Wind loads on low-rise buildings: a review of the state of the art

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This paper refers to the most recent research on wind loads on low-rise buildings. Novel measurement techniques and methodologies are reviewed, and selected experimental results from various studies are presented. Particular emphasis is given to works aimed at the formulation of codified data, i.e. results appropriate for incorporation into design standards and codes of practice. Only either full-scale studies or those done under conditions simulating the earth's atmospheric boundary layer have been considered. Comparisons between full-scale and laboratory results are discussed. Areas requiring additional research and analysis are identified.

Key words: wind loads, low rise buildings

Historically, wind loads on low-rise buildings have not received the attention they deserve when the relatively large investment in such structures is considered. Furthermore, much of the currently available research data were obtained from model tests before the importance of correctly simulating the atmospheric boundary layer was widely appreciated. During the past 20 years, very few projects have considered the low-rise problem using correct simulation techniques, or through direct full-scale measurements. This is discussed in references 1 and 2 which include some insight into the historical development of the field.

In fact, much of the early research into wind loading was concerned with low-rise buildings. Amongst the earliest wind tunnel tests performed were the experiments by Irminger in the 1890s on small models of gabled houses, as described by Jensen.[3] It is interesting to note that some of the early ideas have stood the test of time. As early as 1884, Baker[4] stated that the mean wind pressure on a large area must be less than that on a small area because 'threads of the currents moving at the highest velocity will strike an obstruction successively rather than simultaneously'. In his notable experiments during the early stages of the design of the Forth Bridge Baker[4,5] corroborated the expectation finding that the pressures on a wind-gauge board 300 ft^2 in area were some 50% less than those on a board 1.5 ft^2 in area. In 1924 Stanton[6] invented a wind pressure recorder to use for averaging pressures measured at different points for large areas.

Between the wars, several countries undertook systematic studies of the aerodynamic pressure coefficients on building shapes in wind tunnels. Some of these studies were extremely thorough such as those in Russia by Bounkin and Tcheremoukhin[7] who carried out systematic experiments on the magnitude and distribution of wind loads on various types of houses and established stability criteria. In Denmark, Irminger and Nokkentved[8,9] extensively studied the wind pressure distribution on models of buildings of various shapes and sizes, and the development of flow around them. They realized the importance of internal pressures and attempted systematic measurements for different building porosities for the first time. The results of Ackeret's studies[10] are given in the Swiss Normen[11] and were included in the 1965 edition of the Canadian National Building Code.[12]

However, the problem of wind loads on low-rise buildings was highlighted by a few full-scale measurements. Bailey[13] was the first to carry out a full-scale experiment on a railway car shed to determine wind pressures on buildings. Although the records were made photographically and were therefore instantaneous, the pressure tubes were long and presumably damped out much of the higher frequency fluctuations. Wind tunnel tests carried out in uniform steady flow showed lower suctions and somewhat greater pressures than those measured in full scale. Some years later, Bailey and Vincent[14] undertook a new series of wind tunnel experiments in boundary layer flow and their results agreed considerably better with the full-scale data as has been described by Davenport.[15] Similar discrepancies between full-scale and wind tunnel data measured under uniform flow conditions have been noted by Arnstein and Klemperer (in 1936) on the Akron Airship dock.[16]

Experimental work on wind loads on low-rise buildings was marred by the fact that the flow in the aeronautical type wind tunnels or hydraulic water flumes, then in use, did not adequately simulate the turbulent flow of the natural wind and its velocity variation with height.

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Although several researchers had recognized this need, the requirement was not asserted definitively until Jensen[17] proposed the 'model law for phenomena in natural wind' in 1958. To achieve similarity, Jensen suggested that scaling of the 'roughness length' (z_0) of the ground surface in the wind tunnel should be the same as that for the model itself. He therefore roughened the floor of the wind tunnel by using a surface of suitably rough texture; corrugated cardboard, sandpaper, wood slats; depending on the full-scale surface being considered. The series of full-scale and model experiments, which he undertook to demonstrate the effect of this scaling, showed that the uniform flow case produces radically different pressure distributions from full-scale experiments but that the latter are in agreement with the model tests for the equivalent H/z_0 ratio.

This paper aims to review the most recent activities in the research of wind loads on low-rise buildings. Problems of experimental measurements and techniques applied will be examined. When available, results appropriately formulated for incorporation in standards and codes of practice will be presented. Comparisons with full-scale measurements, which provide 'benchmark data' for validation of wind tunnel tests will be discussed. Finally, areas of required additional research and analysis will be indicated.

Experimental methodologies

Wind loads on low-rise buildings can be determined from full-scale tests or by modelling of pressures, both external and internal, in a wind tunnel. Aeroelastic modelling is not required since low-rise buildings have high natural frequencies and are not expected to vibrate under wind action. In several aspects, however, the determination of wind loads on low-rise buildings is more difficult than in the case of tall buildings. This is due to the variety of geometrical configurations of these buildings and their surroundings and to the increased turbulence and wind speed gradient to which they are exposed because of their low height. Consequently, the wind loading appears highly fluctuating and the dynamic effects imposed have to be carefully evaluated.

One of the first problems encountered in wind tunnel testing of low-rise buildings is the determination of geometrical scale. The problem arises because the 'ideal scale', i.e. the scale at which the wind structure in the wind tunnel can be matched most closely to full scale, ranges between 1/200 and 1/2000 in contemporary wind tunnels (using naturally grown boundary layers)[18] and naturally this results in building models of nearly matchbox size! This, in turn, creates instrumentation problems and makes it impossible to model the architectural details such as eaves, parapets, etc. which play an important role in the wind loading function. Two different methodologies have been applied to the solution of the question of scale.

The first methodology[19–21] attempts the simulation of only the lower region of the atmospheric surface layer and employs larger model scales, 1:50 to 1:100 say. By comparing full-scale and wind tunnel results, reference 21 tentatively concludes that close simulation of the turbulence intensity and development of a turbulence integral scale at least as large as the largest model dimension are required for proper simulation of the fluctuating wind pressures.

The second methodology[22] is based on Jensen's experiments[17,23] on similarity parameters for the wind tunnel determination of mean pressures on models of houses. Jensen found that a factor of 2 or 3 in the determination of model height leads, under the worst possible conditions, to a maximum error of 10% in the pressure measurements. Jensen's work has been very extensive but results are restricted to scaling effects on mean pressure coefficients only. The procedure described in reference 22 was to test similar models of low-rise buildings at different geometrical scales with the same terrain surface roughness length. The smallest scale employed comes closest to matching the wind characteristics of the wind tunnel with the full-scale conditions. Results are consistent with Jensen's findings indicating that a factor of 2 in the geometrical scale leads to small and rather conservative discrepancies for both mean and fluctuating pressure components. In contrast, larger factors (e.g. 5) in the geometrical scale appear to introduce new phenomena near the edges of buildings which are unrepresentative of the smallest correct scale case. Nevertheless, more work is required for the understanding of the relaxation of scaling parameters.

Local pressures are measured in models of low-rise buildings in the same way as in models of tall buildings. Short duration peak loads acting over the tributary area of interest are generally required for design. For loads over larger areas (as opposed to pressures at local points), a simple economical method has been developed.[24] The technique consists of pneumatically averaging the pressures from a number of taps connected in a carefully controlled fashion through a multi-input manifold to a pressure transducer. The transducer then reads the instantaneous spatially-averaged pressure acting on the area associated with the pressure tap locations. This method yields very good results as has been found through comparisons with results obtained by large flush diaphragm transducers.[25]

A limitation in the measurement of area loads is the finite grid effect which arises through the inherent assumption that the pressure measured at a point applies over the entire tributary area of that point ($1/N$ of the area in an N point symmetric grid). In fact this assumption breaks down for the highest frequency components of the load. Thus, although the reduction in overall load on an area due to the difference in correlation or phase from one point to the next is correctly estimated, the contribution of the highest frequency pressures which, in fact, are not even correlated over the area associated with a single grid point is overestimated. This effect has been examined in detail[25] and has been found to be very small and conservative for typical low-rise building geometries.

A different technique for area load measurements has been used by Marshall[26] in his full-scale measurements of wind loads on low-rise buildings. Individual pressure transducers are used for each pressure tap located in the area of interest and their outputs are summed electronically after they have been multiplied by appropriate weighting factors to account for the various sizes of the tributary area each tap represents. For irregular transducer spacing, the choice of these weighting factors is somewhat subjective, but in any case it is implied that all pressure fluctuations sensed at a point by a transducer act with equal intensity over the entire surface area assigned to the transducer. The main disadvantage of this methodology is the high cost of instrumentation because of the large number of pressure transducers required for accurate evaluation of wind loading.

A similar method has been used in another full-scale experiment for the measurement of instantaneous wind load acting on a flat square roof.[27] Four load cells (instead of pressure transducers) have been placed at the corners of the roof and their output signals are instantaneously averaged through a summing junction box. The average load is amplified and recorded on a magnetic tape.

More recently, another procedure has been used in combination with the pneumatic averaging technique to increase its potential and make possible the measurement of other structural loading components, such as bending moments, shear forces, etc. This is the computer weighting technique[28] (see *Figure 1*). The model design is such that the entire bay load is approximated by eight 'purlin loads' on the roof and two 'wall loads'. The required combination of these loads depends on the end purpose. Any combination can be written in the form:

$$B_i = \sum_{j=1}^{10} Y_{ij} P_j$$

where P_j are purlin and wall loads for a bay and Y_{ij} are influence factors required to provide the generalized bay load of interest B_i. For example one set of $Y_{ij}, j = 1$ to 10, would give total uplift force; another total bay shear; another bending moment in the frame at the knee, etc. A specialized computer program may perform this summation 'on-line'. This technique (with minor differences) has also been used for measurements of generalized load coefficients in models appropriate to simulate both external and internal pressures.[29] A simplified pressure tap array for purlin and wall loads was used and the differences of the external and internal pressures, derived by using both sides of the transducers with appropriate calibration, were sampled by the digital computer and multiplied by the influence factors to provide the total bay load coefficients B_i as before.

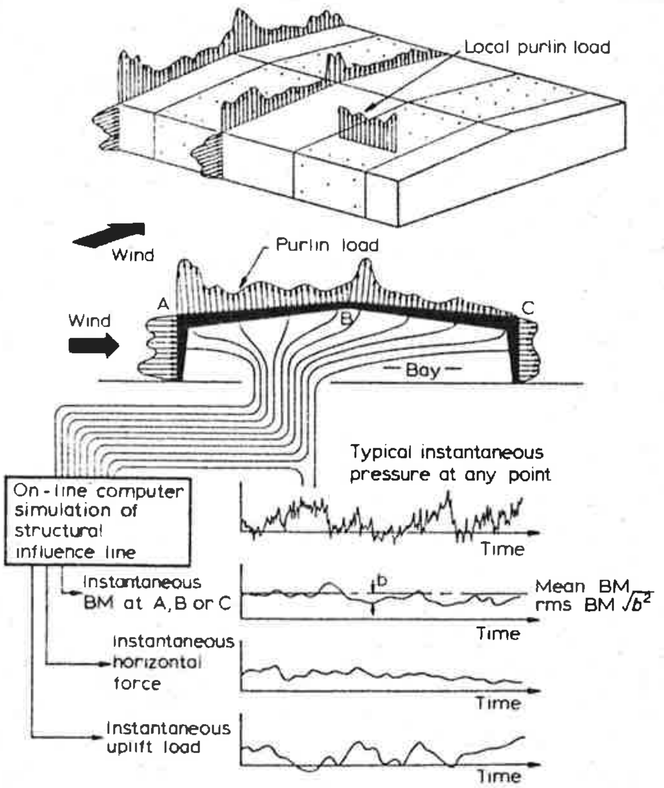

Figure 1 **Measurement of unsteady wind loads on a low-rise structure**

The duration of the peak load action is a significant factor affecting structural behaviour. For example, the collapse load for steel frames increases substantially if the time of application of the load decreases.[30] However, the assessment of the magnitude of the highest wind gusts whose action lasts for a small fraction of a second is difficult because of experimental limitations. In fact, pressure measurement systems used in most wind tunnels suitable for building aerodynamics testing respond to pressure fluctuations on the model of the order of 100 Hz or more with negligible attenuation or distortion. For typical length and velocity scales, this corresponds to averaging times of roughly a second full scale. This appears to be a reasonable averaging time for most design purposes. Peak pressure coefficients based on shorter durations are higher than those based on one-second intervals. This was shown, for example, by measurements of peak pressures based on 1/32 s duration of gust in a full-scale experiment of wind loads on low-rise buildings.[31] Considering that the magnitude of the collapse load depends also on the properties of the materials, the structural systems and the construction techniques used, further research is required to evaluate the possible need for measuring peak loads averaged over intervals shorter than a second and to develop suitable laboratory techniques for measuring such loads. More experimental methodologies and procedures can be found in reference 32.

Experimental results and discussion

Aerodynamic loads applied on the roof and the walls of a low building are determined by the interaction of wind flow with the surface of the building. This interaction depends primarily on the geometry of the building and the flow characteristics. Deflection and acceleration of the wind over the roof and along the side walls of a building produces negative pressures, i.e. suctions on the roofing system and all but the windward wall. It is well known that the wind flow passing over a building can be divided into an outer region where there is no essential influence from the viscosity and a wake region characterized by the energy dissipation which takes place due to the action of viscosity. Although the flow is turbulent, the time average flow is irrotational upstream and far downstream but strong vorticity appears in the wake where the velocity and, consequently, the pressure distribution become complicated. A possible reattachment of the flow on the building surfaces, depending on the curvature of the streamlines at separation points may create a different picture with a subsidiary zone of high vorticity and suctions.

The modification of the general wind flow determined by a large-scale pressure field creates a new local unsteady flow regime with the addition of small-scale turbulence. Small eddies are superimposed on larger ones with the result that wind speeds and pressures vary greatly from place to place and from moment to moment. High suctions appear along the edges of walls and the roof. With wind at 45° to the face of the building there will be a pair of strong conical vortices from the apex travelling along the concurrent edges. Very high suctions are, therefore, developed at the roof verges close to the roof corner.

Determination of wind loads requires knowledge of mean wind speed with its averaging time and probability of occurrence, terrain characteristics and design pressure coefficients. Wind pressures acting on low-rise buildings can be calculated using the code format:

$$P = \tfrac{1}{2}\rho V^2 C_e C_p$$

in which V is the wind speed, ρ is the air density, C_e is the exposure factor and C_p the appropriate pressure coefficient including gust effects (design value). Experimental data on wind loads acting on area A are usually presented in this convenient pressure or force coefficient form ($P/(\frac{1}{2}\rho V^2)$ or $F/(\frac{1}{2}\rho V^2 A)$), whereas details about the exposure (terrain roughness, etc.) are given separately. Attention is required when comparing experimental results from various studies to be certain that the reference wind speeds (V) correspond to similar heights and averaging times, or special corrections have to be made.

In the following paragraphs, recent data of wind pressure coefficients measured for low-rise buildings are reviewed and characteristic trends are discussed. Studies carried out at either full scale or in boundary layer wind tunnels which simulate the atmospheric flow have been considered. It must be clearly stated that very few studies have addressed the problem of wind loads on low-rise buildings with a variety of parameters and configurations. The majority of studies have examined the wind loads on a single building of a particular configuration. Consequently, the task of generalizing the results becomes extremely difficult.

Effect of geometrical parameters

Effect of length. It has been suggested[33] that roof pressure coefficients have little dependence on length of buildings for length-to-width (L/W) ratios between 1.2 and 2.0. This has also been found[34] for even higher L/W ratios (up to 2.4) with the addition that pressures are consistently smaller on the longer walls than on the shorter walls. *Figure 2* shows some results taken from reference 35 regarding mean pressure coefficients on block-type buildings. As is clearly indicated for low-rise buildings, i.e. for small height-to-width ratios, the length effect is insignificant for all length-to-width ratios from 1.0 to 3.0.

Effect of height. Although wind loads increase with the height of a building, it has been found[34] that the dependence of peak, mean and root-mean-square pressure coefficients on height can be reduced considerably by referencing them to the velocity pressure at eave height. The data given in *Figure 2*, however, suggest a rather consistent small increase of mean pressure coefficients for flat roof areas referenced to roof height. But the extensive data on mean pressure coefficients presented in reference 23 lend to support the hypothesis of weak dependence of pressure coefficients on height.

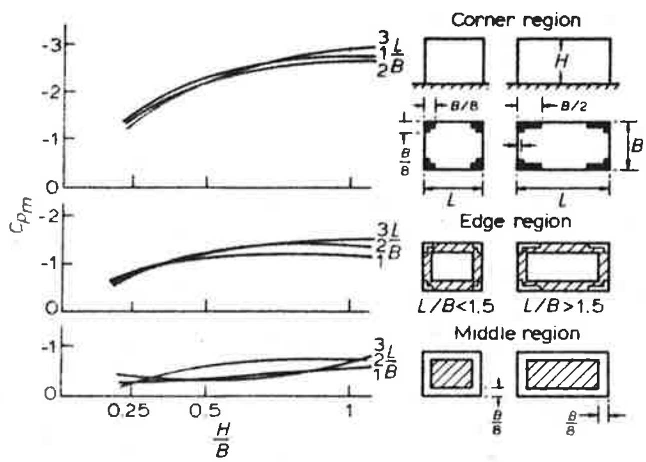

Figure 2 Mean pressure coefficients for various regions of rectangular buildings (after reference 34)

Effect of roof slope. All studies of wind loads on low-rise buildings agree that roof slope is a very significant parameter for both magnitude and distribution of wind loads. This is certainly expected since the roof slope is the major factor determining the wind flow pattern above a roof. Reference 36 has examined mean and root-mean-square values of pressure coefficients acting on low buildings of three different roof angles (0°, 22.5° and 45°) and has concluded that the high suctions appearing at the edges and corners of flat roofs decrease for the 22.5° roof and disappear on the 45° roof. Regarding the windward wall pressures, they have been found to be independent of roof slope.

Vickery[37] examined four low-rise buildings with roof angles of 0°, 6°, 12° and 22°. He found that for the 0° and 6° cases the pressure distribution is essentially continuous across the ridge; at 12° there is a marked change at the ridge and the pressure coefficient immediately behind the ridge is similar to that at the leading edge but falls away rapidly towards the trailing edge; and at 22°, the leeward pressure coefficient is roughly constant. The observed distributions have been explained by Vickery with reference to the sketches of the shear layers shown in *Figure 3*. At very low roof slopes, the flow separates at the leading edge and then reattaches and remains attached over the ridge and through to the trailing edge. At intermediate roof slopes, the flow reattaches on the windward slope but separates again at the ridge before reattaching on the leeward slope. At steep slopes, the flow does not reattach after separation at the ridge and the leeward slope is in a region of constant pressure. Vickery also suggested that for higher structures, the flow would not reattach.

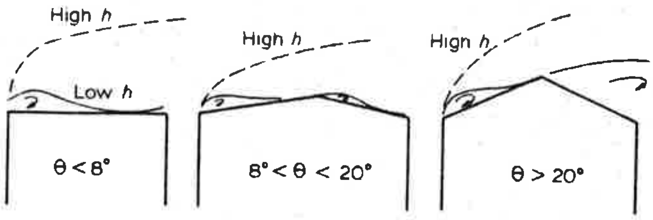

Figure 3 Wind flow patterns over roofs (after reference 36)

Stathopoulos has reached similar conclusions by examining flat roofs[25] and three different roof slopes, 1:12, 4:12 and 12:12.[34] In particular, it was found that the 4:12 roof is subjected to significantly higher mean and peak suction coefficients for edge and ridge regions than the other roof slopes. It has also been pointed out that several standards fail to specify high suction loads for ridge regions of intermediate roof slopes. Edge corners of the 12:12 roof were found under large peak suctions and root-mean-square pressure coefficients were significantly higher for steeper roofs. More data on the effect of roof slope are included in references 38 and 39.

Effect of wind direction

The drastic effect of wind azimuth on the magnitude and distribution of wind pressures has been shown in almost all studies of wind effects on low-rise buildings.[2,23,25,27,31,33,34,40–45] *Figure 4*, taken from reference 45, shows a typical variation of maximum, minimum, mean and root-mean-square pressure coefficient (referenced to eave height) for a roof pressure tap. Considering that wind loading varies so much for each point of the building envelope for the various azimuths, the fact that generally no detailed analysis of the wind climate is carried out for the selected location of a low-rise building and also that the designers of most prefabricated low buildings do not know in advance the actual building orientation on site, it has been suggested[34] that the worst loads that would occur, regardless of wind direction, should be considered for design. However, such design would obviously involve considerable conservatism.

In order to reduce the above-mentioned conservatism and establish design pressure coefficients on a realistic basis, some detailed probabilistic analysis must be carried out. A preliminary step towards this direction has been taken[46] and it was suggested that the designated coefficient for design could be established at 80% of the maximum measured value. The adoption of this percentage was not the result of any exact calculation but was based on several considerations which collectively suggest a weighting factor of at least this order. In any case, this adoption is still arguable and may be considered as tentative awaiting some detailed reliability analysis.

An alternate approach based on a fully-probabilistic design method has been suggested.[47] The method consists of the integration of value distribution of loading coefficients obtained in wind tunnels or full scale for various wind directions. This approach cannot apply, however, if the extreme-value analysis of directional wind data is not available.

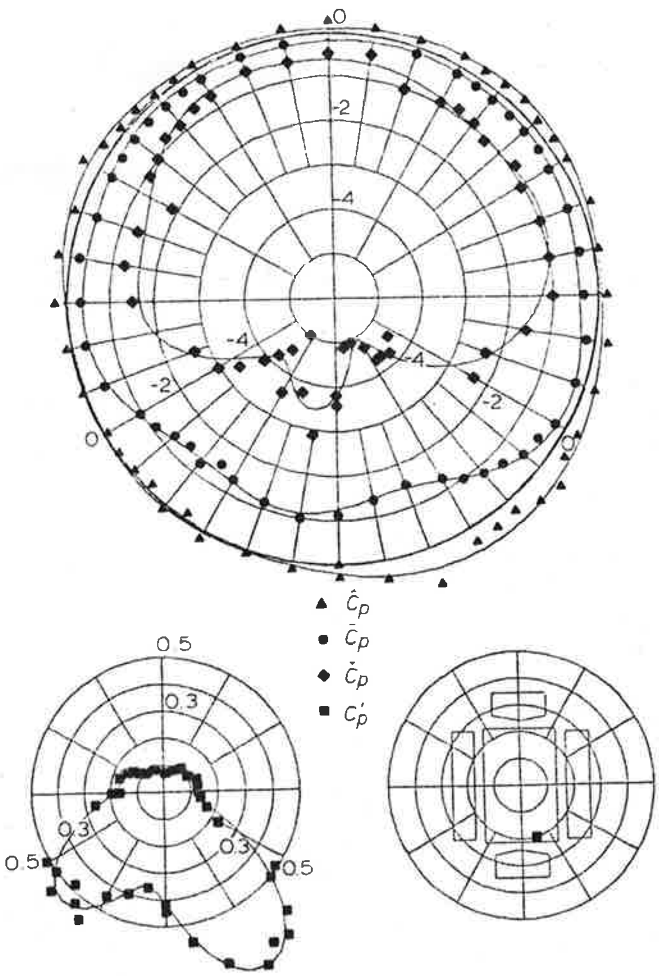

Figure 4 Azimuthal variation of extreme, mean and rms pressure coefficients (after reference 45)

Effect of terrain roughness

It is well known that wind pressures on buildings are affected by ground roughness, but this effect is felt much more on low-rise buildings, which are almost invariably immersed in the surrounding objects and the high turbulence. Rougher terrain generally alters the breakdown of the loading towards more dynamic and less static loading. Also, the rougher the terrain, the larger the magnitude of the pressure coefficients. This is particularly true of peak coefficients, reflecting the increased gustiness over the rougher terrain which is not accounted for by the mean eave height reference speeds. Some standards and building codes of practice utilize a gust speed related to terrain roughness to calculate gust loads in order to compensate for this effect. *Figure 5* shows the terrain roughness effect on mean pressure coefficients measured on the roof and the walls of a model of a low-rise building.

It should be noted that, although the peak pressure coefficients measured for rougher terrain are generally larger, this does not necessarily imply that the peak wind loads themselves are larger than those for the smoother terrain. This is so, because the velocity pressure at eave height is smaller over a rough terrain than over a smooth terrain for the same storm (same gradient wind speed) conditions. This alleviation is not currently recognized in most standards and codes of practice for the design of low-rise buildings. Nevertheless, the peak loads are generally less in built-up exposures.

Effect of tributary area: area loads

The influence of tributary area on the determination of pressure loads has been found to be very significant. The first experiments to quantify this effect for peak wind loads acting on low-rise buildings were reported in the 1970s. Reference 25 reports a significant alleviation of the total peak pressure load acting on flat roof areas in comparison with the average of instantaneous extreme pressures acting on a number of points inside those areas. Kim and Mehta[27] verified the findings of reference 25 through a full-scale experiment. In Australia, Vickery[37] also reported that his experimental investigations of wind-induced loads on a hangar roof confirmed the significant overestimation of area loads if derived by a combination of independent extreme component loads without considering the non-simultaneity of their occurrence. Marshall[26] carried out full-scale measurements of wind loads on a mobile home and found reductions of peak pressure fluctuations occurring in various areas as indicated in *Table 1*. These reductions have been determined by comparing results of multiple-point analysis (providing true area pressures) with average values based on single-point results. It is obvious from *Table 1* that the reductions of peak pressures depend not only on the size of the tributary areas but also on their location.

A detailed experimental study of the tributary area effect in the wind loading of low-rise buildings[34] concludes that the very high instantaneous suctions encountered locally on roof surfaces, particularly near eaves and corners, are reduced considerably if a tributary area

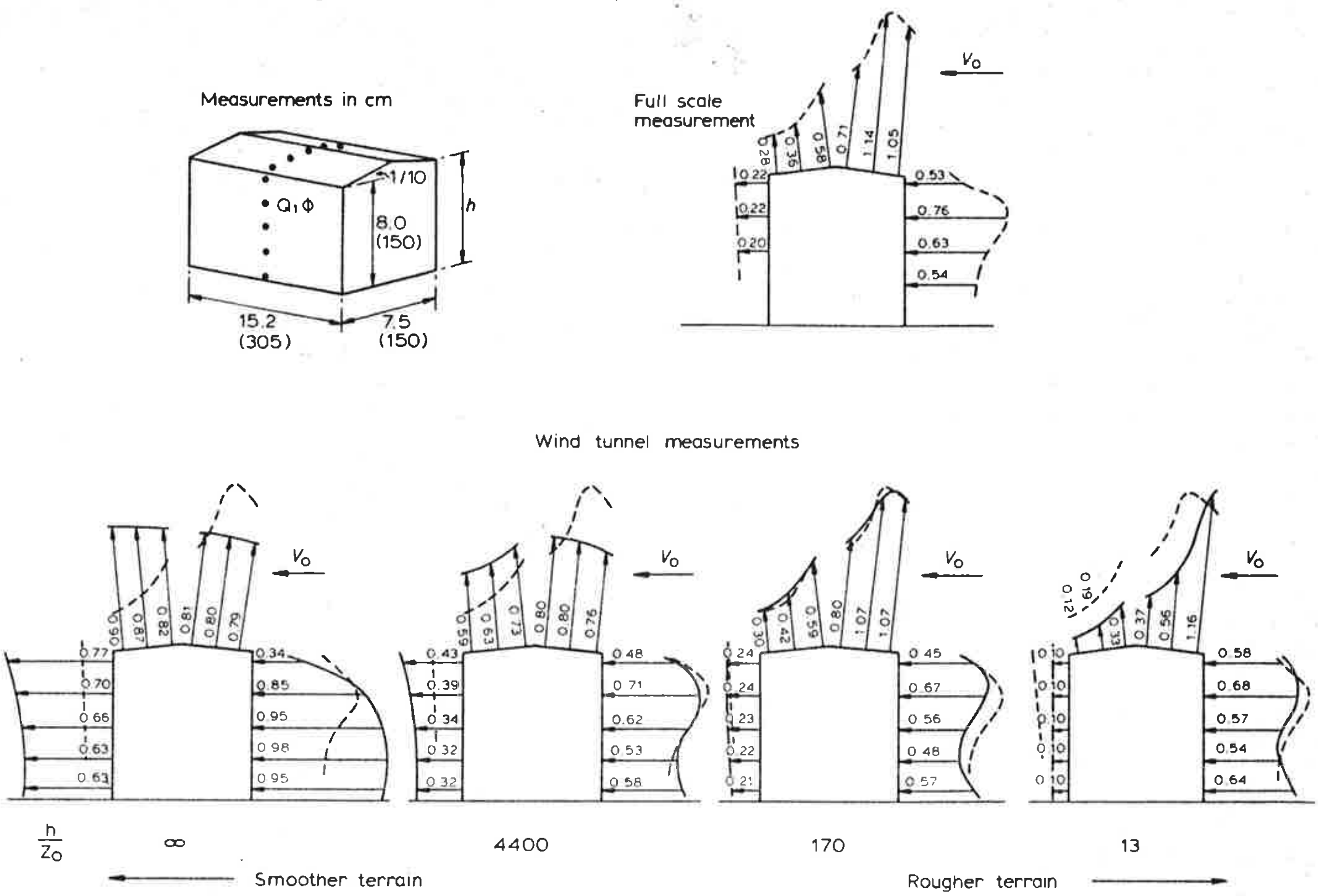

Figure 5 Comparison of full-scale and wind tunnel measurements of wind pressure (after reference 17)

Table 1 Reduction of peak pressures for various tributary areas

Building surface	Area (ft²)	Peak pressure fluctuations (% reduction)
Windward wall	10	16
	13	3
	24	5
	30	18
	50	9
	120	44
End wall	5	–*
	11	7
	16	32
	19	12
Roof	16	22
	16	33
	16	34
	20	–*
	20	10
	30	–*
	30	3
	30	9
	30	11
	30	14
	40	23
	50	–*
	50	24
	60	–*

* Value not obtained because range of recorder was exceeded

representative of a roof or wall panel is considered. A typical example of this effect is shown in *Figure 6*, for roof corners of 1 : 12 roof-sloped buildings for which most codes and standards suggest very high suctions. Six different diagrams correspond to three different building heights and two different corner sizes. Each diagram shows several measures of the load. Instantaneous peak suction coefficients are plotted against wind direction for the four individual pressure taps indicated, i.e. 100, 179, 180 and 181 for the smaller corner ($0.1w \times 0.1w$, where $w = 80$ ft is the width of the building) and 93, 94, 100 and 101 for the large corner ($0.25w \times 0.25w$). The true spatially-averaged suction coefficient is also given together with the arithmetic mean of the non-simultaneously registered peaks. The reduction from the loads indicated by the individual peaks is most significant for the smaller roof corner and for the most critical wind directions. It has also been found that for steeper roofs, the area load reduction becomes more significant at the ridge corner rather than at the verge roof corner. Data shown in *Figure 7* for two terrain roughnesses also clearly indicate the reduction of peak load coefficients for areas of constant size at different roof locations. The closer to the roof edge the area is, the more the alleviation effect appears, at least for the critical wind directions examined. Tributary areas of various structural elements in different locations and configurations have also been considered and effective peak values of several generalized loads have been determined. All integrated loads (vertical uplift forces, horizontal thrusts and bending moments) acting on the building structural frames show appreciable effects of spatial averaging of the dynamic forces.

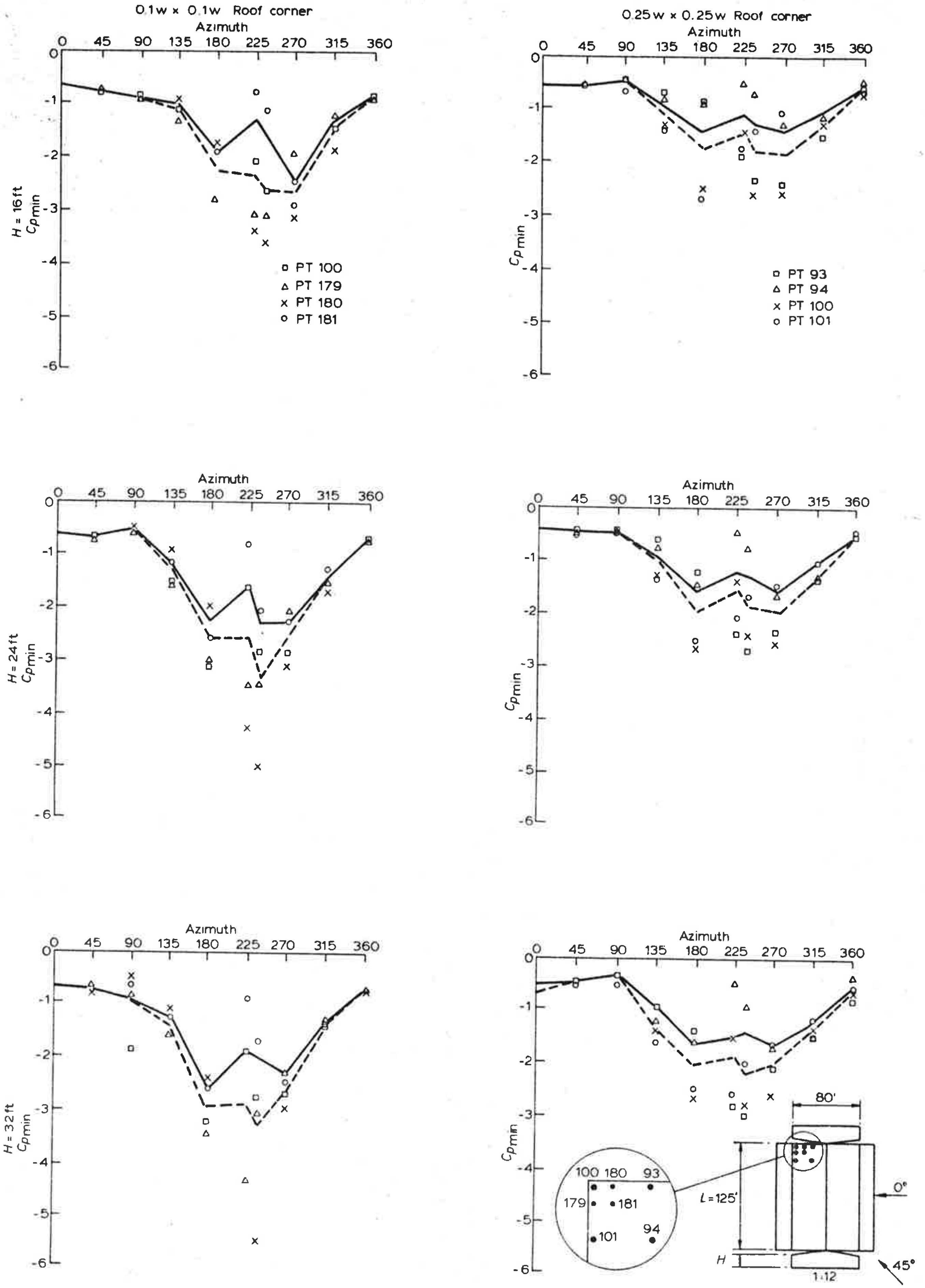

Figure 6 Peak suction coefficients on roof corners of different size using instantaneous (——) and noninstantaneous (– – –) spatial averaging

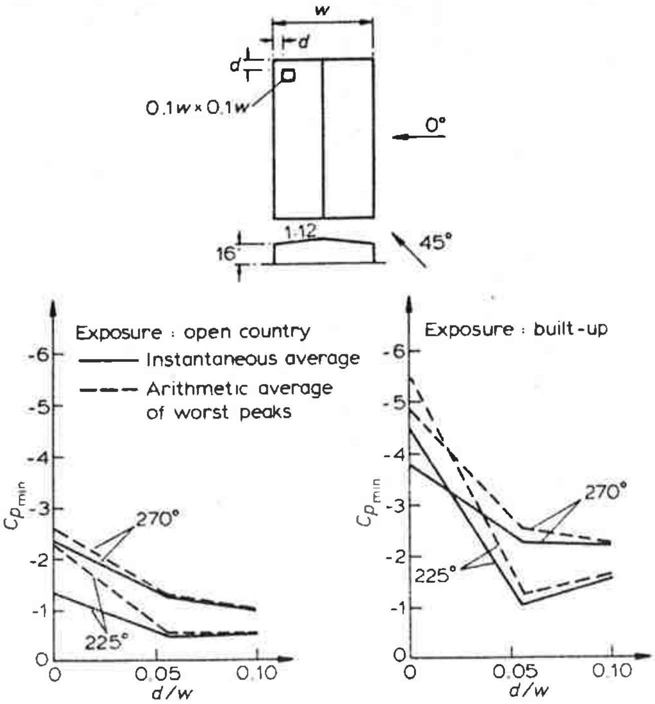

Figure 7 Peak suction coefficients on roof square areas of constant size

Effect of architectural features

Mullions, eaves (overhangs-canopies), parapets, balconies and different edge profiles are representative types of architectural features which affect the wind flow in the building proximity and may generally modify the wind pressure coefficients for low-rise buildings. From the following, it will become apparent that a limited amount of information is available with respect to the influence of architectural features and that much research work is still required on the subject.

Mullions: There is no information available about the effect of mullions on low-rise buildings. Two studies[48,49] deal with the effect of mullions on tall buildings. Despite the scaling difficulties encountered, it has been found that the mullion effects depend greatly on the overall building geometry. In general, mean and fluctuating pressures decrease in the presence of mullions, whereas some increase has been noticed on building sides where reattachment occurs.

Eaves (overhangs-canopies): In the assessment of wind loads on roofs, the effect of eaves is sometimes overlooked. However, windward eaves are severely loaded, since the deflected flow from the windward wall gives rise to a pressure on the lower eave surface, which reinforces the high suction of the upper eave surface immediately after separation. Only a limited amount of information is available on the subject.

Reference 40 examined local pressures on upper and lower eave surfaces and has concluded that pressures underneath the overhangs can account for 50% of the total wind load acting on the overhangs. Reference 33 reports that the presence or absence of eaves does not influence the magnitude of the pressures a great deal, whereas reference 45 recognizes that combining negative peak values on the top with the positive peak values under the eave is somewhat conservative since peak values do not occur together. Reference 50, however, deals with this effect through experiments on 1:12 roof-sloped models with two different eave widths exposed to two terrain roughnesses. *Figure 8* shows some characteristic results of the latter study regarding peak uplift coefficients acting on eave corners. It is interesting to note that the maximum total uplift coefficients are slightly higher (and for some azimuths even lower) than the suction coefficients loading the upper eave surface. This is attributed to the low positive pressure acting underneath the 10 ft eave due to the building corner together with a favourable correlation of loads acting on the two eave surfaces. These results show the amount of conservatism involved when the upper bound load coefficient, which is derived by simple subtraction of the data for the worst cases measured independently for upper and lower surfaces, is considered.

Table 2 compares the extreme local pressure coefficients reported from measurements on upper and lower eave surfaces. Despite the fact that there were geometrical and minor terrain roughness differences between these studies, data show a fair agreement; the higher values of reference 45 may be attributed to the higher 'eave width over building width' ratio. Nevertheless, more data are required to increase confidence in the reported values.

Parapets: The effect of parapets on the magnitude and distribution of pressure coefficients on low-rise buildings has been a controversial subject. Reference 51 concludes that, for flat roofs, parapets do not have any effect on the mean roof loading. This is in contrast to previous results from studies carried out in uniform flow conditions. Davenport and Surry[2] have tested the effect of parapets (parapet height/roof height = 0.083) on mean and peak

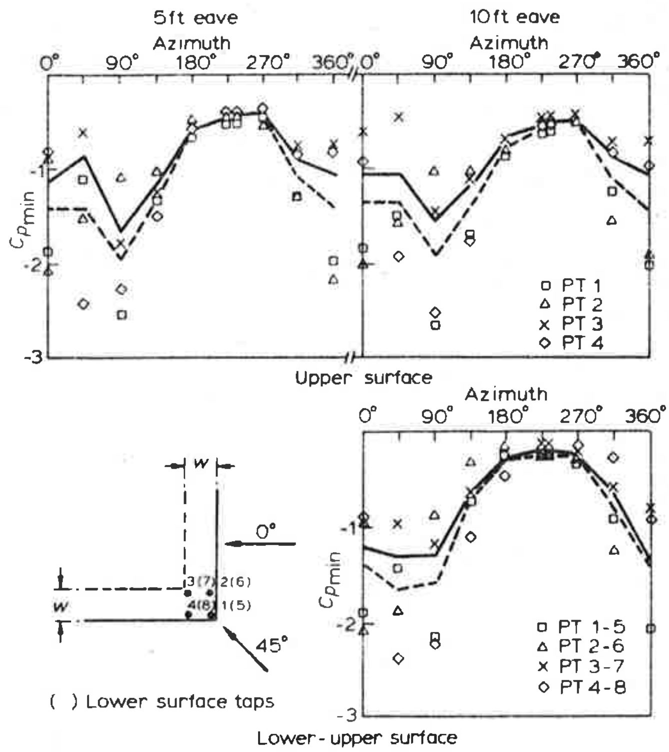

Figure 8 Peak suction coefficients on eave corner areas using instantaneous (——) and noninstantaneous (– – –) spatial averaging — 1:12 roof slope, 16 ft high building, perimeter eaves, open country exposure

Table 2 Extreme local pressure coefficients for upper and lower eave surfaces

Roof angle (°)	Eave width / building width	Extreme pressure coefficients: Upper surface	Extreme pressure coefficients: Lower surface	Ref. number
13	0.11	−3.50	+1.60	40
10	0.17	−5.04	+2.82	45
5	0.06	−3.01	+2.07	50
5	0.12	−3.25	+1.62	50

pressures acting on flat roofs. Their data show that, in the presence of parapets, local mean suction loads acting on roofs become worse, particularly for oblique wind directions. The general level of peaks, however, was not substantially changed. When castellated parapets were used, both mean and peak local loads were also increased, but not by so much.

Higher parapets (parapet height/eave height = 0.125-0.250) have also been tested,[52] and although the results agree generally with the previous studies, some recent analysis of the data has revealed some reduction of the local highest roof suctions. Mean roof suctions are somewhat lower with the exception of the roof corners for which the parapets induce very high mean suctions and strong correlation of the local loads. This is also supported by the experimental results of the study described in reference 53. There has been no study, to the author's knowledge, regarding wind loading on parapets themselves.

Balconies: Figure 9, taken from reference 35, shows the effect of balconies on roof mean pressure coefficients measured under open country conditions. For square buildings roof pressure coefficients increase with the number of balconies, particularly in the corner regions. The opposite trend appears for rectangular buildings. Results are presented for 45° wind direction only and the geometrical characteristics of the balconies are fixed. Additional work appears necessary in this area.

Different edge profiles: Reference 54 has been unique in describing an experimental study of wind pressure distribution on flat roofs with different edge profiles. Both mean and peak pressures have been found to be lower when the edge of a flat roof is rounded in elevation. This occurs for all wind directions and is more pronounced for greater rounding. Results, however, may be Reynolds number dependent. Unfortunately, no other research investigations are available on the topic.

Effect of large nearby structures

It is pertinent to determine how the pressure load distribution on a building may change when a new structure (or structures) is built in its neighbourhood. Obviously this is a complex problem, even for a single additional building, since there are a large number of wind loading interaction parameters, including the size of the two buildings, their relative positions and the wind direction. A literature review indicates that little information is available on this critical subject. In fact, the bulk of information used for code formulation of the wind loads on buildings is based on model tests of free-standing structures.

There are various reasons which appear to justify the adoption of this simple testing procedure for routine

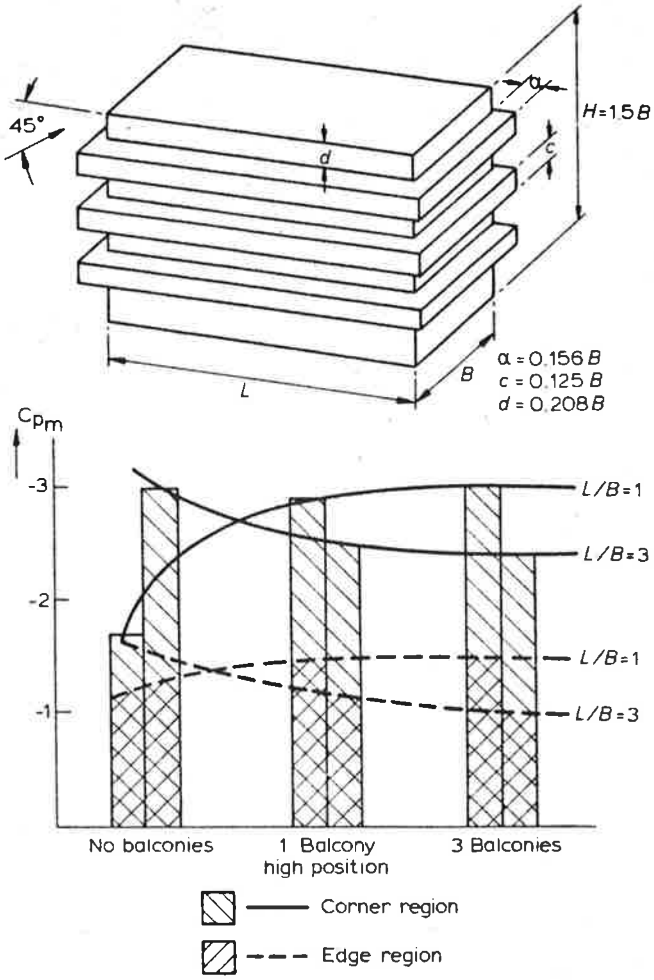

Figure 9 Mean pressure coefficients on flat roofs — effect of balconies (after reference 35)

investigations. First, it is not possible to anticipate all the environmental conditions to which a particular structure type may eventually be subjected and second, according to a widely held notion, the wind loading of a building is expected to be generally less severe if it is surrounded by other structures than when it is free-standing.

It is this last reason which becomes arguable, since several studies in both uniform and simulated atmospheric flows have shown quite adverse effects. Peterka and Cermak[55] studied the effect of four octagonal nearby structures on the pressures on the circumference of a central circular structure. They found that adverse effects can be encountered depending on the relative placement of structures in the approaching wind. These effects may be decreased by introducing variations in building geometries. A more systematic study has been reported by Zambrano *et al.*[56] on wind load interaction on an adjacent building. A series of tests were made to determine pressures on a principal building by varying the height of an obstructing building, the distance between buildings and the wind direction. Adverse effects, found in a few cases, were small.

This building interaction effect has also been studied for wind loads on low-rise buildings. Vickery[37] measured pressures on a low-rise building model while placing it in various positions among other buildings of the same height. He found that, in all cases, the effect of other buildings in the neighbourhood was sheltering and pressures were decreased for the building examined. Reference 57 also reports that mean drag coefficients of low-rise buildings are lower when these are part of a large group of similar buildings. Holmes and Best,[58] however, measured some adverse effects on mean pressure coefficients of grouped houses. Isyumov and Davenport[59] found that wind pressures induced on low-rise buildings located at the base of the CN Tower in Toronto were significantly influenced by the presence of the tower. Peak suctions were found to be much higher than values usually associated with low-rise buildings in an urban environment.

The above results can be explained when the boundary layer flow around high-rise buildings is considered. The pressure on the front face of a building decreases downwards due to the decreasing velocity in the boundary layer. Consequently, the pressure gradient induces a downward flow which can result in substantial velocities (and pressures) at lower levels. This has been described by Baines[60] and may result in adverse effects to nearby low-rise buildings. The clearance between high-rise and low-rise is a significant factor for these adverse effects. It appears that a clearance at least two or three times the high-rise building width is necessary to avoid critical interaction.

In a recent study[61] pressure coefficients found for an isolated low-rise building were compared with values measured under similar conditions with a single nearby structure located in various positions. The nearby structure was a 250 ft high building, 125 ft x 125 ft in plan view. Results for three different building positions presented in *Figure 10* indicate amplification factors for the peak suction coefficients measured along one edge of the low roof. The low-rise building considered is 32 ft high and has a 1:12 roof slope. As may be easily observed, a significant amplification of roof peak suction coefficients occurs in cases A and B whereas a sheltering effect is noticed in case C.

Generally, it appears that a major nearby structure may cause significant adverse effects on the loading of a low-rise building when the major structure is significantly different from its surroundings. It would be expected, however, that increasing the number of nearby structures of significant size would be less serious and would, in the limit of a built-up city, lead to net shielding effects.

The complexity of the problem indicates that, with the present state-of-the-art, it would be extremely difficult to treat this nearby building situation with any degree of generality. At present, for building code purposes, this problem could be treated by providing a warning of possible adverse situation and allowing local building officials to require the use of higher loads when circumstances warrant them.

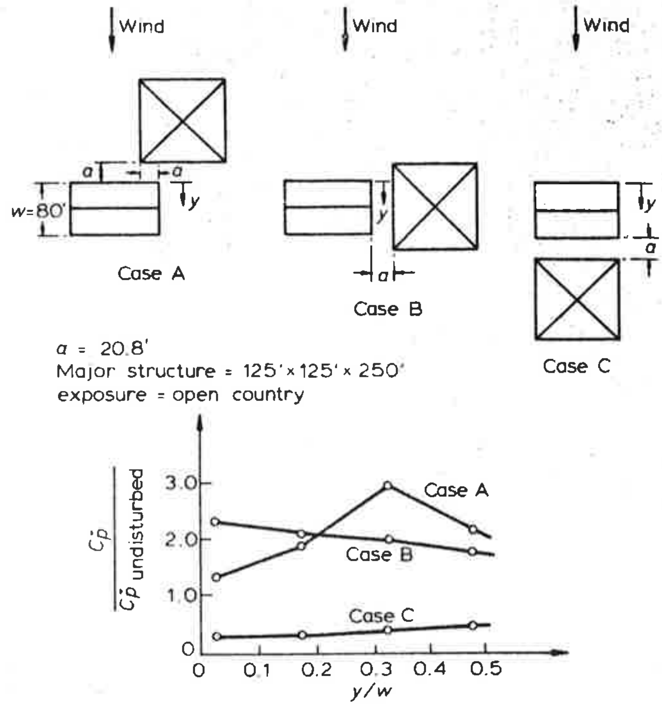

Figure 10 **Variation of peak suction coefficients for various nearby structure locations**

Effect of internal pressures

Internal pressures have traditionally received much less attention than external pressure despite the fact that, particularly for low-rise buildings, internal pressures can be a significant proportion of the total loading. For the structural designer, it is important to account for the internal pressures for all likely conditions of permeability and wall openings. Furthermore, a precise description of the net load requires the knowledge of correlation between external and internal pressures.

Two detailed experimental studies[29,62] have been reported recently on internal pressures of low-rise buildings induced by wind. Parameters examined include the building porosity and the effect of wall openings. The results of these studies are in fair agreement and can be summarized as follows:

(i) Internal pressures fluctuate significantly, but their overall magnitudes are generally less than those of the local external pressures. The overall gust factor, the ratio of the peak pressure to the mean, is roughly two in open country exposure.
(ii) The fluctuations in internal pressure show little or no spatial variation except in regions close to dominant openings.
(iii) A high correlation between external and internal pressures has been found, particularly for the component of pressure participating in the overall structural loading. Computation of peak pressure difference between external and internal local pressures by subtracting the peak values of the two measured separately only overestimates by 10 to 20%. Typical data appear in *Figure 11* for equal windward and leeward wall openings (21.6%).
(iv) The largest internal pressures occur when the wind direction is perpendicular to the wall with dominant openings.
(v) When the dominant openings are to the lee of the structure and the windward wall is closed, the internal pressures are generally negative and are not very sensitive to the size of wall openings or to the background porosity.
(vi) For windward openings, although internal pressure coefficients are generally positive, cases with high background porosity combined with small openings produce zero or slightly negative coefficients. For wall openings of significant size (more than 20% of the wall area) the internal pressure coefficients become essentially independent of the background porosity. The lower the background porosity, the smaller the necessary size of the wall opening needed to make the internal pressure coefficients insensitive to further increases of the wall opening. Typical results for extreme, mean and rms internal pressure coefficients are shown in *Figure 12* for a 1:250 scaled building, with plan

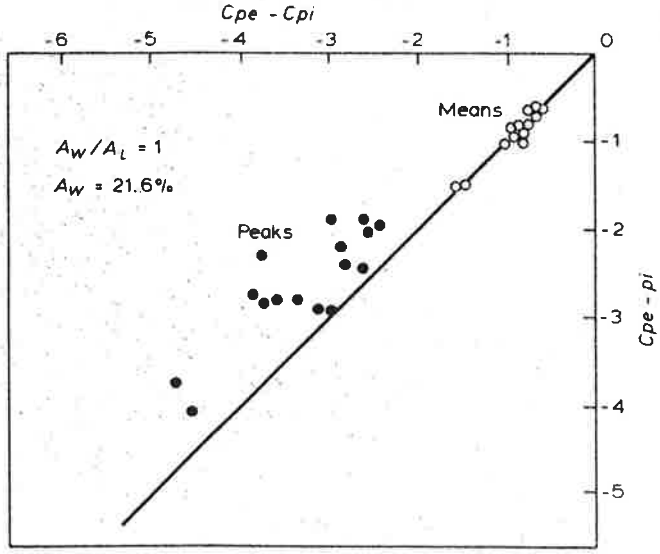

Figure 11 **Effect of correlation between external and internal peak pressure fluctuations for structural loading (after reference 62)**

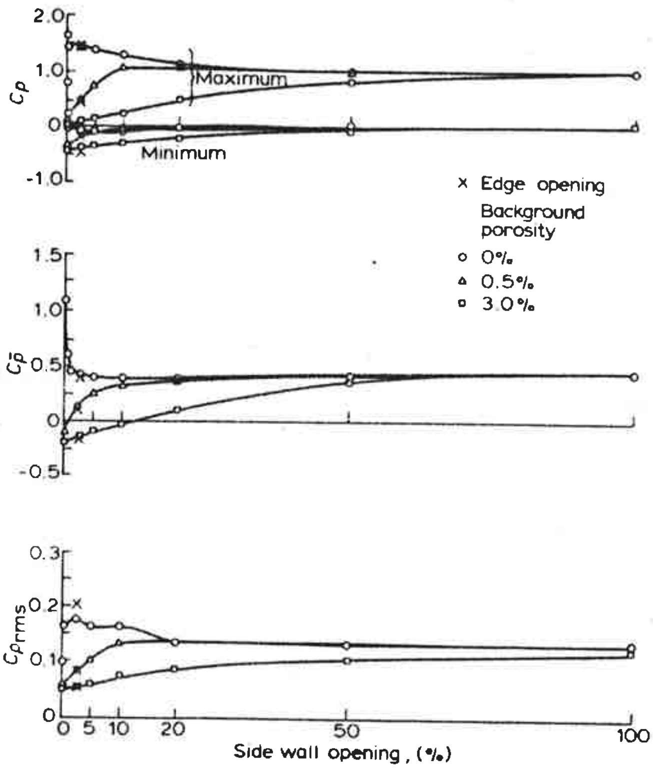

Figure 12 **Variation of internal pressure coefficients for various porosities and single wall openings**

dimensions 312.5 ft × 200 ft and an eave height of 32 ft exposed in open country terrain. The building has been assumed with no end-wall opening and the wind blows perpendicular to the wall with the openings.

(vii) Inertial effects of the air moving in and out of the building may be significant if a sudden change in external pressure, such as that due to a window failure, occurs for large openings.

The results of the above-mentioned studies show an encouraging agreement with some limited data of mean internal pressure coefficients reported in references 35 and 37. External pressure distributions appear unaffected by either the porosity or the openings on the building envelope when large flows are not permitted through the building. The latter has also been noticed by Kandola[63] and by Surry *et al.*[64] in some recent experiments.

One of the major problems encountered in the determination of internal pressures acting on low-rise buildings is associated with the building porosity ratios. First, it is very difficult to measure or even to estimate actual building permeabilities since they vary significantly even for the same type of buildings. Tamura[65] measured air leakages through six different one- or two-storey houses in Canada. From his reported results, an overall porosity up to 0.09% has been calculated, although this permeability ratio does not include leakages through doors and windows. Newberry and Eaton[66] suggest porosity ratios of the order of 0.01–0.1% or more, as for instance 0.2% for the study of Royex House[67] in England. An *ad hoc* survey among several members of the Metal Building Manufacturers Association in the USA suggested typical values of about 0.5% for metal buildings without windows.[29] For buildings with windows, it was estimated that the porosity would be as large as 1.0 to 3.0%, although these upper bounds are likely to significantly decrease with increasing awareness of energy losses. Furthermore, it is obvious that the various climatic conditions and construction techniques in different countries naturally yield a variety of building permeability ratios.

The effect of internal pressures in cavities such as those under tiled roofs has been examined recently.[68] It was reported that an impermeable backing to an air-permeable cladding reduces the wind load on the cladding. The results of the study have been codified and submitted to the British Code of Practice. Additional experimental results on this effect are presented in reference 69.

Some analytical work has also been carried out regarding internal pressures of low-rise buildings. Reference 70 develops a linear theory for the estimation of time required for the transmission of pressures inside volumes partially enclosed. Reference 71 suggests an analytical method for the calculation of mean internal pressures in low-rise buildings with porosities and wall openings of different sizes. Results compare well with the experimentally determined coefficients. Finally, some recent preliminary work has been reported[72–74] on the analytical prediction of peak internal pressure coefficients.

Comparisons between laboratory and full-scale measurements

Wind tunnel testing is the only method available to provide the mass of data required to derive simple loading models appropriate for incorporation within codes and standards for low-rise buildings. Central to the use of the wind tunnel is of course the reliability of such model testing. Comparisons of wind loads measured on tall buildings in model and full scale have generally been encouraging when the model testing was performed under conditions simulating the natural wind regime. However, correct geometrical scaling of low-rise buildings often results in various experimentation problems, as discussed previously in this paper. Relaxation of scaling and/or other modelling characteristics requires validation through full-scale measurements.

There are only a few full-scale measurements of wind loads on low-rise buildings. These studies have been carried out by the National Bureau of Standards in the USA and by the Building Research Establishment, in England. Reference 42 reports on the comparison of wind pressures measured on a single-family dwelling at Malmstrom Air Force Base, Montana, and a 1:50 scaled model of this house tested in the wind tunnel of Colorado State University.[40] Satisfactory agreement has been found between model and full-scale spectra for both velocity and pressure fluctuations. Mean and peak pressure coefficients, however, appear underestimated from the wind tunnel tests; this has been attributed to improper simulation of the variation of turbulence intensity with height.

Reference 33 reports on the comparison of wind tunnel pressure results obtained at Virginia State University for a 1:70 scale model of a test house at Quezon City, Philippines. The building has a gable roof at an angle of 10°, a height-to-width ratio of 0.43, a length-to-width ratio of 1.20 and perimetrical eaves with an eave-length-to-building-width ratio of 0.10. Despite some minor differences in the model/full-scale correspondence, the rms pressure coefficients measured agree fairly well. Discrepancies found in the mean and peak pressure coefficients have been attributed to drifts contaminating the accuracy of full-scale data. However, the general comparison between full-scale and model pressure coefficients has been described as remarkably good.

Some excellent full-scale measurements have been performed at the full-scale test house facility at Aylesbury, England.[31] The experiment has provided some of the most sophisticated data available for this type of configuration. They include both mean and fluctuating pressures and wind data. Several wind-tunnel studies have attempted to reproduce the full-scale results. Reference 33 has reported that, for most cases, mean pressure coefficients from the Aylesbury data are larger in magnitude, as compared to the wind tunnel results for almost geometrically similar structures. References 75 and 76 also report some scatter in the comparison of the 1:50 and 1:100 scale models with full-scale measurements. The scatter appears for both mean and fluctuating pressure coefficients and has been largely attributed to the internal scatter in the full-scale data. It has also been reported[76] that the modelling of hedges present at the Aylesbury site had little effect on the profiles of mean velocity and turbulence intensity, and on the measured pressure coefficients. The latter is in contrast with reference 77 which, after detailed experimentation of 1:500 scale models in the University of Western Ontario, concludes that model results are generally in agreement with full scale, if the surrounding terrain is adequately modelled. In fact, it is expected that model results would be sensitive to terrain details for low houses submerged in the surface roughness. This has been confirmed through further measurements[78] and has also been noticed in a previous study[40] in which the existence of a solid fence upwind of a house has been found to decrease mean pressures and increase peak pressures.

Figure 13 shows a typical comparison of model and full-scale pressure coefficients. Here, the general trends appear very good especially for the larger peak values. Scatter increases, however, for skew wind angles. In order to determine how good a comparison can be expected, *Figure 14* shows a similar set of graphs for two full-scale data runs under similar conditions. As can be observed, the scatter is of similar order to that in *Figure 13*. Part of this scatter is attributable to the natural variability in such random data samples, part due to the variability in structure of the full-scale wind over and above that modelled in

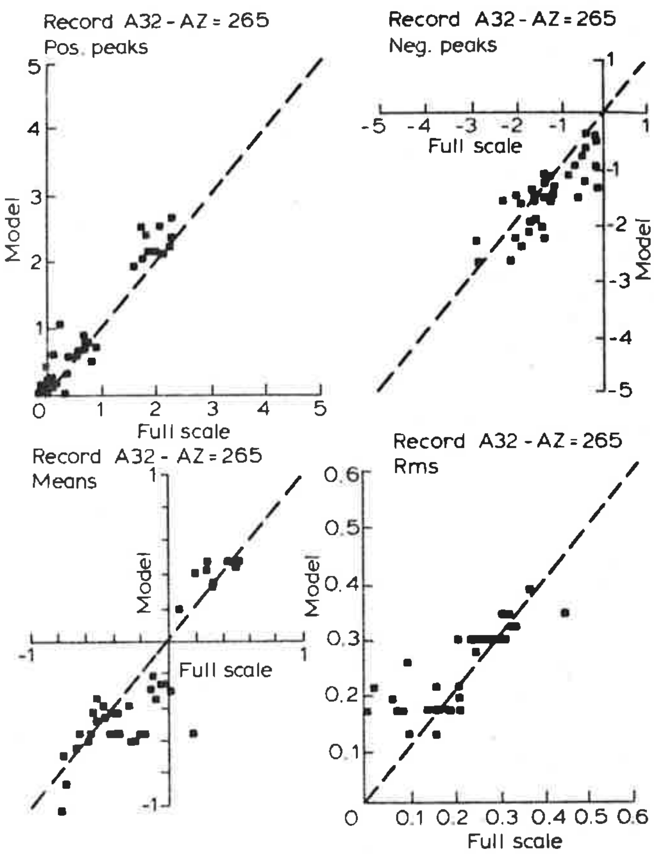

Figure 13 **Comparison of model and full-scale pressure coefficients – roof slope 22.5° (after reference 77)**

the wind tunnel (e.g. stability effects) and part due to slight mismatches in such experimental parameters as averaging times, record lengths, frequency bandwidths and wind directions.

Finally, researchers at Oxford, England, have carried out extensive comparisons not only between the Aylesbury data and their own experimental results, but also between the various other wind tunnel experiments attempted to reproduce the full-scale data.[79,80] Detailed analysis of the data has concluded that, despite the relatively good agreement for the majority of the cases, some non-random discrepancies exist. The most significant of these is the excessive mean suction in all the small-scale experiments near the windward edges of roof surfaces. It has been suggested[80] that, although this may be a scale effect associated with modified corner-separation characteristics in the low Reynolds number experiments, some further study should be made on the reliability of wind tunnel measurements in these sensitive corner regions.

In general, all these comparisons have been valuable in the assessment of the quality of the wind-tunnel data and have shown the paths to be followed for the improvement of simulation techniques and procedures for wind-tunnel testing of low-rise buildings.

Codification of wind loads

The number of possible low-rise building geometries and the complexity of the interaction of such buildings with their environment preclude any precise definition of the relevant wind loads. The best that can be done is, perhaps, to develop some simplified loading models which provide

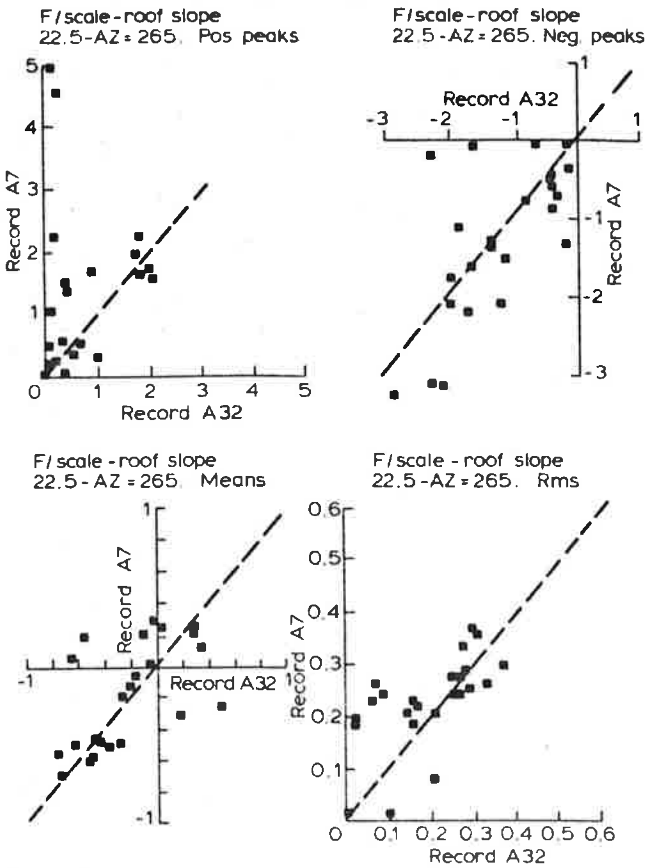

Figure 14 Comparison of two records of full-scale pressure coefficients for nominally similar conditions (after reference 77)

reasonable bounds on the likely loads, while still incorporating the major parameters found to be important in various experimental studies. Taking into account the fact that the bulk of information used in the various standards and codes of practice for the determination of wind loads on low-rise buildings is based on experiments carried out in smooth-flow tunnels, there is an urgent need to update these standards on the basis of the new available data, and the engineering considerations of safety, economy and simplicity. A few attempts have been carried out on these lines in recent years.

Reference 36 (pp. 50–51) suggests values of mean and rms pressure coefficients for low-rise buildings of medium roof angle (22.5°) for wind perpendicular to the side wall. Two different roughnesses (power-law exponents of 0.13 and 0.20) and the effect of the nearby environment have been considered. Peak pressure coefficients can be calculated by virtue of the models of pressure probability density functions suggested in reference 81. The high number of zones considered (14 for one wind direction), however, make the application of such a model difficult in practice.

Recommended wind load design coefficients for mobile homes have been included in reference 26. Of particular interest is the fact that the effect of area load reduction has been measured and considered in the derivation of generalized standard wind loads.

References 44 and 45 suggest design peak pressure coefficients based on dynamic velocity pressure at eave height for high-set and single-storey houses, respectively. *Figure 15* presents the suggested local values which are to be used for all wind directions. Data have been derived from the wind-tunnel testing of two different building models of roof angle equal to 10° with overhangs. Exterior pressure coefficients have been given for the high-set house and total (external–internal) pressure coefficients for the single-storey house. For the latter case, the Australian code value has been used for the internal pressure coefficient (apart from the roof overhangs) multiplied by a gust factor of 2.75 to convert mean values into peak. This high gust factor has been considered appropriate for a dominant windward opening (resulting from an open window, for example). It has been recognized[45] that the high values suggested for the roof overhangs are somewhat conservative since they have been derived by combining the peak values on one side with the peak values of opposite sign on the other side, although these peak values do not occur together.

Some recent work has reported on full-scale measurements of wind loads on glasshouses with multiple roofs.[82] Five different configurations have been examined and results have been simplified into a codified format. Data are valid only for typical geometries of commercial glasshouses.

A model of peak pressure coefficients for low-rise buildings of simple geometry has been provided[46] as the output of a large amount of data comparison and selection.[29,34,61] This particular model is summarized in *Figures 16* and *17* and in *Table 3*. It has been derived from data selected from experiments in a simulated open country exposure. The model is conservative if used in conjunction with any other terrain roughness. Values suggested are referenced to the dynamic velocity pressure based on the hourly mean speed measured at the mean roof height and are valid for all azimuths for buildings with eave heights less than 60 ft. The model has been accepted (with minor modifications) and incorporated in the Commentaries on Part 4 to the National Building Code of Canada 1980 and has been partially accepted (for cladding and secondary structural elements – with modifications) by the American National Standard Committee A58 for the updated version of the 1982 issue of the standard. In the latter case, peak

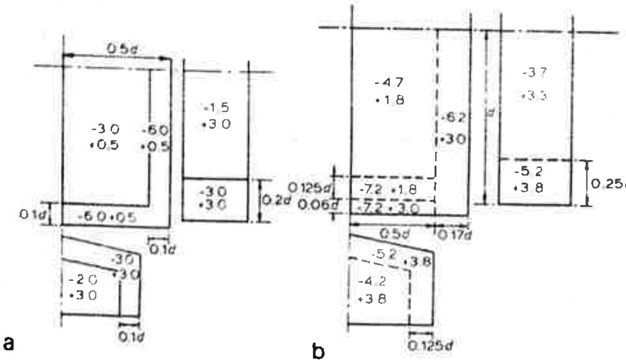

Figure 15 Codification of pressure coefficients (after references 44 and 45). (a) High set house, exterior values of $C_{\check{p}}$, $C_{\hat{p}}$ w.r.t. $\bar{u}_h$. (b), single storey house, total (external–internal) w.r.t. $\bar{u}_h$

Table 3 Internal pressure coefficients (open country exposure)

	Max Cp_i	Min Cp_i
Openings uniformly distributed	0	−0.3
All other cases	1.0	−0.3

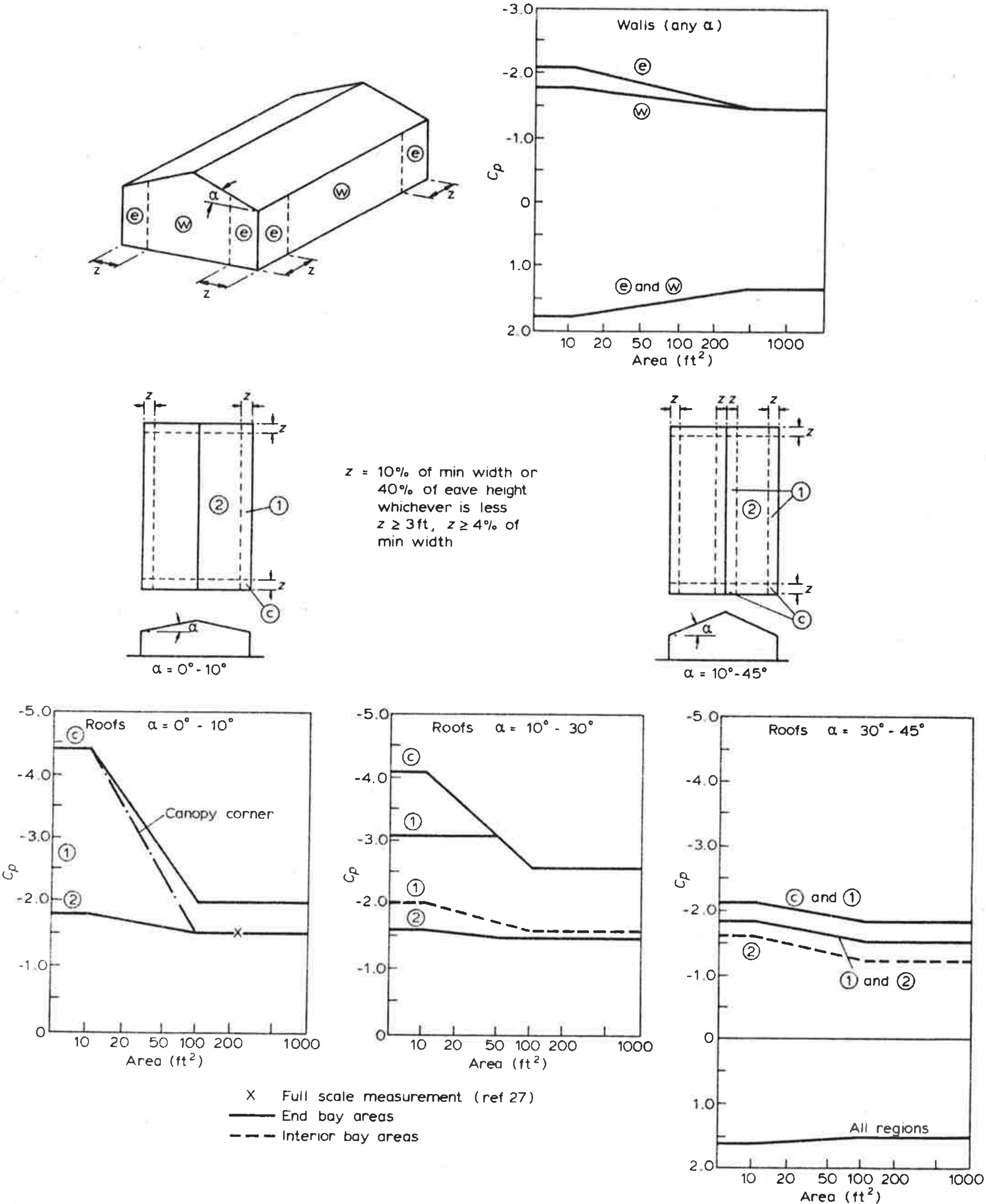

Figure 16 External pressure coefficients for maximum loads on cladding and secondary structural elements

pressure coefficients have been modified to reflect reference to the fastest mile velocity pressure at mean roof height. All the details and the assumptions made for the derivation of the codified model have been included in reference 46.

Figure 16 shows external peak pressure coefficients associated with various tributary areas of structural interest. Different values of pressure coefficients are suggested for the various zones, as indicated. The end-bay areas have a minimum width of $2z$ or 20 ft for buildings without frames.

The small number of peak loading patterns appearing in *Figure 17* reproduces all the critical design wind actions, found experimentally for the primary structural system, such as total uplift forces, horizontal thrusts and bending moments at critical points. The pressure coefficients of *Figure 17* may or may not reproduce true deflections since these were not monitored during the experiments. This matter is being investigated.

The quality of the suggested model will be of course determined in practice. However, at present, it appears of significant interest to compare the model values with full-scale experimental data. Two such studies have been selected for this purpose. First, the work reported in reference 27 shows the worst peak uplift coefficient measured to coincide with the suggested value in the model (*Figure 16*). The second comparison is with the Aylesbury full-scale measurements.[31] Only extreme instantaneous local roof and wall pressures based on 2 s peaks have been considered. The results of this comparison have been summarized in *Figure 18*, which shows the ratio of the simplified model loads (without accounting for the reduced probability of coincidence of maximum wind speed in the worst direction for the building orientation) to the Aylesbury experimental data. A satisfactory comparison here would constitute ratios whose smallest values scatter around one. Considering, however, the uncertainties associated with comparisons of extreme values of coefficients and the scatter of the full-scale data, as previously indicated (*Figure 14*), the comparison is generally encouraging.

A different set of charts of pressure coefficients for suburban exposures appears to be attractive for incorporation in a future standard, possibly as part of a voluntary detailed procedure. Some preliminary work on the analysis of such data has shown that considerable reductions of pressure loads may occur for rougher exposures but more work is required. Also, some analysis of the reliability of pressure coefficients suggested in the various models would be extremely useful.

These coefficients are only to be used in combination so as to develop appropriate loads for design of primary structural system.

Foundations: For design of foundations, but exclusive of anchorages to frame, only 70% of effective load is to be considered.

	End bay* coefficients C_p				Interior bay coefficients C_p			
α	1	2	3	4	1	2	3	4
0-10°	1.15	−2.00	−1.00	−0.80	0.75	−1.30	−0.70	−0.55
10-30°	1.50	−2.00	−1.30	−1.20	1.00	−1.30	−0.90	−0.80
30-45°	−0.90	−2.00	−1.00	−0.90	−0.85	−1.30	−0.70	−0.85
	1.30	0.50	−1.00	−0.90	1.05	0.40	−0.80	−0.70

* End bay loads should be applied between end and first interior frame or $2z$, for other structural systems

Figure 17 External pressure coefficients for primary structural loads on structural systems

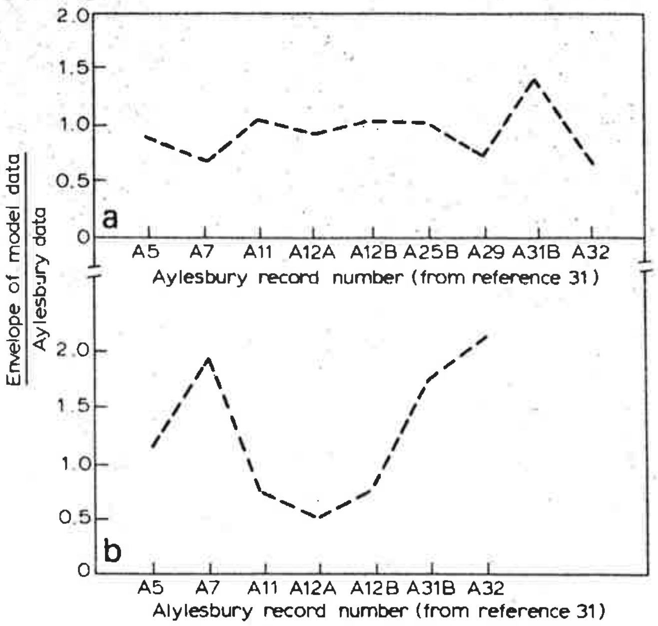

Figure 18 Comparison of codified data and worst data from Aylesbury measurements (after reference 31). (a), Worst wall local suctions; (b), worst roof local suctions

Recommendations for further work

The present paper has indicated the areas on which further investigation of wind effects on low-rise buildings is necessary. In summary, it would be interesting to study wind pressures on buildings with various geometrical configurations, for instance curved roofs; the effect of architectural features and various local protrusions, such as chimneys of different shapes, and sizes placed in different roof locations; and the effect of local environment, for instance the existence of hedges around houses, which may change the wind load distribution dramatically.

The terrain roughness has a significant influence on the loading function. Under some circumstances, major nearby structures induce additional loads on low-rise buildings. Obviously, this is a complex multi-parameter problem and a detailed study would be required to determine the transition from local roughness, introduced by one or two obstacles surrounding the building, to general roughness introduced by an extended urban environment.

The question of structural significance of gusts with very small duration (a small fraction of one second full-scale) may well be an area to be examined in the future. Although for usual materials and construction techniques the response of low-rise building members is not expected to be affected by such high-frequency gusts, there may be circumstances under which the increase of magnitude of these small duration peaks may be significant.

Last, but not least, the general question of structural reliability of pressure coefficients suggested in the various codes and standards has to be studied in detail. The question is closely associated with various aspects of experimentation, such as scaling problems in modelling techniques. Analytical work and full-scale measurements are required to advance knowledge in this field.

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