WIND LOADING OF A TALL BUILDING IN AN URBAN ENVIRONMENT

A COMPARISON OF FULL SCALE AND WIND TUNNEL TESTS

by

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Introduction

An investigation into the actual loading due to the wind on a major tall building in central London has been in progress during the past three years, and some results of the measurements were published recently (1). It was shown that there are marked differences between the full scale measurements and the loads that would have been expected on the basis of wind tunnel tests. The overall structural loads due to gusts were much greater than the mean loads averaged over 1 minute (which is the basis of assessment in the current code of practice (2), but on the other hand the overall drag coefficient was much less than that predicted from the model test. Moreover, on the actual building it was found that virtually the whole of the wind load was carried by the windward face whereas model tests had shown, and current practice assumes, a sharing of the load between the windward and leeward faces. These results, which require further verification, could have a far-reaching influence on structural design to resist wind loads, and in consequence there has been further analysis of some of the results of the full-scale tests, and additional exploratory work to obtain corroborative evidence and to ascertain whether the results of this particular case could be applied more generally.

The building is an 18-storey office block having a rectangular plan with sides of 42 m (142 ft) and 18 m (58 ft) and with relatively smooth facades. The height is 72 m (220 ft). The building, known as Royex House, is shown in figure 1, and a site plan showing the position of neighbouring buildings is shown in figure 2. It will be noticed that there are no tall buildings close to Royex House on the west side, so westerly winds are relatively unobstructed, whereas easterlies are modified by the presence of several blocks with heights up to that of Royex House itself. Pressures were recorded simultaneously from 48 pressure transducers, arranged 12 on each face at the 17th, 13th and 7th floors as shown in figure 3.

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Features in the full-scale results

The first feature to which attention was directed was the low drag coefficient which was found from the full-scale measurements. Further readings of the face pressures on the building under a wide range of wind speeds were therefore examined. The previous value of the drag coefficient (0,8) was confirmed at wind speeds gusting to about 17 m/sec (38 m.p.h.) but there is some indication that the drag coefficient (C_d) depends on wind strength, and falls to even lower values as the strength of the wind increases. The results are given in table 1 and are shown graphically in figure 4.

The apparent reduction of drag coefficient in strong winds is a feature that needs further investigation. Whilst it may be a real effect resulting from the increased turbulence in strong winds, it is possible that the change may have resulted from an excessive wind speed indication due to turbulence affecting the anemometer under these conditions and the result should be treated with caution until the performance of the anemometer which was used to establish the reference wind speed has been checked. The measurement of wind speed in an urban environment and its correlation with the pressure readings is one of the most difficult aspects of an experiment such as that at Royex House.

The suggestion that the drag coefficient varied with the averaging period used for load and wind speed measurements, which had been made in the earlier paper (1) has not been substantiated. The conclusion had been drawn from drag coefficients calculated as the ratio of the mean pressure on the building over a given averaging period to the pressure head of the gust over the same averaging period, the latter value having been computed from Durst's gust ratios as modified by Shellard (3). Data are now available from open scale records of wind speed taken at the Post Office Tower in London (4) and these have been used to compute the gust speeds, at Royex House roof level, over various averaging periods, for each of the recordings at Royex House; and the drag coefficients have now been based on these values of gust speed. It is seen from table 1 that the drag coefficient is virtually independent of the averaging time adopted for load and wind speed, even down to the shortest (2 second) gust, a striking indication of the relevance of the gust in relation to the overall wind loading of a structure of the size of Royex House.

3.4

In view of the above result, two records of wind pressures which had been taken at a chart speed of 10 mm/sec were measured at intervals of 0,1 sec. to determine the effects of even shorter load-averaging periods. The results are included in the graphs in figure 5. It is seen that the total wind load on the building continues to increase as the load-averaging time is reduced. The load over 0,1 sec is about 5 per cent greater than that averaged over 1 sec. This indicates that the lateral dimensions of short gusts are adequate to produce a spread of loading on a building as large as Royex House. The critical limit of the load duration thus depends on the natural frequency of the structure rather than on the dimensions of the gust.

The next feature investigated was the distribution of wind load as between the windward and leeward faces. Discussion with Mr. Dalgliesh, of the Division of Building Research of the National Research Council of Canada, elicited the information that in an experiment he had carried out on a large building in Montreal the evidence tended to corroborate the B.R.S. finding that the pressure drop is almost entirely across the windward face and that the load on the leeward face is very small, though a precise quantitative assessment in the Canadian experiment was masked by the disturbing influence of the heating and ventilation system in the building.

A small-scale corroborative experiment

A small scale open-air experiment was therefore initiated at B.R.S. to make a further check on this feature. A closed box 1,52 m x 1,52m x 9,92m (5 ft x 5 ft x 3 ft) was set up in a situation in the Station grounds where there were no immediate major obstructions but the environment was such as to give rise to turbulent flow. The box was mounted on scaffold tube supports so that the base was 3,05 m (10 ft) above the ground, the major faces of the box being set square to the direction of the prevailing wing. The arrangement is shown in figure 6. The interior of the box was vented to atmospheric pressure. A wind pressure gauge was mounted flush with the centre of each of the major faces, and strain gauges were attached to the scaffold tube supports, near the lower ends, to measure the moment of the wind force and hence the total drag force due to the wind. A cup-generator anemometer was mounted nearby on a height of 3,8 m (12,5 ft). Simultaneous recordings were made from all the instruments.

Measurements were made when the wind was blowing normal to the major face of the box, and it was found that under the wind speeds obtaining at the time of the test (gust speeds ranging from 7,5 to 11,5 m/sec i.e. 17 to 23 m.p.h.) the pressure on the windward gauge, relative to the interior of the box, was consistently about 1,0q, while the pressure on the leeward gauge, again relative to the interior of the box, was consistently zero. The overall drag coefficient on the box was about 0,85.

Wind tunnel tests

In view of the increasing evidence that there are important differences between the wind forces due to the natural wind in an urban area and the forces as usually measured in the wind tunnel, it was decided to make a special test in the B.R.S. wind tunnel to compare the wind loads on a model of Royex House under a range of conditions from smooth unobstructed flow to something approaching the conditions of the full scale test.

The model used was one to a scale of $\frac{1}{120}$ that had been made and previously tested at the National Physical Laboratory (5) in smooth uniform flow and also in a flow having a vertical gradient of velocity approximating to that in the natural wind. The model was made of wood and the walls were nominally impermeable. An initial check was made in the B.R.S. tunnel, with a vertical wind gradient, on the model as tested at N.P.L. in order to establish a reference condition. The pattern of the results was generally similar, although coefficients tended to be rather smaller in the B.R.S. tunnel, due possibly to the greater degree of turbulence in the air flow as compared with that at N.P.L. (Table 2).

The major buildings in the vicinity of Royex House were then modelled in the wind tunnel around the test model and the measurements of pressure coefficients were repeated. The results for the measuring positions on the major faces are given in Table 3, columns (3) and (8) for a westerly, that is a relatively unobstructed, wind. It is to be noted that the pressure coefficients on the windward face are generally slightly lower than those for the isolated model, column (2) though it is of interest to note that the flow disturbance has led to a slight increase of pressure at the W1 position at all three floor levels. The coefficients on the leeward face are, in general, appreciably lower than the corresponding ones on the isolated model, column (7).

The next step was to introduce some permeability into the walls of the model of Royex House to simulate approximately the minimum permeability of the cladding of the building, that is, the condition with all the windows closed. This was estimated at 0,2 per cent of the surface area. The previous test was then repeated, with the external pressures being measured relative to the pressure inside the model building. The results are given in table 3 in columns (4) and (9). It is to be seen that a further marked change has occurred in the pressure pattern. The pressures on the windward face have significantly increased whilst those on the leeward face have decreased.

This result is, in fact, largely due to the change of reference pressure, but this form indicates more clearly the loads that act on the individual walls of the building and, for purposes of comparison, is to be preferred to the method of presentation generally adopted in wind tunnel tests.

<u>Comparison of full scale with model tests</u>

The coefficients for the full scale test, based on pressure and wind speed averaging periods of 60 seconds, are given in columns (5) and (10) of table 3. It is seen that the model with some permeability in the walls has come reasonably close to the conditions of the full scale test, and had the permeability of the model been increased to simulate the effect of a few open windows it seems likely that an even closer correspondence would have been achieved. The distribution of pressure at the 13th floor level of Royex House, for the four conditions of test, is shown in figure 7 which clearly indicates the improvement towards full scale conditions that can be obtained by the introduction of a scaled permeability into the walls of the model.

The overall drag coefficients are given in table 4 for the various conditions of test. The introduction of neighbouring buildings has effected a noticeable reduction in the effective drag coefficient, (measured in relation to the wind speed at the top of the building) as compared with the test on the model in isolation, even though, in the case of the westerly wind, the obstructions were mainly downwind of the test model. The introduction of the small percentage permeability has not significantly altered the drag coefficient even though it has considerably changed the distribution of loading as between the windward and leeward faces.

The effective drag coefficient on the full scale building in the westerly wind is in reasonable agreement with what was measured in the wind tunnel when steps were taken to simulate the actual conditions, the values of 0,84 and 0,90 being, however, significantly less than what has generally been found for isolated buildings of this shape in wind tunnels with smooth flow.

In the case of an easterly wind which traversed several tall buildings in its approach to Royex House, very large reductions of wind load were found in the full scale measurements. The reduction of load was partially reproduced in the model tests but some differences between the full scale and model results need further investigation before they can be usefully discussed.

Conclusions

The distribution of wind load as between the windward and leeward walls of this typical rectangular tall building is confirmed as being almost entirely on the windward wall. In normal circumstances the load on the leeward wall is negligibly small.

Short duration gusts are significant in loading the building. The gust load is critical down to load averaging periods that are commensurate with the natural period of the building.

The effective drag coefficient of this building, which is typical of many tall rectangular blocks projecting above the general level of their surroundings in an urban environment, appears to be about 0,85 calculated by reference to the maximum speed of the unobstructed wind at the level of the top of the building.

Reasonably close agreement between wind tunnel and full scale tests in the matter of overall drag coefficient can be achieved by using the usual solid models and simulating, as in current practice, the environment and the vertical gradient of wind speed and the natural turbulence; but an assessment of the pressure distribution on the surface of a building to indicate the loads on the individual faces requires a model with permeable walls to represent t e actual permeability of the building. The pressures should be measured relative to the internal pressure inside the model, or the internal pressure should be separately measured and the differential pressures across the faces should be given.

Acknowledgments

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Table 1

Variation of Cd with wind strength and load averaging period

Max gust speed		Load averaging period (seconds)						
m/s	M.P.H.	2	3	5	10	15	30	60
16	36	0,87	0,88	0,89	0,86	0,89	0,80	0,81
17	38	0,77	0,79	0,83	0,84	0,87	0,84	0,80
18	40	0,67	0,68	0,69	0,67	0,66	0,66	0,65
21	47	0,70	0,72	0,72	0,70	0,75	0,63	0,70
21	47	0,72	0,72	0,74	0,77	0,80	0,75	0,74
29	65	0,51	0,52	0,54	0,51	0,51	0,48	0,48

Table 4

Overall drag coefficients - in a westerly wind

(based on a summation of loadings on the windward and leeward faces, those on individual floors referring to a 1 foot deep slice of the building at the level of the pressure-measuring points)

	Isolated model	Model in-situ (impermeable walls)	Model in-situ (permeable walls)	Full scale
17th floor	1,19	1,01	1,05	0,87
13th floor	1,11	0,92	0,93	0,92
7th floor	0,96	0,85	0,85	0,82
whole building	1,05	0,91	0,90	0,84

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Table 2

Pressure coefficients on model of Royex House

Isolated model tested at B.R.S. for comparison with earlier N.P.L. tests.

With wind gradient

Wind on to west face

Pressure coefficients at the 48 gauge positions

Gauge position	N.P.L.	B.R.S.	Gauge position	N.P.L.	B.R.S.	Gauge position	N.P.L.	B.R.S.	Gauge position	N.P.L.	B.R.S.
17 W1	,7	,60	17 E1	-,6	-,50	17 N1	-,6	-,46	17 S1	-,7	-,52
W2	,8	,75	E2	-,6	-,51	N2	-,6	-,46	S2	-,6	-,55
W3	,8	,76	E3	-,6	-,52	N3	-,6	-,49	S3	-,6	-,54
W4	,6	,62	E4	-,6	-,52	N4	-,6	-,50	S4	-,6	-,54
13 W1	,6	,50	13 E1	-,6	-,50	13 N1	-,6	-,48	13 S1	-,7	-,52
W2	,9	,70	E2	-,6	-,50	N2	-,6	-,48	S2	-,7	-,52
W3	,8	,67	E3	-,6	-,51	N3	-,6	-,53	S3	-,6	-,52
W4	,6	,48	E4	-,6	-,52	N4	-,7	-,54	S4	-,6	-,57
7 W1	,4	,42	7 E1	-,6	-,48	7 N1	-,6	-,46	7 S1	-,7	-,50
W2	,7	,59	E2	-,5	-,45	N2	-,6	-,49	S2	-,6	-,51
W3	,7	,54	E3	-,6	-,48	N3	-,7	-,51	S3	-,6	-,52
W4	,4	,35	E4	-,6	-,51	N4	-,7	-,51	S4	-,6	-,52

Table 3

Royex House - comparison of pressure coefficients for various conditions

Westerly wind (based on 60 sec averaging period)

Windward face					Leeward face				
(1) Gauge position	(2) Isolated model	(3) In-situ model (impermeable)	(4) In-situ model (permeable walls)	(5) Full scale	(6) Gauge position	(7) Isolated model	(8) In-situ model (impermeable)	(9) In-situ model (permeable walls)	(10) Full scale
17 W1	,60	,64	,83	,74	17 E1	-,50	-,41	-,24	-,11
W2	,75	,63	,84	,94	E2	-,51	-,36	-,17	-,06
W3	,76	,66	,90	1,14	E3	-,52	-,36	-,17	+,03
W4	,62	,57	,83	1,03	E4	-,52	-,38	-,20	0
13 W1	,50	,52	,67	,89	13 E1	-,50	-,46	-,27	-,20
W2	,70	,60	,78	,80	E2	-,50	-,35	-,17	-,06
W3	,67	,53	,78	,97	E3	-,51	-,37	-,17	-,03
W4	,48	,38	,60	,89	E4	-,52	-,39	-,21	-,06
7 W1	,42	,47	,61	,54	7 E1	-,48	-,47	-,32	-,34
W2	,59	,50	,65	,74	E2	-,45	-,39	-,19	-,06
W3	,54	,45	,61	,89	E3	-,48	-,40	-,21	-,06
W4	,35	,26	,43	,37	E4	-,51	-,36	-,20	-,11

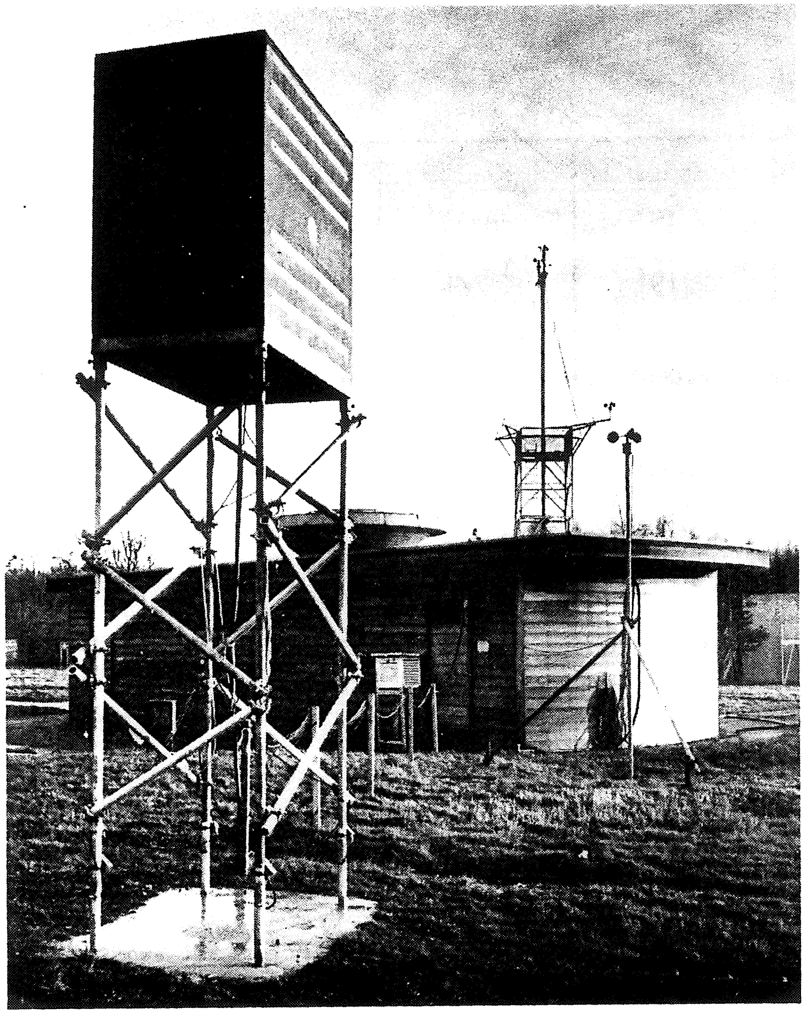

Fig. 6 Arrangement of test object for measurement of wind pressures in the natural wind.

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Fig. 1 Royex House, Barbican, viewed from N.E.

64.401.4

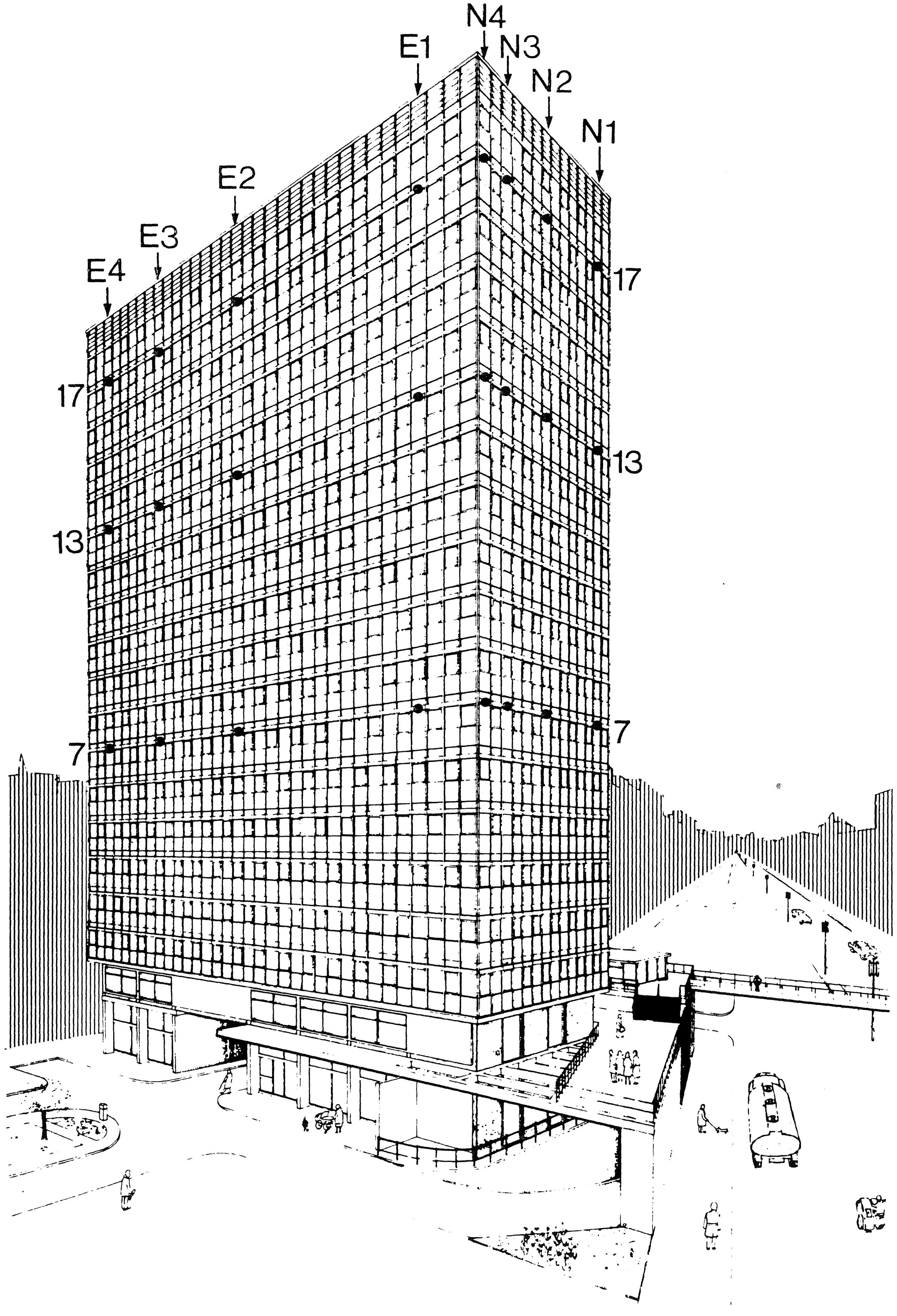

Figure 3 Arrangement of wind-pressure transducers on the face of Royex House.

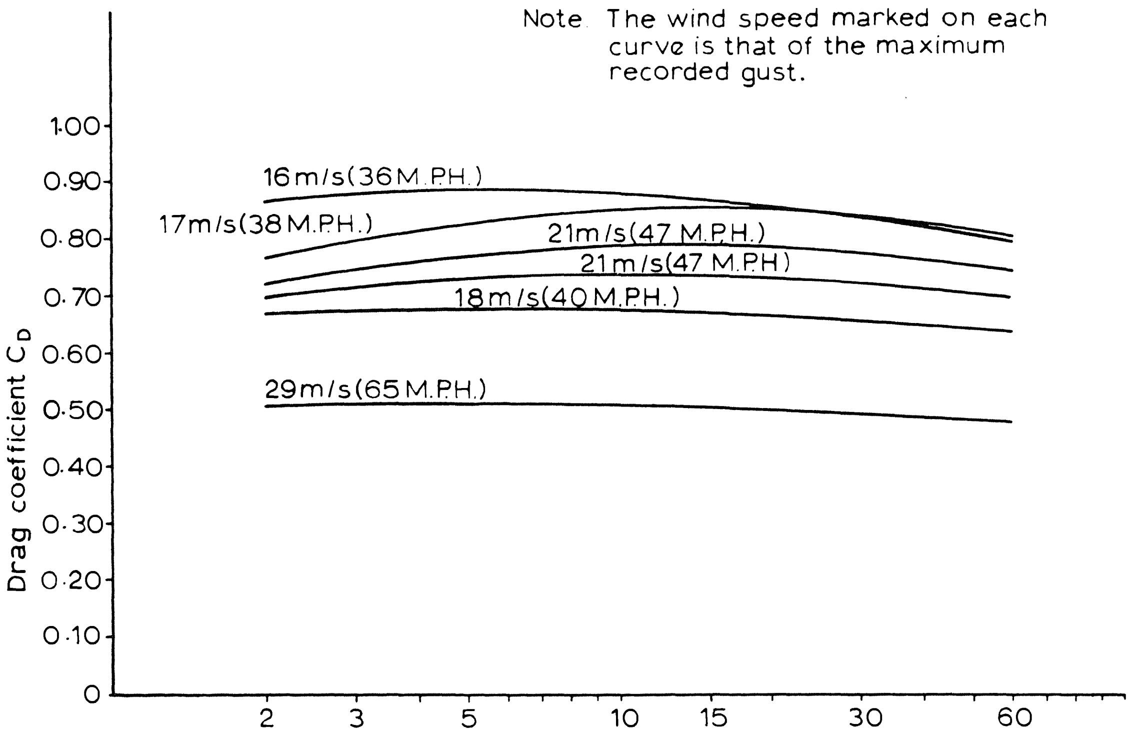

Figure 4 Variation of drag coefficient with averaging period over a range of wind strengths

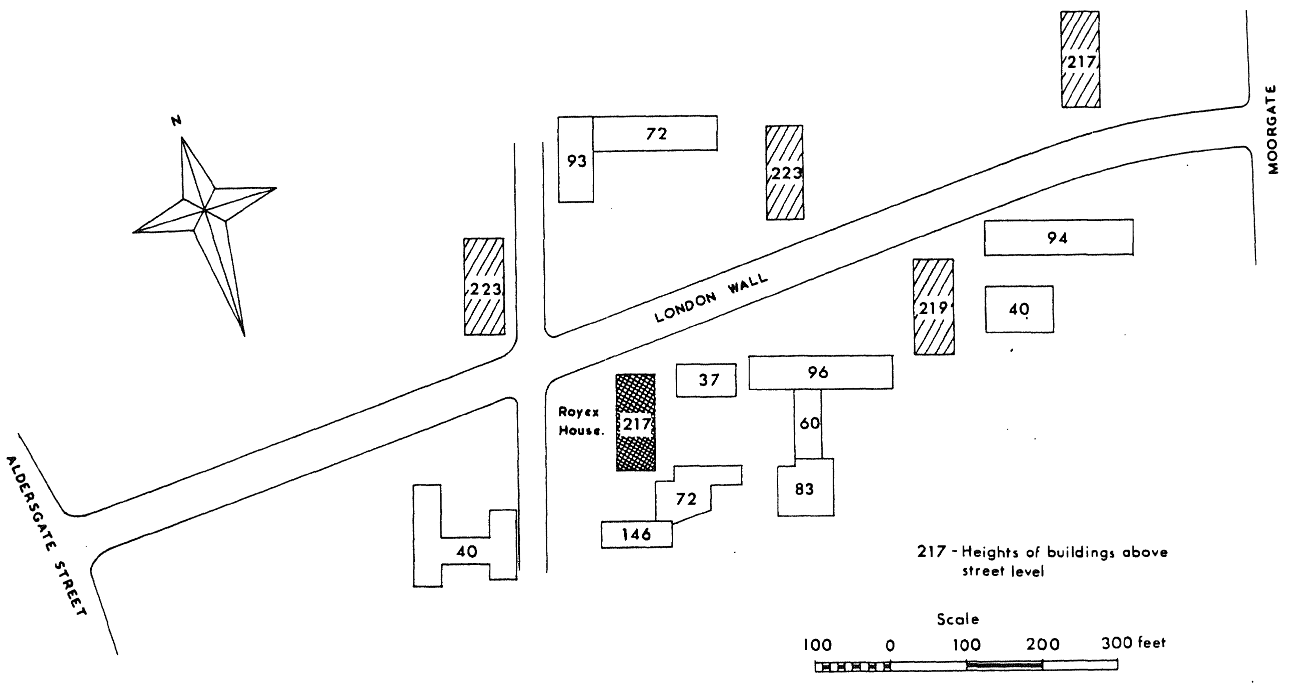

Figure 2. Site plan of area around Royex House

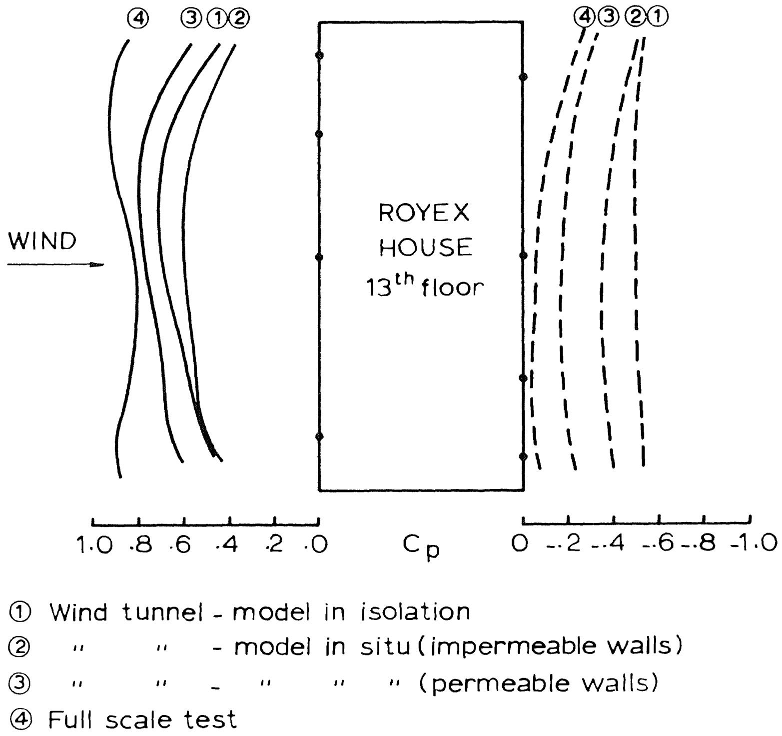

Figure 7 Distribution of pressure on faces of Royex House

Comparisons between full scale and model tests

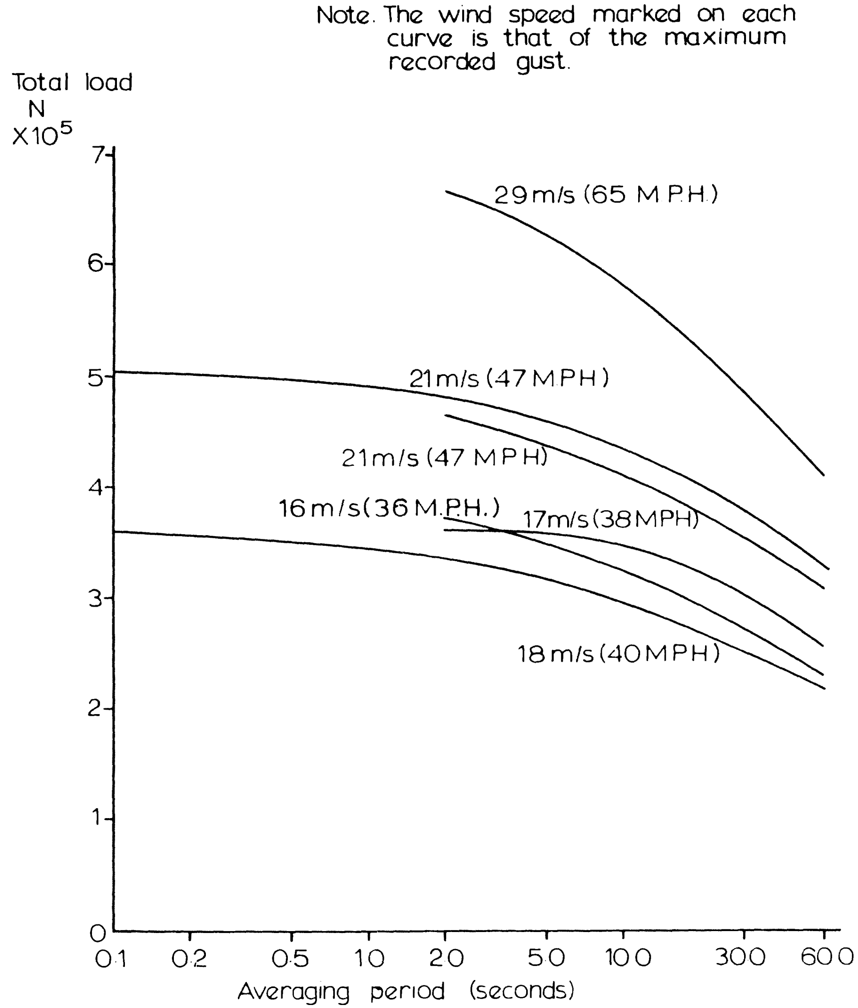

Figure 5 Variation of total wind load on Royex House with averaging period for a range of wind strengths