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BY

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SOMMAIRE

Des expériences récentes de brisure du verre causée par le vent dans des tours de bureaux ont indiqué la difficulté d'identifier les zones susceptibles de créer des problèmes et la nécessité de mieux comprendre l'amplitude et la nature des charges de parement.

L'auteur présente les résultats de mesures de la pression superficielle du vent faites simultanément en 32 endroits dans une tour de bureaux de 57 étages à Toronto. En plus des relevés à intervalles d'une demi-seconde durant des vents violents, on a enregistré la pression moyenne et la pression quadratique moyenne une fois l'heure pendant cinq minutes et on a calculé les coefficients de pression relativement à la pression dynamique en écoulement libre à 286 m pour fins de comparaison avec les données en soufflerie ayant servi au calcul du parement.

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COMPARISON OF MODEL/FULL-SCALE WIND PRESSURES ON A HIGH-RISE BUILDING*

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Summary

Recent experience with wind-induced glass breakage in high-rise office towers has demonstrated the difficulty of pin-pointing potential problem areas on a building and hence the need for a better understanding of the magnitude and nature of cladding loads.

Results of surface wind pressure measurements made simultaneously at 32 points on a 57-storey office tower in Toronto are reported. In addition to readings taken at ½-second intervals during high winds, mean and root-mean-square pressures were recorded for a 5-minute interval once each hour, and pressure coefficients referred to the free stream dynamic pressure at 286 m were computed for comparison with wind tunnel test information which was used in the design of the cladding.

Introduction

Recent occurrences of wind-induced glass breakage in high-rise office towers [1, 2, 3] have emphasized the need for a better understanding of the magnitude and nature of cladding loads and for increased ability in pin-pointing potential problem areas on a building. Wind tunnel studies on scale models are an important source of cladding design information but it is equally important to acquire measurements from full-scale buildings to verify the general applicability of the wind tunnel data to practical design situations.

In this paper, results of surface wind pressure measurements made simultaneously at 32 points on a 57-storey office tower in Toronto are reported. Readings were taken at ½-second intervals during high winds and, in addition, mean and root-mean-square (r.m.s.) pressures were recorded for a 5-minute interval once each hour. Pressure coefficients referred to the free stream dynamic pressure at 286 m have been computed for comparison with wind tunnel test information which was used in the design of the cladding.

* Paper presented at the Symposium on Full-Scale Measurements of Wind Effects on Tall Buildings and Other Structures, University of Western Ontario, 23—29 June 1974.

Wind load design for cladding and structure

Wind pressures on cladding are generally different from those experienced by the structure, particularly in high-rise buildings. The differences arise because the wind-induced pressures on building surfaces are both non-uniform in space and unsteady with time and because the size and dynamic properties of cladding panels differ from those of the structural frame. On the one hand, pressures that produce a load on a structure are averaged over a much larger area than those on a single window or spandrel panel; on the other hand, there can be dynamic amplification of those fluctuations in the flow that correspond approximately to the natural frequencies of the building. Although occasionally rapid fluctuations can be generated, *e.g.*, by vortex shedding around some small obstruction to flow, in general the bulk of the turbulent energy in wind occurs at frequencies that are even lower than the lowest natural frequencies of the structure as a whole. Except in rare cases, therefore, dynamic response is not likely to have a significant effect on cladding, but for tall slender buildings it is usually important in determining wind loading on a structure.

Calculating wind pressures for cladding design

Wind action on structures and cladding, although actually dynamic in nature, is reduced for design purposes to a problem in statics by multiplying a time-averaged reference wind pressure by a "gust effect" factor. In its simplest form, the gust effect factor is a constant value considered appropriate for a large range of conditions. In the National Building Code of Canada, for example, values of 2.0 for structure and 2.5 for cladding are used in conjunction with a reference wind pressure averaged over 1 hour [4].

A more sophisticated procedure is required by the Code for tall slender buildings; the commentary on wind loads contained in Supplement No. 4 [5] to the Code outlines a detailed procedure for calculating a gust effect factor for a structure. It takes account of the turbulence characteristics of approaching winds as well as the size and dynamic properties of a structure.

Although the detailed procedure gives reasonable guidance for the dynamic effect of wind on a structure as a whole, it was not expected that it would be applied to cladding except in certain specific situations. Wind pressure fluctuations on cladding result from fluctuations, not only in wind speed, but also in wind direction. Both variations are implicit in the term "wind turbulence", but the gust effect factor calculated by the detailed method deals explicitly only with fluctuations in speed. Fluctuations in wind direction appear to have a greater influence on local pressures than on the effective loading of the structure as a whole and, as a result, detailed information for cladding design is more difficult to obtain.

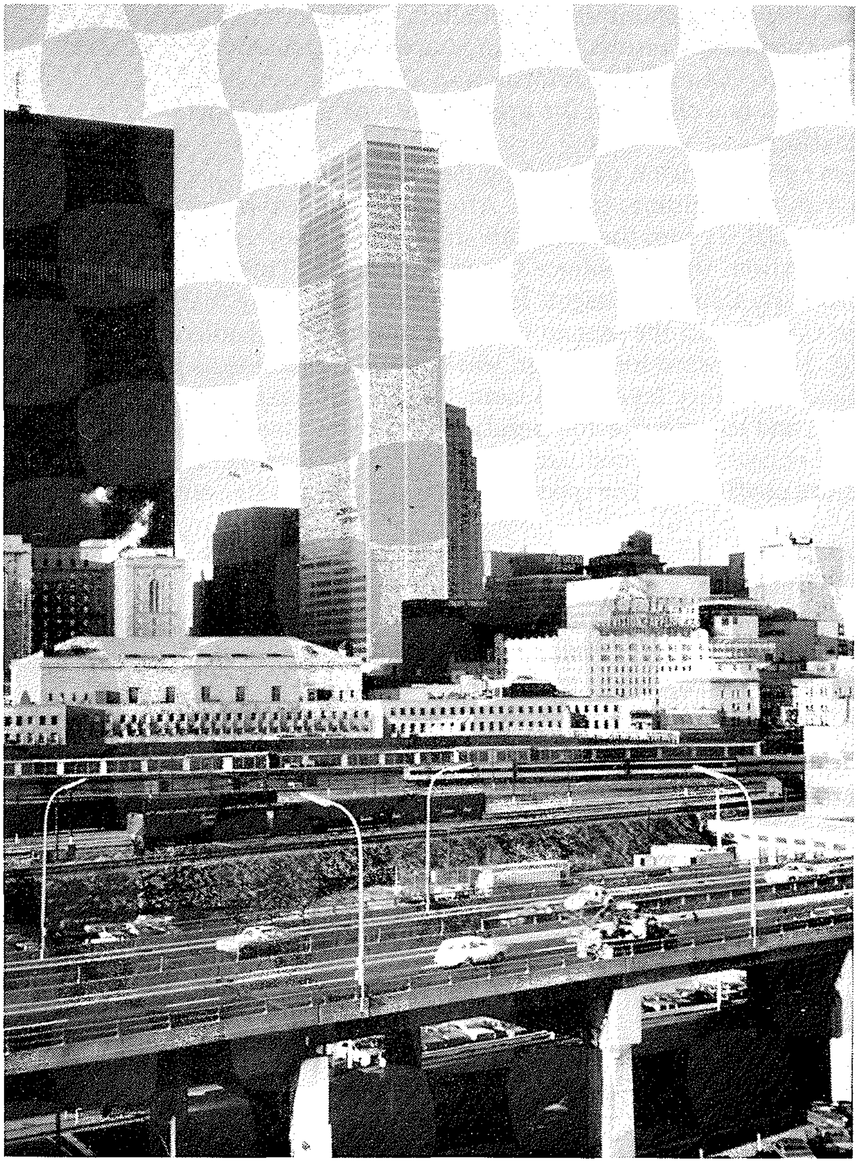

Fig. 1. Commerce Court Tower from the south; (south-west relative to building axis description).

Wind pressure measurements on buildings

Wind pressure design information for a specific building is often derived from wind tunnel tests. Both cladding and structure can be dealt with in this way. If the structure, its immediate environment, and the characteristics of the approaching flow are correctly modelled, the experimental approach should give dependable results. Wind pressure measurements on full-scale buildings can provide essential information about the conditions to be modelled as well as a check on the applicability of wind tunnel data to practical design situations.

Members of the Division of Building Research began making field measurements on high-rise buildings in 1964. After studying two buildings in Montreal, one 34 storeys [6, 7] and the other 46 storeys [8], they instrumented a 57-storey office tower, the Commerce Court building, in Toronto. This building, 36 m by 70 m by 239 m in height, is at the time of writing the tallest office building in Canada and the second tallest in the world outside of the United States (Fig. 1). The wind load design was based on model tests performed in the turbulent boundary layer wind tunnel at the University of Western Ontario [9], and so with the co-operation of the architectural, structural and wind tunnel consultants, a comparison can be made between model and full-scale pressure coefficients for specific points on the building surfaces.

Instrumentation

The following are the essentials of the instrumentation used for estimating mean and r.m.s. pressure coefficients of the Commerce Court building:

(a) 12 holes on each of 4 levels drilled through sill units of 12 windows (2 on each of the narrow walls and 4 on the long walls);

(b) 32 (of a possible 48) differential pressure transducers with a range of ± 960 pascals;

(c) a common internal reference pressure, that of the recording room on the 33rd floor;

(d) a three-cup anemometer and vane (U—2A, Canadian Meteorological Service) mounted on a radio mast 286 m above street level; and

(e) a computer-controlled data acquisition system recording digitally on magnetic tape.

Sampling and recording

Full-scale pressure coefficients were computed from 5-minute mean and r.m.s. pressure differences recorded hourly (with some unavoidable gaps) over the period from January 1973 to January 1974. During each hour for which records were available, mean and r.m.s. values for each sensor for that 5-minute period having the highest average wind speed, as well as for the 5 minutes at the end of the hour, were recorded. The sampling rate for each sensor was 0.5 seconds or a total of 600 samples per 5-minute period.

Mean pressure coefficients

Mean pressure coefficients were obtained from the 5-minute averages in two stages. First, the total wind effect on the pressure difference between the internal reference and the external surface tap was separated from the effects of temperature and mechanical equipment operation by linear regression analysis using the reference dynamic wind pressure at the 286-m level (also averaged over 5 minutes) as the independent variable. Second, the total wind effect was separated into an external and an internal pressure coefficient by arbitrarily setting the external pressure coefficient of one external tap, located in the wake region, equal to the average value for that tap as determined in the wind tunnel experiments. The tap chosen was located as close as possible to the centre of the east, south, west or north wall (depending on wind direction) at approximately two-thirds the height of the building.

Fluctuating pressure coefficients

The r.m.s. pressure coefficients presented less difficulty in that the external wind effect was assumed to be the only significant cause of pressure fluctuations over the 5-minute sampling period. Large fluctuating components are typically present in pressure records from taps located either on the windward wall, where the mean external pressure coefficient is positive, or on a side wall with the wind glancing along the surface, where the mean external pressure coefficient is negative. In the wake regions, however, the fluctuating component is

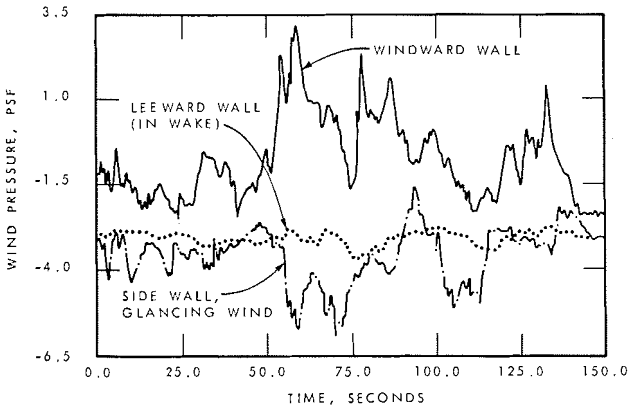

Fig. 2. Characteristic surface pressure fluctuations in different regions of flow.

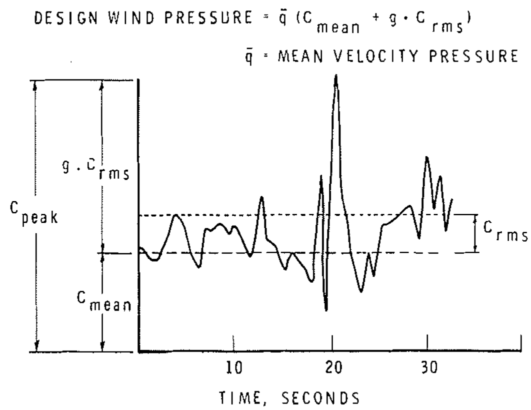

Fig. 3. Portion of actual record of surface pressure illustrating terms used in wind load design.

usually much less important, and the mean external pressure coefficient, although negative, is not as large on the side wall (Fig. 2). The relation between the mean and r.m.s. pressure coefficients, and the peak pressure that the designer must estimate can be demonstrated by a portion of an actual pressure record (Fig. 3). The breakdown of the procedure for predicting local peak pressures (C_{peak}) into the determination of two pressure coefficients (C_{mean} and C_{rms}) and a peak factor is a convenient way to summarize results of observations, both in model and field experiments.

Comparison between tests on models and actual buildings

Model and field full-scale mean pressure coefficients and the r.m.s.m. pressure coefficients (root mean square about the mean) are compared in Figs. 4—13. A definition sketch shows the Commerce Court building in plan and indicates which of the eight instrumented tap locations on one of 4 levels is represented in the graphs of r.m.s. pressure coefficient (above) and mean pressure coefficient (below) plotted against wind direction. The open circles are the model data as provided at the design stage and the solid lines join estimates derived from actual observations of pressure differences on the building during 1973. The shaded areas indicate the standard deviation of the full-scale estimates (Figs. 4—11).

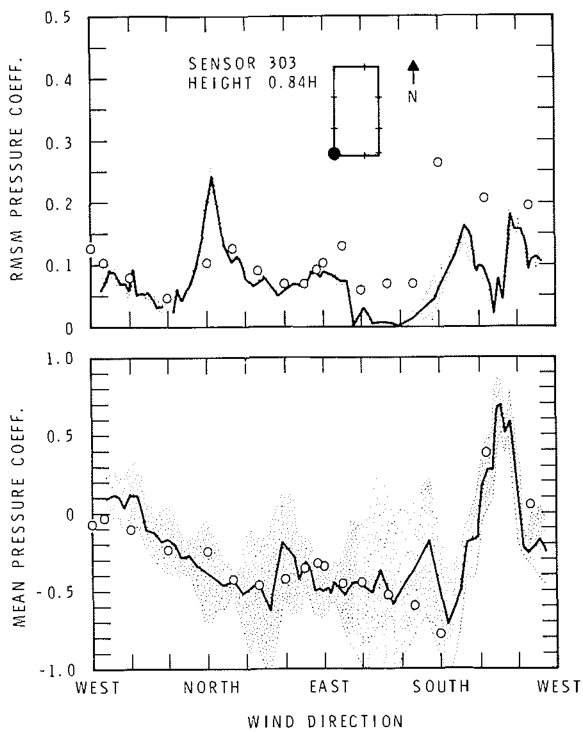

Fig. 4. West wall tap 3.6 m from S.W. corner, 50th floor.

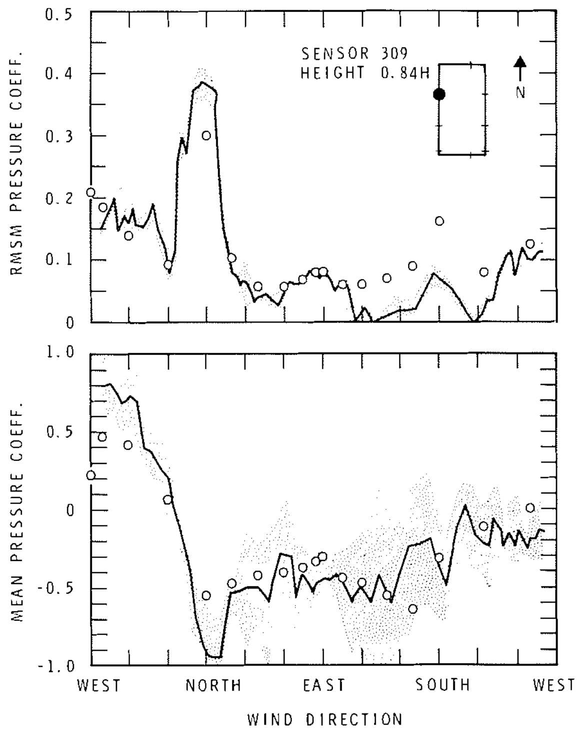

Fig. 5. West wall tap 20.6 m from N.W. corner, 50th floor.

The influence of variations in wind direction on the magnitude of local peak pressures can be readily appreciated from the graphs, which typically indicate large r.m.s. pressure coefficients in conjunction with steep slopes in the graph of mean pressure coefficient *versus* wind direction. This usually occurs when the wind is nearly parallel to the building surface on which the tap is located, *e.g.*, just west of north for sensors 309 and 409 on the west wall (Figs. 5 and 6). For sensors 312 and 712 on the north wall, rapid changes occur for wind directions just north of east (Figs. 7 and 8).

The shelter provided to the west by other tall buildings is apparent from the results for sensors 303, 309 and 409 on the west wall, where the mean pressure coefficient for westerly winds is nearly zero. Where examples are given of sensors vertically in line, but from different levels, it is also possible to observe the reduction in wind pressure as the ground level is approached (Figs. 10 and 11). Finally, the over-all agreement between model and full-scale can be indicated in terms of base shear and moment in the west-to-east and the south-to-north directions respectively (Figs. 12 and 13).

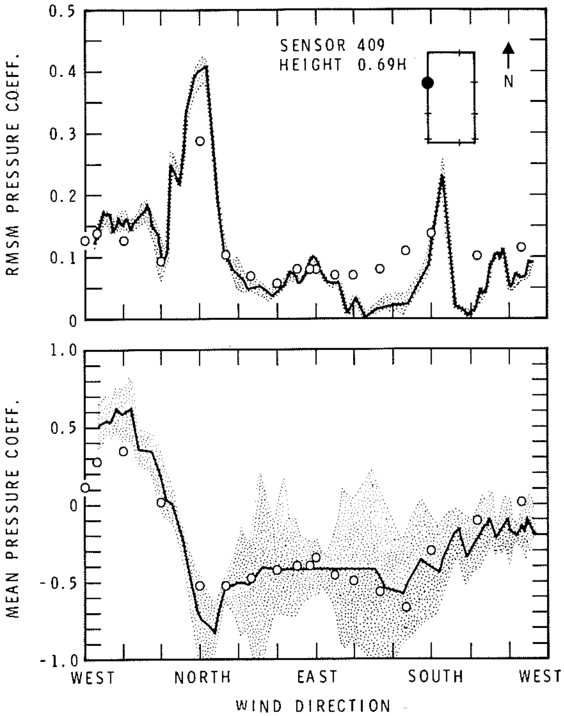

Fig. 6. West wall tap 20.6 m from N.W. corner, 41st floor.

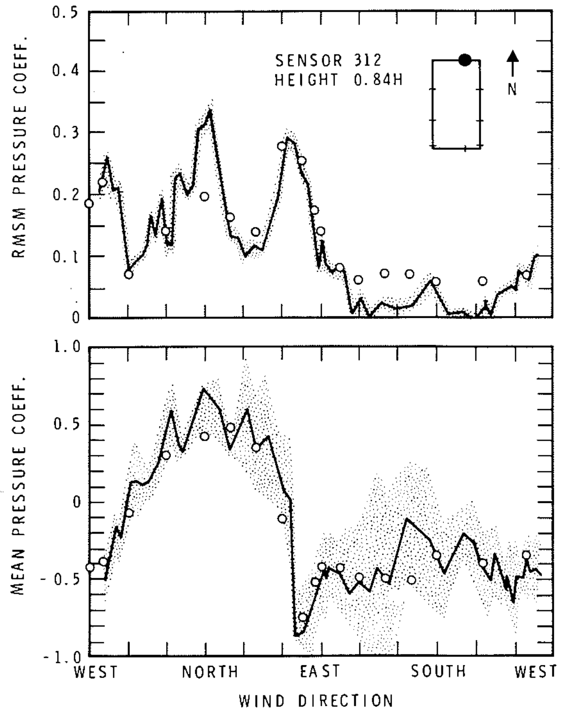

Fig. 7. North wall tap 10.7 m from N.E. corner, 50th floor.

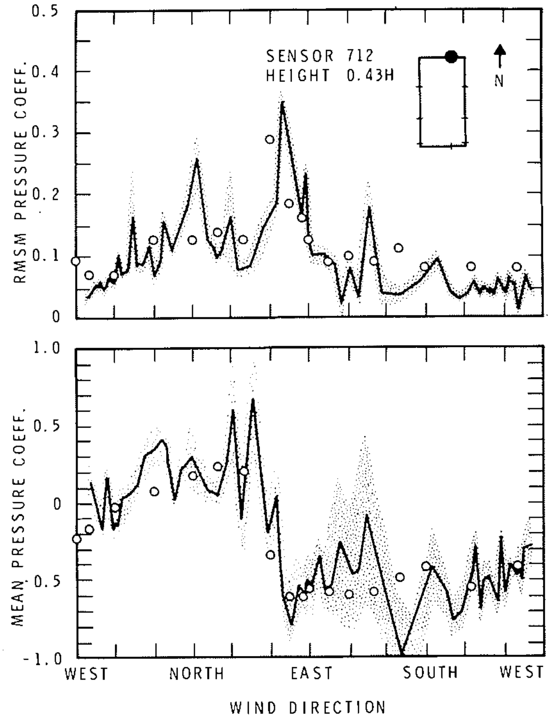

Fig. 8. North wall tap 10.7 m from N.E. corner, 25th floor.

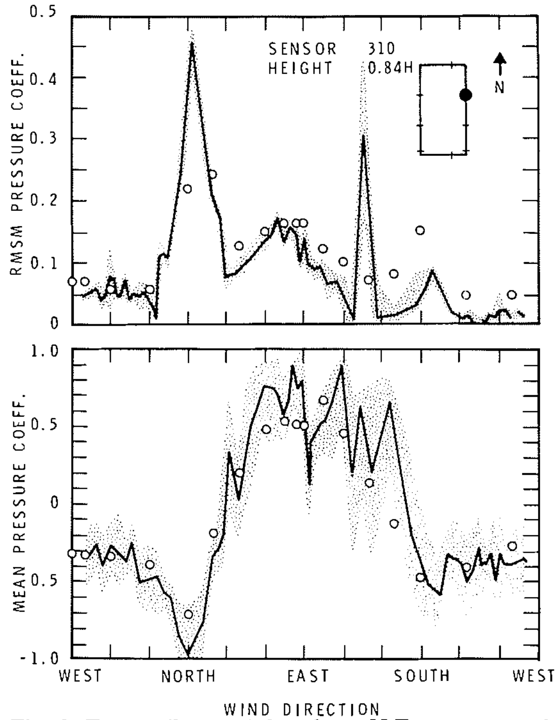

Fig. 9. East wall tap 20.6 m from N.E. corner, 50th floor.

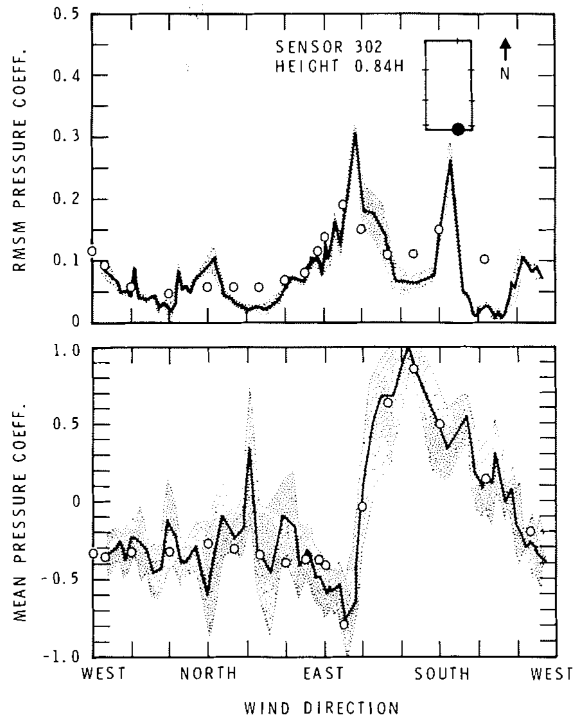

Fig. 10. South wall tap 10.7 m from S.E. corner, 50th floor.

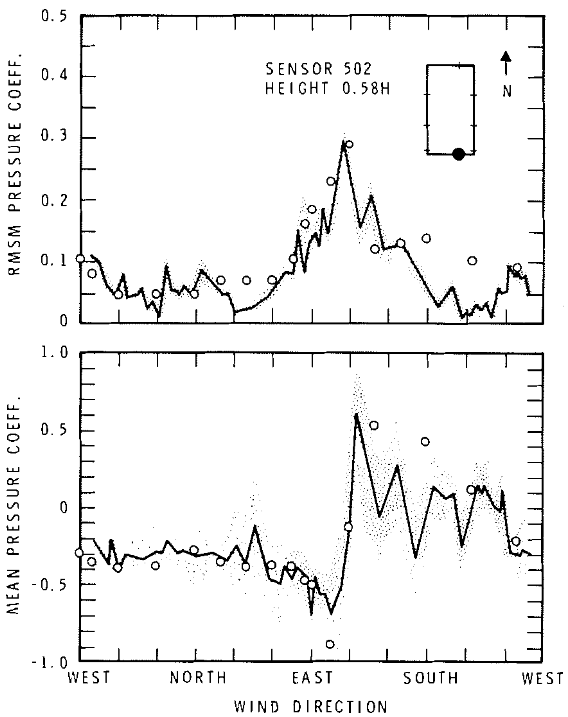

Fig. 11. South wall tap 10.7 m from S.E. corner, 34th floor.

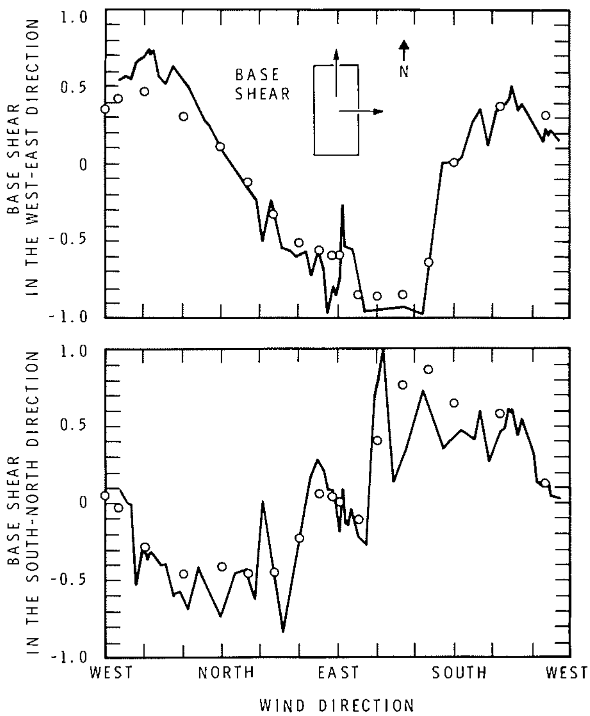

Fig. 12. Base shear coefficients as the weighted sums of individual pressure coefficients.

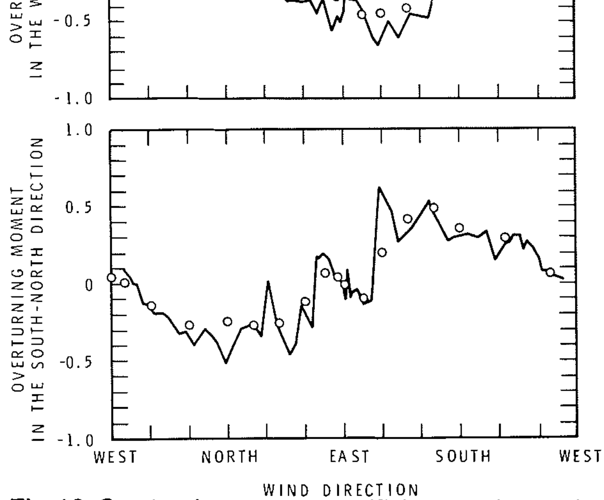

Fig. 13. Overturning moment coefficients as the weighted sums of individual pressure coefficients multiplied by distance to base.

Discussion and conclusion

Although, at this early stage in the project, only a preliminary assessment can be offered, the results so far indicate satisfactory agreement between model and full-scale measurements of mean pressures. The agreement between model and full-scale mean pressure coefficients is within the limits of the experimental error in full-scale observations, but it is too early to say the same for the r.m.s. pressure coefficients. One reason for this is that winds from the south have not been frequent enough or strong enough to provide sufficiently reliable r.m.s. data. Fluctuations in wind direction are an important factor in determining local peak pressures and suctions, particularly near the leading edges of walls almost parallel to the wind. The full-scale observations will be continued for another two or three years and additional wind tunnel tests may be carried out.

Acknowledgements

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