Journal of Industrial Aerodynamics, 4 (1979) 207—228 207

COMPARATIVE MEASUREMENTS OF WIND PRESSURE ON A MODEL OF THE FULL-SCALE EXPERIMENTAL HOUSE AT AYLESBURY, ENGLAND*

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Summary

The two-storey house at Aylesbury, England, built by the Building Research Establishment for the full-scale measurement of wind pressures, has been modelled at 1 : 500 scale in a boundary layer wind tunnel so that the reliability of simulation could be verified for low-rise buildings. Wind tunnel tests of building models of 5° and 22.5° roof slope are described. Surface pressure measurements are compared with full-scale data for various wall and roof locations.

For the model terrain best modelling full-scale conditions, the results show agreement which is encouraging. In particular, for winds normal to a face, agreement between experiment and full-scale is as good as between two similar full-scale runs obtained on different days.

However, the results have been found to be sensitive to local roughness elements in the upstream terrain. This not only places bounds on the accuracy with which the experiments can be expected to reproduce full-scale, but also suggests that there are practical limitations to the accuracy with which pressure coefficients can be predetermined for design. Furthermore, since the apparent roughness length (z_0) is obviously limited in its ability to characterize the local roughness near the measuring site, the traditionally used similarity parameter h/z_0 (height of building/roughness length) is probably not sufficient to ensure similarity when significant isolated local roughness elements are present.

1. Introduction

The wind loading of low-rise buildings has been receiving increasing attention in recent years; however, the number of possible building geometries and the complexity of the interaction of such buildings with their environment preclude any precise definition of the relevant wind loads in the near future, or possibly at all. Probably the best that can be done is to develop some

*Paper presented at the 3rd Colloquium on Industrial Aerodynamics, Aachen, June 14—16, 1978.

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a working section about 25 meters long, 2.5 meters wide and about 2 meters high. Most of this fetch is required for the natural production of a boundary layer which grows in a manner paralleling the atmospheric process under neutral conditions. The surfaces in the wind tunnel can be changed to represent different terrains. Boundary layer depths ranging from 0.6 to 1.2 meters are obtained at the test section with different surface roughnesses. In relation to the atmospheric boundary layer this implies that geometric scales of between 1 : 400 and 1 : 500 are most appropriate for studies of wind effects on buildings and structures. The maximum free stream speed and that at which these tests were carried out, is approximately 15 m/s.

The models were built at a scale of 1 : 500. Because of their physical size (see Fig. 1), two models for each roof slope were made. These contained a total of 114 pressure taps, the positions of which are shown in Fig. 2a, together with the full-scale locations. For all tests, the two models of the same roof slope were mounted in the wind tunnel at the same time. They were mounted 203 mm apart to avoid interference effects. Four models in all were constructed, representing two for a 5° roof slope and two for a 22.5° roof slope. Full-scale measurements were made for roof slopes from 5° to 45°.

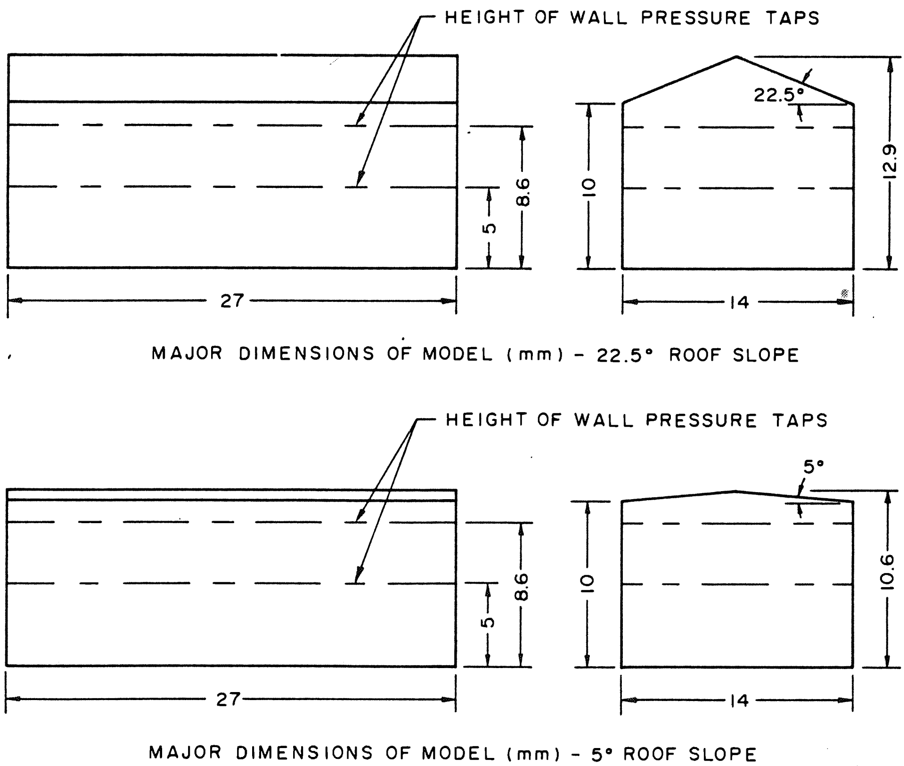


Fig. 1. Dimensions of 1 : 500 scale models of Aylesbury experimental house.

2.1 The measurement of surface pressures

All pressure taps on the models are 0.76 mm. diameter. They connect to transducers via plastic tubes which are 1.6 mm I.D. and 610 mm in total length with a damping restriction placed 356 mm from the tap. The resulting pressure measuring system responds to pressure fluctuations on the model of up to about 100 Hz with a gain factor of about 1 ± 10%. Low pass filters set at 120 Hz were used to increase the attenuation for higher frequencies. Several pressure measurements were made in parallel, each sampled at a rate of about 1,000 times per second by an on-line digital computer. Record lengths of a minute in real time were sampled during which the computer recorded, for each input, the maximum and minimum values that occurred and computed the mean and root mean square values. The reference dynamic pressure was measured in the free stream above the boundary layer in the same way. At the end of the sampling period the measured pressures, consisting of the maximum and minimum, mean and RMS values for each channel, were converted to pressure coefficients by dividing each by the reference dynamic pressure. These have been analysed further on a larger computer.

Similarity considerations lead to the determination of velocity and time scales of the order of 3:10 and 1:150 respectively. Consequently, the experimental sampling rate corresponds to about 7 samples per second per channel in full-scale and pressure fluctuations with frequencies up to about 0.7 Hz in full-scale can be detected without significant distortion or attenuation. Hence, peak pressures on the model correspond roughly to peaks with a one to two second averaging time in full-scale.

The use of a one minute wind tunnel sample provides a statistically stable estimate of mean and RMS pressures, and a conservative assessment of the peak values corresponding to full-scale data based on the hourly mean wind speed. This arises because the wind tunnel does not represent fluctuations in wind speed with periods of greater than a few minutes.

2.2 Definition of the pressure coefficients

The pressure coefficients presented here were initially referenced to the ambient conditions above the boundary layer, which correspond to gradient height in the atmosphere. They are defined as follows:

$$C_{\bar{p}} = \frac{\dfrac{1}{T}\displaystyle\int_0^T p(t)\,\mathrm{d}t}{q_g}\;;\quad C_{\bar{\bar{p}}} = \frac{\left(\dfrac{1}{T}\displaystyle\int_0^T (p(t)-\bar{p})^2\,\mathrm{d}t\right)^{½}}{q_g}\;;\quad C_{\hat{p}} = \frac{p_{\max}}{q_g}\;;$$

$$C_{\check{p}} = \frac{p_{\min}}{q_g}$$

where $C_{\bar{p}}$, $C_{\bar{\bar{p}}}$, $C_{\hat{p}}$ and $C_{\check{p}}$ are their mean, RMS, maximum and minimum values respectively; all pressures are differential pressures with respect to the

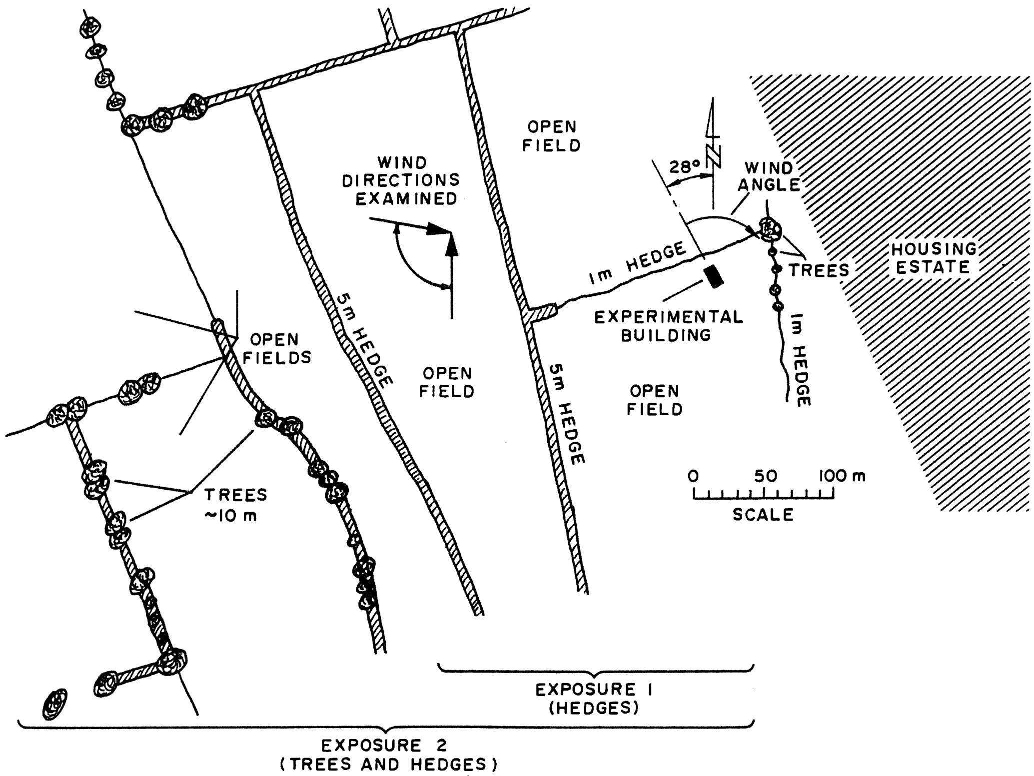


Fig. 2b. Sketch of full-scale site showing approximate position of major terrain features modelled.

4. Results

4.1 Boundary layer characteristics

Four different model exposures have been considered:

Exposure 1: a carpet surface with the addition of local hedges (see Fig. 2b).
$z_0 = 80 \times 10^{-4}$ cm (= 4 cm full-scale)

Exposure 2: a nylon cloth surface plus local hedges and trees (see Fig. 2b).
$z_0 = 4 \times 10^{-4}$ cm (= 0.2 cm full-scale)

Exposure 3: the nylon cloth alone
$z_0 = 4 \times 10^{-4}$ cm (= 0.2 cm full-scale)

Exposure 4: the smooth painted-wood wind tunnel floor alone
$z_0 = 3.5 \times 10^{-4}$ cm (= 0.18 cm full-scale)

Vertical profiles of mean speed and longitudinal turbulence intensity are given in Fig. 3. Figure 4 is a log plot of these velocity profiles, from which the surface roughness parameter z_0 was derived. On each of these graphs are plotted the full-scale 30 minute mean velocity measurements as reported in [12] normalized with the wind tunnel data at a height corresponding to a full-

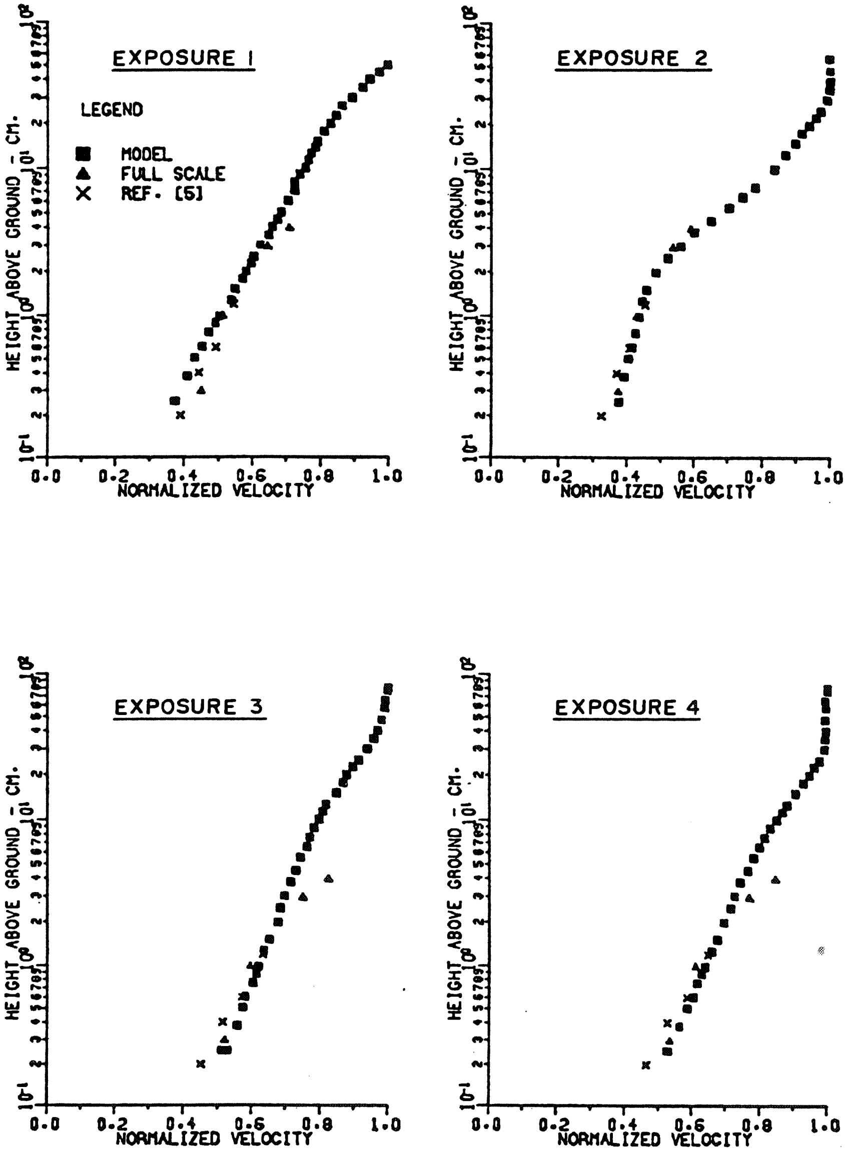


Fig. 4. Logarithmic plots of mean velocity profiles.

scale height of 10 meters. Also plotted is the velocity profile measured by Jensen and Franck [5] at Albertslund, similarly normalized. The values of z_0 appear to primarily reflect the basic surface characteristics near the measuring site and not any residual flow changes due to the isolated obstacles upstream. This may be partly a result of the mean velocity deficit due to obstacles dying away more quickly than the turbulence intensities induced, and partly due to the fact that the values of z_0 are biased by the lowest part of the boundary layer which largely reflects the surface roughness nearest the measuring location.

Although each of the profiles appears to fit the full-scale data and data from [5] quite well, Exposure 2, which most closely modelled the full-scale environment, was the best fit to the full-scale mean velocity profile data and also provided turbulence intensities similar to those given in [13]. Thus Exposure 2 was adopted as the basis for comparison with full scale results. It is noteworthy that this simulation implies that the flow at the site is very much influenced by the effects of the upstream hedges and trees, contrary to the conclusion arrived at in [12] on the basis of velocity profiles over a limited height range.

Figure 5 shows velocity spectra at three different heights for the full-scale measurements and for the corresponding positions in the wind tunnel. The spectra agree quite well, particularly at the 10 m height and they also agree well with the Davenport curve [15] which is also shown. The reduced frequency used on the x-axis uses a value of Davenport's length scale parameter, L, of 1200 m full-scale. The corresponding value used for the wind tunnel data is 2.4 m.

4.2 Presentation of pressure data

Data determined for the models placed in all four experimental exposures are presented in detail in [10], which also includes graphical presentation of some of the full-scale data and comparative plots. Only a few examples are included below, drawn primarily from the 22.5° roof slope model.

The format for presentation is:

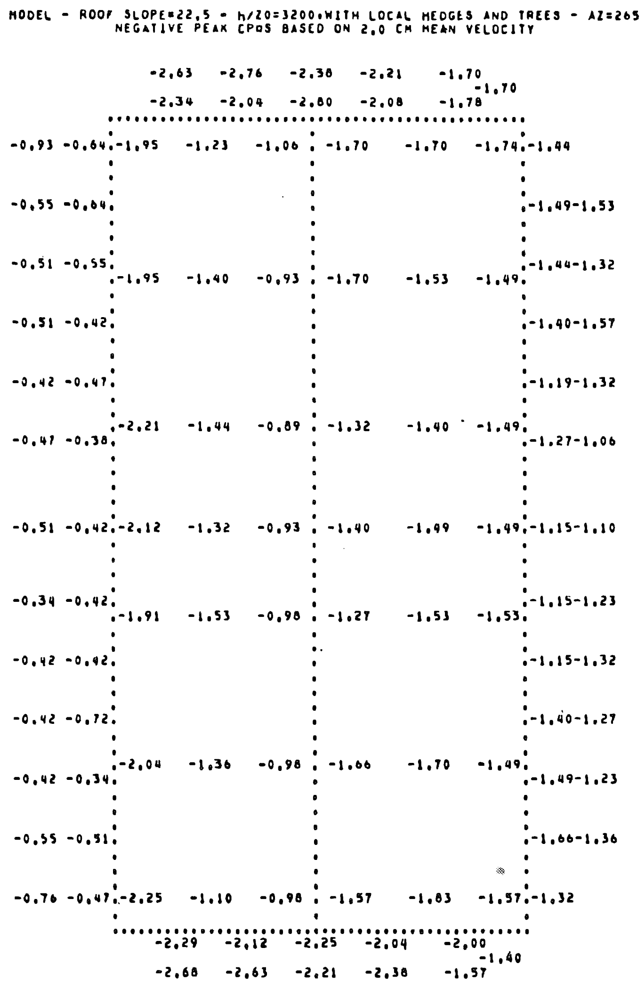
(A) Presentation of data on an exploded view of the building similar to that used in Fig. 2a. Two such views are usually provided side by side to allow comparisons to be made.

(B) For a particular azimuth, two sets of data are plotted against each other. Perfect agreement would result in all points lying on a diagonal line.

(C) Two sets of data for a particular building location are plotted against azimuth.

Using these techniques, a variety of comparisons can be made to illustrate specific differences and/or trends in both model and full-scale data. Coefficients referenced both to mean speed at 10 m and to gust speeds of various durations have been considered, as well as gust factors derived from the coefficients.

Pressure spectra have also been measured.



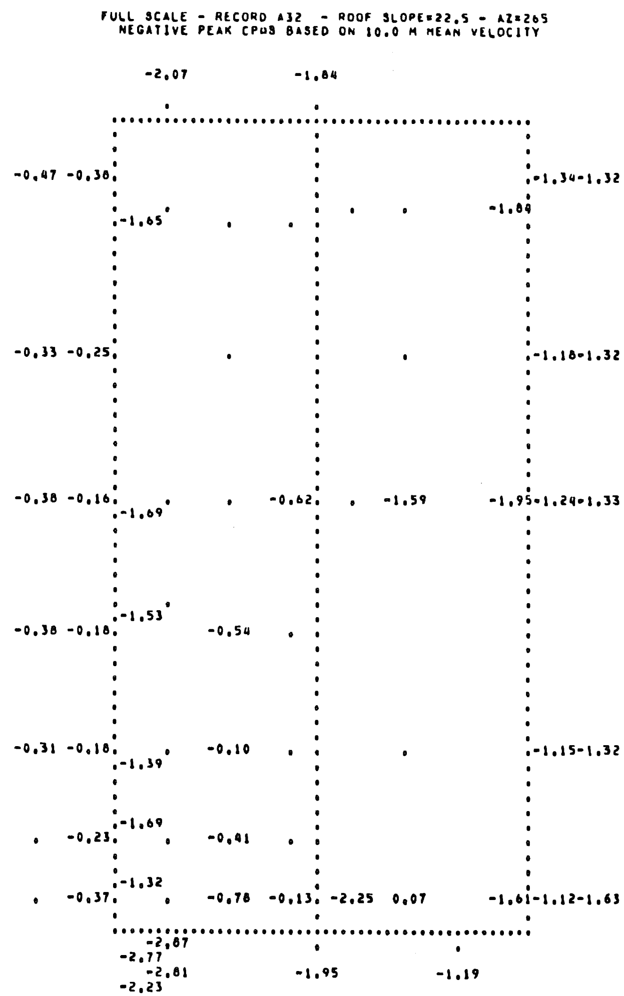


Fig. 7. Model and full-scale negative peak pressure coefficients.

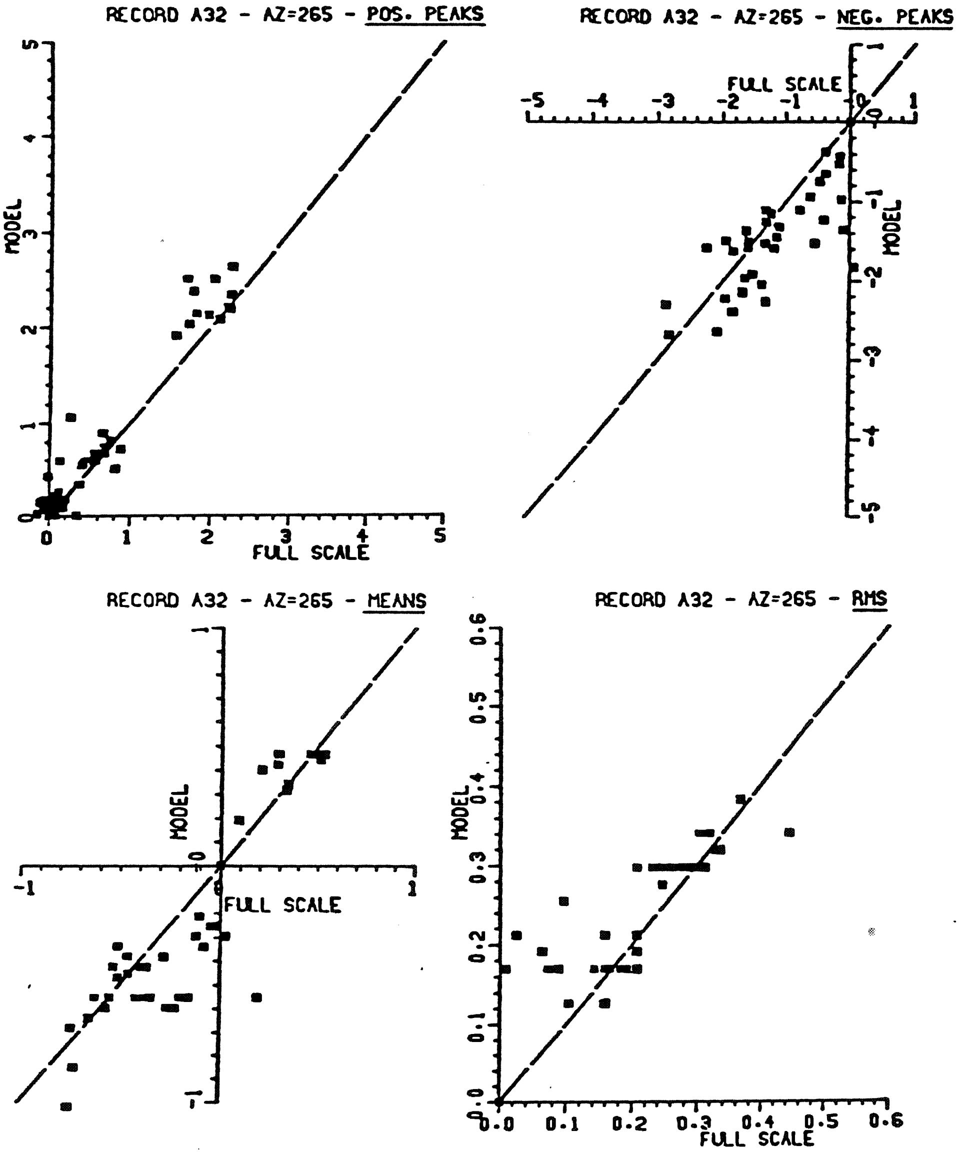


Fig. 8. Comparison of model and full-scale pressure coefficients (roof slope 22.5°).

and full-scale except for isolated cases where the full-scale results deviate considerably from the trend and appear suspect. In general, wall results give better agreement for both positive and negative peaks than roof points. There is some indication for points on the roof of intense RMS and peak data in the full-scale results which occur over very local areas but are not obviously spurious. These are not repeated in the model data.

Detailed comparison of the fluctuating pressure coefficients, however, must recognize differences in the frequency response of the model and full-scale measuring systems and differences in the record lengths examined. The effectively longer model record lengths (150 minutes full-scale compared to actual full-scale records of about 17 minutes) lead to higher peak estimates for the same averaging times. Furthermore, a peak is derived as a single datum from a long record and hence not only is subject to statistical scatter, but also is particularly susceptible to error due to spurious inputs. This appears to be the reason for some particularly large full-scale values which are not in context with neighbouring points. Certainly, this is a common experimental event in the more benevolent model environment.

With regard to frequency response differences, the model essentially provides pressure data good to about 1 Hz (full-scale), hence providing peaks roughly equivalent to one-second averages. Thus, if the pressure signal contains a large amount of high frequency energy — say due to a very local flow disturbance, then significant differences in RMS and peak pressures between model and full-scale could occur; however, the practical significance of such a discrepancy may be small, since such high frequency content will tend to be associated with small correlation lengths. Nevertheless, such discrepancies are worthy of further investigation.

Measurements of pressure spectra, made at four selected points on the model, provide some insight into the frequency content of the pressures. The points were chosen to correspond to points at which similar measurements were made on the full-scale building. An example is shown in Fig. 10 for a point at the 5 m level on the west wall and for a point on the east roof. The full-scale pressure spectra from [12] are shown at the corresponding positions in these figures. The wave numbers for the model spectra have been divided by the length scale to allow direct comparison. The model results are unsmoothed. There are general similarities evident in the spectra for model and full scale; however, the response of the tubing system and filtering has caused a rapid fall off in the spectrum at higher frequencies in the model results. The missing energy does not appear to be a significant fraction of the total. The two peaks appearing in the spectrum from the east roof are evident in many spectra made in regions of separated flow. Somewhat similar results are shown by Stathopoulos [17] for a different model study and by Marshall [18] and Kim and Mehta [19] in full-scale results. These correspond to the peak of the full-scale spectrum at a wave number of approximately 0.001.

Both English and Australian building codes provide for the calculation of wind loads based on peak coefficients determined using peak speeds. Such peaks have been defined for a range of averaging times for the full-scale data. For the model data, as explained previously, the peak pressures correspond to roughly one-second peaks. However, the speed measurements in model scale are much less restricted and provide model gust velocities conservatively estimated as averages over about 1/10 second or less. This produces somewhat of a mismatch when computing model peak coefficients which tends towards underestimation. Nevertheless, positive and negative peak coefficients based on peak speeds are extensively compared for full-scale and model results in [10]. Agreement is generally good where good agreement has been obtained for coefficients based on mean values and agreement is generally worse for skew wind directions.

In an effort to determine how well a model may be expected to accurately predict the range of pressures occurring in the full-scale, the worst positive and negative peaks over all azimuths considered for each comparable point on the building have been plotted against each other in Fig. 11. The left plot shows the comparable maximum coefficients where both the full-scale wind and pressure data are based on 2 second peaks which is very nearly equivalent to that for the peak pressure in the model situation. The agreement obtained is quite reasonable, particularly when it is realized that scatter of these peak values could be expected simply because of statistical sampling. The line of best fit through these points shows that the model results are generally a little larger

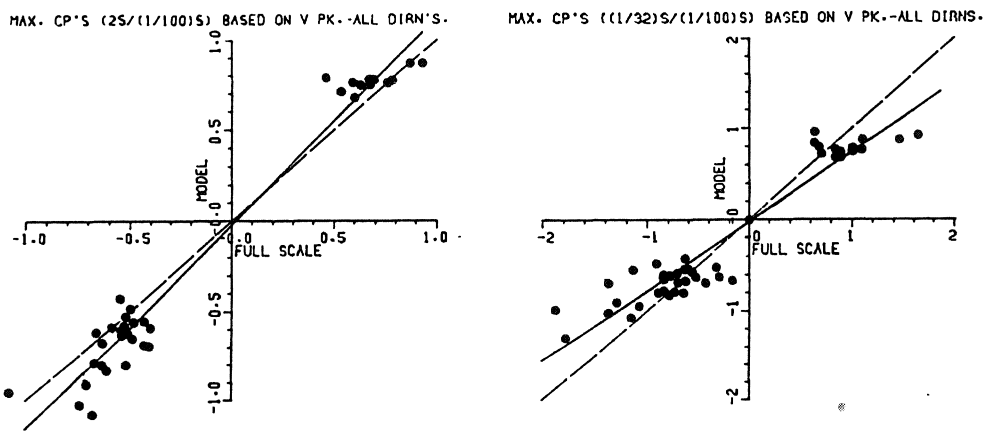


Fig. 11. Comparison of the largest model and full-scale pressure coefficients (based on peak speeds at 10 m) observed for the range of wind directions studied (roof slope 22.5°).

than those occurring in full-scale, even though the model peak speed considerations above should lead to underestimation of the model values. This is probably due to compensating higher peak model pressures resulting from the longer record lengths used. The graph on the right shows that the full-scale peaks based on the 1/32 second pressure data and 2-second wind data are underestimated by the model. This might be expected, since the frequency content of the full-scale results is not reproduced by the model, as discussed above. However, interpretation of this result requires some care. The data indicate that the wind tunnel is successfully reproducing pressure peaks of the order of 0.5 seconds or so but not peaks of 0.03 seconds duration. Such short term peaks are of questionable design significance particularly for significant tributary areas. Typically a 0.03 second duration peak might be correlated over an area of about 100 cm^2 for a 30 m/s wind.

The peak factor is used in many approaches to design. The peak factors, defined as [peak-mean]/RMS have been calculated and typical results are shown for both model and full-scale in Fig. 12. The full-scale data use the 2-second peaks. Exact agreement between model and full-scale peak factors cannot be expected considering the statistical variability inherent in this quantity; however, both in Fig. 12 and in the additional data given in [10], maximum values obtained from the model data are generally less than 10, as are the majority of the full-scale peak factors. It should also be noted that the peak factors obtained on the walls are quite large. Particularly for the windward wall, peak values near 6 are not consistent with a Gaussianly-distributed wind speed and quasi-steady theory; however, there is growing evidence that this deviation is due to skewness in the wind speed distribution near the ground. It is encouraging to note that such high peak factors are evident in both model and full-scale results.

Some values obtained from the full-scale results (not shown here) are quite startling — such as a value of 32 obtained on the west roof near the ridge and a value of 16 near the middle of the west roof. However, values of 9 and 5.5 respectively were recorded at adjacent positions, suggesting again that some of the full-scale data may be suspect.

5. Conclusions

An extensive comparison between model and full-scale pressure and velocity data for the two-storey experimental house at Aylesbury leads to the following conclusions:

1. Model results are generally in agreement with full scale, if the surrounding terrain is adequately modelled.
2. Model results are sensitive to terrain details as might be expected of a structure submerged in the surface roughness. In particular, turbulence intensities in the flow must be reproduced for adequate modelling.
3. Since full-scale pressures must be similarly sensitive to roughness details, there are practical limits, both to the accuracy with which experiments can be expected to reproduce full scale, and to the accuracy with which pressure coefficients can be predetermined for design.

References

1 C. Kramer and H.J. Gerhardt, Windkräfte auf flachen und wenig geneigten Dachflächen, 2. Kolloquim über Industrieaerodynamik, Aachen, 1976.
2 G. Barnaud and J. Gandemer, Determination en soufflerie simulant le vent naturel des coefficients de pression sur les structures basses, Section Aerodynamique des Constructions ADYM—12 74, Centre Scientifique et Technique du Batiment, Etablissement de Nantes.
3 G. Hellers and S. Lundgren, Wind loads on generally shaped house bodies — Model tests, Report R22, 1974, National Swedish Building Research Summaries.