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WIND LOADS ON LOW RISE BUILDINGS – A REVIEW

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ABSTRACT

A review of knowledge of the pressures and forces exerted by wind on low rise buildings is presented. The fluctuating and turbulent nature of the wind pressures is described, together with the mechanisms causing the fluctuations.

Although all the available reliable data on wind loads on flat and gable roof buildings are reviewed, emphasis is placed on the extensive wind tunnel data obtained recently in Canada and Australia. These data are described in some detail.

Finally, a summary of the recent changes to the Australian Standard on wind forces (AS 1170 Part 2) affecting low rise buildings is given.

Keywords: Low rise buildings, Model tests, Wind loads, Wind tunnels.

1. INTRODUCTION AND HISTORICAL BACKGROUND

1.1 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 that for taller buildings and other larger 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.

1.2 Historical

Studies of the wind loading of low rise buildings by wind tunnel and full scale testing have been carried out for at least 90 years. However, it has been only recently that relatively reliable measurements have been made. This was due to a combination of a lack of suitable instrumentation and high response measuring techniques, together with a lack of 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 (1894) in Copenhagen, and Kernot (1893) at Melbourne University. Isolated studies were carried out in the next 30 years at the National Physical Laboratory (NPL) in Britain, the Göttingen Laboratories in Germany, the National Bureau of Standards in the United States, the Central Aero-Hydrodynamical Institute of the USSR, and elsewhere. These early measurements, however, showed some disagreement with each other, although they were all measurements of steady wind pressures in nominally steady flow conditions. This was probably due to small, but differing, turbulence levels in the various wind tunnels.

In Denmark, Irminger and Nokkentved (1930) carried out quite extensive wind tunnel studies in the early 1930s. Although, again, these tests were carried out in unrealistic, steady, uniform flow conditions, an innovation was the use of wind tunnel models with porous walls, and the measurement of internal as well as external pressures. One of their data sheets is shown in Figure 1, showing measurements of external-internal pressure differences. Similar, but less extensive, measurements were carried out in Australia in this period, by Richardson and Miller (1932).

Some progress was made by Bailey and Vincent (1943) at the NPL in explaining differences between wind tunnel and full scale measurements of wind pressures on a shed. However, it was not until the 1950s that Jensen (1958), at the Technical University of Denmark, explained satisfactorily the differences between full scale and wind tunnel model measurements of wind pressures. Figure 2 shows some of his measurements and illustrates the importance of using a turbulent boundary layer flow to obtain pressure coefficients in agreement with full scale values. Jensen and Franck (1965) later carried out extensive wind tunnel measurements on a range of building shapes. Although their measurements were of mean pressures only, and the surface roughness used was representative, in many cases, of very smooth terrain, many of their data are still the only available for many low rise building shapes.

In the early 1970s, 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 double 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 development in electronic instrumentation and computer-based statistical analysis techniques that had occurred in the previous two decades. The results (Eaton and Mayne 1975; Eaton *et al.* 1975) emphasized 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 1978b; Apperley *et al.* 1979) showed up a number of inconsistencies. Data from two measurement 'runs' on the isolated house, with the 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 reanalysis 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 reliable and consistent pressure and force coefficients for use in codes and standards on wind loading. However, continued model-full scale and model-model comparisons are an essential component.

In the following sections, a description of the nature and characteristics of wind loadings on low rise buildings is followed by descriptions of recent extensive wind tunnel studies carried out at the University of Western Ontario (UWO), Canada, and James Cook University (JCU) of North Queensland, Australia. Other recent wind tunnel and full scale studies are then summarized more briefly. This is followed by an assessment of the current Australian Standard AS 1170 Part 2 (Standards Association of Australia 1981), as a means of prediction of wind loads on low rise buildings, and some discussion of relevant changes to the Standard, that have recently been approved.

2. GENERAL CHARACTERISTICS OF WIND PRESSURES ON LOW RISE BUILDINGS AND MODEL-SCALING CRITERIA

2.1 Introduction

As discussed previously, the Aylesbury full scale studies and subsequent turbulent boundary layer wind tunnel tests showed very clearly the highly fluctuating nature of wind pressures, loads and load effects on low rise buildings. There is variability both in time and in space (i.e. over the surface of the building). The fluctuations are attributable to two basic sources:

(i) Pressure fluctuations induced by upwind turbulent velocity fluctuations, which are intense at the height of low rise buildings. In the grouped building or urban situation, the upwind turbulence may originate from the wakes of upwind buildings.

(ii) Unsteady pressures in the separated flow regions occurring near sharp corners, roof eaves and ridges. This includes vortex shedding effects.

Interactions between the two mechanisms above, further complicate the situation.

Other sources of pressure fluctuations are in the small scale flow separations that occur behind local cladding features and discontinuities on the walls or roofs of low rise buildings. However, as well as being localized, these are much smaller magnitude than those originating from the main sources listed above. These have been ignored in this discussion of wind loading, but could be of significance in some cases of local cladding loads, and as a source of unwanted noise.

2.2 Pressure Coefficients

Pressures on bodies are normally expressed in the form of a non-dimensional pressure coefficient, defined as follows:

$$C_p(t) = \frac{p(t) - p_o}{\frac{1}{2} \rho \bar{u}^2} \qquad (1)$$

p_o is a static (ambient, atmospheric) reference pressure, ρ is the air density and $\bar{u}$ is a mean velocity measured at a convenient reference height. In the case of low rise buildings, this is most often taken to be the eaves height of the building (but away from the influence of the building). Since the pressure at any point on the building surface is fluctuating with time, the pressure coefficient can also be treated as a time-varying quantity.

Figure 3 shows a section of a pressure record taken from a model building in a wind tunnel test, and shows four important particular values of pressure coefficient:

- $\bar{C}_p$ – the mean or time averaged value;
- C_p' – the root mean squared (rms) fluctuating value, representing the average departure from the mean;
- $\hat{C}_p, \check{C}_p$ – the maximum and minimum values occurring in the period of the record – in full scale, this period is typically 10 minutes to one hour.

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.

2.3 Wind Tunnel Model Scaling

For the sharp-edged bluff body configurations characteristic of the majority of low rise buildings, the flow patterns are insensitive to viscous effects and Reynolds number variations. This means that, provided an adequate reproduction of the turbulent flow characteristics prevalent in the atmosphere is used in wind tunnel tests, and the model is correct geometrically, the pressure and force coefficients measured are applicable to full scale buildings at design wind speeds.

A non-dimensional parameter that has been used to indicate similarity in mean velocity profiles is the ratio h/z_o, i.e. the ratio of the building height to the roughness length in the logarithmic velocity profile. However, the importance of simulating correctly full scale turbulence intensities at heights around the eaves height of low rise building models also needs to be emphasized, as there is a strong dependence of the fluctuating and peak pressure coefficients, and a weaker, but significant, dependence of the mean pressures, on this parameter. The turbulence intensity similarity will only be achieved with h/z_o equality, if the simulated boundary layer in the wind tunnel correctly simulates the high turbulence inner surface layer of the atmosphere, over the full height of the low rise building model and above.

Turbulence length scales need also to be matched, as closely as possible, to the model geometric scales, although there are difficulties in producing sufficiently large scales to suit the 1/50 to 1/300 geometric scales required for practical modelling of low rise buildings. However, results have shown that some relaxation of this criterion can be made, as long as the turbulence scales, closely related to major eddy sizes, are several times larger than the building dimensions.

2.4 Flow Patterns and Mean Pressure Distribution

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

Figure 4 shows the main features of the flow over a building with a low low pitched roof, 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 reattachment region of the shear layer closer to the leading edge and to reduce the bubble size. It has been suggested that the very small scales in the upwind turbulence enhance the entrainment of air into the growing shear layer and increase its curvature (Gartshore 1973). However, in the case of atmospheric turbulence approaching an isolated low rise building, the main turbulence scales containing energy are generally much larger than the building dimensions, and the phenomenon is more complicated than this.

The intensities of turbulence at the roof height of low rise buildings are typically 20% or greater, and the separation bubble lengths are quite small compared to those occurring in low turbulence or smooth flow (Fig. 4). 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 reattached 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. Recent modifications to Appendix B of the Australian Standard AS 1170 Part 2, have recognized this phenomenon, and pressure coefficients from this source are shown for comparison in Figure 5.

The situation described above is applicable for roof pitches up to 5° to 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, reattachment 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 reattachment occur downwind of the ridge, giving relatively uniform suctions on the leeward roof face.

Figures 6 and 7 show a number of recent wind tunnel measurements of mean pressures on gable roofs of buildings with dimensions characteristic of domestic houses. These measurements were carried out 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 3.2). Again values from AS 1170 Part 2 for structural loading are shown for comparison.

Similar flow separation and reattachment, as described in the foregoing for roofs, occurs on side walls. Pressures near the stagnation region on windward walls are positive with respect to the freestream static pressure. Leeward walls are influenced by the recirculating wake, and generally experience small suctions, but the values measured depend on the building dimensions, including the roof pitch angle.

2.5 Fluctuating Pressures

The rms fluctuating pressure coefficient is a measure of the general level of pressure fluctuations occurring at a particular point, and for a particular wind direction. The numerical value depends on the turbulence intensity in the flow field upwind, and on the position on the building surface. In open country terrain, where the turbulence intensity at eaves height is around 20%, values of C_p' of 0.3 to 0.4 occur on windward walls.

In separated reattaching flow regions on side walls, values of 0.6 or greater can occur. Even higher values can occur on roofs for those conditions, with values greater than 1.0 being not uncommon. Correspondingly larger values occur in built-up terrain; the largest value of C_p' on a roof, measured in the UWO tests described in Section 3.1, was greater than 1.4.

The probability density function (pdf) and cumulative distribution function (cdf) are measures of the distributions of amplitude in the pressure fluctuations at any point. Even though the upwind velocity fluctuations may have distributions close to Gaussian except very near the ground, the probability distributions of the pressure fluctuations are found to be skewed (Holmes and Best 1978a; Stathopoulos 1980). Figure 8 shows a wind tunnel measurement of the cdf for the pressure fluctuations on the windward wall of a house model showing the strong positive skewness. This can be explained, at least partly, by the 'square-law' transfer relating pressure and velocity (Holmes 1980b). Negative skewness occurs for pressure fluctuations in separated flow regions with large negative mean pressures.

An explanation for the intermittent and short-duration peaks in suction occurring under separating and reattaching shear layers on both high rise and low rise buildings has been given by Melbourne (1979).

3. RECENT STUDIES AT THE UNIVERSITY OF WESTERN ONTARIO AND JAMES COOK UNIVERSITY

The following sections describe the test methods and main results of two recent extensive wind tunnel test programs in which the wind loading of low rise buildings was studied.

3.1 Industrial Building Study at the University of Western Ontario

(Davenport *et al.* 1977, 1978; Surry *et al.* 1978).

3.1.1. Wind tunnel and flow properties. The boundary layer wind tunnel at the University of Western Ontario was one of the earliest of its type used for studying wind effects on structures (Davenport and Isyumov 1967). It has a working section about 25 m long, 2.5 m wide and 2.0 m high. Simulated atmospheric boundary layers are grown naturally over roughness distributed along the floor of the test section. This method of boundary layer simulation produces mean flow and turbulence characteristics appropriate to geometric scales at about 1/500. At this scale, however, low rise building models have rather small dimensions, and most of the UWO tests in this series were carried out with models at a nominal geometric scale of 1/250. Thus, at typical model eaves heights, both the turbulence intensities and the scales were slightly smaller than optimum.

Figure 9 shows the mean velocity and turbulence intensity profiles for the two simulated terrain types: smooth terrain corresponding approximately to Category 2 in the

Australian Standard, and built-up terrain corresponding approximately to Category 3.

3.1.2 Phase I of the study – effect of scale and length. The model configurations used in the UWO tests are shown in Figure 10. Phase I of the study consisted of exploratory experiments in which a single roof pitch (1:12 ≅ 5°) configuration was used. As indicated in Figure 10, the effects of geometric scale and building length were investigated. Models at geometric scales of 1/500, 1/250 and 1/100 were made although, as stated previously, the 'correct' scale on the basis of the flow properties was 1/500.

The basic pressure-measuring system was stated to have an adequate frequency response to about 100 Hz. This gave measurements of peak pressures averaged over about 1 second in full scale.

A comparison of the rms and peak pressure coefficients showed a slight reduction going from the 1/500 to the 1/250 scale, and then a more significant increase to the 1/100 scale. This apparently contradictory result can be explained by considering the relative contributions of two effects going in opposite directions. An increase in geometric scale (without changing the flow properties) by increasing the height of the model, puts the building surfaces in a lower turbulence region, which tends to produce lower pressure fluctuations. Conversely, the large size of the model means that the frequencies of the contributions from the 'building-induced' turbulence are generally lower for the same wind velocity, and the pressure measurement system has a better frequency response relative to the pressure fluctuations being measured. However, the differences between the results from the 1/250 and 1/500 scale models were not large, and nearly all of the subsequent tests in the UWO series were carried with the larger models and a nominal scale of 1/250.

Varying the length of the models was found to have little effect on the measured pressures and structural loads, and all measurements in Phase II of the project were carried out with a single length (about 38 m in full scale).

3.1.3 Phase II – effect of roof pitch and eaves height. In Phase II of the study, tests were carried out on models with rectangular planforms of dimensions about 24 x 38 m in full scale, with three roof pitches (approximately 5°, 18° and 45°) and different eaves heights (approximately 5 m, 7.5 m and 10 m) as shown in Figure 10. The results of the tests in this phase are of more general interest than the other phases of the study and are discussed in some detail below.

The measurements carried out in Phase II consisted of point pressure measurements at about 200 pressure taps on each model and also the on-line measurement of several structural effects associated with an end bay. Figure 11 shows diagrammatically the procedures used for the latter measurements. Instantaneous purlin loads were measured by summing 'pneumatically' (Surry and Stathopoulos 1978) the pressures from several pressure taps. These loads were then digitized by a minicomputer system, weighted by appropriate structural influence coefficients, and summed by the computer. In this way 'on-line' instantaneous values of various structural effects influenced by large areas of building surface were obtained. The following bay loads were determined in this way:

(i) Vertical uplift force
(ii) Horizontal force
(iii) Bending moments at the ridge for a two-pinned frame.
(iv) Bending moments at the knee for two and three-pinned frames.

Finally, some area-averaged instantaneous roof loads were measured for a square area, with a side length equal to one-tenth of the building width (approx. 2.5 m in full scale), at the corner of the roof of each model.

The above measurements were taken at 45° intervals of wind direction.

3.1.4 Peak point pressures. The worst peak point pressures ($\hat{C}_p$, $\check{C}_p$) for any wind direction are shown in Figures 12–14 for each of the three roof pitches, respectively. Clearly, the peak pressures and suctions are significantly greater in the built-up terrain, as expected. For any given roof pitch, there is not a large variation with eaves height, remembering that the pressure coefficients are calculated using the eaves height mean velocity in each case. Since the fluctuating pressures are also closely related to the turbulence intensities, lower peak pressures might be expected at greater eaves heights where the turbulence intensities are lower and, in fact, there is a tendency for this to occur in Figures 12–14. However, the local pressures are also influenced by building-induced flow separations, and hence by the relative building dimensions.

The worst suctions occur on the 18° pitch roofs near the ridge at the gable end. For 5° pitch, there is a more even distribution of the worst suction regions around the edge of the roof. For 45° pitch, the corner region generally has the worst suctions, especially at the lowest height. Positive peak pressures are also significant on the 45° pitch roof.

3.1.5 Structural loads. Figures 15 and 16 show representative measurements of structural parameters obtained using the method described previously. It is clear from these figures that there is a considerable range of fluctuation between the maximum and minimum values, especially in the built up terrain, again reflecting the higher turbulence levels associated with the latter. The largest magnitudes occur for the wind directions for which the mean is also the largest, and the largest peak pressures have the same sign as the mean. In fact, good approximations to the peak values can be obtained by multiplying the mean value by a 'gust factor' of about 2 for open-country terrain, and about 3 for built-up terrain. These stable values of gust factor are useful when 'equivalent static' loads are required for code purposes (see Section 5).

3.1.6 Area averaging at a corner. Figure 17 illustrates the effect of tributary area at a corner, where the instantaneous combined pressures at four points connected together (solid line) is plotted together with the arithmetic mean of the peak pressures measured independently and non-simultaneously. A significant reduction is seen in the effective pressure occurring over this area, which is about 2.5 x 2.5 m in full scale, assuming a geometric scale of 1/250. However, lesser reductions were found at the higher roof pitches.

3.1.7 Phase III – effect of overhanging eaves and large nearby structures. In Phase III of the UWO study, the effects of overhanging eaves, parapets, and of large nearby structures were investigated, and internal pressures were measured. These topics were also covered in the JCU tests described below, so this phase of the UWO study will not be discussed here. However, full details are given by Davenport *et al.* (1978); aspects were also covered by Stathopoulos *et al.* (1979), Stathopoulos (1981a) and Stathopoulos (1981c).

3.2 Study of Domestic Houses at James Cook University (J.C.U.)

3.2.1 Introduction. Model studies of wind loads on domestic houses were commenced at James Cook University in 1977, following the severe damage to those structures during tropical Cyclones Althea in 1971 and Tracy in 1974. Although emphasis was given to shapes characteristic of tropical-style houses, the models were also representative of many Australian houses in southern regions.

Figure 18 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, 1978b). Since then, a range of Australian-style domestic house shapes, with overhanging eaves and gable ends, has been studied. Five roof pitches from 3° to 30° have been tested, and the effect of elevating the house, as in the 'high-set' configurations common in Queensland and the Northern Territory, was also examined, (Holmes and Best 1978a; Best and Holmes 1978; Holmes and Munarin 1979; Holmes 1981b). 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 1980a; 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 18.

Most of the above studies have been summarized by Holmes (1980c).

3.2.2 Wind tunnel and flow simulation. The dimensions of the wind tunnel test section at James Cook University are: length, 17.5 m (recently extended from 13.7 m); height, 2.0 m (adjustable); and width, 2.5 m. It is of the open return type, with the fan mounted downwind of the test section. In order to produce models of a reasonable size, geometric scales of 1/50 and 1/100 were used. At these scales, it is not possible to reproduce the full height of the atmospheric boundary layer, and a 'partial' boundary layer simulation was used, in which atmospheric flows are simulated up to equivalent full scale heights of 50 to 100 m. The turbulent boundary layer flows were generated by a combination of carpet roughness on the floor of the tunnel together with a plain fence at the start of the test section. The carpet provides roughness of the correct length z_0, and hence gives the required mean velocity profile. The fence serves two purposes: firstly, it acts as a momentum 'trip' to accelerate the boundary layer growth, and secondly, it acts as a generator of turbulence of large scale and intensity, in the form of its decaying wake. The height of the fence is varied to suit the geometric scale being simulated (Holmes 1977).

Figure 19 shows the profile of mean velocity and longitudinal turbulence intensity used for the 1/50 scale testing. Good agreement is shown with profiles computed from the 'logarithmic' law with a roughness length z_0 of 35 mm – a value appropriate to Category 2 terrain (open country) in the AS 1170 Part 2. Figure 20 shows the spectrum of the longitudinal turbulence component compared with a standard empirical expression appropriate to the roughness length of 35 mm (Engineering Sciences Data Unit 1974). This figure indicates that the scales of turbulence were, in general, about half those desirable for a 'correct' representation of the real atmospheric situation. However, this must be viewed in the light of the wide variability in full scale measurements of wind spectra. Also, as indicated previously, the turbulence scales are many times larger than the building dimensions, and a discrepancy of this order is expected to have little effect on the measured pressures and forces.

3.2.3 Measurement techniques. As in the UWO tests, the measurement of point pressures was carried out with a tube-restrictor system having a flat frequency response to about 80 Hz. At a time scale of around 20, this corresponded to about 4 Hz in full scale. The system was found to attenuate the peak suctions at points in separated flow regions by about 10% (Holmes 1981b), but this is offset partly by the translation of these point pressures to those on finite areas of building cladding. A PDP8/E minicomputer data acquisition system was used to sample all velocity, pressure and force signals and for statistical data processing.

3.2.4 Model and full scale comparison. Models of the Aylesbury experimental house at geometric scales of 1/50 and 1/100, and with roof pitches of 10° and 22.5°, were made, and comparisons with full scale results were made for three wind directions. Correlation coefficients of 0.79 and 0.86 were found for the full scale to 1/50 scale model comparisons for mean and peak pressure coefficients respectively. These values were, in fact, better than those obtained when two equivalent full scale runs were compared. Regarded in this light, the model to full scale comparisons were considered to be satisfactory until more statistically 'stable' full scale data are available.

3.2.5 Mean pressure coefficients. A comparison of mean pressure coefficients for low set and high set (elevated) houses with 10° pitch roofs is shown in Figures 21 to 24, for wind directions of 0°, 45°, 60° and 90° respectively. (At 0°, the mean wind direction is normal to the ridge.) Roof suctions 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 $30° < \theta < 70°$, 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.

The effect of roof pitch angle on the mean pressure coefficients is shown in Figures 25 and 26 for roof pitches of 15°, 20° and 30°, and for wind directions of 0° and 90°. Pressures and suctions on the walls are largely insensitive to the roof pitch, and 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.

However, 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 reattach after the second separation, as discussed in Section 2.4, giving a nearly uniform $\overline{C}_p$ over the leeward surface of around -0.5 in each case.

3.2.6 Peak pressure coefficients. The contours of worst peak suction $\check{C}_p$ for any wind direction are shown in Figures 27 and 28. These figures can be compared directly with Figures 12 to 14 showing results from the UWO tests. However, in the JCU tests, a smaller wind direction increment, averaging 10°, was used to identify better the wind directions producing the worst peaks.

The effect of increasing roof pitch is to emphasize the gable end as the worst loaded region. The eaves along the long wall are only loaded heavily 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 1981b).

Plots such as those in Figures 12-14 and 27-28, 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 are also important. Large changes of pressure coefficients with wind direction can occur, especially for roof suctions, and this is illustrated by Figure 29, which shows the variation of all four pressure coefficients with wind azimuth for two points on a house model.

3.2.7 Internal pressures. A special model of a double storey house for studying internal pressures was constructed at a 1/50 scale. A number of panels with different open areas were used to study the effect of both the absolute open area and the ratio of windward to leeward open areas.

Figures 30 and 31 show the variation of mean and rms fluctuating pressure coefficients as a function of the ratio of windward to leeward open areas; 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):

$$\overline{C}_{p_i} = \frac{\overline{C}_{pw}}{1 + (A_l/A_w)^2} + \frac{\overline{C}_{pl}}{1 + (A_w/A_l)^2} \qquad (2)$$

where $\overline{C}_{pw}$ and $\overline{C}_{pl}$ are the mean pressure coefficients at the windward and leeward openings respectively, and

A_w and A_l are the areas of the windward and leeward openings respectively. Equation (2) is shown plotted with the experimental data in Figure 30.

Both the mean and fluctuating pressure coefficients show a monotonic 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. As shown in Figure 32, the case can be treated simply as a damped Helmholtz resonator, well known in acoustics. In simple terms, the system can be regarded as a mass-spring-damper vibrating system, in which the mass (or inertia) is that of the air 'slug' due to the resistance of the air inside the volume to changes in pressure, and the damping is represented by the energy losses of the flow through the opening.

A computer simulation program that used the theoretical model described above was developed, and Figure 32 shows a section of the computer-simulated record of internal pressure fluctuations for the case of an internal volume of 600 m^3 and windward opening area of 1 m^2; the mean wind speed was 30 m/s. The pressure record shows a small resonant effect at a frequency of about 2.4 Hz; frequencies up to the resonant frequency in the external pressure are felt with little or no alteration inside the building.

Experimental results compared quite well with the results of the simulation method described above (Holmes 1978).

3.2.8 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 studies described previously. Many grouped-house configurations were examined and, for most of these, various wind directions were 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.

A 'standard' suburban spacing between rows of houses of 40 m was established as shown in Figure 33. However, both larger and smaller spacings than this were used in the tests.

Figure 34 shows the effects on the mean pressure coefficient of adding an extra half row of houses to each side of an isolated low-set house. A significant increase in the roof suctions occurs. However, some reduction in the suctions then occurs when an extra one or two rows is added **downwind**. Similar but reduced effects occur 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 35. The ratio of eaves height to row spacing was found to be the main parameter affecting the mean pressures. The only shielding effects of any significance occur on the windward wall and at the leading edge of the roof. The effects are quite severe when the shielding row is 20 m upwind, gradually reducing as the separation distance is increased. At the 'normal' suburban spacing of 40 m, a reduction of about 50% in the leading edge suction occurs. 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 is about 25%.

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 ratio of height to spacing, as indicated earlier. This is illustrated in Figure 36, 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 combinations of upwind and downwind rows were tested in each case.

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

3.2.9 Overall forces, moments and structural effects. All the JCU wind tunnel tests results described previously in Sections 3.2.4 to 3.2.8 were obtained from individual measurements of pressures at single points on the building surface. However, the actual loading on structural components will be influenced by the simultaneous fluctuating pressures occurring over all areas of the building exposed to the wind, weighted appropriately by the influence function associated with the particular load or effect.

Direct measurements of total forces and moments have been carried out using a three-component force and moment balance (Roy and Holmes 1981). A configuration of three sensitive force transducers was used on the balance. The output of these transducers was digitized by a mini-computer and weighted with a matrix of coefficients determined by static calibration, to obtain instantaneous horizontal and vertical forces, and overturning moment.

Figure 37 shows values of mean, rms fluctuating and peak force and moment coefficients measured on a model of a single-storey house with a 10° pitch roof.

Each value represents an ensemble average of about 20 separate runs, each of a duration equivalent to about 10 minutes in full scale.

An approach used at the University of Western Ontario for the determination of structural loads and effects was described in Section 3.1.3. This method has practical disadvantages for wind tunnel studies, in that a number of pressure transducers are required to be operating simultaneously. Also, if further structural effects are required, a new set of wind tunnel tests must be carried out.

An alternative approach requiring only two transducers and instrumentation channels to be operating simultaneously has been developed at James Cook University (Holmes and Best 1981). The method is illustrated diagrammatically in Figure 38. The required aerodynamic information is the mean and rms pressure coefficient together with the rms coefficient of the derivative of the pressure fluctuations for a number of panels on the building surface in the region affecting the required loads. The correlation coefficients for the fluctuating pressures and their derivatives for every pair of panels are also required. Double summations will then give the rms fluctuating value, and the rms derivative of any structural effect for which the influence coefficients are known can then be computed, as shown in Figure 38. Finally, the expected peak value of the structural effect can be determined, assuming a Gaussian distribution for the effect. This method was used to compute fluctuating and peak values of a number of structural and overall loads for the central bay of a single storey house (Holmes and Best 1981).

However, the Gaussian assumption appears to be unconservative for many structural loads and effects associated with low rise buildings. A modification to the covariance integration method described above allowing for non-Gaussian effects is described by Holmes and Rains (1981). A completely different approach based on 'coincident peaks' is described by Holmes (1982).

4. OTHER STUDIES

A number of other studies of wind loading of low rise buildings have been carried out in the last 10 years. Space does not permit a full description of all this work here, and the reader is referred to the references cited below for further details. The work described below consists of either full scale measurements, or boundary layer wind tunnel measurements in which acceptable mean velocity profiles and turbulence intensities were used.

4.1 Aylesbury Wind Tunnel Tests

As well as the work of Holmes and Best (1978b), and Apperley *et al.* (1979) mentioned previously, other wind tunnel studies of the BRE full scale Aylesbury experiment have been carried out by Barnaud and Gandemer (1974), Greenway and Wood (1977-78), Tieleman *et al.* (1980), and Tieleman *et al.* (1981). A comparison of mean pressure coefficients for several of these wind tunnel studies for a particular roof slope and wind direction has been made by Holmes and Best (1978b). High correlation coefficients were found, but some differences in absolute values were apparent; these could be explained by differences in the mean velocity profile and static pressure reference used in the various tests. Less good agreement was found between the fluctuating pressure coefficients and this could be explained by differing turbulence intensities.

Tieleman *et al.* (1981) also, made a detailed comparison of the available full scale and model data from the Aylesbury building. Differences were large enough to justify further comparisons, taking closer note of the inhomogeneous site conditions in full scale, and of the varying modelling techniques used.

4.2 Other Full Scale Studies

Several full scale studies have been carried out by the National Bureau of Standards (NBS) of the United States. Full scale point pressure measurements were carried out on a US Air Force house in Montana. Mean and fluctuating pressures were recorded for six points on the gable roof of the building for various wind directions. The results, together with wind tunnel tests carried out at Colorado State University, are described by Marshall (1975). Earlier wind tunnel tests on the same model are described by Dreher and Cermak (1973). Fairly good agreement between the mean pressure coefficients recorded in full and model scale was found, with some differences explained by drift problems in the full scale measurements. The rms fluctuating pressure coefficients showed less good agreement; the wind tunnel values were substantially smaller. However, this could be explained readily by the low turbulence intensity used in the wind tunnel tests.

A comprehensive set of measurements on a mobile home were also carried out by the NBS, and are described by Marshall (1977). The measurements consisted of point pressures on the roof and walls, and total lift and drag forces on the complete building. An indication of the area averaging effect, described previously in this paper, was obtained by combining numerically the fluctuating pressure recordings from several taps. The relatively small reduction when pressures along the line of the leading edge of the roof were combined, was a notable feature.

The NBS also measured point pressures on some small single storey houses in the Philippines. The results, together with corresponding wind tunnel results from tests carried out by the Virginia Polytechnic Institute and State University, are described by Tieleman and Reinhold (1976).

The total lift force on a small flat-roof building was measured by Kim and Mehta (1977), together with the upwind mean velocity and turbulence properties. The amplitude probability density of the fluctuating lift force was fitted with a Gamma distribution. A close relationship was found between the spectrum of lift force fluctuations and that of the upwind velocity fluctuations.

Leicester and Hawkins (1979) described preliminary measurements on a one-third scale model house situated in the natural wind. Loads on the central section of the gable roof building with a 14° roof pitch were measured using a series of 'floating' panels supported on strain -gauged elements. This technique has advantages in that the building can be orientated easily in any required direction in relation to the wind, and surrounding non-instrumented buildings can be placed in a variety of arrangements. However, there are some problems in interpreting the results in relation to full scale buildings.

Another field measurement facility is described by Kavanagh (1979). Roof and wall 'subsystems' of known dynamic characteristics were mounted independently in a low rise structure of 20° roof pitch. The deflection responses of the subsystems can be used to derive the resultant forces on roof and walls.

Point pressure measurements at 12 locations on the roof of a flat roof test building were carried out by Handa (1980). Amplitude probability densities and spectra and cross-spectra for pairs of fluctuating pressures were measured. However, because there were no separate internal pressure measurements, no direct measurement of mean external pressures could be made.

Full scale measurements of wall pressures on a small experimental building for comparison with wind tunnel data were made by the Virginia Polytechnic Institute and State University (Tieleman *et al*. 1980). Generally, larger pressure coefficients were found in the full scale measurements. This was explained partly by the lack of stationarity in the full scale records, but the turbulence scales were apparently somewhat smaller than optimum in the wind tunnel tests.

4.3 Other Wind Tunnel Studies

Following Cyclone Tracy in Darwin in 1974, preliminary studies of wind loads on low rise buildings were carried out by Vickery (1976) and Jancauskas and Sharp (1977). Point pressure and force measurements on roof panels, complete roofs and complete house models were made. Jancauskas and Sharp also measured internal pressures. Many of these measurements were repeated in more detail in the JCU studies described in Section 3.2. With a few exceptions, general agreement was found.

Wind tunnel measurements on flat-roof building models at UWO and JCU, were described by Stathopoulos *et al*. (1981), Stathopoulos (1981b) and by Holmes and Rains (1981). In the latter case, measurements on a curved-roof model were also made. In both studies, measurements of loads on various roof panels were made. In the JCU study, correlation coefficients were obtained between panel loads enabling rms and peak loads on roof sections of various areas to be computed. The effect of increasing tributary area on reducing the fluctuating loads was shown clearly.

Wind tunnel studies of various aspects of wind loads on low rise buildings are discussed by Kramer *et al.* (1980). As part of this work, a comparison is made of pressures on one of the models tested in the UWO study, described in Section 3.1; equivalent measurements on the same model tested in the UWO tunnel and in the Aachen wind tunnel, in which artificial growth methods of atmospheric boundary layer simulation are used, showed fairly good agreement.

Finally, a study which is of relevance to the wind loading of grouped low rise buildings is that of Hussain and Lee (1980). Drag and lift forces on rectangular blocks set in arrays of various sizes were measured.

5. ASSESSMENT OF THE AUSTRALIAN STANDARD

5.1 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 approaches in codes or standards at best only a fair approximation to reality. However, most low rise buildings in Australia are designed by direct application of the Australian Standard AS 1170 Part 2 (Standards Association of Australia 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 loading acting on the surface of a building in a wind code format is:

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

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 Part 2, the general formula is not (3), but the following:

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

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

Implicit in the use of equation (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 to 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 linearized relationships between fluctuating velocity and pressures.

For structural loading, AS 1170 Part 2 uses values for the pressure coefficient C_p that 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 values 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.

5.2 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 accepted recently for those sections of the AS 1170 Part 2 relating to low rise buildings.

A review of the available data on mean pressure coefficients for low-rise gable roof buildings has produced the proposed pressure coefficients for Appendix B of AS 1170 Part 2 shown in Table 1. Except for large h/d ratios, there is a reduction in the roof suctions from the values in the 1981 edition of AS 1170 Part 2. When the mean roof pressure is near zero, there is an allowance for the changing sign of the pressures as a result of turbulence. However, it should be noted that the important variation of pressure coefficients with h/d ratio, as well as roof pitch has been retained (unlike the recently published Canadian Code, National Research Council of Canada 1980.)

Table 5.3 in AS 1170 Part 2 is a table of reduction factors for roof loads, which are essentially correction factors to the implied gust factor in AS 1170 Part 2 as described in Section 5.1 of this paper. After an examination of relevant wind tunnel data from James Cook University and the University of Western Ontario, the revised table shown in Table 2 of this report has been proposed and accepted.

The values in this table 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 amendments, the local pressure factor used depends not on the **location** of the area under consideration, but on its **size**. Two different sizes using appropriate local pressure factors (either 1.5 or 2.0) are specified.

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 variablity 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 *et al.* 1980). Using such approaches, the effect on the predicted wind loads is greatest for cladding loadings where the coefficients of variation are largest.

Another consideration 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 1981a). A value of 0.9 has been accepted for AS 1170 Part 2 for structural loads on the basis of these studies.

6. CONCLUSIONS

This paper has attempted to provide a state of the art review of the knowledge of wind loading of low rise buildings, with some emphasis on Australian conditions. After an historical review and a brief discussion of the fluid mechanics of wind flow around low buildings, a summary of recent wind tunnel and full scale research studies has been given. Some discussion of the design approach in the Australian Standard AS1170 Part 2 has been given, and present and future developments in relation to the design of low buildings for wind loads are discussed.

From this paper, it should be apparent that much progress has been made in the last 10 years or so, in understanding the nature and mechanisms of wind loading, and in developing measurement techniques for wind tunnel and full scale studies. Probabilistic design concepts for wind loading are developing in parallel with general reliability approaches for the design of structures. Further progress can be expected in these directions in the near future.

7. ACKNOWLEDGEMENT

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TABLE 1

CHANGES TO APPENDIX B OF AS 1170 PART 2

AS 1170 Part 2, Table B2.1

External pressure coefficients (C_p) for roofs of buildings with h/d < 0.5* 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 ⩾ 0.5, for $\theta = 0°$, use Table B2.2 with $\alpha = 10°$

AS 1170 Part 2, Table B2.2

External pressure coefficients (C_p) for gable roofs of buildings for $\theta = 0°$ with $\alpha \geqslant 10°$

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:

(i) Where two values are listed, the roof shall be designed for both values.

(ii) Linear interpolation may be used to obtain intermediate values for 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

NEW REDUCTION FACTORS FOR ROOFS

Area	Reduction factor, R_A
10 m^2	1.00
25 m^2	0.90
$\geqslant$ 100 m^2	0.80

Notes:

(i) Area = load tributary area

(ii) These factors are for the calculation of loads on the major roof supporting structure and not on cladding elements

(iii) Intermediate values may be obtained by interpolation