-152)	Univ. of Oxford England	L.S.W.T. O.C. 4.0x2.0 tst.sect.	1:75	Aylesbury test hse. + estate houses	72 (25S) 44 (21S)	1 1(ref.) ---	72 44	--- ---	MRES
G.Barnaud J.Gandemer	C.T.S.B. France	----- ----	1:50	Aylesbury test hse.	---	---	---	---	M
A.E.Holdø E.L.Houghton F.S.Bhinder (153)	Hatfield Poly.	I.A.W.T. O.C. 1.2x1.5 tst.sect.	1:50 1:60 1:80 1:200	Aylesbury test hse.	---	---	---	---	xLu/D
A.E.Holdø (51)	Hatfield Poly. and SINTEF Trondheim Norway	as above	1:200	Aylesbury test hse.	---	---	---	---	MRSX
C.G.Bray	Univ.of Bristol England	Dept.Aero. W.T.	1:150	Aylesbury estate houses	44	1	41	---	MRE
N.Cook	B.R.E. England	B.R.E.		Aylesbury test hse. (isolated model)	72	1 1(ref)	---	---	M

Additional references:- Schriever, Allen and Dalgliesh (154)

Investigators	Affiliation/ Organisation	Wind Tunnel Used	Scale	Name of Building	Pressure Measurements Full Scale Ext.	Full Scale Int.	Model Scale Ext.	Model Scale Int.	Analysis
d) Model Buildings in the Real Wind									
I.Kamei (131)	Dept. Arch. Engng. C.I.T. Nihon Univ. Narashino, Chiba Japan	Nihon U. L.V.B.L.W.T	1:12	model hse on shore	112	---	112	---	M
M.Jensen N.Frank (17)	Technical Univ. of Denmark	O.C. 0.6x0.6 tst.sect.	1:20	Model hse. H=1.63 L=3.05 W=1.05 Albertslund 20km W of Copenhagen Denmark	14	---	16	---	M (plane of symmetry)
H.W.Tieleman R.E.Akins P.R.Sparks (38)	VPI&SU Blacksburg Va. U.S.A Univ. of Western Ontario Canada	O.C. Sh.Sec VPIS&U +UWO B.L.W.T.	1:24	Model test house mounted on a turntable complex terrain Prices Fork Va. U.S.A.	---	---	---	---	MRE(1)M(r)

There are numerous examples of wind tunnel studies on models of real buildings, but where no full scale measurements were made. Most of the larger organisations involved in building design will have these, and may be approached directly for access to the data.

Investigators	Affiliation/ Organisation	Wind Tunnel Used	Scale	Name of Building	Parameters considered
e) <u>Wind flow around buildings</u>					
I.Kamei E.Maruta (155)	Coll. Ind. Technology Nihon Univ. Japan	B.L.W.T. Nihon Univ. 2.7x1.8 test section	1:500	Shinjuku Development area	velocity distribution flow pattern
A.D Penwarden A.F.E.Wise (18)	B.R.E U.K.	O.C.Sh.Sec B.L.W.T.	1:192 1:192 1:192	1)St.Georges House Croydon 2)The Merrion Centre Leeds 3)Edmonton Green, Enfield,London 4)Cowley Centre 5)New Strand Centre Bootle, Lancs. 6)Queens Market Newham,London 7)Corby Town Centre	flow pattern velocity distribution
S.Murakami K.Uehara H.Komine (134)	Inst. Industl. Science, Univ. of Tokyo Japan	O.C. B.L.W.T 1.2x1.8 test section	1:500	Mita-1 chome Minato ku Tokyo, Japan	flow pattern, velocity distribution wind amplification factor due to the construction of a high rise building.
P.M.Jones C.B.Wilson (156)	CIRIA U.K.	O.C. BLWT (5'x3'6) test section a=1/3 open jet.	1:500	Liverpool City Centre	Mean velocity expressed as a shelter parameter.
J.Kursis J.O.Mattson M.Glaumann B.G.Wiren (157)	National Swedish Inst. for Building Research Gävle, Sweden	A.W.T.,C.C., 3x1.5x11m test section Umax=23m/s spires + roughness	.....	Dwelling area with high rise buildings, Malmö, Sweden	Ground wind speed distribution full scale and wind tunnel tests.

Table (A2.2) Wind tunnel model studies

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
a) General pressure distribution - isolated models				
J.Ackeret (6)	Inst. Aerodyn. Zurich Switzerland	C-V?	Various structures, rectangular blocks, with flat, gabled (both symmetric and asymmetric) hipped, sawtooth, domed roofs, with or without overhanging eaves. Free roofs. Buildings with open walls, ridge vents. vertical cylinder with smooth,ribbed,toothed and angled surfaces, + some structural members.	Average pressure coefficients on a side, roof etc. Wind directions from :- 0,15,45,60,90,180 degrees (Used in Swiss building code)
M.Chien Y.Feng H.Wang T.Siao (J.W.Howe) (158,159)	Iowa Inst. of Hydraulic Res. State Univ.of Iowa, U.S.A	A.W.T. C-V, low turbulence 3-D	gabled rectangular block type structures, thin walls, hangar type structures and simple building groups. L/W=1,2,4:H/W=0.5,1,1.5 Roof slopes 0,15,30,45 Walls:L/H=6:1,4:1,3:1, 3:2,2:1,1:1,1:2 Hangar:W=6",L=3",6",12",24"	probable distribution of wind pressure. Discusses effects on building codes and construction techniques. Wind angles 0,30,45,60,90 degs.
J.Armitt (160)	C.E.G.B. G.B.	C.E.R.L. L.S.W.T. C-V & B-L Counihan method	rectangular block, floor mounted. H=0.305, W=0.152, L=0.763, approx equiv. to power station boiler house.	Cp M(f)R Wind directions, 0 to 360 degrees in 15 degree intervals. Looked at effect of plain parapets p/W=0.025,0.083,0.166 B-L = "open country terrain"

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
Junji Katsura (57)	----------	O.C. 0.5x0.5 test section C-V & B-L 2-D & 3-D v=12.5m/s	Box shaped models. square section. L=W=10cm:H=2.5cm, 5cm,10cm & 15cm. L=W=5cm:H=5cm & 15cm.	Cp M Wind direction:-0,20,30,45 degs. Looked at dependence of Cp on windspeed & variation of peak Cp. Indicated that mean Cp is reduced at lower windspeeds.
G.Lusch E.Truckenbrodt (161)	T.H.Munich Germany	O.C. L.S.W.T Institut fur Stromungs -mechanik TH Munchen	rectangular block, floor mounted. L/W=2, H/L=1/4, 1/2,3/4,1 roof pitch = 0,20,30,40, and 60 degs.	Cp M Wind directions, 0 to 360 degs.
G.F.Hamilton (25)	Dept. Mech. Engineering Univ. of Toronto Canada	Inst. of Aerophysics L.S.W.T (C-V) Dept. of Mech. Engineering L.S.W.T (B-L)	Isolated 6"x6"x6" cube + roof at 0,15,30 & 45 degrees, block 6"x6"x24" isolated walls=6"x12"x1" 12"x12"x1",18"x12"x1". 80 piezometers.	Cp(r), ME Investigated sensitivity of Cp peak values to windspeed. Also investigated effects of a neighbouring building on the sidewall pressure distribution.
I.Kamei (131)	Dept.Archl. Engineering C.I.T. Nihon University Narashino Chiba,Japan	B.L.W.T. (grid)	Rectangular cylinder L=20cm,30cm D=10cm,20cm H=10cm,20cm,30cm.50cm.	Wind profile V=V(0).(H/H(0))**(1/n) looked at n=4, n=8 Cp M Looked at dependence of Cp on L/D, H & V(z), also position of maximum +ve Cp with wind angle.
D.Surry T.Stathopoulos A.G.Davenport H.Homma (162-165)	Univ. of Western Ontario Concordia University Montreal Canada	U.W.O. B.L.W.T.	Low rise building models. Equivalent scales: 1:100, 1:500, mainly 1:250. Equivalent lengths in feet:- L=100,112.5.125, 137.5,187.5 : W=80 H=16,24,32 to eaves. Uniform porosities of 0%,0.5%,3% and Openings in the end and side wall are examined. Roof slopes 1:12,4:12	Cp: MREIS(i) (e), 2 terrain classes time scale 1:150, velocity scale 3:10. Wind directions selected from:- 0,10,45,90,225,270,293,300,315 degs. for various configurations. (Data is stored in computer form.)

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
M.Jensen N.Frank (17)	Wind Lab. Technical Univ. of Denmark	O.C. 0.6x0.6 test section	key:-H:L:W d=desk,h=hip s=saddle. Roof slope in degrees:- 2.4:1:1: (0) 5:5:1(0), 1:2:1(0,5.7sh, 6d,10dhs,15d,20s,25d,30s, 45s), 0.5:2:1(0*,5.7s,6d, 10dh,15d,20s,30s,45s), 2:4:1(5.7ds,20s,45s), 1:4:1(5.7s,20s). *= overhanging eaves Also data on free roofs desk, trough and saddle	Cp M 8 different types of roughness. various wind directions. (Information in pictorial form)
J.D.Holmes (54,75)	James Cook U. of N.Queensland Townsville Australia	B.L.W.T.	1:50 scale model of a 2 storey house.	Cp(e) MRI (also computer simulation)
H.W.Tieleman T.A.Reinhold (40)	VPI&SU Blacksburg Va. U.S.A.	VPI&SU Sh.Sec. O.C. B.L.W.T.	Roof Cps for traditional rectangular plan pitched roof buildings. Roof slopes:- 0,10,20,30 degrees. L/W:=1.2, 2.0: H/W:=0.43, 0.86: E/W:=0, 0.1 W=8.9cm.	Wind angle 0-360 continuous record. MRESX
R.E.Akins J.A.Peterka J.E.Cermak (36,37)	VPI&SU Blacksburg Va. U.S.A. Colorado State Univ. Fort Collins Colorado U.S.A.	Colorado State Univ. M.W.T.	13 rectangular section flat roofed building models. L/W=1,2,4 H/W=1,2,4,8 Up to 512 pressure taps. 4 different boundary layer structures equiv. to terrain classes. H/h=3.3,5,6.6,10,20 Area density = 11% Turntable clear to radius 0.84 to 1.27m. staggered array.	Cp (local) MRXS peak probability spectrum, max mean, min mean. Cp (roof) MRXS Values local to taps and whole side averages. Wind directions:- 0,10,15,20,25, 30,35,40,50,70,90 degrees Also averaged values w.r.t. H/W and boundary layer type.

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
B.G.Hellers S.Lundgren (166)	National Swedish Inst.for Building Research	F.F.A. I.A.W.T. 0.4x1.0 test section V(max)=22m/s	traditional house form side ratio 3:1,6:1 saddle roof, slope =14 degs. 2,3,4 & 8 storeys high 2.7m per storey (eaves height)	Cp (e), max mean, min mean. Results displayed in pictorial Wind directions: -10,0,30,40,50, 60,90,100 Also displayed as isobars.
W.D.Baines (167)	Univ. of Toronto Canada	C-V & B-L L.S.W.T. O.C. 4'x8'test section	rectangular block, flat roof, H/L=8, B/L=1. also isolated walls.	Cp M (fps units) Wind directions 0,45,90 degs. Simulated urban terrain.
M.Kiyu M.Arie H.Tamura (168)	Hokkaido University Sapporo Japan	Free-jet from a rectangular	circular cylinder d=30mm	Cp M investigated variation with B-L d/Zg = 0.38,0.44,0.53,0.65,0.85 U*/U = 0.25,0.5,0.75
T.C.Corke H.M.Nagib (24)	Illinois Inst. of Technology Chicago Il. U.S.A.	I.I.T. E.W.T. 4'x6' test section counter jet Closed circuit.	square prism, h=7.75" b=l=4", 47 pressure taps on top and 2 sides of model	Cp, M(f)R(f)SM(l) 4 types of boundary layer. 0 and 45 deg. orientation. Looks for universal form of Cp. Looks at sensitivity to B-L form.
H.J.Gerhardt C.Kramer (169)	Fachhochschule Aachen	Eiffel type W.T. Open Sec. 2.0x1.6 test section,a=0.2 Umax=32m/s Lx=4	Permeable rectangular H/B=0.25,0.5,1.0,1.5 for L/B=1.0 or 2.0	Cp M(r)EP Looks at effect of leakage on the pressure drop across the facades.
B.S.Kandola (170)	Dept.Fire Safety Engng. Univ. of Edinburgh Scotland	L.S.W.T. Open jet Univ. of Edinburgh 1.07x1.52 test section	Cubical building 25cm x 25cm. with internal partition leakage holes:- 0.1%A(0.1)1% range used for front, rear or partition walls. 48 external pressure taps 2 internal " "	Cp M(r)I Looks at effects of leakage on pressure. Wind directions: 0,45,90

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
J.D.Holmes	UWO, Canada	1:500,a=0.28 I=0.10, 2.4x2.1 test section	CAARC Standard Tall Building Model. flat topped, without parapets, mullions, etc.	Cp M(r)RSP Wind angles 0,15,30,45,60,75,90 degs. referred to the normal to the wider facade.
T.V.Lawson	Univ.of Bristol England	1:500,a=0.3 I=0.1, 2.0x1.0	20 pressure taps at z/H=2/3 full scale equivalent	B-L equivalent to urban/forest terrain, (6 to 15 m)
W.H.Melbourne	Monash U. Australia	1:400,a=0.25 I=0.09, 2x2.5	dimensions:- H=183.88 (600) W=30.48 (100)	
D.E.Walshe J.A.B.Wills P.Jones	N.P.L. England	1:240,a=0.25 -0.3,I=0.085 2.7x2.1	L=45.72 (150)	
K.R Cooper R.L.Wardlaw	N.A.E. Canada	1:400,9.1x9.1 a)Sh.Sec. a=0.28,I=0.09 b)L.Sec. a=0.26,I=0.10		
D.M.Sykes (66)	City Univ. London England	1:690,a=0.23 I=0.08, 0.76x0.60		
W.Balchin E.J.Plate A.Kamarga (171)	Institut Wasserbau III Univ. of Karlsruhe FRG.	B.L.W.T. 1.8x0.8 test section a=0.1,0.15, 0.23. grid +fence (delta)=450mm	3 cuboid buildings H/(delta)=0.22,0.33 0.44,0.67,0.81,0.89 1.0: L=150mm, W=50, 100 or 150mm 48 static pressure taps.	Cp. M(r) Wind angle 0 degs. only Looked at pressure distribution on the roof.
N.Toy W.D.Moss E.Savory (172)	Dept. of Civil Engineering Univ.of Surrey Guildford England	B.L.W.T. open circ. (delta)=265mm or 360mm. 1.372x1.067 test section	Dome shaped structure (hemispherical) 225mm dia. scale 1:700 to 1:1000, e/d=0.001 reference wind at height of dome. 18 pressure taps at 5 deg. intervals, on one meridian.	Cp M(r) vel. MR Looked at mean pressure distribution on, and velocity distribution around the dome for 2 boundary layer structures.

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
B.G.Wiren (173)	Dept. of Aerodynamics Royal Inst. of Technology, Stockholm Sweden	A.W.T.,C.C 2.1x1.5x4.6m test section Umax=40m/s grid + roughness	Rectangular plan, arched roof buildings, arch height/building width = 1:5, 1:7, L/W=1,1.5,2.0 280 pressure taps on roof.	Cp(local, time average) Wind angles = 0,20,30,45,60,90 degrees. simulated rural terrain
J.C.Phaff (174)	IMG-TNO Delft Netherlands	B.L.W.T. scale 1:200 v=8m/s Zo=0.3-0.4 2.8-3 6.4-7m (f.s.e)	rectangular flat roofed blocks, 30 pressure taps model L B H(m) 1) 15 15 3 2) 15 15 45 3) 48 12 12	Cp (g) M V(z) Wind angles 0(30)180 degrees.
C.Y.Shaw G.T.Tamura (175)	DBR-NRC Canada	NRCC wind tunnel. 1.83x2.74 test section a = 1/3	rectangular block, flat roof. 1:400 scale H= 183m (f.s.e.) B= 31m, L= 46m. 46 pressure taps.	Cp(r) M (vertical distribution of M) + computer model for air-infiltration. Wind directions 0(15)180 degrees.

Additional references:- Joubert, Perry and Stevens (115,176), Berneburg (177)

b) <u>General pressure distribution - effects of neighbouring buildings</u>

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
A.J.Bowen (67)	Nat.Aeronaut. Establishment N.R.C. Canada	N.R.C. 6'x9' A.W.T. extended working section T.B.L using spires	1:400 scale approx. rectangular block, L/W=3/2, H/W=0.5,1,2,3 H/h=1,2,4,6. surrounding blocks with same L/W in rectangular array, separation W, height h	Time averaged Cp's Used power law velocity profile exponent 0.43. Wind directions:-0,5,10,15,30,45, 60,75,80,85,90,135 degrees. + space averaged Cp's for various z/H. Eaves reference velocity. Area density 30%.

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
B.E.Lee B.F.Soliman M.Hussain (27-34)	Dept.of Bldg. Univ. of of Sheffield England	Sheffield Univ. B.L.W.T. Sh.Sec,O.C. 1.2x1.2 test section	Investigated arrays of cuboid and rectangular prism models. Up to 33 pressure taps on top and one side of the central model. The following H:L:W ratios were used:- 1:1:1, 1:1:0.5, 1:1.5:1, 1:2:1, 1:4:1, 0.5:1:1, 0.8:1:1, 0.9:1:1, 1.1:1:1, 1.2:1:1, 1.3:1:1, 1.4:1:1, 1.5:1:1, 1.7:1:1, 2.0:1:1, 3:1:1, 4:1:1	Cp M Looked at effects of size and layout of blocks on Cp, drag and lift coeffs. Also considered fetch and area density. Area densities used were:- 3.125%, 5%, 6.25%, 7.5%, 10%, 12.5%, 15%, 17.5%, 20%, 25%, 30%, 40%, 50% The velocity profiles and pressure distributions for these parameters were also examined.
W.J.Kelnhofer (178)	Dept.Mech.Eng. Catholic Univ. of America Washington D.C.,U.S.A.	O.C,C-V & B-L Inst.fur Stromungs- mechanik Tech.Univ. Munich,FRG	Model A: 180 pressure L=H=200mm,W=0.25H Model B solid,same L,W as A, H(B)/H(A)=0,0.1, 0.25,0.5,0.75,1	Cp MI(f) separation: L/H(A)=0.25,0.5, 0.75,1,1.5,2,2.5,3,3.5,4 Wind angles: 0,22.5,45,67.5,90, 112.5,135,157.5,180 degs.
A.Bailey N.D.G.Vincent (179)	Dept.Sci.& Ind. Res.Engng.Lab. N.P.L. England	(3x3) test section natl.B-L. (open country)	1:240 scale approx. 7 floor mounted models. L=5,W=2.12 (A) 23.5 degs.He=1.2" 13 pressure taps (B) 45 degs.He=1.2" 17 pressure taps (C) 45 degs.He=2.5" 17 pressure taps (D) 30 degs.He=1.2" 13 pressure taps (E) 0 degs.H=1.2" 17 pressure taps (F) 0 degs.H=2.5" 17 pressure taps (G) stepped,L=8.0 25 pressure taps W=2.0,Ht=5.2	Cp M looked at buildings in isolation and in combination in 2's and 3's at

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
B.G.Wiren (180)	National Swedish Inst. for Building Res. Gävle,Sweden	B.L.W.T.,C.C, 3x1.5x11.0 test section Umax=23m/s spires + roughness	1.1/2-storey house, scale 1:100, regular arrays of surrounding 122 pressure taps on walls and roof	Cp M local +average) Wind angles: 0,15,30,45,60,75 90 degrees
H.van Dalen (21)	IG-TNO Delft Netherlands	B.L.W.T. Scale 1:120 Zo=4m f.s.e.	flue on test building 5 positions. roof pitch 0,30,45 degrees H(facade)=5.4m B=7.32m,L=25.2m adjacent to taller flat roofed rectangular building L=49.8m B=10.92m, H=11.16,22.32m 33.48,44.64m measurement points:- low bldg. 30 taps on and above the roof, 1 each on front and rear facade. tall bldg. 1 on the roof 2 per 11.16m unit on front and rear facade.	Pressures on and above roof of test building, referenced to the gradient wind. for separations a= 18.4m to 58.2m Wind angles: 0,45,90,135,180 degrees.
J.E.Cermak W.Z.Sadeh (181)	Dept. Civil Engng. Fort Collins Co. U.S.A.	CC.M.W.T Colorado State Univ. L.S.W.T.	two identical towers 1:384 scale (H=666 ft)	Pressure, MRESP

Additional references:-
Chien et al.(157), Hamilton (25), Aynsley (182,183)
Phaff (20), Vickery, Baddour and Karakatsanis (184)

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
c) <u>General pressure distribution - effects of building details</u>				
B.G.De Bray (185)	School of Engineering Univ. of Auckland N.Z.	Sh.Sec O.C.(grid induced turbulent boundary layer)	Simple tall building shape, with sunshades equiv. to a continuous 3' strip, sloping down at 30 degrees around each floor. 23 storeys, full scale equiv. height =207ft L=W=45ft. 23 taps, 1 at mid point of each storey, + 24 on 16th storey.	Wind angles:- 0,20,40,50,60 degs. Looked at vertical variation of centre line pressure wrt. eaves pressure, also w.r.t. mid point pressures.
C.Kramer H.J.Gerhardt S.Scherer (186)	Fluid.Mech. Laboratory. Fachhochschule Aachen, F.R.G.	------	Block shaped building H/W=0 to 1,L/W=1,2 & 3	Cp MREI (e) Looks at effect of balconies, parapets,roof superstructure, corrugated roof structure and partially open buildings.
H.J.Leutheusser (187)	Fluid.Mech.Lab Dept.Mech.Engng. University of Toronto Canada	C-V,O.C. (8x4) test section 2 W-T's 1) v=25fps 2) v=60fps	Rectangular block shape L/W=2,1:H/W=0.5,1,2 parapet height P/H=0, 1/48,1/24,1/12,1/6. eaves length E/H, as P/H mullions: C/W=1/27, spacing=1/27,3/27,5/27.	Cp M(f) Considers the effects of parapets roof projections and wall mullions.
G.Lythe D.Surry (188)	University of Western Ontario London Ontario Canada	UWO B.L.W.T. (8'x7') test section	Flat roofed rectangular structure, scale 1:500 H=40',70',100',200',500', W=400', D=40',70',100', 200',500'	Looks at the effect of parapets on roof pressure distribution. Equivalent terrain classes II & IV Wind angles 0,45 degs.

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
R.M.Aynsley (182,183)	University of Sydney,N.S.W. Australia	O.C. 0.45x0.30 test section (a=0.28) (v=7.8m/s)	1) 1 storey, pitched roof +overhang, H:L:W= 2.6:12.2:6.1 2) 1 storey, pitched roof projecting walls.	Looks at mid-wall height pressure distribution. Cp M(d) (for wooded suburban terrain)
			3) as (1) on piles. 4) as (2) on piles +balcony 5) 2 storey,pitched roof 5.5:13.4:4.8 6) 1 storey flat roof.	Looks at the effect of openings.
J.M.Bruce (189)	Scottish Farm Buildings Investigation Unit Aberdeen Scotland	B.L.W.T	rectangular plan animal house at 1:50 scale. Full scale equivalent L=29m, W=9m,13.2m,22m	Cp M Wind angles: 0,30,60,90 Looks at different types of ridge ventilator, effects of various combinations of gap, upstand & cap.

Additional references:-
J.Armitt (160), Columbus (190), Sockel and Taucher (191), Stathopoulos (192,162)
Lugtenburg (22), de Gids and den Ouden (193), Edwards (194), Packer (195),
Handa and Karrholm (196)
General pressure distribution- flexible structures :- Niemann (197)

d) Pressure distribution - Effects of Scale

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
A.Hunt (198)	College of Aeronautics Cranfield Inst. of Technology Cranfield Bedford England	B.L.W.T. at B.R.E. 1:180 & 1:360	simple cube of diam. 50,100,200,400mm roughness area density 15%, staggered blocks 50x50x100mm := suburban terrain, also smooth terrain. 25 pressure taps on roof and one side.	Cp, considered MRE w.r.t. z(0),d(0), roughness Re (U(*).z(0)/(ν)) Correlates area averaged pressures with dimensionless groups:- (-<uw>/U**2),(xLu/h),(σ u/U) at h Wind directions 0 & 30 degrees.

Additional references:-
Surry et.al (164), Neal (199)

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
e) Studies of the effects of turbulence				
D.G.Petty (200)	Dept.Aeronaut. Engineering Queen Mary College, Univ. of London.	C.C, Sh.Sec B.L.W.T 2-D	7 square prisms L=W=12,15,18,21,24,30,	Looked at the effects of turbulent intensity and length scale Lu on base pressure, drag, press.diff.
B.E.Lee (201)	Dept. Building Sci. Sheffield University & CERL Labs. of the C.E.G.B.	C.E.R.L L.S.W.T. C-V & B-L 4.58x1.53 test section	2-D square cylinder 18 pressure taps at mid span and 36 on one face.	Cp, MRSX Wind direction 0-45 degs. Looked at the effects of turbulent intensity and scale.
J.Blessman (202)	Universidade Federal do Rio Grande do Sul, Porto Alegre Brazil	TV-1,TV-2 W-T's of UFRGS, TV-1 C-V TV-2 B-L (alpha)=0.34	rectangular building models with trough roof p/H=0,0.05,0.1,0.2 roof pitch -10,-15 L:W:H=1:1:0.5, or 2:1:0.5	Cp ME local mean + area avge. Looks at the effect of parapet height and turbulence on the roof pressure distribution . Wind direction:- every 15 degrees.
f) Studies of windbreaks				
J.Gandemer (203)	A.D.Y.M C.S.T.B. Nantes France	T.B.L.W.T	model windbreaks of various forms. Rural flow profile, scale 1:200, full scale equiv. L=120m,H=5m for walls, grids, rods, etc. porosities:-0,20,40,45, 47,54,70% + combinations	Looks at effects on mean velocity turbulence, effective shelter. Looks at effect of thickness porosity distribution, and effect of flow directing devices.

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
M.D.A.E.S. Perera (97)	B.R.E. Garston Herts. England	B.R.E. B.L.W.T. O.C.	2-D model solid and porous fences. porosity 0 to 0.5, 3 forms: vertical slats horizontal slats, and circular holes.	Looks at velocity deficits, excess shear, normal stress perturbations, + power spectra for the solid fence. for simulated rural A.B.L. Used pulsed HW anemometer.
G.Guyot (96)	I.N.R.A. Montfavet France	-----	Effects of wind profile on windbreaks, also a review of windbreak aerodynamics. Stability wind angle etc. reviewed.	roughness Zo, porosity (phi), protection length, efficiency, turbulence amount. (v from 5 to 25 m/s)
Von H.Blenk H.Trienes (204)	Institut fur Stromungs-mechanik T.H.Braunschweig	2 W-T's C-V 1)0.6x1.0 v=40m/s 2)0.5x0.6 v=9.4m/s	Traditional house shape gabled rectangular block, H=5cm, LxW=5.5sq.cm, roof pitch 45 degs. Model has 10 pressure taps. "hedge" L=10cm,H=5cm. porosity 48%	Cp M Studied effects of separation between house and "hedge": inf,H/4,H,2H,4H,5H, 10H,14H,18H and H/23 when the house is at 45 degs to the "hedge" Wind directions 0 to 180 considered.
G.E.Mattingly E.F.Peters (205)	Princeton University New Jersey U.S.A.	L.S.W.T. natl.b-l growth Sh.Sec.	qualitative 2D study with smoke, + quantitative 3D on floor mounted 4 house terrace row. 1/48 scale Similar to houses at Twin Rivers. 71 pressure taps.	Tests house orientation, solid fences adjacent houses, tall evergreen trees. Cp M (refs to full scale tree study) (Blockage factor approx 8%)
J.K.Raine D.C.Stevenson (98)	Univ. of Canterbury Christchurch New Zealand	B.L.W.T. 1.2x1.2 test section a=1/6,Zo=50mm neutral b-l	Looks at fences of porosities:-0,0.2,0.34 0.5. Scale 1:300 u'/U=approx. 0.2 (delta) = 0.9m	V MRS Gives empirical relation for mean velocity and turbulent intensity.

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
g) Studies of wind flow around buildings				
I.P.Castro M.Dianat (100)	Dept. of Mech. Engineering Dept. of Civil Engineering University of Surrey	L.S.W.T. (4'6"x4'0") test section U*/Ur=0.051 Zo=0.27mm	H/(delta)=0.19, H/Zo=220 W/H=9.0, L/H=1.0 or 2.0	V. M Looked at flow near the surface of a body in a thick boundary layer w.r.t. body geometry and upstream flow effects on attachment/reattachment points.
B.H.L.Gowda H.J.Gerhardt C.Kramer (206)	Fachhochschule Aachen	open jet tunnel 0.3x0.12 test section	L/B=0.5(0.5)4.0 H/B=0.1,0.25,0.5,1.0, 1.5,2.0,2.5,3.0,3.5, 4.0	v. used flow visualisation to examine wake size and shape as a function of B,L,H
W.T Beranek H.van Koten (207)	T.N.O Delft Netherlands	B.L.W.T.	Used W-T visualisation techniques + optical dynamometer. Rectangular block models H:L:B=7:4:2,5:8:1,3.5:16:1 also L-shaped blocks.	looked at zone of influence of buildings, streamlines etc.
A.D.Penwarden A.F.E.Wise (18)	B.R.E.	O.C. Sh.Sec B.L.W.T. at B.R.E.	Rectangular block forms	Looked at ratio of heights and separation on the flow around a pair of buildings.
S.Murakami K.Uehara H.Komine (134)	Inst.Industl. Science, Univ. of Tokyo Japan	O.C. B.L.W.T 1.2x1.8 test section	rectangular blocks:- L=D=10, H=2.5,5,7.5, 10,15,20,25,30 const volume test:- L=D=5sqrt2,H=10 L=D=2sqrt5,H=25 pedestal:- L=D=5 on base L=D=10, H=20 inc. base of 2.5 various plan, H=20 L=D=5sqrt2 L=5sqrt15/2, D=2.5 triangle, L=5sqrt3 hexagon, L=5 octagon, L=3.83	Looks at H/h combinations for effects on velocity distribution, flow pattern, and wind amplification ratio. l=d=10,h=2.5,5,7.5,10 for the roughness blocks.

Investigator(s)	Affiliation/	Wind Tunnel	Model Forms Considered	Parameters Considered
T.C.Corke H.M.Nagib J.Tan-atichat (23)	Illinois Inst. of Technology Chicago Il. U.S.A.	I.I.T.E.W.T. 4'x6'test section. counter jet closed return.	square prism,h=7.75" l=b=4", 47 pressure taps on top and 2 sides of model.	samples velocity M and R for the wake at various z/H. 4 types of B-L, 0 and 45 degree orientation.
J.E.Fackrell J.E.Pearce (99)	C.E.G.B Marchwood Engineering Laboratories	TBLWT 0.9x0.75 test section Sh.Sec.	rural wind profile simple rectangular blocks, + power station buildings-basic shapes.	flow regimes around a building. Wind angles:- 0,22.5,45,67.5,90 degs. looks at size of "zone of influence" (main interest, pollution dispersal)
B.G.Wiren (208)	Department of Aerodynamics Royal Inst. of Technology Stockholm Sweden	A.W.T.,C.C., 2.1x1.5x4.6m test section Umax=40m/s grid + roughness	Rectangular blocks, L/W=2 to 10, H/W=0.5 to 2. Various combinations of 2 blocks: width of passage way b/w= 0.33, 0.5, 0.75	Looks at wind amplification ratios in passage ways at 2m height above ground. Wind angles 1 to 180 degs.
Additional references:- Tani, Iuchi, Komoda (209)				
h) Modelling wind profiles				
J.Counihan (210,211)	C.E.R.L. Leatherhead Surrey	B.L.W.T scale 1:4000 L.S.W.T. scales 1:250, and 1:500	Full B-L modelled using various roughnesses with castellated barrier for accelerated B-L growth.	V MRXSP
Additional references:- Cook (212-214), Gandemer (215), Morkovin et.al. (216), Tan-atichat and Nagib (217), Nagib et.al. (218), Templin (219), Teunissen (220)				
j) Flow over topographical features				
J.C.R.Hunt K.J.Richards R.E.Britter (92,93)	University of Cambridge Inst. Oceanog. Sciences, Godalming Surrey	Warren Spring 4.3x1.5 test section Sh.Sec.	2D-hill model, rough, bell shaped, height h. max slope=0.26, d=10h, Zo=0.02h, equivalent to 1m full scale, (urban/wooded) a=0.34	V MR, considers speed up, roughness effect and turbulence.

Additional references on instrumentation and measurement methods

Bergh and Tijdeman (221)
Hoxey and Wells (222)
Irwin (223)
Lam (224)
Mayne (225)
Meert and van Ackers (226)

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