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WIND TUNNEL RESEARCH ON LOW RISE BUILDINGS

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WIND TUNNEL RESEARCH ON LOW RISE BUILDINGS

G.F. Reardon

and

J.D. Holmes

SUMMARY

Although wind tunnels were used to study low rise buildings at the end of the last century, the importance of boundary layer tunnels was demonstrated only about twenty years ago. Wind tunnel results of tests on 1/50 and 1/100 scale models compare well with full scale studies, and show similar fluctuations in pressures at various positions on the building. Flow patterns on the models are also similar to those observed in full scale.

The effect on pressure coefficients of various parameters such as roof pitch, size of wall openings, high set and low set houses, groups of houses has been studied and the results outlined.

Some discussion of the design approach in the Australian Standard is given and present and future developments in relation to the design of low buildings for wind loads are discussed.

PREFACE

This report is an overview of much of the work conducted at James Cook University by Dr. Holmes and his colleagues over the past four years. It is meant to present to engineers, architects and construction managers, in broad outline, the type of research being conducted and the results obtained. Emphasis has been placed on the practical aspects of the results and therefore the report avoids any reference to instrumentation or the intricate mathematics and computer programmes that are necessary to properly analyze the data obtained from each test run. Such information can be obtained from the list of references included herein.

This paper uses material from a C.S.I.R.O. Division of Building Research, Technical Paper : "Wind Loads on Low Rise Buildings - A Review" by J.D. Holmes to be published shortly.

1. INTRODUCTION

In the decade 1970-1980, an amount of damage approaching $1000 million was sustained by structures as a result of windstorms in Australia. The majority of this damage was incurred by low rise buildings, and a single event, Cyclone 'Tracy' in Darwin, accounted for over half the total damage.

These facts and figures have led the structural engineering and architectural professions, and the construction and insurance industries, to express concern at the lack of knowledge of the loads imposed on low rise buildings by wind, and of how to design structures economically to resist these loads. Following nearly two decades in which researchers in the field of wind loading have devoted most of their attention to high rise buildings and other large structures, more emphasis is now being devoted to low rise buildings both in Australia and overseas.

Two significant factors make the assessment of wind loads for low rise buildings at least as difficult as for taller buildings and other large structures:

(i) Low rise buildings are usually immersed within the layer of aerodynamic "roughness" on the earth's surface. Here the turbulence intensities are high and interference and shelter effects are important.

(ii) Roof loadings, with all the variations due to changes in geometry are of more importance for low rise buildings. The highest loadings on the surface of a low rise structure are generally the suctions on the roof, and many structural failures are initiated there.

On the credit side, however, dynamic effects (i.e. inertia loading) due to wind, can normally be neglected for low rise buildings.

2. WIND TUNNELS AND GENERAL CHARACTERISTICS OF WIND PRESSURE

2.1 Development and Operation of Wind Tunnels

Studies of the wind loading of low rise buildings by wind tunnel and full scale testing have been carried out for at least ninety years. However, it has been only recently that relatively reliable measurements have been made. This is due to a combination of more suitable instrumentation and high response measuring techniques, together with an appreciation of the importance of simulating atmospheric turbulence in wind tunnel tests.

Some of the earliest applications of wind tunnels were in the study of wind pressures and forces on low rise buildings. The two earliest known studies are those by Irminger in Copenhagen (Irminger, 1894) and Kernot (1893) at Melbourne University. However, it was not until the nineteen fifties that Jensen (1958), at the Technical University of Denmark, satisfactorily explained the differences between full scale and wind tunnel model measurements of wind pressures. He illustrated the importance of using a turbulent boundary layer flow to obtain pressure coefficients in agreement with full scale values. The standard technique used is to introduce roughness on the wind tunnel floor to generate a turbulent air flow. These obstructions must be of the correct proportions to reproduce the mean wind velocity profile of the atmospheric boundary layer. Thus the wind tunnel can be used to reproduce, in small scale, the wind effects from ground level to a height of about 500 metres.

Reproducing the natural wind profile to 500 metres in a wind tunnel one or two metres high means that only very small scale models of buildings or building components can be tested. However, in order to increase the scale of the models it is not uncommon to use the tunnel to model only portion of the natural wind profile. For low rise building tests the wind tunnel at James Cook University simulates atmospheric flows equivalent to full scale heights of 50-100 m. In this way models having geometric scales of 1/50 and 1/100 can be used.

The James Cook University wind tunnel shown in Figure 1, has a test section 17.5 m long, 2 m high and 2.5 m wide. It is open ended with the fan mounted downwind of the test section. The turbulent boundary layer flows are generated by a combination of carpet roughness on the floor, and a low fence at

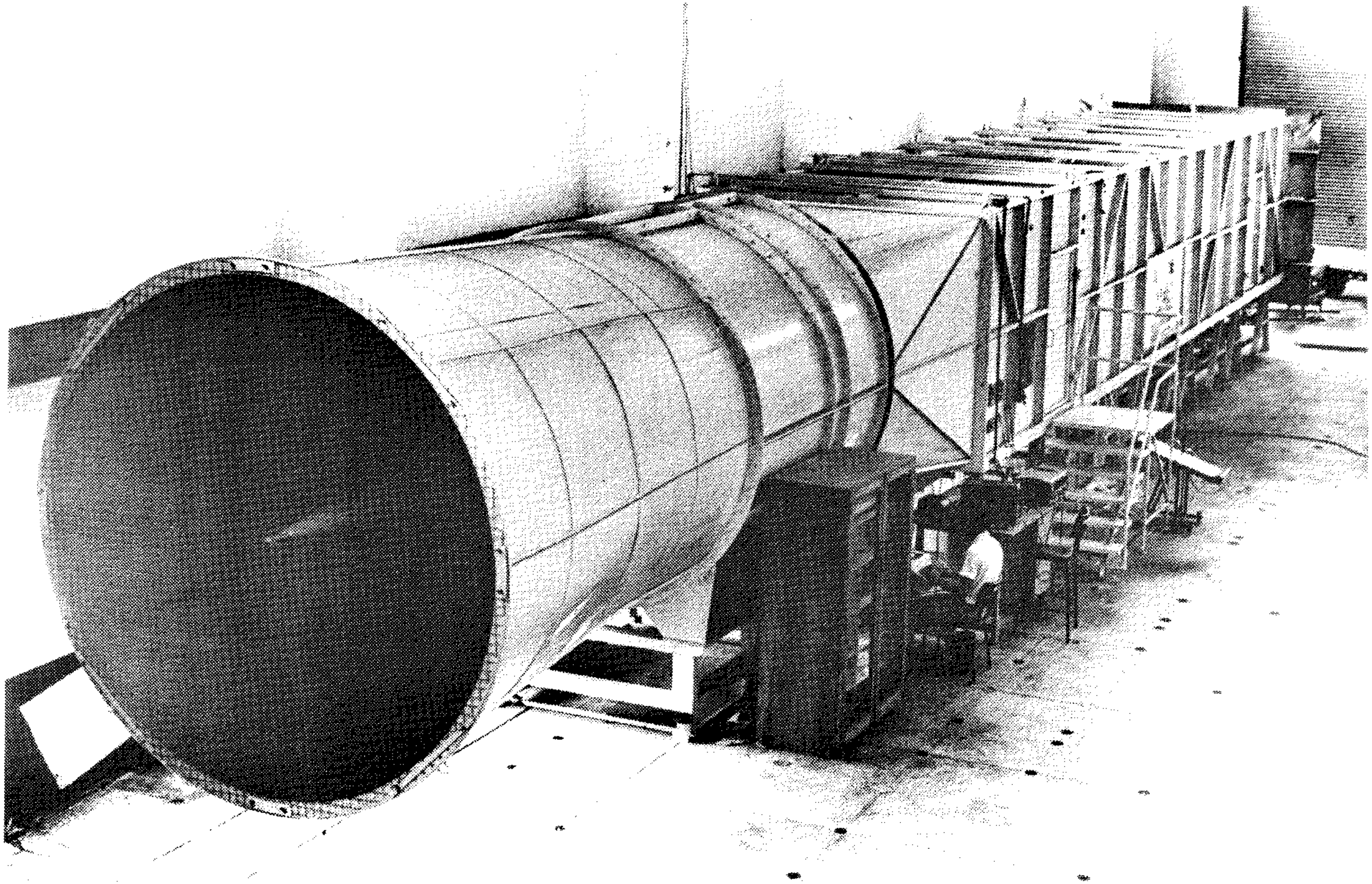


Figure 1 Boundary Layer Wind Tunnel

the upstream end of the tunnel. These are both clearly visible in Figure 2. The figure also shows a 1/50 scale model of a high set house and the relative location of the hot film probe, used to measure wind velocity during test. Measurements of turbulence in the tunnel have shown good agreement both with computed theoretical profiles and with available full scale data. (Holmes, 1977).

2.2 Full Scale Tests

In the early nineteen seventies, the Building Research Establishment of the United Kingdom, following a survey of building damage due to wind in that country, commenced a program of full scale measurements of wind pressures and forces on two storey houses at Aylesbury, England. As well as measurements on existing terraced houses, an isolated house with a gable roof of variable pitch angle was specially constructed, and extensive pressure measurements were made. In this study, advantage was taken of the considerable developments in electronic instrumentation and computer-based statistical analysis techniques, that had occurred in the previous two decades. The results (Eaton and Mayne, 1975; Eaton, Mayne and Cook, 1975), in particular, emphasised the highly fluctuating nature of the wind pressures. High suction peaks in separated flow regions that were being observed, concurrently, in boundary layer wind tunnel and full scale studies of high-rise buildings, were also strongly evident in the Aylesbury study. However, later appraisals of the data, during comparisons with wind tunnel studies (Holmes and Best, 1978 (ii); Apperley, Surry, Stathopoulos and Davenport, 1979) showed up a number of inconsistencies. Data from two measurement "runs" on the isolated house, with same roof pitch and mean wind direction showed significant differences. A number of reasons have been advanced for these inconsistencies: for example, measurement problems such as a fluctuating static pressure reference and uncorrected zero drifts in the pressure transducers. The effect of natural variability in the wind, such as sudden changes in wind direction and changes in atmospheric stability conditions may also be important. At present, some re-analysis of the Aylesbury data is being undertaken.

It appears, at present, that properly conducted boundary layer wind tunnel tests are the most satisfactory means of obtaining consistent pressure and force coefficients for use in Codes and Standards on wind loading. However, it is essential to continue model/full scale and model/model comparisons.

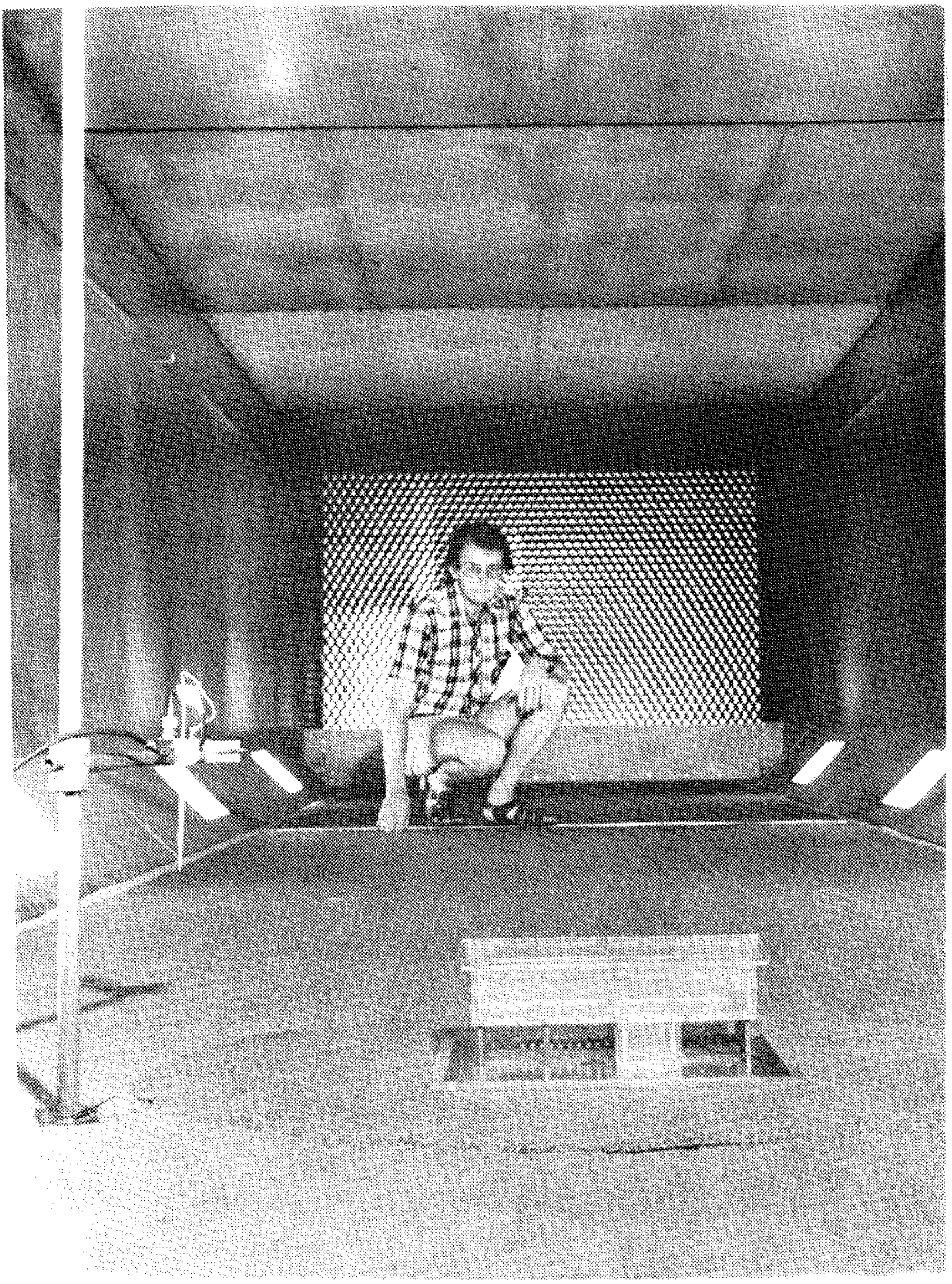


Figure 2 Location of Model and Hot Film Probe During Testing

pressure, at any point on the building surface, is fluctuating with time, the pressure coefficient can also be treated as a time-varying quantity. Thus the notation p(t) and $C_p(t)$ indicate pressure and pressure coefficient varying with time.

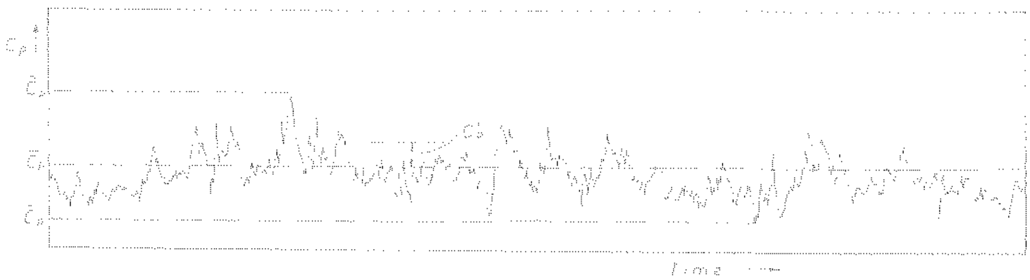


Figure 3 Typical wind pressure record and definition of basic pressure coefficients.

Figure 3 shows a section of pressure record taken from a model building in a wind tunnel test, and clearly demonstrates the fluctuations in pressure coefficient with time. In full scale, the period shown would represent 10 minutes to one hour. Also shown on Figure 3 are four important values of pressure coefficient.

$\overline{C}_p$ - the mean or time averaged value

C'_p - the root mean squared (r.m.s.) fluctuating value, representing the average departure from the mean

$\hat{C}_p, \check{C}_p$ - the maximum and minimum value occurring in the period of the record.

Coefficients of total forces and moments, and other relevant structural effects are defined in a similar way to the pressure coefficient, with the inclusion of appropriate reference areas and heights.

2.5 Flow Patterns and Mean Pressure Distributions

Some gross features of the flow patterns around low rise buildings and the effects on mean pressure distributions, particularly on roofs, will now be examined.

Figure 4 shows the main features of the flow over a low pitched roof building, and illustrates the effect of turbulence in the upwind flow on the average size of the separation "bubble" downwind of the leading edge of the roof. The external flow is separated from the bubble by a thin but growing shear layer - a region of high velocity gradients and high local turbulence and vorticity. The effect of the upwind turbulence is to move the mean re-attachment region of the shear layer closer to the leading edge and to reduce the bubble size.

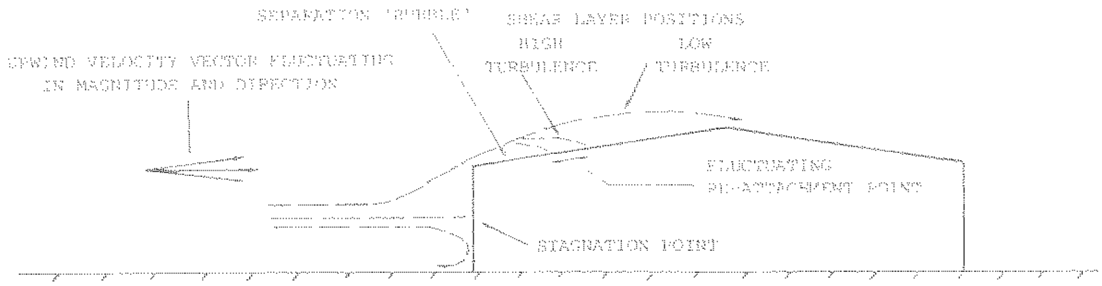


Figure 4 Flow around a low rise building

Small separation bubble sizes with high shear layer curvatures are associated with low mean pressures i.e. high suctions, but rapid pressure recovery downwind to the re-attached flow region. Figure 5 shows mean pressure coefficients measured on flat roof building models at the University of Western Ontario (Davenport and Surry, 1974), and illustrates the rapid reduction in suction to a very low value in 1 to 2 building heights downwind from the leading edge. The most recent (1981) edition of the Australian Standard, AS 1170/2, has recognised this phenomenon, and pressure coefficients from this source are shown for comparison in Figure 5.

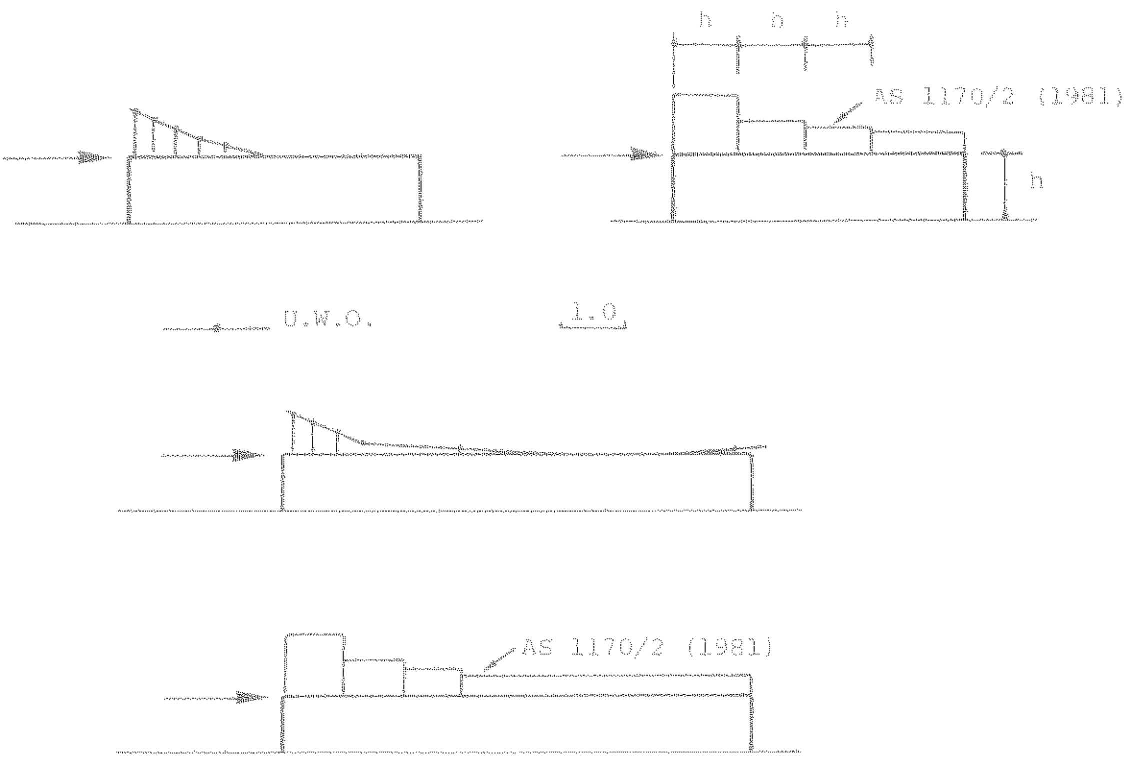


Figure 5 Mean pressure distributions on flat roof buildings

The situation described above is applicable for roof pitches up to 5-10°; these low pitch roofs can be called "aerodynamically flat". For pitch angles in the range 10° to 20°, approximately, the second flow separation at the ridge causes further high suction regions on both sides of the ridge. Downwind of the ridge re-attachment of the flow again occurs with an accompanying recovery in pressure. At roof pitches greater than 20°, positive pressures occur on the windward roof face, and fully separated flows without re-attachment occur at the ridge, giving relatively uniform suctions on the leeward roof face.

Figure 6 shows a number of recent wind tunnel measurements of mean pressures on gable roofs, with dimensions characteristic of houses. These measurements were carried at the Virginia Polytechnic Institute (Tieleman and Reinhold, 1976), the Technical University of Denmark (Jensen and Franck, 1965) and at James Cook University (references given in section 3). Again values from AS 1170/2 (1981) for structural loading are shown for comparison.

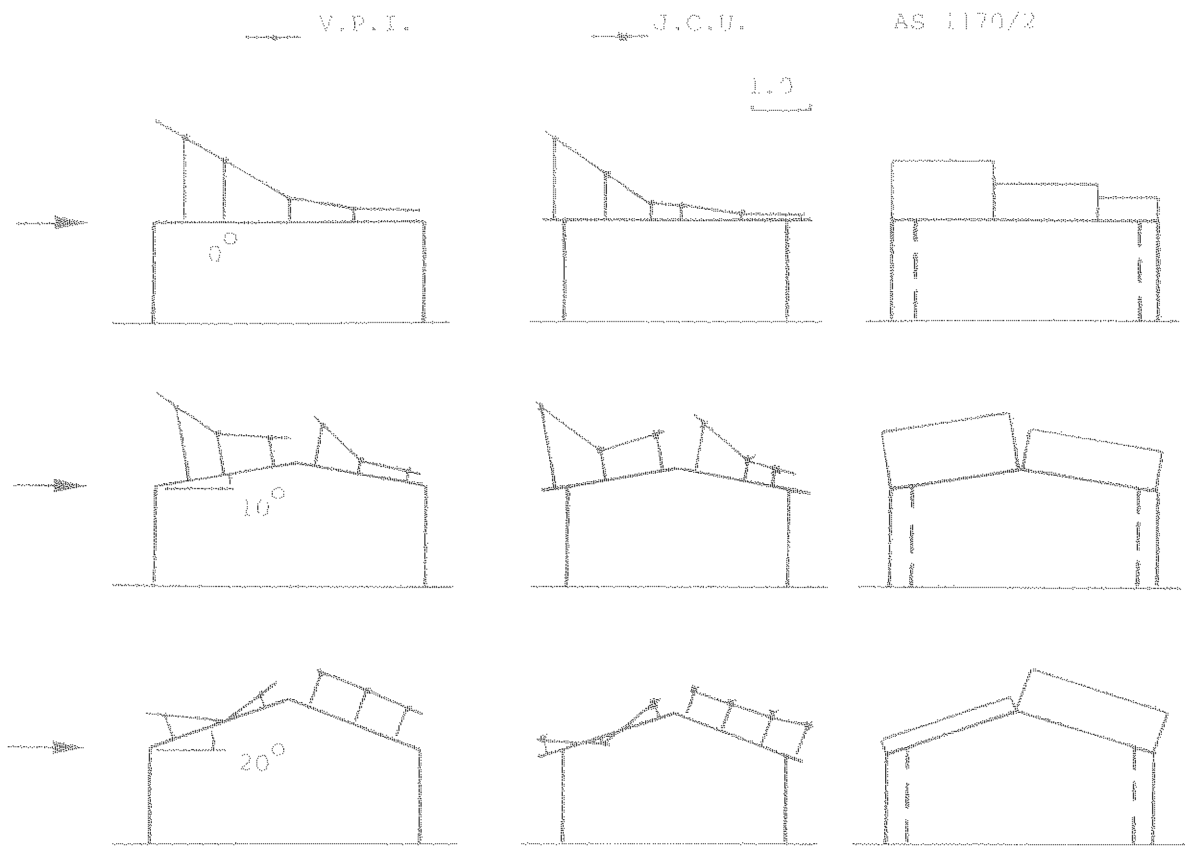


Figure 6 Mean pressure distribution on single storey houses

3. WIND TUNNEL STUDIES OF HOUSES

3.1 Range of Studies

Model studies of wind loads on houses and other low rise buildings were commenced at James Cook University during 1977. Shapes were chosen to be characteristic of a wide range of Australian houses, including the high set house typical of the Queensland and Northern Territory cyclone regions.

Figure 7 shows the range of configurations tested in this study. An initial phase consisted of a comparison of wind tunnel model test results with the full scale results from the experimental house at Aylesbury [Holmes and Best, 1977, 1978 (ii)]. Since then, a range of Australian-style house shapes, with overhanging eaves and gable ends, has been studied. Five different roof pitches from 3° to 30° have been tested, and the effect of elevating the house, as in the "high-set" configuration was also examined, [Holmes

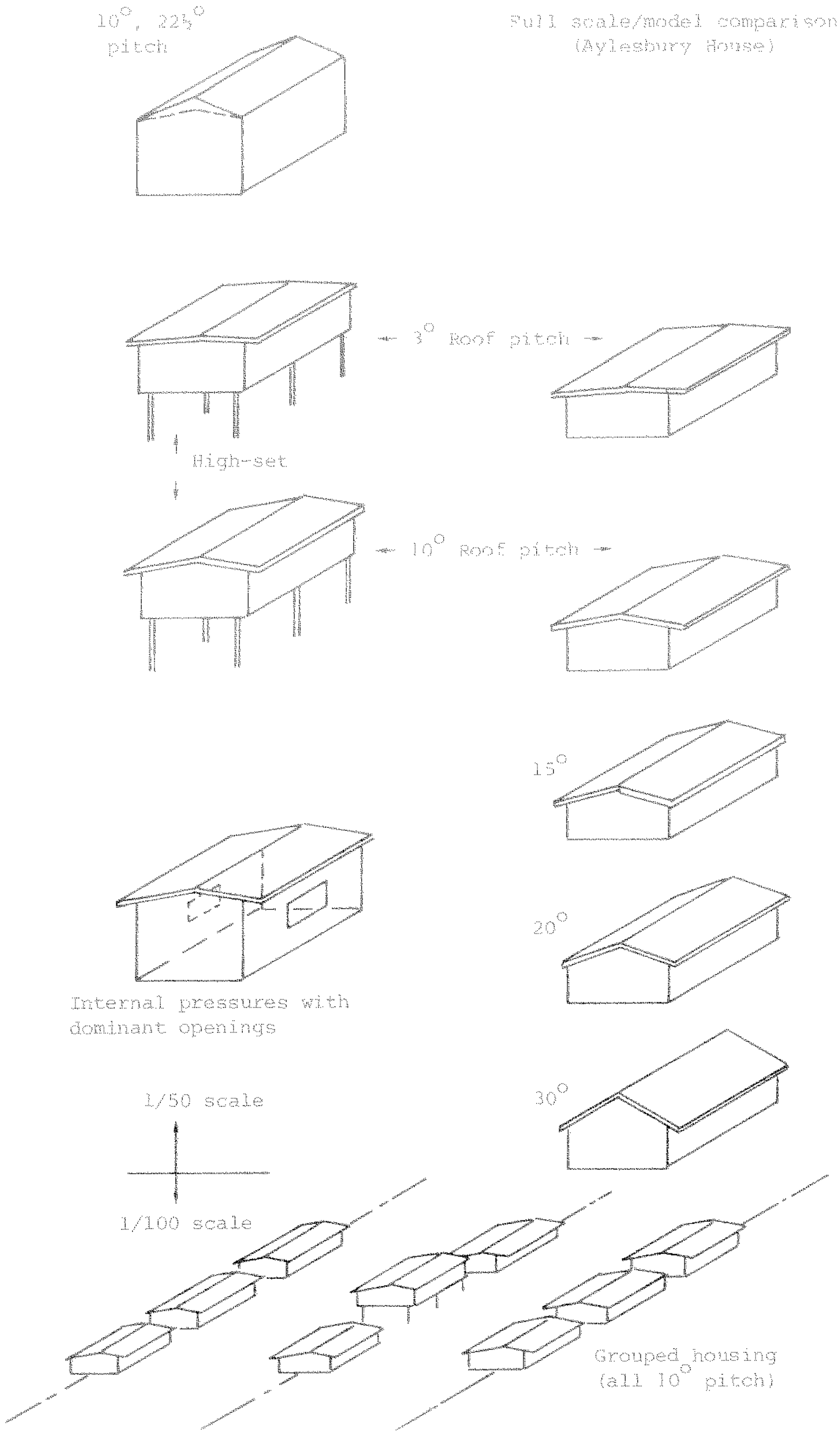


Figure 7   Configurations used in James Cook University tests

and Best, 1978 (i), 1979; Best and Holmes, 1978; Holmes and Munarin, 1979; Holmes, 1981 (ii)]. The early emphasis was on the measurement of point pressures on the roof and walls - more relevant to the prediction of the loading on cladding elements of small extent. However, in later work attention was switched to the measurement of loads and structural effects influenced by larger surface areas applicable to the design of structure and foundations. (Holmes, 1980 (i); Holmes and Best, 1981; Best and Holmes, 1980; Roy and Holmes, 1981). Internal pressures (Holmes, 1978) and the sheltering effects on houses within suburban groupings (Holmes and Best, 1979), have also been investigated, as shown in Figure 7.

3.2 Comparison with Full Scale Tests

Models of the Aylesbury experimental house were made at geometric scales of 1/50 and 1/100, and with roof pitches of 10° and 22½°. Comparisons with full scale results were made for three different wind directions. When comparing the full scale results with the 1/50 scale model, correlation coefficients of 0.79 and 0.86 were calculated for the mean and peak pressure coefficients respectively. (A correlation coefficient of 1.0 indicates perfect correlation). In fact, these values were better than those obtained from a comparison of two similar full scale tests, due to the problems outlined in Section 2.2. Regarded in this light, the model/full scale comparisons were considered to be satisfactory until more statistically "stable" full scale data becomes available.

3.3 Mean Pressure Coefficients

3.3.1 Comparison of high set and low set houses

A comparison of mean pressure coefficients for isolated low-set and high-set (elevated) houses with 10° pitch roofs is shown in Figures 8 and 9, for wind directions of 0° and 45°, (at 0°, the mean wind direction is normal to the ridge). Roof pressures are invariably negative for all wind directions, and the worst suctions are generally higher on the high-set house. Wall pressure coefficients are also higher for the high-set house, particularly on the windward walls, and on the windward edges of the side walls. The worst mean roof suctions, independent of direction, occur along the edges near the windward corner, but not at the corner itself. In fact, for wind directions,

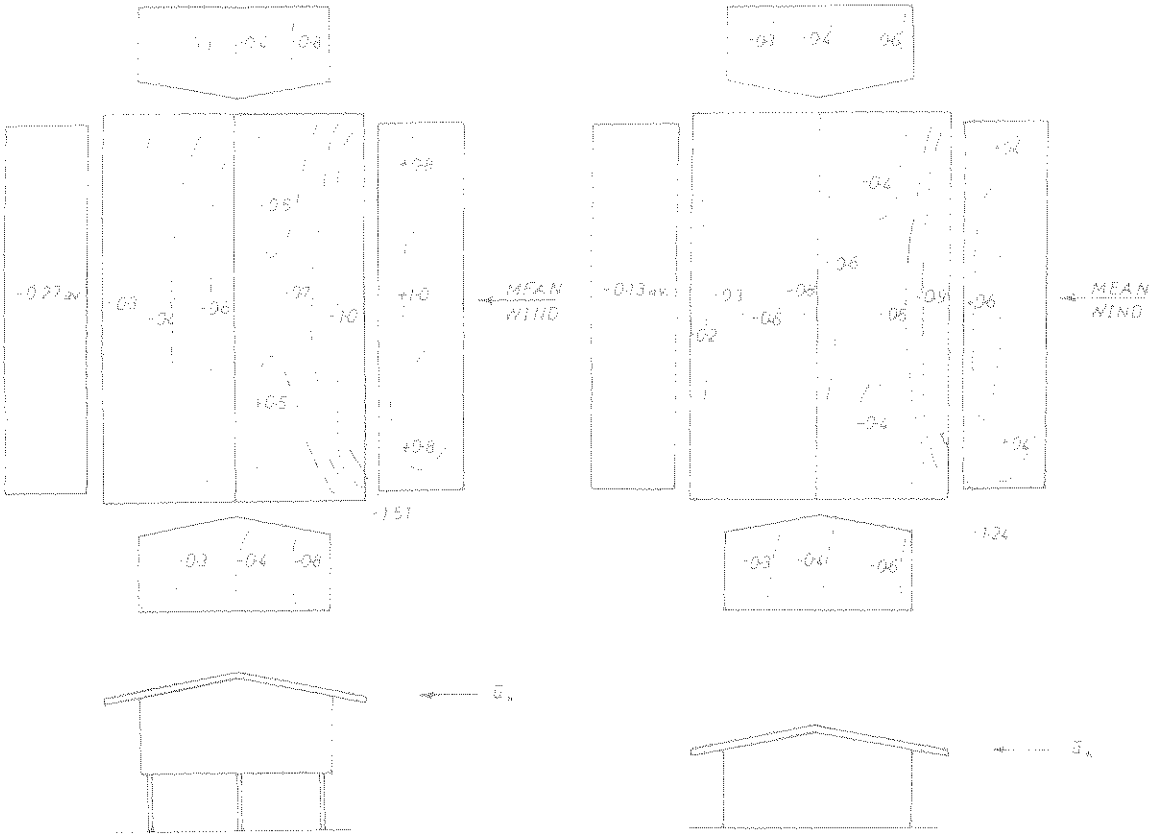


Figure 8 Mean pressure coefficients on high set and low set houses $\alpha = 10^{0}$, $\theta = 0^{0}$

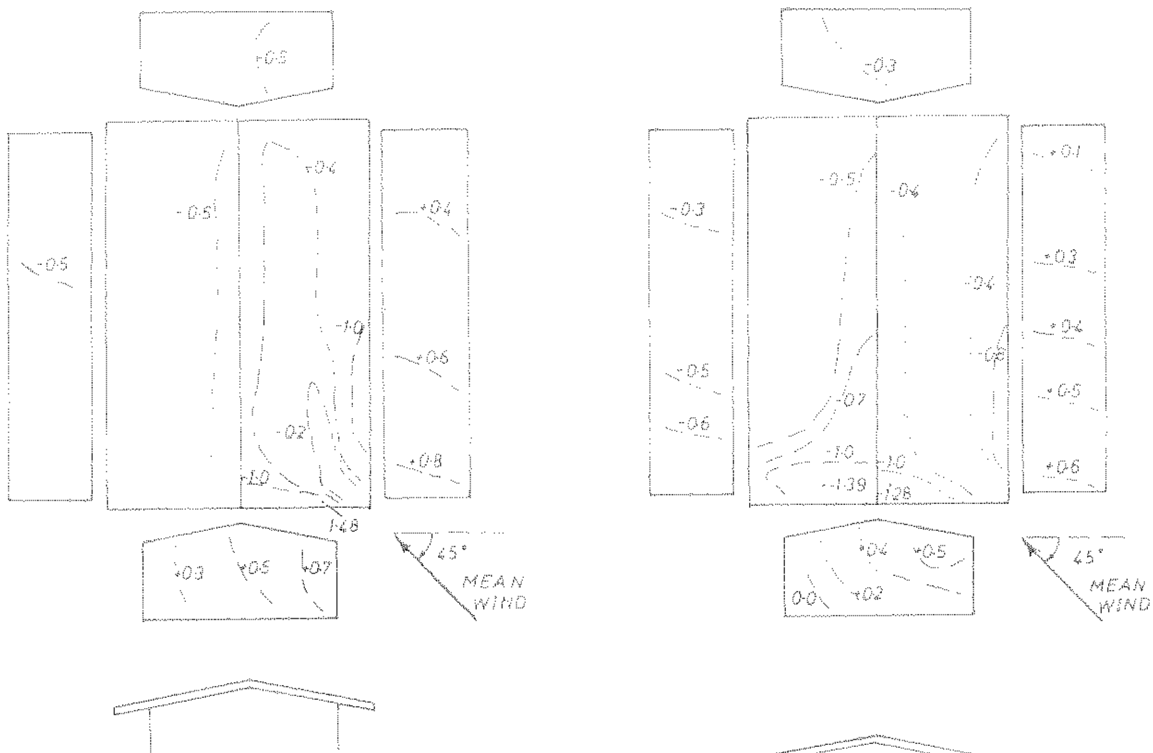


Figure 9 Mean pressure coefficients on high set and low set houses $\alpha = 10^{0}$, $\theta = 45^{0}$

$30° < \theta < 70°$, the region of low suction extends right to the corner itself. This phenomenon is due to the occurrence of conical vortices along the edges of the roof, near the corner, in a similar manner to those on a delta winged aircraft at incidence; the effect may be amplified by the roof overhangs.

3.3.2 Effect of roof pitch

The effect of roof pitch angle on the mean pressure coefficients is shown in Figure 10 and 11 for roof pitches of 15°, 20° and 30°, and for wind directions of 0° and 90°. Pressure and suctions on the walls are largely insensitive to the roof pitch. This is also true of the roof suctions at the wind direction of 90°. At that angle, the roof effectively presents a zero slope to the wind. However, the net roof uplift, computed from the vertical component of the pressures will tend to reduce at high roof pitches.

The effect of roof pitch on mean roof pressures for the 0° wind direction is considerable. On the windward face, the roof pressures change from being all negative at 15° pitch, near zero at 20° and almost all positive at 30°. The effect of the second separation at the ridge on the roof suctions is largest at the lower roof pitch. At 20° and 30° pitch, the flow does not re-attach after the second separation, as discussed in section 2.4, giving nearly uniform mean pressure coefficient over the leeward surface of around -0.5 in each case.

3.3 Peak Pressure Coefficients

The contours of worst suction peak, $\check{C}_p$, for any wind direction are shown in Figure 12. The effect of increasing roof pitch is to emphasise the gable end region as the worst loaded. The eaves along the long wall are only heavily loaded for roof pitches of 10° or lower. The worst positive peaks (not shown plotted) occur on the gable end walls for all roof pitches [Best and Holmes, 1978; Holmes, 1981 (ii)].

Plots of $\check{C}_p$ such as those shown in Figure 12 are often used as a guide to the specification of cladding loads for design. However, these can be somewhat misleading, as they only show the worst pressure coefficients independent of direction. The pressure coefficients occurring at other wind directions

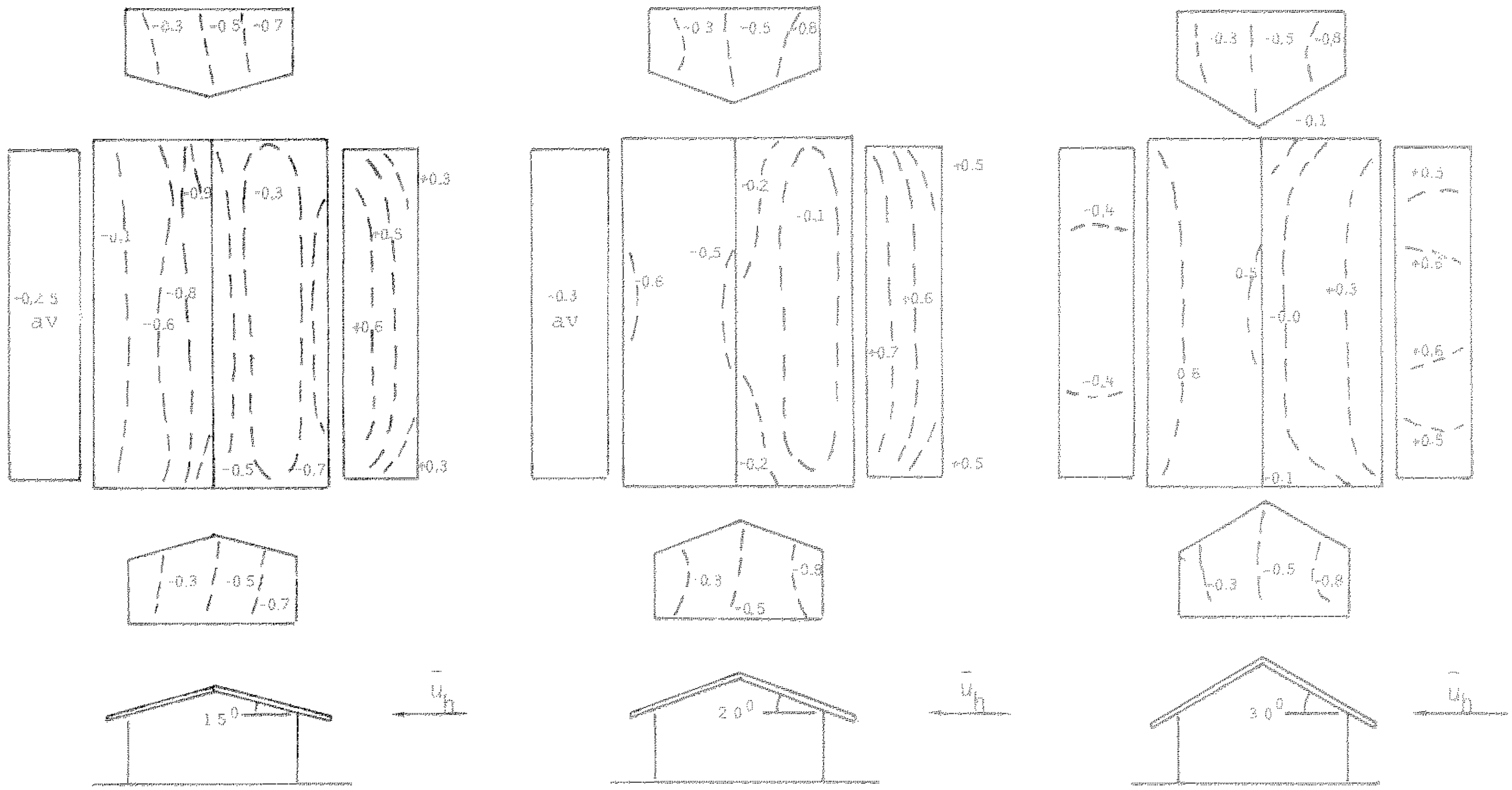


Figure 10 Mean pressure coefficients for α = 15°, 20°, 30°, θ = 0°

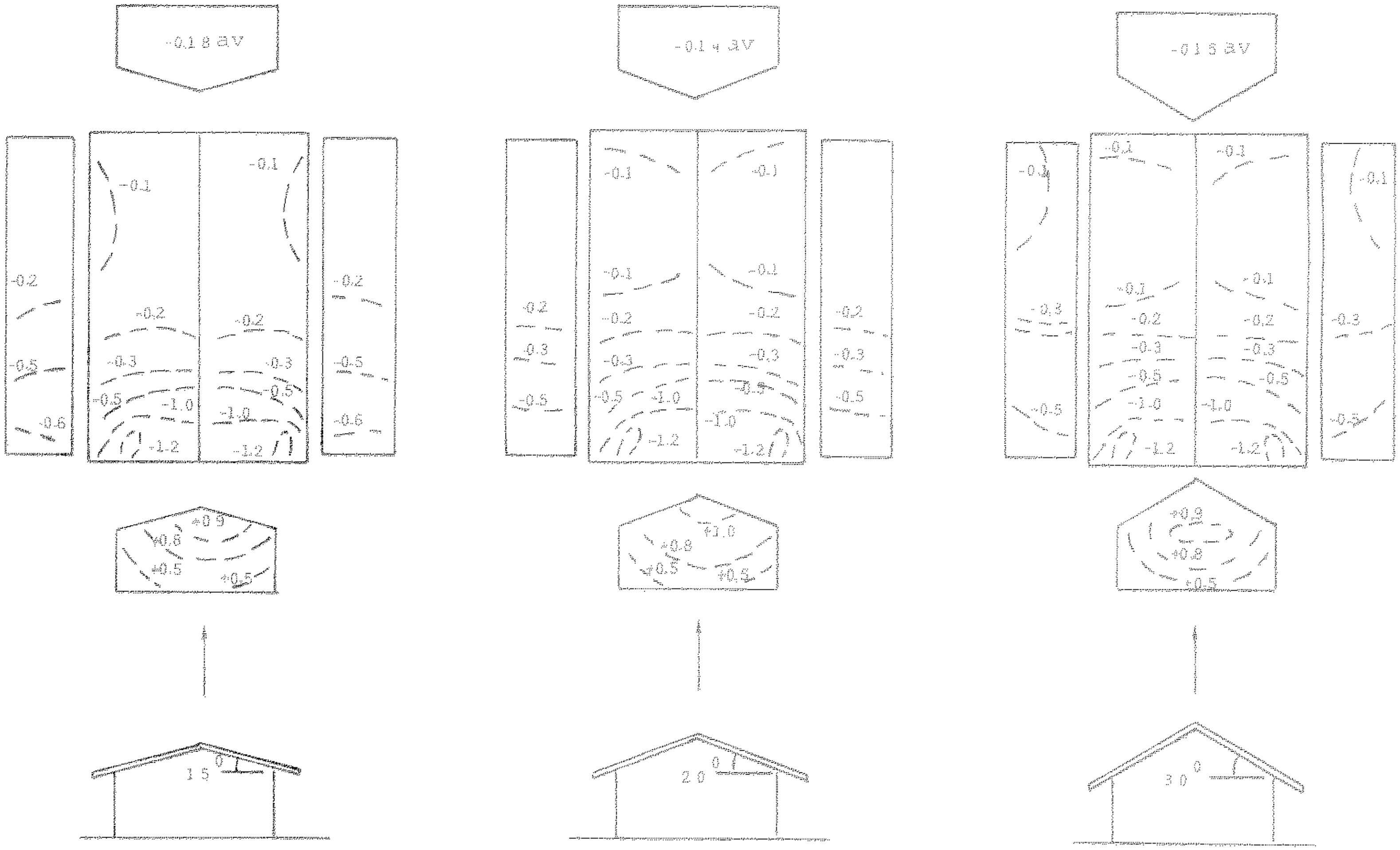


Figure 11 Mean pressure coefficients for α = 15^0,20^0,30^0, θ = 90^0

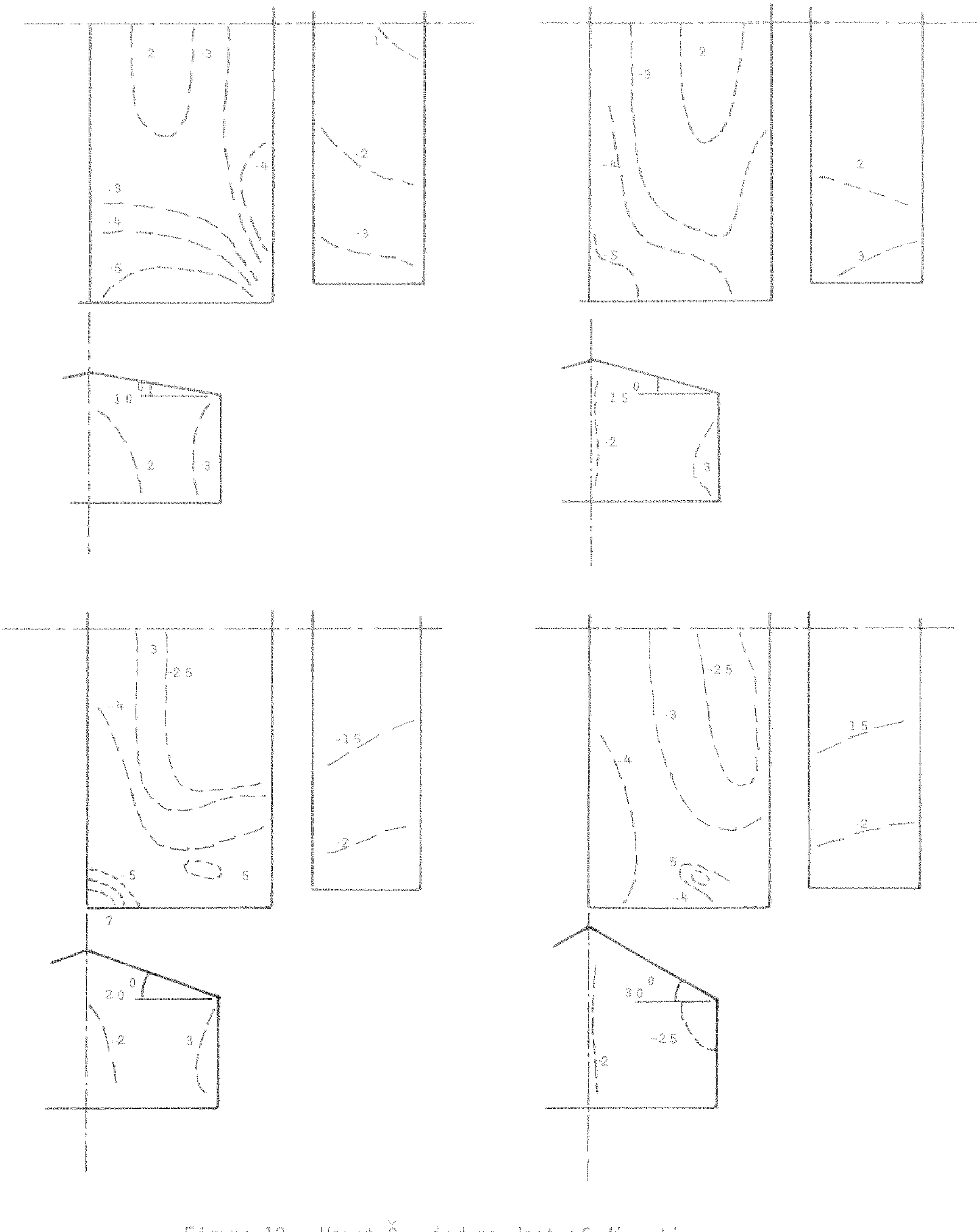
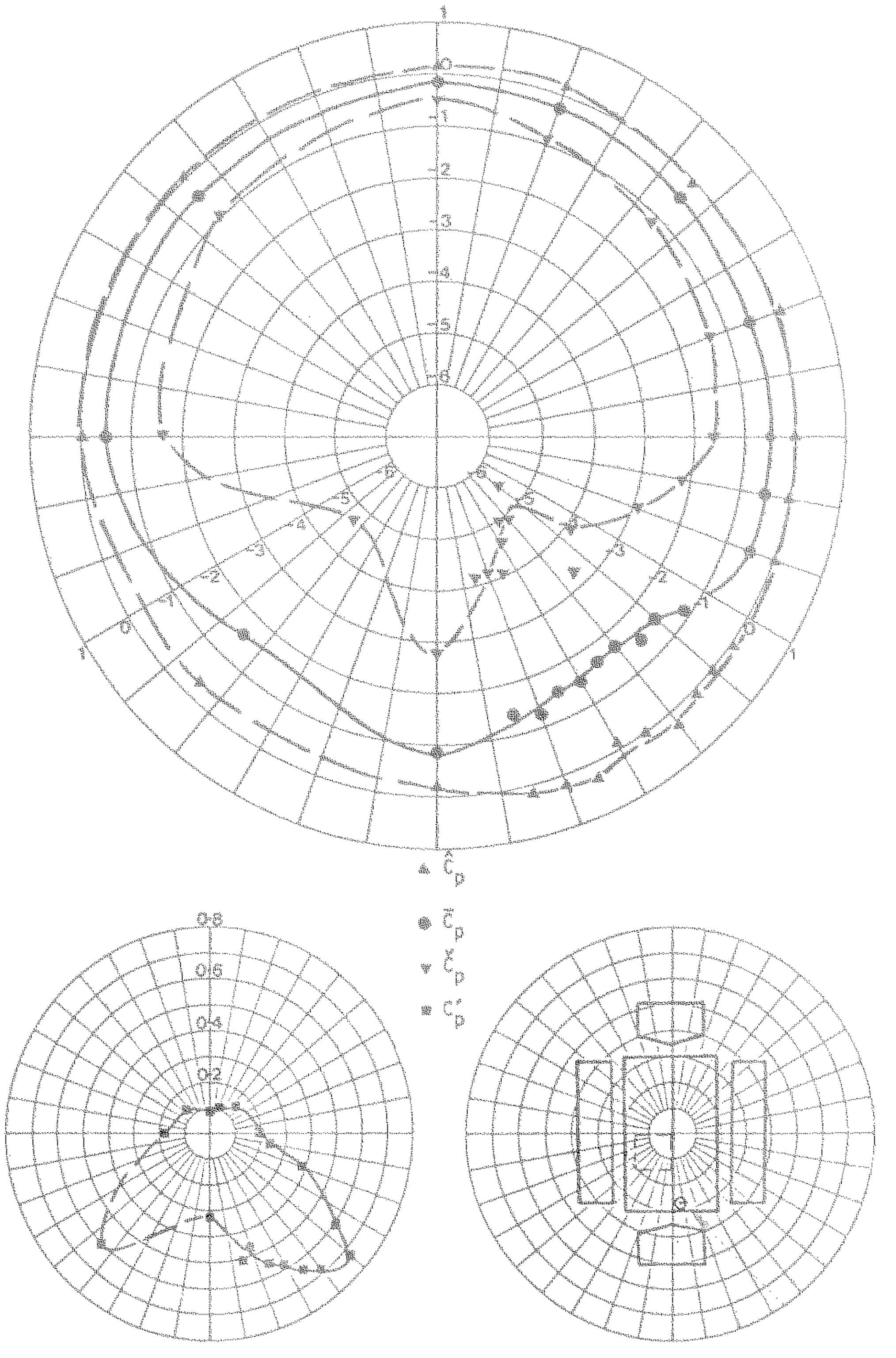


Figure 12 Worst $\check{C}_p$, independent of direction

are also of importance. Large changes of pressure coefficients with wind direction can occur, especially for roof suctions, and this is illustrated by Figure 13 showing the variation of all four pressure coefficients with wind azimuth for a point on the roof of a house model.



Position of tap

Figure 13 C_p versus wind direction

3.4 Effect of Openings on Internal Pressures

A special model of a two-storey house for studying internal pressures was constructed at 1/50 scale. A number of panels with different size openings were used to study the effect of both the absolute size of opening and the ratio of windward to leeward openings.

Figure 14 shows the variation of mean pressure coefficient as a function of the ratio of windward to leeward openings; the mean flow direction was normal to the windward wall. The mean internal pressure coefficient can be predicted fairly accurately from the following formula, obtained by considering the flow through the openings and mass conservation (Holmes, 1978):

$$\bar{C}_{p_i} = \frac{\bar{C}_{p_W}}{1 + (A_L/A_W)^2} + \frac{\bar{C}_{p_L}}{1 + (A_W/A_L)^2} \qquad \text{.....(2)}$$

where $\bar{C}_{pW}$ and $\bar{C}_{pL}$ are the mean pressure coefficients at the windward and leeward openings respectively, and A_W,A_L are the areas of the windward and leeward openings. Equation (2) is shown plotted with the experimental data in Figure 14.

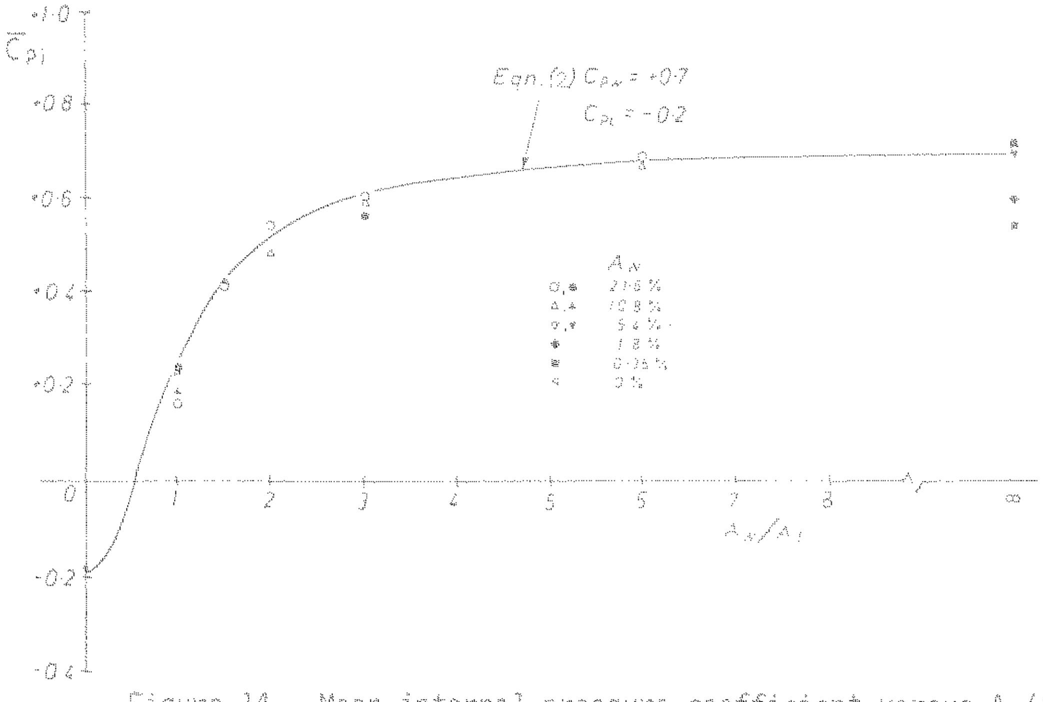


Figure 14 Mean internal pressure coefficient versus A_W/A_L
Open symbols - averages over pressure taps
Solid symbols - ensemble averages for single floor tap

Both the mean and fluctuating pressure coefficients show an increase with increasing A_W/A_L. Clearly the highest internal pressures will occur when there is a single windward opening. This case was studied in more detail both experimentally and theoretically. A computer simulation programme was developed using the theoretical model described above. Experimental results compared quite well with the results of the simulation method (Holmes, 1978).

3.5 Grouped Houses

The effect of the grouping of houses in characteristic suburban street patterns was studied using models at a geometric scale of 1/100 compared with the 1/50 scale used for the previously described studies. A large number of different grouped house configurations were examined and for most of these a number of different wind directions was used. Up to four rows of houses were contained in the groups. All the houses used had 10° pitch gable roofs, but both high and low-set configurations were used.

The object of this exercise was to investigate the shielding effect of a small group of houses on a house in an exposed environment. The wind tunnel test section was not large enough to accomodate any more than four rows of buildings, as considerable length is required to develop the flow associated with the upwind rural terrain.

A "standard" spacing of 40 m between rows of houses was established as shown in Figure 15. However both larger and smaller spacings were also used in the tests.

Figure 16 shows the effect on the mean pressure coefficient of adding extra low-set houses on each side of an isolated low-set house. A significant increase in the roof suctions occurred. However some reduction in the suctions then occurred when an extra one or two rows was added downwind. Similar but reduced effects occurred on high-set houses.

The effect of a single row of shielding houses upwind of a row containing the instrumented high-set house is shown in Figure 17. All the houses used for this run were high-set. The ratio of eaves height/row spacing was found to be the main parameter affecting the mean pressures. The only shielding effects of any significance occurred on the windward wall and the leading

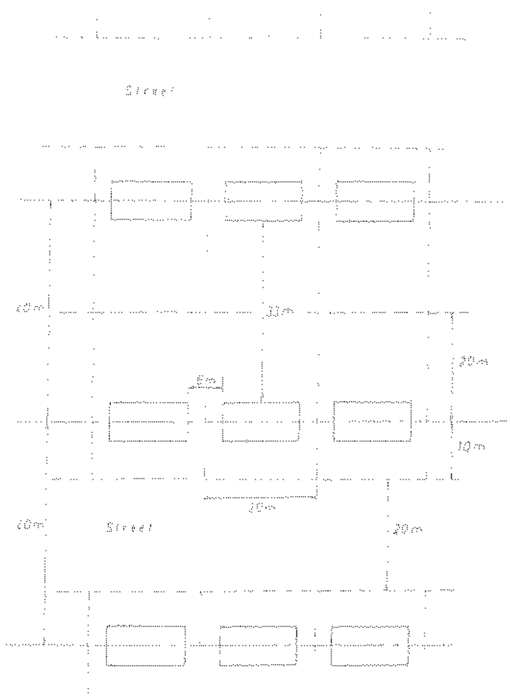


Figure 15 "Standard" suburban house spacings

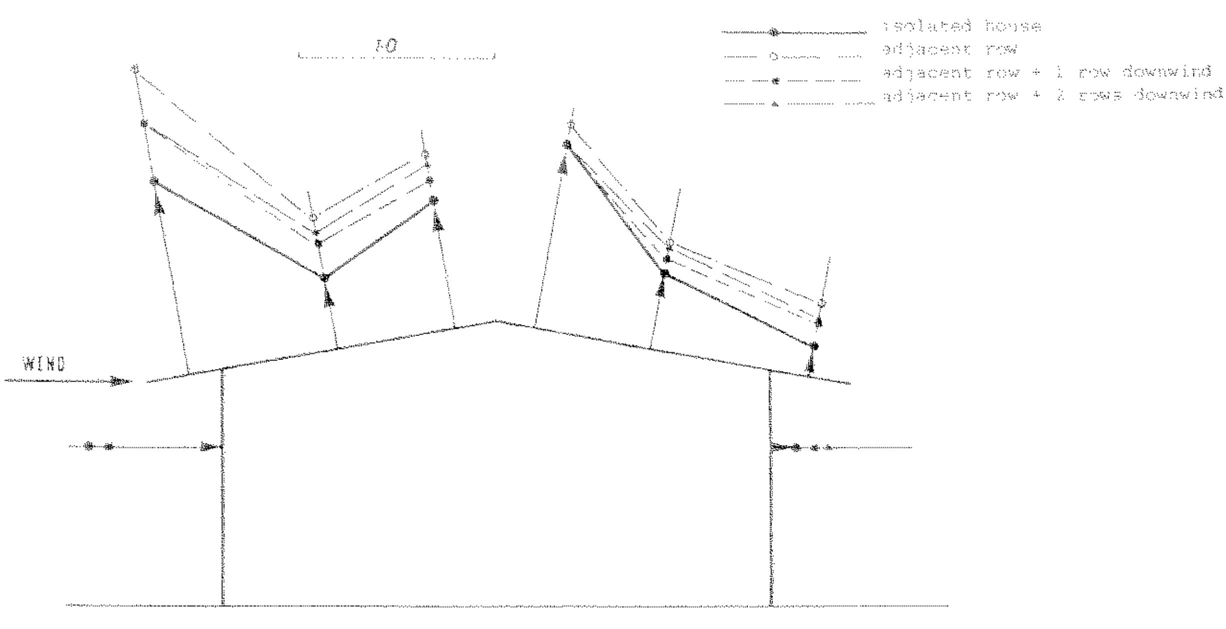


Figure 16 Effect of adjacent and downwind rows on centreline mean pressures

edge of the roof. The effects were quite severe when the shielding row was 20 m upwind but gradually reduced as the separation distance was increased. At the "normal" suburban spacing of 40 m, a reduction of about 50% in the leading edge suction occurred. For the same absolute separation distances, there was less reduction due to shielding, on the low-set houses, because of the reduced building height. The reduction in leading edge suction at the "normal" spacing of 40 m was about 25%.

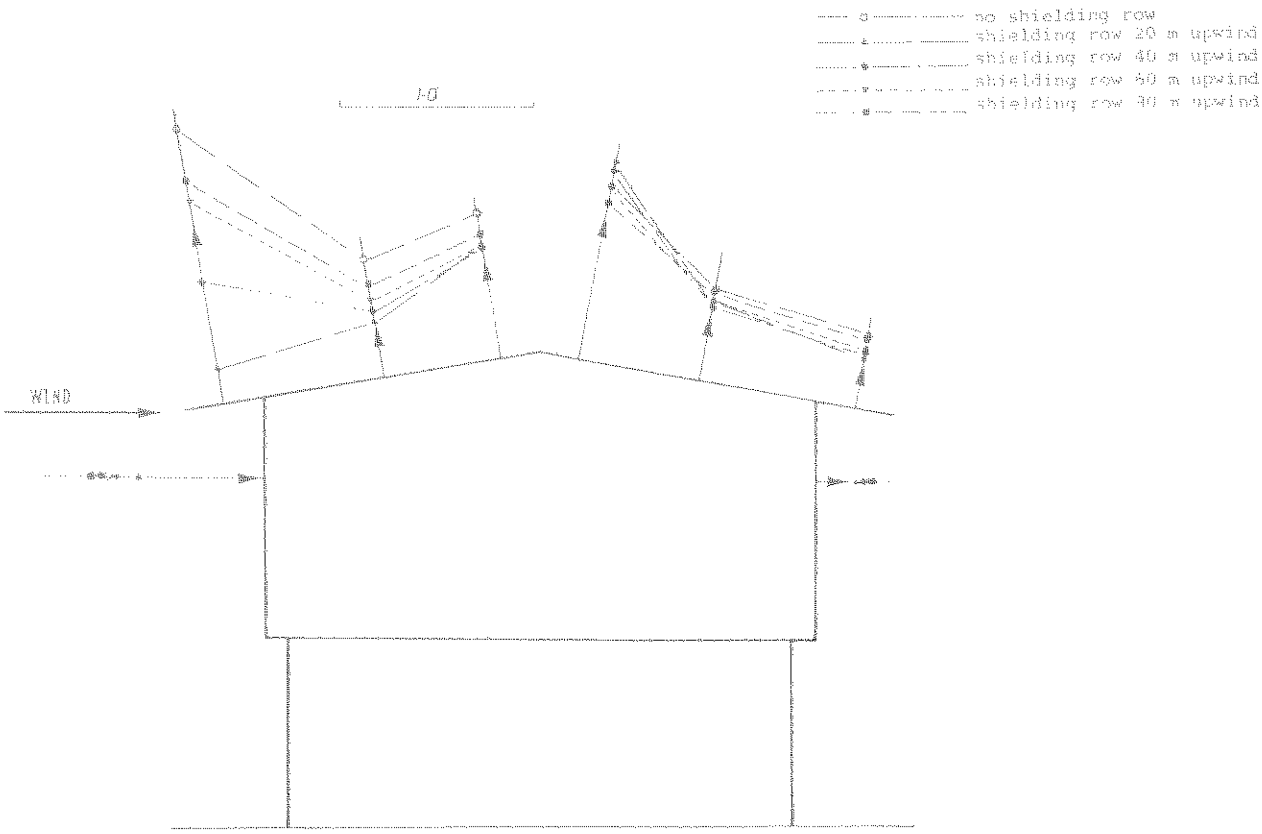


Figure 17 Single row shielding - effect of row spacing on centreline mean pressures

The maximum number of upwind rows that could be accommodated in these tests was three. It was found that the centreline mean pressures were largely insensitive to the number of upwind rows but sensitive to the height/spacing ratio, as indicated earlier. This is illustrated in Figure 18, for both high and low-set houses, where the range of centreline pressure coefficients for the standard 40 m spacing is shown compared with the values measured on the isolated house. Six different combinations of upwind and downwind rows were tested in each case.

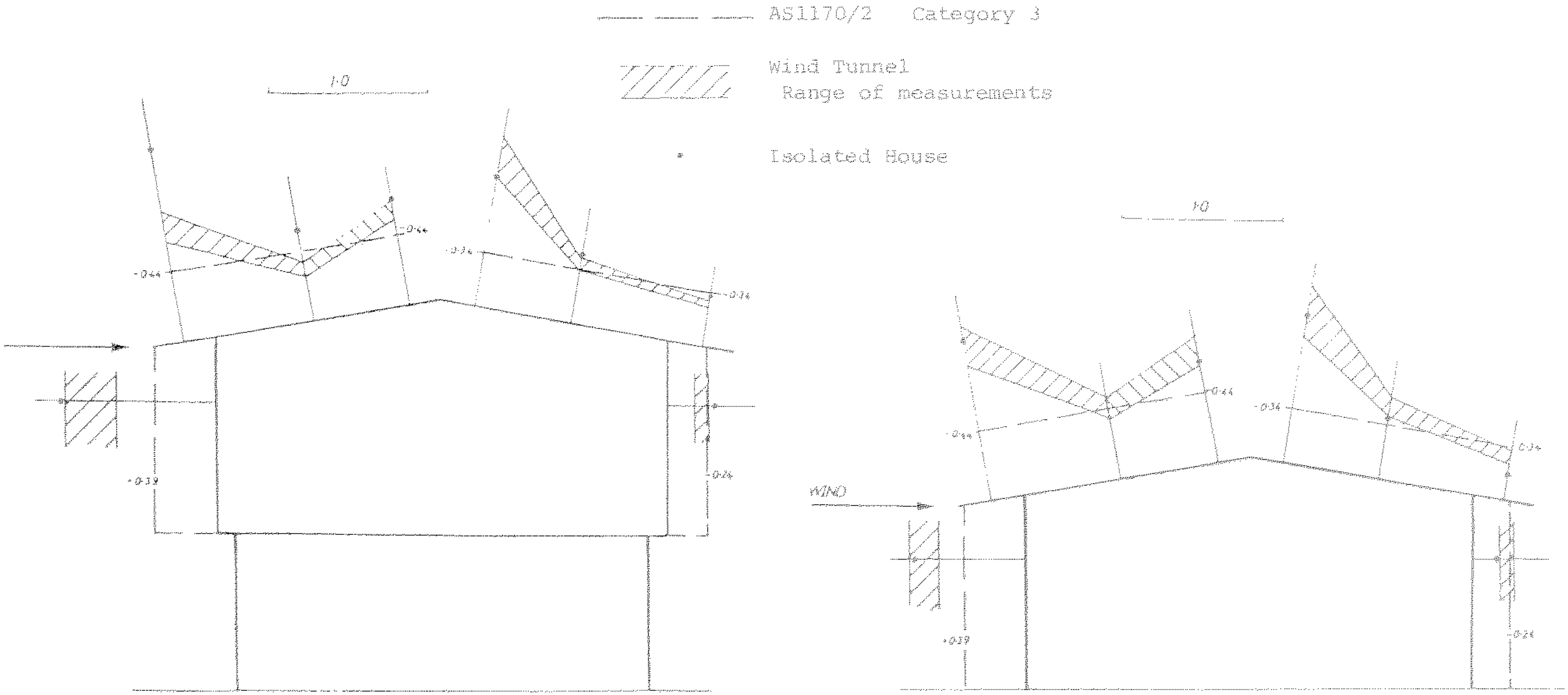


Figure 18 Centreline mean pressure coefficients

However, it should be noted that as the number of upwind rows increases further, a gradual reduction in pressures will occur as the flow adjusts to the new suburban terrain and energy is withdrawn from the mean flow velocity. This gradual adjustment process should be distinguished from the direct shielding effects which were investigated in the tests described.

Less effect of shielding was apparent on the r.m.s. and peak pressure coefficients compared with the mean pressure coefficients.

4. AN ASSESSMENT OF AUSTRALIAN STANDARD AS 1170 PART 2

4.1 Introduction and Quasi-Static Format

The highly fluctuating nature of wind velocities, pressures and structural loads, as described previously, makes the prediction of wind loads by simplified Code or Standard approaches at best only a fair approximation to reality. However, for economic reasons, and perhaps for reasons of habit, most low-rise buildings in Australia are designed by direct application of the Australian Standard AS 1170 Part 2 (S.A.A., 1981). However, it should be noted that clauses 2.1 to 2.5 of the Standard allow the use of boundary layer wind tunnel tests and other "state-of-the-art" techniques for the determination of wind loads.

A general form for the effective design pressure load acting on the surface of a building in a wind code format is:

$$\hat{p} = \tfrac{1}{2}\,\rho\,\bar{u}^{\,2}.\;\bar{C}_p.G_p \qquad .....(3)$$

Where G_p is a gust factor for the effective pressure to take account of the effects of turbulence, both in the upwind velocities and induced by the building. In AS 1170/2, the general formula is not equation (3), but the following:

$$\hat{p} = \tfrac{1}{2}\,\rho\,\hat{u}^{\,2}\,\bar{C}_p = \tfrac{1}{2}\,\rho(G_u\,\bar{u})^2\,\bar{C}_p \qquad .....(4)$$

By comparison with equation (3), it may be seen that the effective gust factor used in AS 1170/2 is equal to the square of the gust factor for velocity, $G_u = \hat{u}/\bar{u}$, where $\hat{u}$ is defined as the peak gust acting over 2-3 seconds, with an appropriate return period (normally 50 years).

Implicit in the use of equation (12.4) is the assumption that the pressures on the building follow faithfully the upwind velocity variations, in a quasi-static manner, although a small amount of filtering has been introduced by the use of the 2-3 second gust rather than the absolute peak velocity. Such an approach is probably a reasonable one for a simplified Code format for small, relatively rigid, structures, but is not suitable for larger structures and areas for which the dynamic (resonant) response is significant. One advantage of equation (4) is that the non-linear square law relationship between velocity and pressures is retained, whereas the more sophisticated approaches for taller structures usually use linearised relationships between fluctuating velocity and pressure.

For structural loading, AS 1170/2 uses values for the pressure coefficient $\bar{C}_p$ which are averaged over the area of the principal surfaces of the structure. For cladding near the edges of roofs and walls, edge factors are provided, principally to take account of the variation of mean pressure and the higher mean C_p's in these regions. However, these factors can also be "calibrated" to take account of the high instantaneous suctions in these regions measured in both wind tunnel and full scale tests.

4.2 Recent Developments

With the recent resurgence of interest of researchers in the wind loading of low-rise buildings as described in this paper, several changes, in both format and detail, have been recently proposed for those sections of the Australian Standard relating to low-rise building.

New tables of External Pressure Coefficients (Tables B2.1 and 2.2) have been proposed. These have been based on existing reliable wind tunnel data on gable roof low-rise buildings including those described in this paper. The proposed values are shown in Table 1.

Table 2 is a table of Reduction Factors for Roof Loads; these, essentially, are correction factors to the implied gust factor in AS 1170/2 as described in section 4.1. After an examination of relevant wind tunnel data from James Cook University and the University of Western Ontario, the factors in Table 2 have been proposed.

TABLE 1

PROPOSED CHANGES TO EXTERNAL PRESSURE COEFFICIENTS IN AS 1170/2

TABLE B2.1

EXTERNAL PRESSURE COEFFICIENTS (C_p) FOR ROOFS OF BUILDINGS WITH $h/d < 1.0$*
FOR $\theta = 0°$ WITH $\alpha < 10°$, AND $\theta = 90°$ FOR ALL α

Distance from Windward Leading Edge	External Pressure Coefficient C_p for Slopes D and E
0 to 1 h	-0.9
1 h to 2 h	-0.5
2 h to 3 h	-0.3
> 3 h	-0.1

* For $h/d \geq 1.0$, for $\theta = 0°$, use Table B2.2 with $\alpha = 10°$

TABLE B2.2

EXTERNAL PRESSURE COEFFICIENTS (C_p) FOR ROOFS OF BUILDINGS FOR $\theta = 0°$ WITH $\alpha \geq 10°$

h/d	Slope D Angle α, degrees								Slope E Angle α, degrees		
	10	15	20	25	30	35	45	≥60	10	15	≥20
≤0.25	-0.7	-0.4	-0.3,+0.2	-0.2,+0.2	-0.2,+0.3	+0.4	+0.5	+0.01α	-0.2	-0.5	-0.6
0.5	-0.9	-0.6	-0.4	-0.3,+0.2	-0.2,+0.2	-0.2,+0.3	+0.4	+0.01α	-0.5	-0.5	-0.6
≥1.0	-1.3	-1.0	-0.7	-0.5	-0.3,+0.2	-0.2,+0.2	+0.3	+0.01α	-0.5	-0.6	-0.6

NOTES Notes 1 and 2 as in AS 1170/2 at present.

3. Where two values are listed the roof shall be designed for both values.

4. All values shall be used with the value q_z applying at height h. Height h is taken to the highest point of the windward edge of the roof, (i.e. eaves or ridge, depending on wind direction).

5. Linear interpolation may be used to obtain intermediate values for roof slopes other than those shown, or for h/d ratios other than those shown. Interpolation should only be carried out between values of the same sign.

TABLE 2

PROPOSED REDUCTION FACTORS FOR ROOFS

Area	Reduction Factor, R_A
>10 m^2 and <25 m^2	0.90
>25 m^2 and <100 m^2	0.85
>100 m^2	0.80

These values are considerably less than the existing ones, but the independence from building shape and size has been retained.

A change in format is proposed for the Local Pressure Factors in Appendix B of the Standard. At present different Local Pressure Factors are specified depending on whether a corner region or an edge region is under consideration. In the proposed amendments, the Local Pressure Factor used would depend not on the location of the area under consideration, but on its size.

4.3 Future Developments

Most Codes and Standards for wind loading are based on a semi-probabilistic approach in which the design wind velocities are taken to be variable, and to be only predictable by probabilistic methods, whereas the pressure and force coefficients are treated as deterministic i.e. fully specified. A recent approach by Cook and Mayne (1979, 1980) considers the variability of pressure coefficients as well as of wind velocities.

In the development of recommended load factors for the American National Standard on the loading of structures, non-zero coefficients of variation for the pressure coefficients and gust factors have also been assigned. (Ellingwood, Galambos, MacGregor and Cornell, 1980). The effect on the predicted wind loads, using such approaches, is greatest for cladding loadings where the coefficients of variation are largest.

Another consideration, which is related to the above, is the question of wind directionality. Conventionally, the practice in specifying code coefficients is to base them on the worst values measured in wind tunnel tests, for any incident wind direction in relation to the building. In reality, when the design wind occurs, only a small proportion of buildings with a particular preferred alignment, will experience the worst pressures. There is thus a need for a reduction factor to be applied to account for this effect. Theoretical reduction factors based on assumed variations of structural response with wind direction have been proposed [Davenport, 1977; Holmes, 1981 (i)]. A value of 0.9 for structural loading has been proposed for AS 1170/2 based on this work.

An alternative approach is to make use of wind tunnel test results of pressure and force coefficients for all wind directions when specifying values in Codes and Standards.

The above factors are actively under consideration by Code and Standard Committees and, no doubt, some changes in format can be expected in the future as a result of this.

5. CONCLUSION

This paper has presented a summary of research conducted at James Cook University on wind loading of low-rise buildings. As other wind tunnel research in Australia has been directed towards tall buildings, or topographical or environmental effects, this paper can be considered to provide a state-of-the-art of Australian research on wind loading on low-rise buildings.

It should be apparent that much progress has been made in the last decade, in understanding the nature and mechanisms of wind loading, and in developing measurement techniques for wind tunnel and full scale studies. Much of this work on low-rise buildings has been incorporated into the Wind Loading Code, resulting in a more rational document for use in the design of houses.

6. BIBLIOGRAPHY

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