WIND LOADING ON TALL BUILDINGS - FURTHER RESULTS FROM ROYEX HOUSE

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Following on from an earlier analysis of results from Royex House, this paper covers some of the unanswered questions and extends the analysis to include an assessment of dynamic effects of the wind on the building. Autocorrelations and power spectra were computed for the 48 pressure transducers, and these showed noticeable fluctuations in the pressures on the windward face, possibly caused by a cushioning effect in front of the building 'leaking' away at regular intervals. The horizontal and vertical spread of gusts as experienced by the building was determined from the cross-correlations between various pairs of transducers. These effective gust sizes are shown to be very much larger than those of the undisturbed wind.

Further wind tunnel tests have been carried out and are reported. The results agreed quite well with the full-scale data, providing all the surrounding buildings were modelled. Small changes in the incident wind direction affected the loading considerably.

Interesting data were obtained for the speed of travel of gusts along a face experiencing a glancing wind. The high suction that such winds cause was investigated in more detail, and it is shown that the peak suctions near the leading corners were greatest when the wind was blowing onto the minor faces. In general, the peak cladding pressures or suctions on any part of the structure were between five and six times the rms pressure in excess of the mean pressure for that particular point.

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by C W Newberry, K J Eaton and J R Mayne

INTRODUCTION

Previous reports[1,2] have given some results of the measurements of wind pressures on Royex House, a tall building in central London. Since those reports were issued further recordings have been examined and, with the availability of better facilities for data processing, more complete analysis of the records has been possible.

Details of the building and the instrumentation were given in the earlier reports, but for clarity a brief description will be presented together with a summary of previous results. The earlier papers should be consulted for more detail.

Essentially, the test building was an 18-storey office block 66 m high, rectangular in plan shape, with sides of 43 m and 18 m and relatively smooth facades. Twelve pressure transducers[3] were located in each face of the building at the 7th, 13th and 17th floor levels at positions indicated in Figure 1, and simultaneous recordings of the face pressure at all 48 positions were made for a range of wind speeds and directions. (Details of the records analysed are given in Appendix 1.) All pressures at each level were recorded relative to a common reference pressure inside the building and were at a chart speed that enabled pressures to be read off at intervals of 1 second or 0.1 second as required[4].

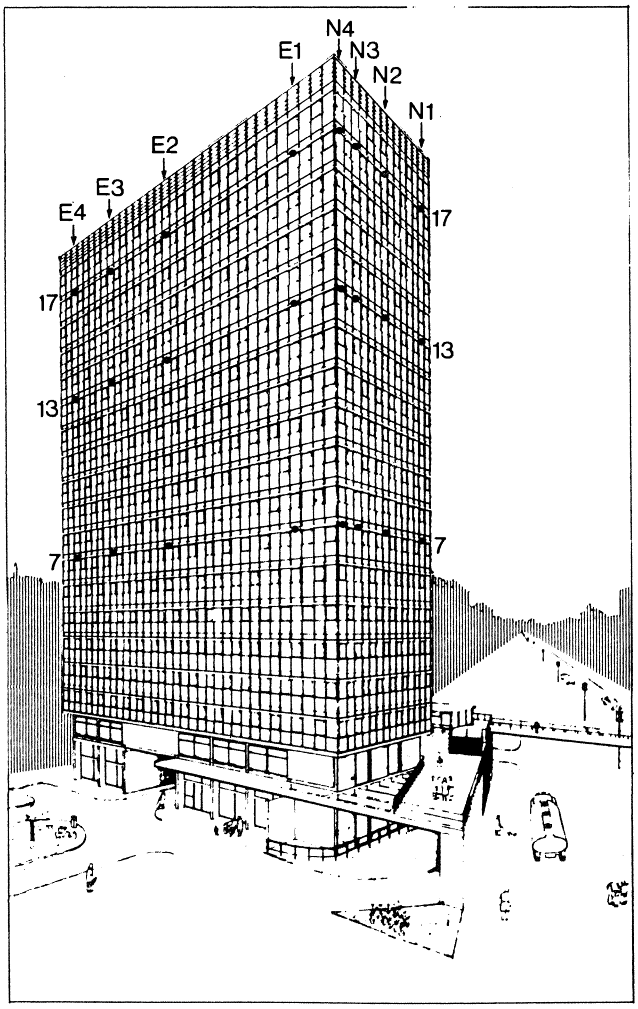

Figure 1 Transducer positions at Royex House

The major facades of the test building faced approximately east and west (axis 17^o east of north). The surrounding buildings were generally about 20 m high with a relatively clear approach from the west; but to the north and east were several buildings similar to the test building, spaced at intervals of about 100 m, which provided a marked degree of shielding against winds from that quarter. There was also a building 45 m high fairly close to the south face of the test building. The site plan is shown in Figure 2.

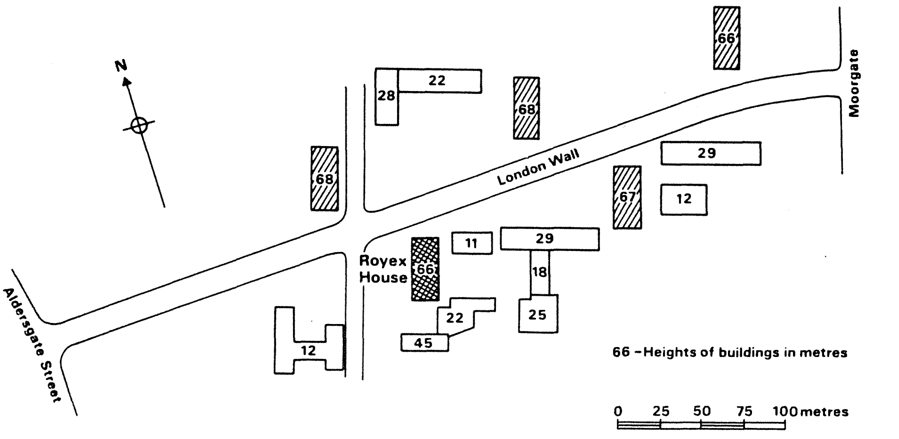

Figure 2 Site plan of area around Royex House

The salient features that emerged from the earlier analysis were (a) that short transient loads are important for the design of cladding and also for the design of the structure, the critical limit of load duration depending on the natural frequency of the structure rather than on the size of gust; and (b) that for the normally permeable building such as the one tested the wind load is taken almost entirely by the windward face rather than being divided between windward and leeward faces as had been the conventional design procedure in the 1952 edition of the Code of Practice for Wind Loading[5].

Several points were left unanswered in the earlier reports; most of these can now be covered as further wind tunnel tests have been carried out, and more records that were taken on the full-scale building (particularly for the north and south faces) have been analysed.

COMPUTATION PROCEDURES

All the results previously published were mean pressures and mean loads, calculated for various averaging periods. Specific computer programs were written to handle the large volume of data, and these same programs have been used for the initial analysis of the extra records that were digitised. This was particularly directed at a further analysis of glancing winds where high peak pressure coefficients (Cp) had been previously measured[1]. The programs, whilst searching for these peak Cp values, automatically calculated the mean Cp and the rms* Cp averaged over the length of the record.

For all the records listed in the Appendix, further analysis was carried out to assess the dynamic effects of the wind. Various research workers have proposed design procedures to allow for this dynamic action[6,7,8,9], all of them defining a gust factor to be applied to the steady wind forces. The Canadian Code of Practice[10] now uses this approach for the design of buildings over 122 m tall, but other countries have not yet adopted the methods because all the meteorological aerodynamic and structural properties have not always been adequately defined. With this analysis from Royex House, it is possible to provide information to assess in some measure these dynamic design methods.

Programs were written using standard digital techniques described by Bendat and Piersol[11], to compute autocorrelations and spectra for all transducers, and cross-correlations and

* Some confusion exists concerning the term rms pressure. Strictly, what has been calculated here is the rms of the pressure differences from the mean value. In building aerodynamics, it is common practice to call this the rms pressure, and this terminology is maintained here.

coherence functions for various pairs of transducers particularly on the windward face of the building. The autocorrelation function describes the general dependance of the pressure values at one time on the pressure values at another time. The associated pressure spectrum represents the distribution of the variance of the pressure fluctuations according to frequency. The cross-correlation and coherence functions of the pressures recorded at pairs of transducers can be used to provide estimates of the size of gusts as experienced by the building. More detailed definitions and explanations of these various functions, with particular reference to wind velocities and pressures, have been given by Harris[12].

CHARACTERISTICS OF GLANCING WINDS

It was previously reported[1] that, under glancing winds the suctions near the windward corners of the east and west faces were quite considerable. Based on a 3-second mean pressure (and 3-second gust velocity), the external pressure coefficients (Cpe) were typically -1. 25, but based on a 1-second pressure Cpe = -2. 2. The transducers giving these high suctions were 3. 4 m from the corners of the building, but on the north and south faces now examined, transducers were only 0. 6 m from the corner. These transducers can be seen in Figure 3 which shows the south-west corner of Royex House, with transducers 7W1 and 7S1 to 7S4 in the cladding panels above the large windows.

Figure 3 Transducers 7W1 and 7S1 to 7S4

Four records (numbers 13-16) were investigated in more detail in order to compare the suctions on the north and south faces in approximately westerly winds with the previous measurements on the east and west faces that are mentioned above. A visual inspection of the records indicated that the suctions were usually most severe near the windward corners; however, this was not always the case. Figure 4 shows part of record 13 (mean direction 260^{o}) and it can be seen that on some occasions the transducers nearest the trailing corner of the face experienced the highest suctions. For example at t = 75 seconds, the suction at position 7N4 was greater than that at 7N1, 7N2 or 7N3. The disturbance, however, was clearly moving from 7N1 (the windward transducer) to 7N4 (the trailing transducer).

On inspection of the anemometer traces for this record, it was seen that the wind direction was extremely variable; at times it was $\pm 80^{o}$ from the mean direction whereas for most of the other records the variation was about $\pm 30^{o}$ to 40^{o}. It is quite likely that at the time referred to a gust could have hit the building from a north-westerly point and caused the high suctions on the trailing transducer positions 7N4, 13N4 and 17N4.

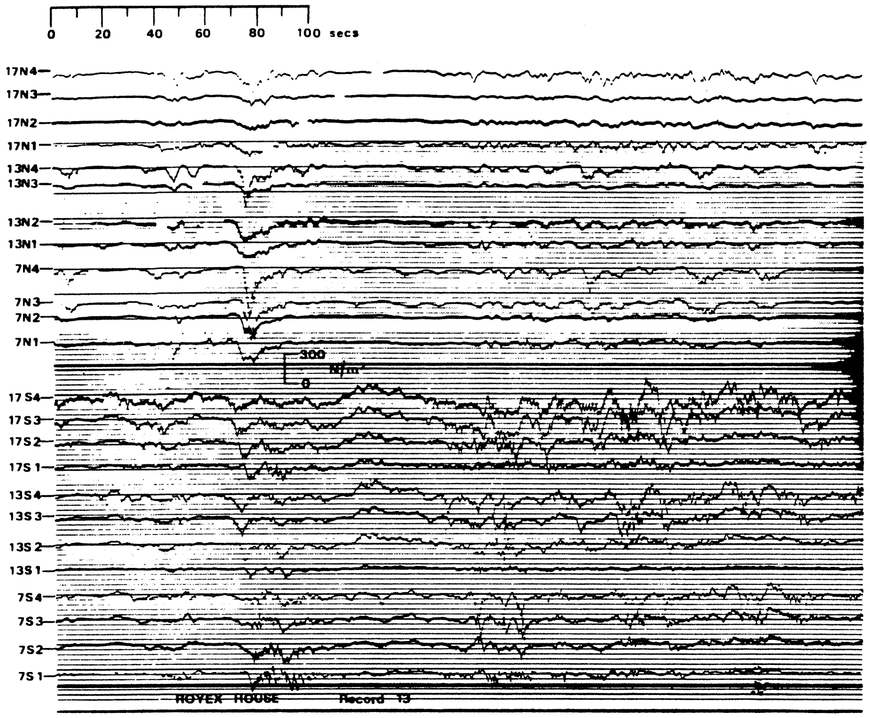

Figure 4 Analogue record of pressures on north and south faces in a westerly (260^{o}) wind

Whilst record 13 is under discussion, it is of interest to notice Figure 5. This shows the same part of the record for the west (windward) and east (leeward) faces. It can be seen that, at about the same time (t = 75 seconds), a high intensity gust occurred in the middle of a relatively calm period. This sort of gust, whilst not typical, can obviously occur and it affects all four faces. (For the gust factors on the windward face see the discussion to reference 1.)

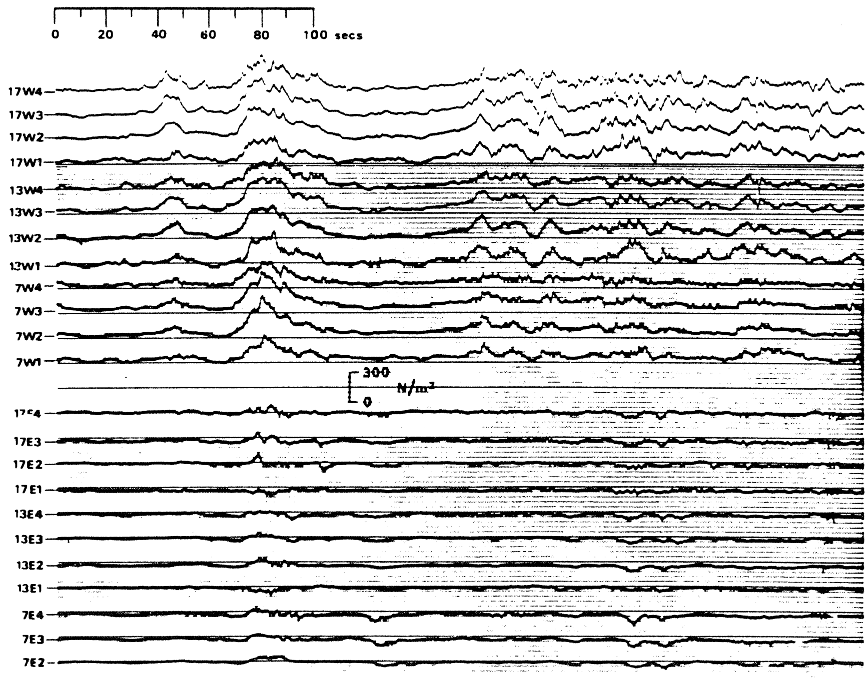

Figure 5 Analogue record of pressures on west and east faces in a westerly (260^{o}) wind

On the windward face there was a gradual build-up in pressure on each transducer from the time the disturbance was first detected. In contrast, on the side faces the suction occurred extremely rapidly reaching peak magnitudes before the positive pressure had reached a peak on the windward face. Figure 6 indicates this diagrammatically, and also gives the onset times of the disturbance at each transducer together with the time at which the pressure or suction reached its peak magnitude. In a full-scale project at Hong Kong, Mackey[13] also noticed similar characteristics in the surface pressures. In particular he reports a pulsation in the positive pressures on the windward face, attributed to a cushioning effect which then leaks away around the sides at a time period of between 7 and 10 seconds.

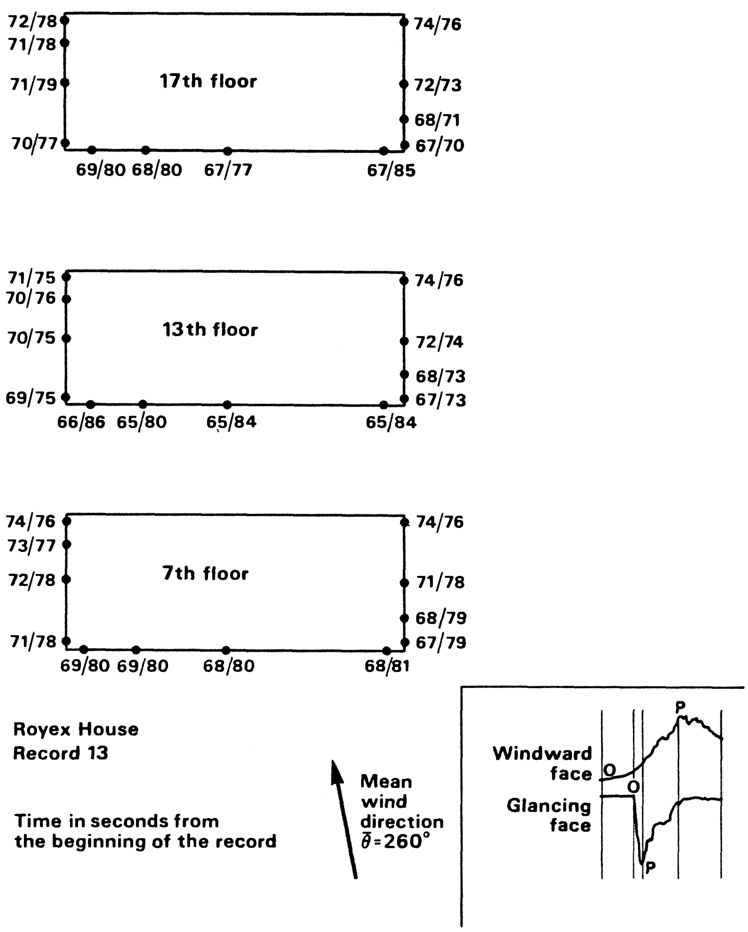

Figure 6 Times of occurrence of gust onset and peak pressure for a particular gust

Apart from this direct analysis of the analogue records, mean, rms and peak pressure coefficients were computed from the digitised data. The results for record 14 are shown in Figures 7 and 8. The mean and rms coefficients (Figure 7) are based on the mean speed at the height of the top of the building and have been averaged over the length of the record, 1100 seconds (18 minutes approximately). The peak coefficients (Figure 8) are based on the maximum 3-second gust, $\hat{V}$. Comparing the two faces experiencing a glancing wind, the suctions on the south face are in general greater than those on the north face. This is due to both the mean wind direction, which was 260^{o} relative to the north-south axis of the building, and a slight channelling effect due to the pressure of the adjacent building to the south. The highest peak suction coefficient (transducer 17S4) was -0.80 (or -0.92 based on the 1-second suction). Considering this was from a transducer only 0.6 m from the corner of the building it was not nearly as large as had been expected. It was actually smaller than the suctions previously reported. In fact no suctions from records 13 to 16 were as large as those recorded in southerly or northerly winds on the east and west faces.

Discussion with Armitt[14] has indicated that the position of the peak suction is not right at the corner, but is a short distance along the glancing faces. In his wind tunnel tests, the position of the peak varies depending on various parameters, including turbulence scale and intensity. However, when further tests have been carried out a more detailed explanation of these full-scale results might be available.

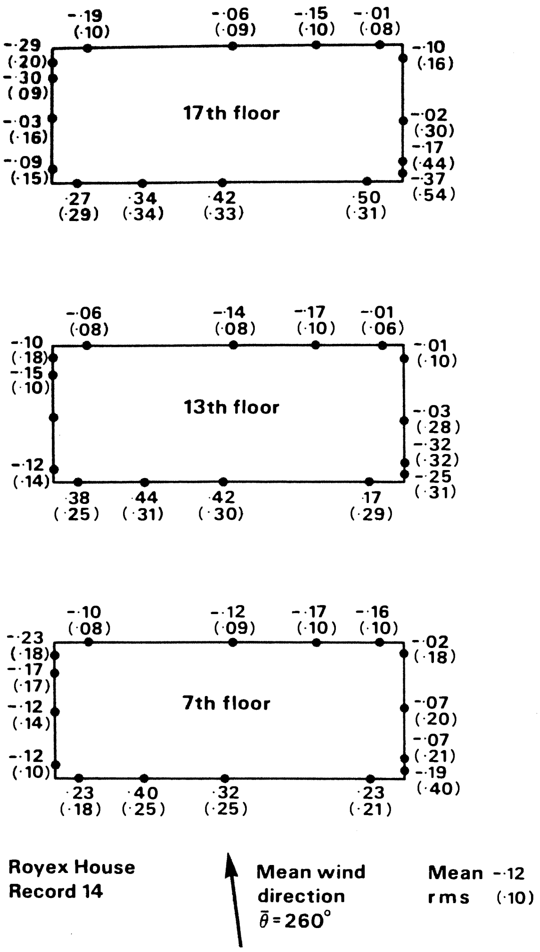

Figure 7 Mean and rms pressure coefficients (based on mean wind speed at top of building)

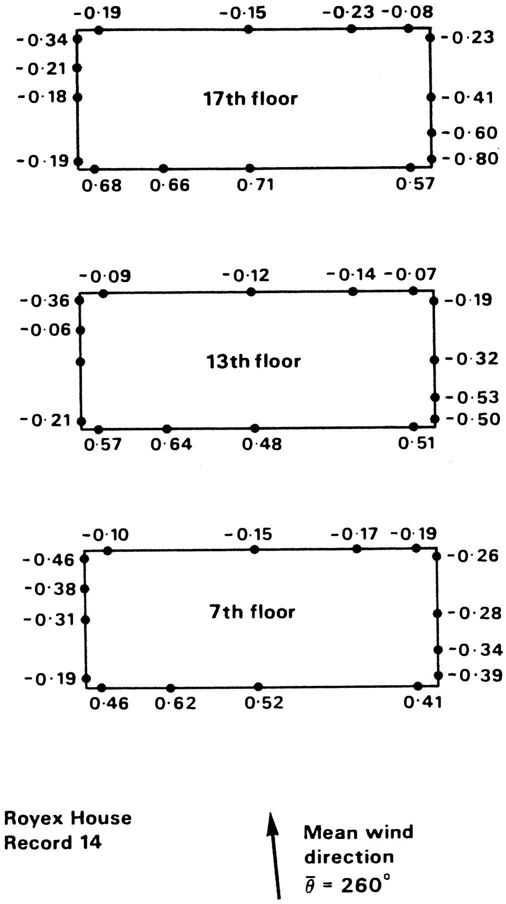

Figure 8 Peak (3-second) pressure coefficients (based on 3-second wind speed at top of building)

TRANSIENT GUST VELOCITY ALONG A FACE

Mention has already been made of the time taken for gusts to travel along a side face under glancing winds. For each of 13 different records the speed with which several gusts travelled along the east and west faces of the building was determined. Average values for the speeds at the 17th floor, v_{60}, and at the 13th floor, v_{46}, are given for each record in Table 1. The results for the 7th floor are not included as there was no clear pattern of movement of gusts, the air stream at that height being much more turbulent due to the surrounding lower buildings.

Also included in the table are the values of the gust velocity in the approaching wind; $\hat{V}_{60}$ was obtained directly from the London Weather Centre anemometer and then a power law adjustment was made to give an estimate for $\hat{V}_{46}$. For each record, it was then possible to calculate the ratios $v_{60} : \hat{V}_{60}$ and $v_{46} : \hat{V}_{46}$, ie the ratio of the gust velocity along the face of the building to the gust velocity of incident wind at that height. At both levels these values could be split conveniently into two groups, depending on the angle of incidence β of the mean wind direction relative to the north-south axis of the building (ie $\beta = 0^{\circ}$ is parallel to the east or west faces). With small values of β the mean values of $v_{60} : \hat{V}_{60}$ and $v_{46} : \hat{V}_{46}$ were 0.36 and 0.34 respectively, whilst for larger angles they were 0.71 and 0.66 respectively.

For the very small angles of incidence the mean flow would have separated from the leading corners of the building, and most of the long side face would have been in this separated region. Under these conditions gusts travelled along the face at about one-third of the free-stream velocity. (Although the mean flow was separated, small gusts, showing as disturbances on the pressure transducers, were moving within the separated region.) However, when the wind was blowing more directly onto the face (between 20° and 60°) the gusts travelled at about two-thirds of the free-stream velocity. In this case the flow would not have been separated, but attached to the face of the building.

Table 1 Gust velocities along the face of Royex House

β	$\hat{V}_{60}$ (m/s)	v_{60} (m/s)	$\frac{v_{60}}{\hat{V}_{60}}$	$\hat{V}_{46}$ (m/s)	v_{46} (m/s)	$\frac{v_{46}}{\hat{V}_{46}}$
48^o	16.5	12.9	0.78	16.0	10.3	0.64
38^o	23.2	14.3	0.62	22.5	16.2	0.72
63^o	25.7	17.6	0.68	25.0	17.6	0.70
18^o	23.7	16.7	0.70	23.0	12.6	0.55
48^o	23.7	18.6	0.79	23.0	15.6	0.68
8^o	18.0	8.7	0.48	17.5	7.1	0.40
8^o	20.6	5.5	0.27	20.0	5.8	0.29
8^o	19.5	8.0	0.41	19.0	6.2	0.33
8^o	18.5	6.4	0.35	18.0	7.0	0.39
-7^o	17.0	5.3	0.31	16.5	5.5	0.33
-7^o	20.6	6.3	0.31	20.0	6.7	0.34
-7^o	19.5	9.7	0.50	19.0	5.8	0.31
-7^o	22.1	5.9	0.27	21.5	6.4	0.30

	Mean value $\frac{v_{60}}{\hat{V}_{60}}$	Mean value $\frac{v_{46}}{\hat{V}_{46}}$
$18^o < \beta < 63^o$	0.71	0.66
$-7^o < \beta < 8^o$	0.36	0.34

AUTOCORRELATIONS AND POWER SPECTRA

Autocorrelation functions were determined for each channel of every record. Some typical plots from west face transducers in a westerly wind are given in Figure 9. These are from the 13th floor, those from the 7th and 17th floors being very similar. They indicate a general decrease in correlation with increasing time lag, showing that, for example, at a lag of 10 seconds the pressure value will be about 0.2 of its value at any time. In general, similar curves were obtained with easterly winds on the east face, and southerly winds on the south face, although in the latter case the adjacent building affected the results at the lower levels.

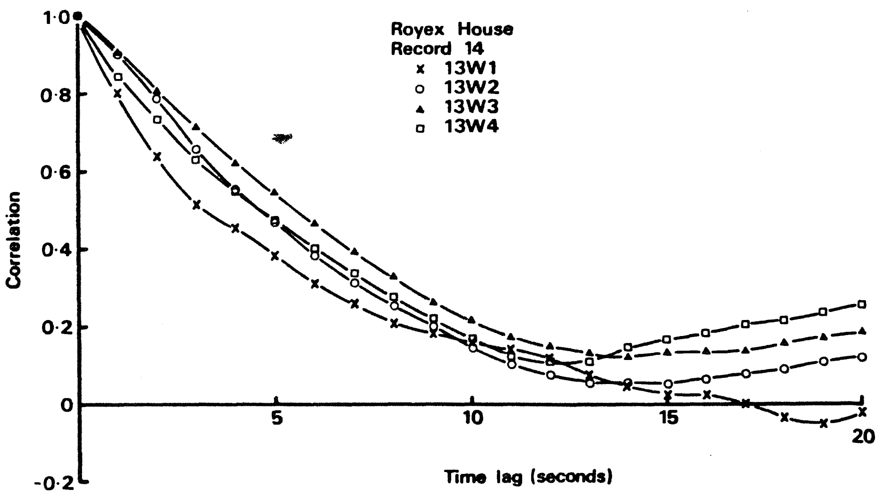

Figure 9 Autocorrelation curves, 13th floor, west face, westerly wind

For the transducers experiencing a glancing wind, the autocorrelation decreased far more rapidly than on the windward face, indicative of the greater fluctuations in the pressure values.

The total variance of a pressure record, σ_p^2, comes from a continuous range or spectrum of simple harmonic signals, ie $\int_0^\infty S_p(n)\,dn = \sigma_p^2$ where $S_p(n)$ is the contribution to the spectrum of the pressure record at frequency n Hz. The presence and magnitudes of peaks in the spectrum may throw light on some basic periodicities which require physical interpretation.

The pressure spectrum (usually called the power spectral density function) was calculated for each channel of each record, and the results were normalised by dividing the ordinates by the total variance of the record. The frequency axis was made non-dimensional by dividing by the mean velocity for the whole record, ie it was converted to the wave number, n/V, so that various records could be compared.

Figures 10, 11 and 12 show some typical spectra for transducers on the windward face, leeward face and a side face (experiencing a glancing wind) respectively. Also shown on Figure 10 is Davenport's universal spectrum for wind speed. In general the shapes of the pressure spectra on the windward face are similar to the wind-speed spectrum. The main peak in the pressure spectrum tends to occur at a slightly higher frequency (a wave number of about 0. 002 cycles/metre), but it was not possible to confirm this definitely as smaller wave numbers could not be obtained (longer records, or higher wind speeds were not available).

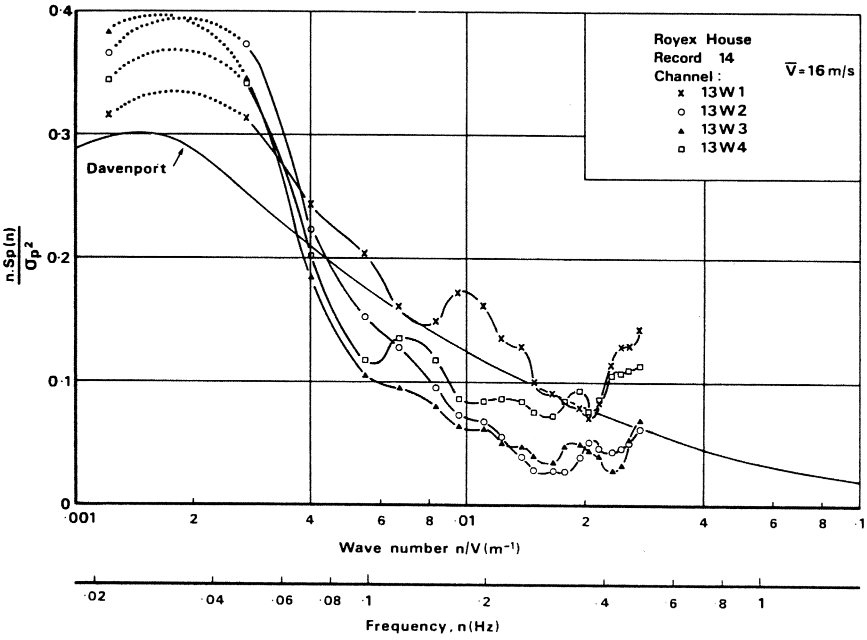

Figure 10 Power spectra, 13th floor, west face, westerly wind

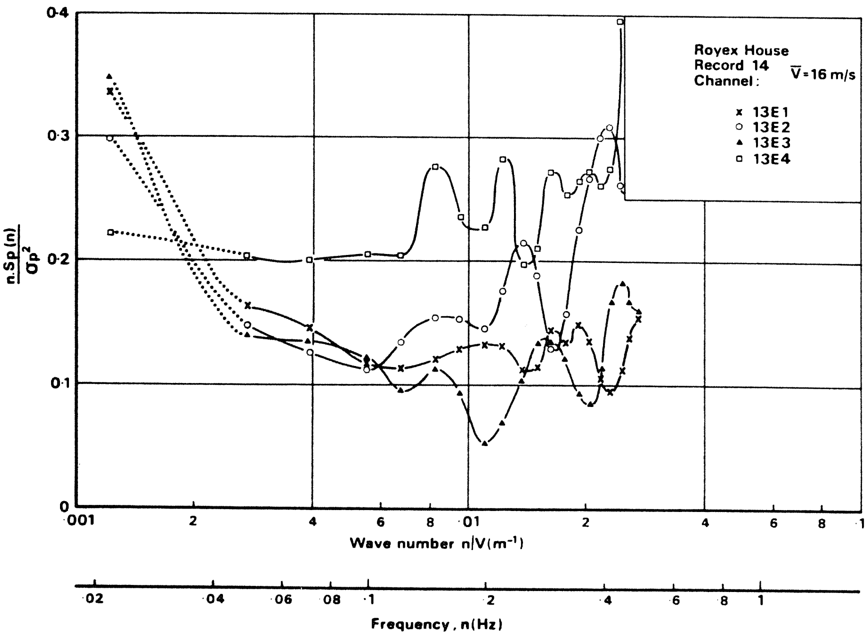

Figure 11 Power spectra, 13th floor, east face, westerly wind

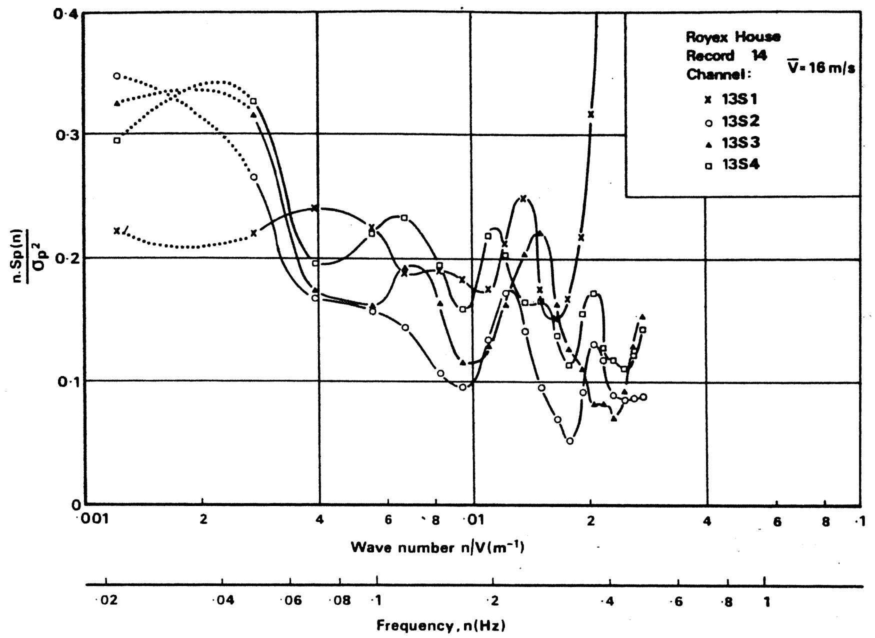

Figure 12 Power spectra, 13th floor, south face, westerly wind

It was also noticeable that for some transducers on the windward face of most records, there were small peaks in the spectrum at a higher frequency. For example, in Figure 10 there is a peak for 13W1 at 0.16 Hz and for 13W4 at 0.1 Hz. The frequency of these peaks varied for different records, but in general they were between 0.1 and 0.25 Hz. This means that there were regular pressure fluctuations on the windward face that had a time period of between 4 and 10 seconds. This could correspond to the pulsations of the windward pressure 'cushion' found by Mackey[13].

The spectra for the pressures on the leeward and side faces do not show much resemblance to the free wind-speed curve. For example, Figures 11 and 12 show some results at the 13th floor level for the east face and south face respectively during record 14 (west wind). In both cases the contribution to the total variance or power is greater at the high frequency end of the spectrum than the corresponding results on the windward face. Eddies were probably being shed from the building itself (and possibly other nearby buildings) causing the turbulence on these faces, whereas the turbulence on the windward face is nearer to that expected from the free wind. (No velocity measurements were actually taken at Royex House, and hence spectra are not available for comparison purposes.)

It has already been stated that it was not possible to investigate the spectrum at lower frequencies, but it was possible to look in more detail at the high frequency end using the results from records 15 and 16 which were recorded at ten times the speed of the other records. For an example the results from all the transducers on the west face in record 15 are shown in Figure 13. Basically this portion of the spectrum is at a wave number (or frequency) that is ten times greater than the previous spectral plots. It can be seen that there is very little contribution to the total variance at these frequencies, with the possible exception of the 7th floor transducers, where there might have been some high frequency disturbances due to the turbulence created by the low building to windward.

By comparison, Figure 14 shows the spectral plots for the 13th floor, east (leeward) face of record 15. Here there is clearly a considerable contribution to the variance at the high frequency end of the spectrum, although the distribution of this could have been modified by aliasing of the data (ie there may be a contribution to the high frequency end of this spectrum from frequencies that are even higher than 5 Hz). However, it is noticeable that the transducers nearer the middle of the face (13E2 and 13E3) show a much greater increase than those nearer the corners of the building (13E1 and 13E4). Without a detailed flow investigation in the lee of the building, no comment on this can be offered at the moment.

CROSS-CORRELATIONS AND COHERENCE

In the same way as the autocorrelation was calculated for individual transducers, so the cross-correlation was calculated for pairs of transducers. This is a measure of the information which is given by the instantaneous value of the pressure at one point, about the value of the pressure at another point and at a time t seconds later. For zero time lag, the cross-correlation is therefore a measure of the relationship between simultaneous values of pressures at different points.

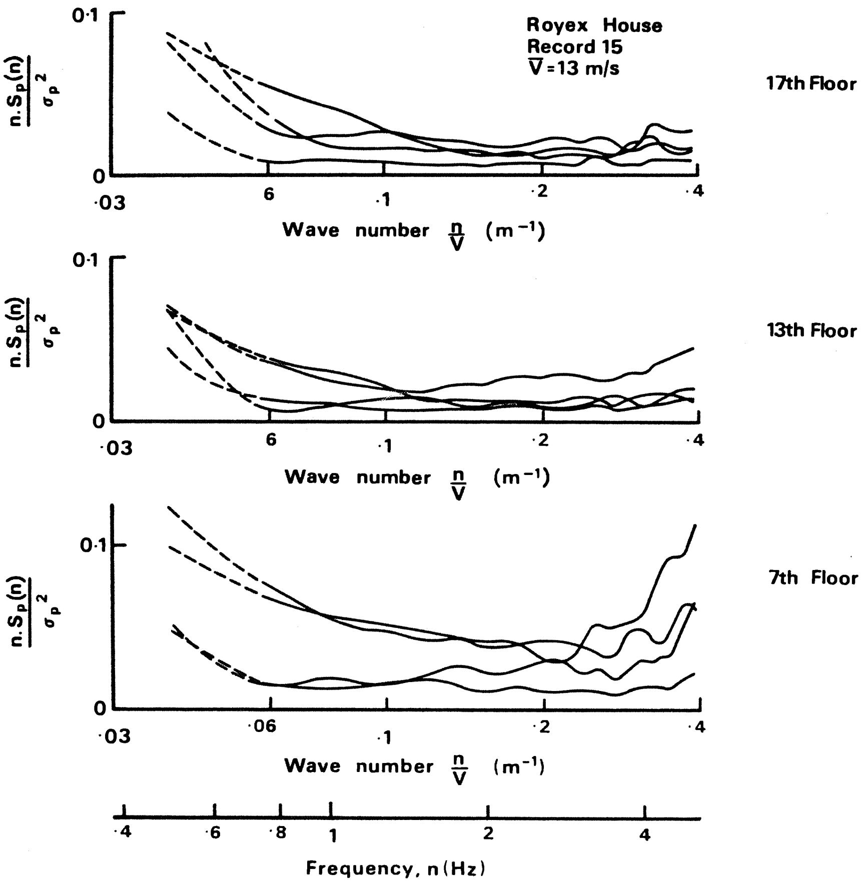

Figure 13 Power spectra, open-scale record, west face, westerly wind

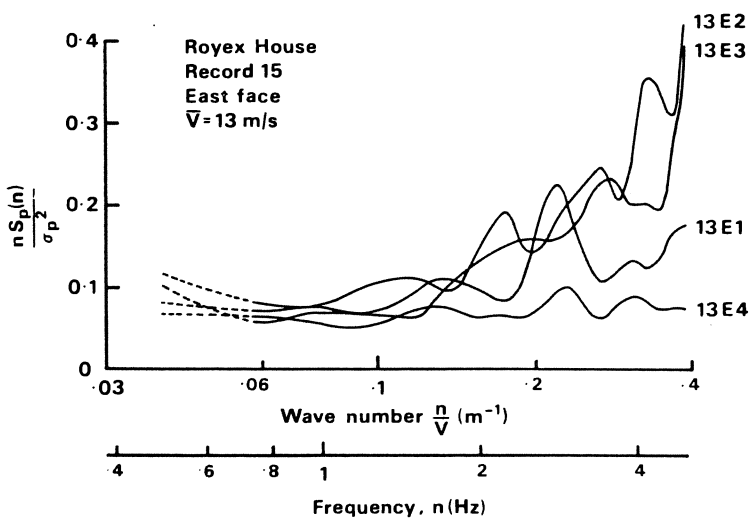

Figure 14 Power spectra, open-scale record, east face, westerly wind

From the cross-correlation, the modulus of the normalised cross-spectrum, called the coherence, was obtained and this gives a measure, for each pair of transducers, of the spatial scale associated with the pressure signals for various frequencies.

Numerous cross-correlations were computed for all the combinations of vertical and horizontal pairs of transducers. Rather than tabulate all the results, the square of the correlation coefficient at zero lag, r^2, was plotted against the distance between transducers. For example, in Figure 15 values of r^2 for vertical cross-correlations are shown for some of the records.

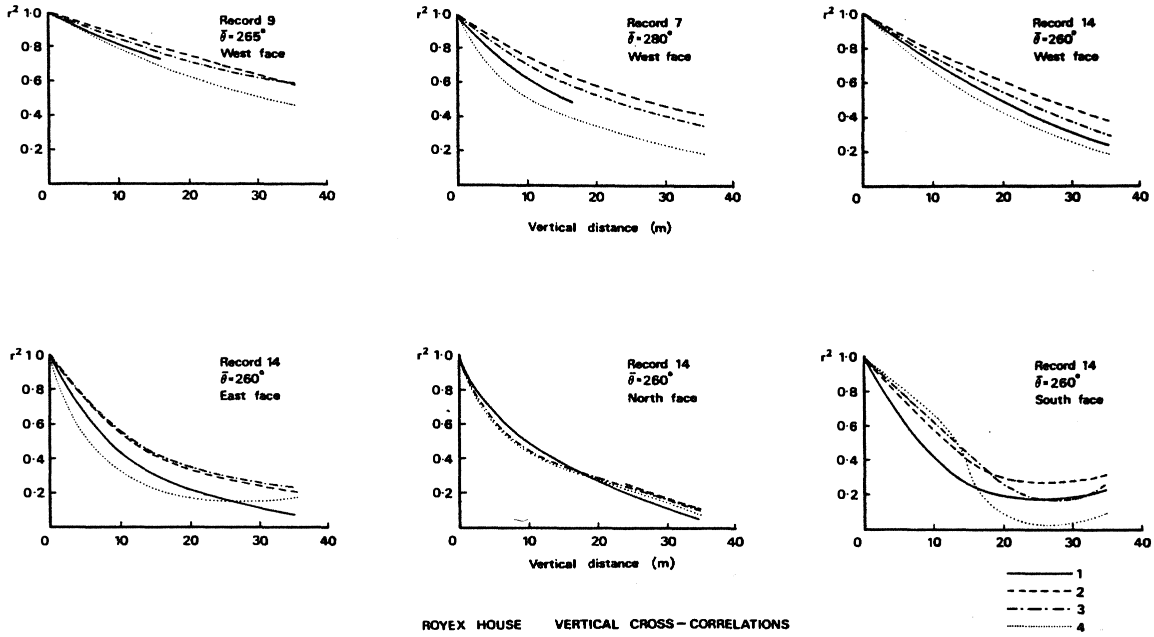

Figure 15 Vertical cross-correlations. Top line: west face, west winds; bottom line: side and leeward faces, west wind

In all cases, as was expected, the correlation decreased as the distance between the transducers increased. The decrease was less on the windward face in a westerly wind, but more rapid in any more turbulent situation. This applied equally well to both horizontal and vertical correlations.

For most cases the pressures on the 13th floor were slightly better correlated horizontally than those on the 17th floor, both levels being better than the 7th floor. Also in most cases of vertical correlation, the pressures in the middle of the face (transducers 2 and 3) were better correlated than those near the edges of the building (transducers 1 and 4).

Values of the square root of the coherence were calculated and plotted against the reduced frequency $nX/\bar{V}$ as for example in Figure 16. The best-fit exponential decay curve was determined in each case, as Davenport suggested[15] that the $\sqrt{\text{coherence}}$ can be expressed in form $\sqrt{\text{Coherence}} = e^{-CnX/\bar{V}}$.

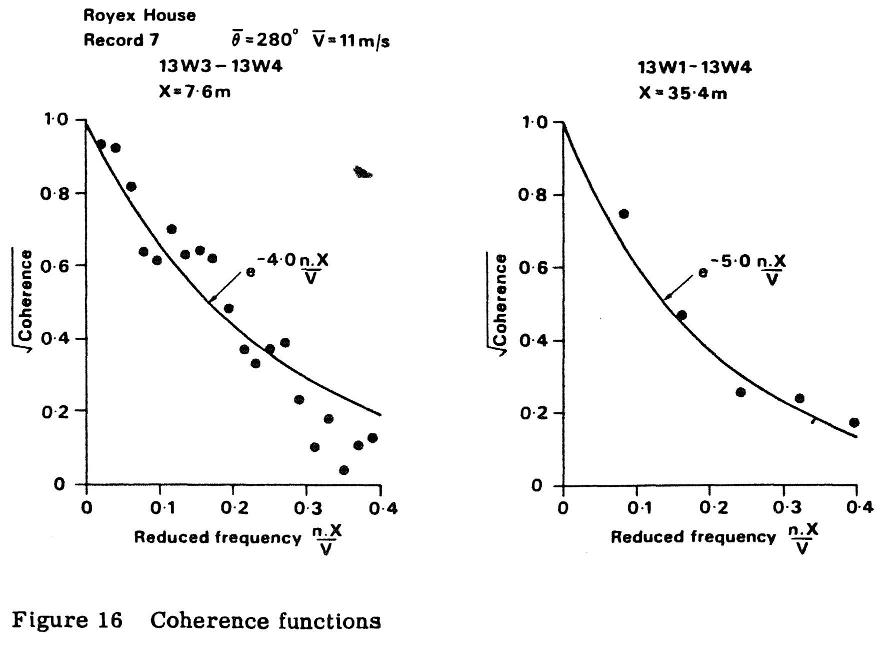

Figure 16 Coherence functions

Having determined the decay constant C, the spatial dimension of a gust can be expressed in terms C and the wavelength of the gust, $\bar{V}/n$, as the 'semi-scale' of turbulence $\bar{V}/n$. Dalgleish[16] uses K for the semi-scale in the horizontal lateral direction, and C in the vertical direction; this notation is retained here.

Over 200 such coherence curves were plotted and the mean values (and standard deviations) for C and K are given in Table 2.

Table 2 Horizontal and vertical decay factors of coherence

	C (vertical)	K (horizontal)
West face, west winds	4.4 ± 0.9	4.3 ± 1.1
East face, east winds	5.3 ± 1.0	5.7 ± 1.1
South face, south winds	8.4 ± 3.2	5.4 ± 3.3

The vertical distances involved in these calculations varied from 13.4 m to 33.6 m; the horizontal distances on the east and west faces were from 7.6 m to 35.4 m and on the south face from 2.4 m to 15.2 m.

Vellozzi and Cohen[17] give values of the empirical constant for eddies in the free wind. These are:
crosswind direction, K = 23
vertical direction, C = 7.7
along-wind direction, 7.7
As the 'semi-scale' of the turbulence can be expressed as $\bar{V}/Cn$ or $\bar{V}/Kn$, these values indicate that eddies are elongated in the direction of the wind, due to the pressure of the ground. However, when the eddies strike a building the constants are smaller, indicating larger gusts as measured by the pressures on the building. Dalgleish[18] found from his pressure measurements that $K = 7.7 \pm 2.6$. The results in Table 2 are, in general, considerably smaller than this. The westerly winds were in 'relatively smooth' flow, whereas those from the east passed over many more tall buildings, and those from the south had to contend with the adjacent 45 m high building. This, as would be expected, caused a lot of turbulence, resulting in smaller gusts, and hence larger decay factors (particularly in the vertical sense).

If the spatial dimension D of a gust can be expressed in terms of C (or K), the mean velocity $\bar{V}$ and the frequency n, as $D = \bar{V}/Cn$ metres then, with C = 4.4 (approximately the same as K), a particular gust duration that should be used for design purposes can be given by $4.4D/\bar{V}$ seconds. This equation is used to show, in Figure 17, design gust durations for a range of wind speeds and sizes of building.

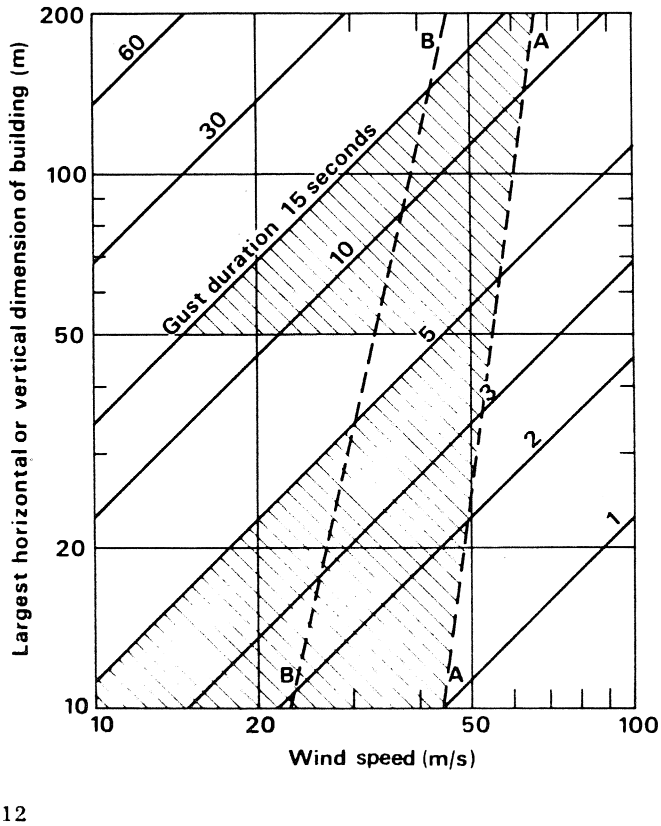

Figure 17 Design gust durations

To design a building for an appropriate gust size, the parameters of building dimension (largest horizontal or vertical dimension) and design wind speed should be used to identify a point on the diagram on or above the line defining the design gust duration. If the point falls below the line which denotes the design gust duration, it is an indication that a shorter gust duration, ie a higher wind speed, is required.

Although the British wind loading Code of Practice[19] uses gust speeds for structural design, there is according to these results a need for reduction of gust averaging times for some buildings. For example, the code uses a 15-second gust for the design of all buildings whose largest horizontal or vertical dimension exceeds 50 m, and a 5-second gust for all smaller buildings. Therefore any building whose dimension and design wind speed bring it within the shaded areas of Figure 17 might require a shorter gust duration and hence a higher wind speed. The line AA represents the upper limit of wind speed that is likely to be used for design purposes anywhere in the United Kingdom, and line BB represents the likely lower limit.

It would therefore seem appropriate that a 3-second duration should be used for the structural design of buildings whose largest horizontal or vertical dimension does not exceed 30 m, a 5-second gust for buildings from 30 m to 50 m, a 10-second gust for buildings from 50 m to 100 m, and a 15-second gust for buildings larger than 100 m.

PERMEABILITY EFFECTS

It is known that the permeability of the face of a building such as Royex House plays a large part in determining the internal pressure and hence the distribution of load between the windward and leeward walls. Permeability is defined as the ratio of the area of openings to the total face area. At Royex House there are openable windows and ventilation louvres, and it is considered that a typical figure for the permeability of the cladding with the windows closed is 0. 2%. It would have been extremely useful if this permeability could have been controlled and varied in order to determine the load variations. This was not possible, but it has been done on another full-scale building. In Hong Kong, Mackey has an experimental building that is to the same proportions, but half the scale of Royex House. It is completely glazed and nominally impermeable, with the exception of special louvres incorporated in each face.

Some preliminary results have been published [20] and these show that the pressures vary, depending on whether the building is in a permeable or impermeable state. One figure from this paper is reproduced in Figure 18.

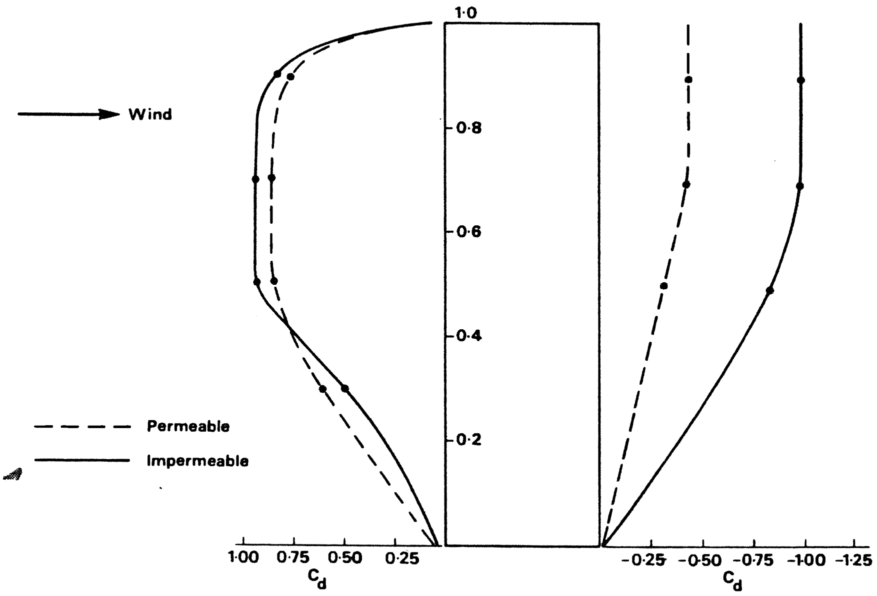

Figure 18 Variation of pressure on the windward and leeward walls for different permeabilities (Mackey)

Mackey's results also confirm another result from Royex House that previously needed clarification[2]. This concerned the low drag coefficient on the (permeable) building; Figure 18 shows that, not only is the relative pressure distribution between the windward and leeward faces altered, but also the overall drag coefficient is reduced when permeability is introduced.

FURTHER WIND TUNNEL TESTS

From the report of the earlier wind tunnel tests[2], some points needed further clarification. The full-scale drag coefficient was very much lower than that in the wind tunnel, and the difference in magnitude of the loads between east and west winds had not been verified in the tunnel.

A new model was therefore constructed, to a 1/200 scale, and this included the surrounding buildings over a much wider area than previously modelled. The model was impermeable, but details such as the roadway beneath the building and parapet on the roof were included. The measurements in a westerly and an easterly wind were repeated, and, with more tall buildings to windward, the results for the east wind were lower than the previous impermeable model, but still not as low as the full-scale results.

Further measurements were then carried out with the wind blowing in turn from directions at $22\frac{1}{2}^{o}$ intervals around the test building. The results are shown in Figures 19, 20 and 21 for the 17th, 13th and 7th floors respectively. In each figure two curves are drawn, one for the model in isolation and the other with the surrounding buildings in position. The results are plotted as force coefficients in the west-east direction regardless of the wind direction, so at 0^{o}, 180^{o} (and 360^{o}) they approach zero. However, the interesting feature is the difference between these two curves at each angular position. From some directions there is relatively little difference, and this is seen to be opposite a position without any tall buildings upwind or lower buildings nearby. (The skyline around Royex House is indicated at the bottom of each figure, the darkest shading representing nearest buildings.) The most notable differences occur in the lee of the other 67 m high buildings; the closer the building the greater the shelter.

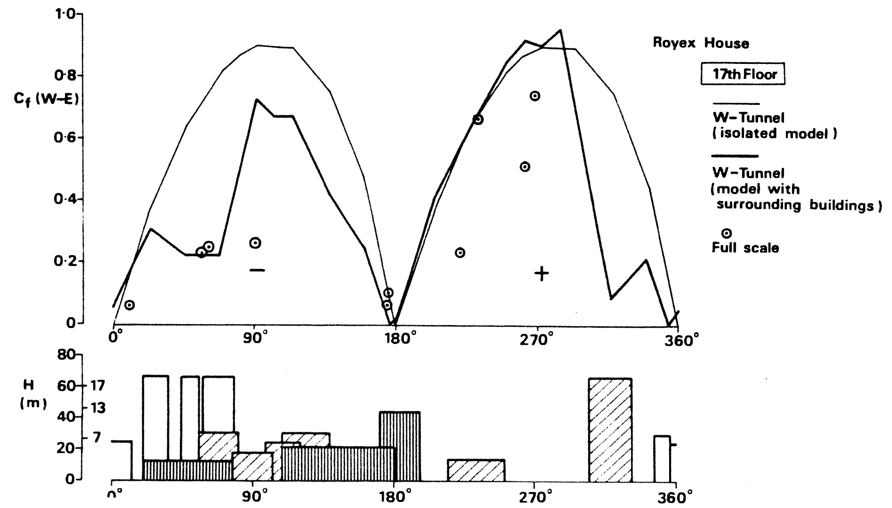

Figure 19 West-East force coefficients, wind tunnel and full-scale tests, 17th floor

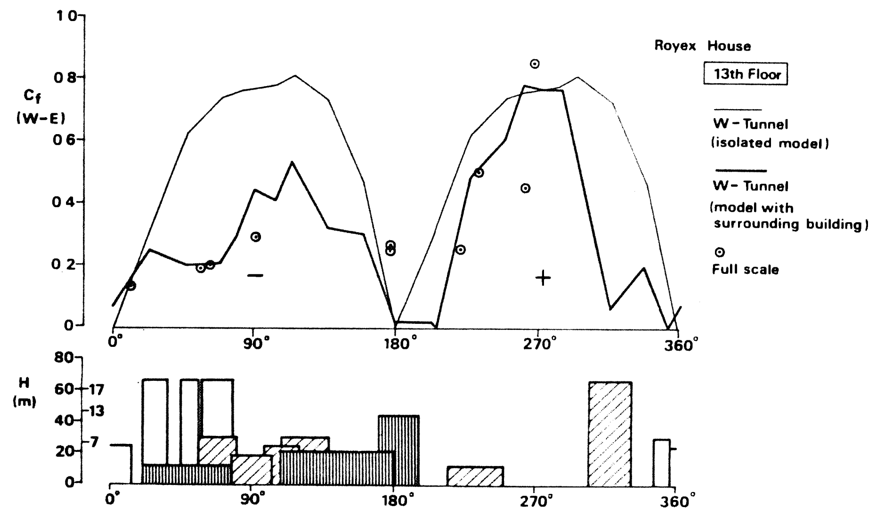

Figure 20 West-East force coefficients, wind tunnel and full-scale tests, 13th floor

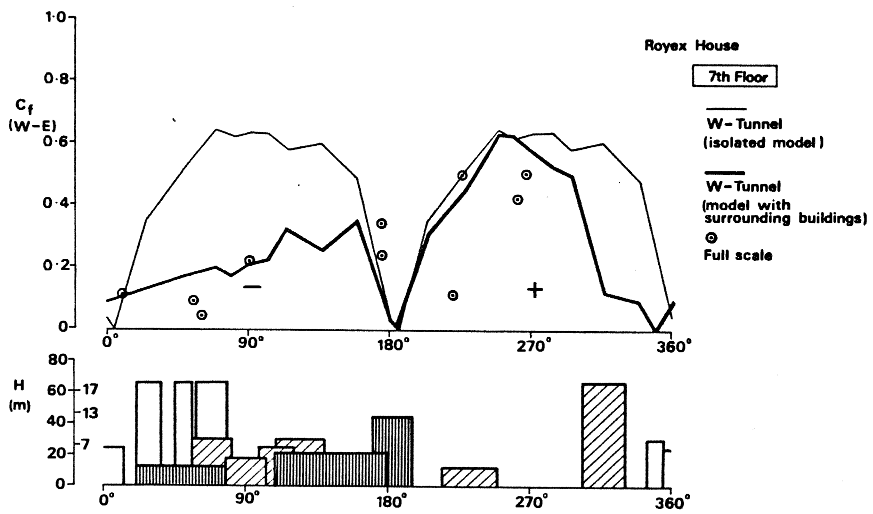

Figure 21 West-East force coefficients, wind tunnel and full-scale tests, 7th floor

For comparison, the full-scale results are also included. In general there is reasonable agreement with the in-situ model, but the results from one or two records cannot be explained except that possibly the mean wind direction, as obtained from the London Weather Centre, did not apply at Royex House. In particular the easterly (90^o) wind might have been blowing locally from nearer 70^o, and this would explain the differences between full-scale and wind tunnel measurements previously found.

Therefore on the full scale the difference between the loading due to westerly and easterly winds is due to the sheltering effect of the nearby tall buildings. The magnitude of the wind tunnel drag coefficients, where measured with all the surrounding buildings modelled, agrees well with the full-scale results.

Whilst this model was in the tunnel, it was possible to look at the cladding loads due to southerly and northerly winds. Differences had been noticed in the full-scale results[1] and this was confirmed in the tunnel as being due to the nearby 45 m high building to the south of Royex House.

DISCUSSION AND CONCLUSIONS

Several points have emerged from this further study of the data from Royex House. The spectra indicate that the pressure fluctuations on the windward face of the building are similar to the velocity fluctuations in the undisturbed wind, whilst the spectra from the other three faces are not similar, indicating that the pressure fluctuations are mainly due to the eddies shed from the building itself. On the windward face there are small peaks in the spectra which indicate a regular frequency of pressure fluctuations at a time period of between 4 and 10 seconds.

The horizontal and vertical scale of gusts, as experienced by the building, is much larger than that of the undisturbed wind due to the cushioning effect on the front of the building. As a result of these measurements of gust sizes, recommendations are made for design gust durations for various sizes of building. In particular, the authors strongly recommend the use of a 3-second gust for the structural design of small buildings.

In determining the peak cladding loads, higher values were obtained (Cpe = -1.6) when the wind was blowing onto the minor face (b/d = 0.42) than when the wind was blowing onto the major face (b/d = 2.4), when Cpe = -0.8. It also appears that the zone of influence of these peak cladding loads might be a greater distance from the leading corners of the side faces than the value of 0.25w which is recommended in CP3 Chapter V[19].

It is unfortunate that dynamic design methods cannot be fully assessed, due to the fact that complete information on velocity, pressure and response is not available. However, pressure spectra are presented so that comparisons can be made with other studies. In particular, the peaks in these spectra due to the pressure pulsations on the windward face could lead to trouble on another building if its natural frequency was similar.

Van Koten[21] has already used the information on gust sizes contained in this paper for a comparison between measured and computed amplitudes of oscillation in buildings. The agreement obtained was good, and indicates the inaccuracies that are likely to occur when using gust sizes of the undisturbed wind.

Dalgleish[22] has applied a statistical treatment to obtain peak gust factors for the design of cladding. He defines the peak gust factor, g, as

$$|\text{Peak pressure}| = |\text{Mean pressure}| + g \; |\text{rms pressure}|$$

From his measurements on a tall building in Montreal he obtained an overall mean value for g of 4. 5. For comparison purposes, results from two records at Royex House have been presented in the same way in Table 3 (record 14, westerly wind) and Table 4 (record 5, northerly wind). These are based on the peak 1-second pressure (or suction) that occurred during the record, together with the mean and rms pressures averaged over the length of the record (790 seconds for record 5, 1100 seconds for record 14). In general, the results are higher than those of Dalgleish, although there are variations at different levels and on different faces of the building. In particular, the factor decreases at higher levels, and is also lowest on the leeward face of the building. Before a value of g can be adopted for future cladding design, it would therefore appear that further work is ncessary to see whether the value of 4. 5 (Dalgleish) or a value between 5 and 6 (this paper) is more appropriate.

Table 3 Peak gust factors, record 14 (westerly wind)

	Windward face		Side face		Leeward face		Side face		Mean
17th floor	W1	4. 4	N1	6. 3	E1	4. 8	S1	6. 2	5. 5
	W2	6. 9	N2	6. 1	E2	5. 4	S2	5. 0	
	W3	6. 2	N3	6. 8	E3	4. 0	S3	4. 6	
	W4	7. 2	N4	5. 4	E4	3. 7	S4	4. 9	
13th floor	W1	6. 1	N1	6. 5	E1	4. 6	S1	6. 9	5. 8
	W2	4. 7	N2	-	E2	4. 3	S2	4. 0	
	W3	6. 3	N3	4. 9	E3	3. 1	S3	6. 2	
	W4	9. 7	N4	8. 4	E4	5. 9	S4	4. 7	
7th floor	W1	6. 2	N1	8. 6	E1	3. 3	S1	5. 5	6. 3
	W2	5. 8	N2	7. 9	E2	4. 1	S2	5. 4	
	W3	6. 9	N3	8. 9	E3	5. 0	S3	6. 6	
	W4	8. 2	N4	8. 7	E4	6. 3	S4	3. 7	
Mean	6. 6		7. 1		4. 5		5. 3		5. 9

Table 4 Peak gust factors, record 5 (northerly wind)

	Side face		Side face		Mean
17th floor	W1	6. 1	E1	3. 3	4. 8
	W2	4. 0	E2	5. 5	
	W3	3. 0	E3	5. 7	
	W4	4. 9	E4	5. 9	
13th floor	W1	6. 7	E1	7. 8	5. 7
	W2	4. 7	E2	5. 0	
	W3	4. 5	E3	5. 1	
	W4	6. 5	E4	5. 2	
7th floor	W1	-	E1	5. 7	4. 6
	W2	3. 4	E2	4. 4	
	W3	4. 0	E3	2. 9	
	W4	8. 7	E4	2. 9	
Mean	5. 1		5. 0		5. 0

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APPENDIX Details of records analysed from Royex House

(Note: $\bar{\theta}$ is relative to the north-south axis of the building)

Record	Date	Time (GMT)	$\bar{\theta}$	$\hat{V}$ (m/s)	$\bar{V}$ (m/s)	T (seconds)	Transducers used E	W	N	S
1	1. 11. 65	11. 10	230°	24	13	800	12	12	-	-
2	6. 11. 65	11. 46	60°	16	11	350	12	12	-	-
3	6. 11. 65	12. 46	55°	18	11	350	12	12	-	-
4	16. 11. 65	06. 59	90°	18	12	640	12	11	-	-
5	20. 11. 65	21. 45	10°	15	10	790	12	11	-	-
6	23. 11. 65	19. 11	220°	23	14	1000	12	11	-	-
7	29. 11. 65	19. 25	280°	16	11	800	12	11	-	-
8	30. 11. 65	10. 51	250°	18	10	780	12	11	-	-
9	30. 11. 65	13. 21	265°	21	13	760	12	11	-	-
10	29. 12. 65	17. 04	175°	19	12	800	12	12	-	-
11	29. 12. 65	17. 57	175°	22	18	770	12	12	-	12
12	29. 12. 65	19. 12	175°	21	18	1200	12	12	-	-
13	27. 3. 66	11. 10	260°	31	17	1100	12	12	12	12
14	27. 3. 66	11. 46	260°	29	16	1100	12	12	12	12
15	16. 11. 66	10. 20	275°	18	13	100*	12	12	12	12
16	2. 12. 66	11. 07	260°	18	12	120*	-	12	12	12

* Sampling interval 0. 1 second.

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