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BY

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The paper provides information on the relation between turbulence in a strong wind in a city environment and the wind pressure fluctuations on an actual building. Preliminary work in co-operation with the University of Western Ontario to compare the full-scale measurements with wind-tunnel measurements indicates that successful simulation of the basic statistical properties of wind pressure fluctuations can be obtained through the use of model complexes in a boundary layer type of wind tunnel.

Résumé

Les auteurs ont analysé des enregistrements, durant de 15 minutes à une heure, de la pression résultante du vent contre les faces d'un édifice élevé de Montréal (Canada) e vue de déterminer les pressions moyennes, les variances, les fonctions d'autocorrélation, et pour des paires choisies de transducteurs manométriques, les transformées de Fourier de leur corrélation. Douze transducteurs manométriques fonctionnant simultanément avaient été placés à deux étages différents espacés de 122 m (400 pi.). Les mesures ont été effectuées au cours de cinq tempetes différentes entre le 5 mars 1964 et le 2 mars 1966. La plupart des pressions enregistrées ont été accompagnées de l'enregistrement concomitant de la direction et de la vitesse du vent à une altitude de 244 m (800 pi.) par une girouette et un anémometre à un poste d'observation voisin.

Le présent exposé fournit des renseignements sur la relation entre la turbulence d'un fort vent soufflant sur une ville et les variations de pression résultante contre les face d'un édifice. Les travaux préliminaires de comparaison effectués en collaboration avec l'Université Western Ontario, entre les mesures en vraie grandeur et celles recueillies en soufflerie, indiquent qu'il est possible d'obtenir une simulation adéquate des caractéristiques statistiques fondamentales des variations périodiques de la pression résultante du ven à l'aide de modèles complexes observés dans une soufflerie d'étude du vent de surface.

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INTRODUCTION

1. Purpose and scope of full-scale measurements

In the past, the two main sources of information for wind load design of buildings have been: (1) meteorological records, from which extreme gust speeds are predicted (Boyd, 1965), and (2) constant-velocity, low-turbulence wind tunnel tests of scale models of buildings, from which pressure coefficients are obtained (Chien, 1951). The term "gust speed" refers to the maximum speed registered at a single point in space by a particular type of anemometer. Since gusts vary in their linear dimensions from several thousand feet to less than ten feet, the minimum length of gust that the anemometer is capable of registering is normally also specified. Measurements on building models in the conventional wind tunnel test, on the other hand, are essentially invariant with time and to further simplify the design calculations, pressures are spatially averaged over the various surfaces of the model.

The usual design procedure of multiplying the extreme gust pressure by spatially-averaged, steady-state pressure coefficients to get the "equivalent static wind pressure" deserves critical examination for at least two reasons. First, the constant-velocity, low-turbulence flow in the usual wind tunnel tests does not properly simulate the turbulent shear flow found in Nature and as a result the pressure coefficients may be significantly in error even for representing time-averaged pressures (Jensen and Franck, 1965). Second, unless the design gust is several times larger than the building the gust pressure may not be completely correlated over the whole structure. The effective gust pressure may therefore be somewhat less than the calculated peak value.

The present design procedure is particularly inadequate in the case of structures for which dynamic amplification of the building response is possible because of one or a combination of (1) vortex shedding, (2) aerodynamic instability, and (3) buffeting by the random gustiness of the wind. Dynamic response should be a major design consideration for very tall, slender buildings and towers. The scope of the present full-scale measurements was limited to wind pressures, however, and since no measurements of deflections or strains were made, no information can be offered about dynamic response.

Wind pressure measurements have been made by the Building Structures Section of the Division of Building Research (and are still in progress) on a 34-storey office building in downtown Montreal to obtain basic information about actual wind loading on buildings. The objective is in the first instance to check the applicability of wind tunnel test results to full-scale buildings and second, to supply information about fluctuating pressures that would be difficult to obtain by other means.

2. Building description and instrumentation

The building is 440 feet high, 119 feet by 173 feet in plan, and is closely surrounded on all sides by other buildings at least ten storeys in height (see Fig. 1). A building over 600 feet high stands to the north-west, which happened to be the wind direction in three of the five best records of strong wind.

External pressures and suctions are measured on the tenth floor 134 feet above the street and on the thirty-third floor 413 feet above the street, mainly because these are the mechanical services floors, and the walls are readily accessible for installing pressure taps. The surface visible at the mechanical floor levels from the outside consists of horizontal, inclined louvers mounted flush with the window and spandrel panel surfaces of the typical office floors. The louvers span 4 feet - 8 inches between mullions which project 8 inches and run the full height of the building. The actual metal curtain wall panel is set 2 or 3 inches behind the louvers and extends the full storey height without any windows. Forty-nine holes 1/8th inch in diameter were drilled through the metal curtain walls, into the open space behind the louvers, at the locations shown in the two plan views of the building, Figs. 2 and 3.

Twelve differential pressure transducers are used to measure the pressure differences between the inside reference pressure and each of twelve selected tapping points in terms of the deflections of thin elastic steel diaphragms. The transducers convert the movement of the diaphragms by means of four-arm unbonded strain-gauge bridges to electrical signals which are recorded simultaneously on a multi-channel oscillograph.

A wind vane and three-cup anemometer of the type U-2A in use by the Meteorological Branch of the Canadian Department of Transport were installed on a mast 800 feet above the street, on top of a building about 1500 feet to the west (all directions measured relative to the building). Wind speed and direction signals are transmitted by telephone wires to the multi-channel recorder. Wind speed and direction signals were not available for the first two runs, however, because the anemometer was not installed until the Fall of 1964.

The measurements of pressures, wind speed and wind direction are recorded in analogue form as displacements of signal traces from individual base lines set at regular intervals across the 7-inch wide chart which runs at a speed of 4 inches/minute. In this form they were suitable only for rough estimation of the behaviour of pressures over the length of building instrumented. For more detailed analysis, portions of the chart records for each of 5 runs were selected (on the basis of fairly constant mean values throughout the selected portion) for digital sampling at one-second intervals. Samples varying in length from 500 to 1600 terms were analyzed by computer to estimate mean and root-mean-square speeds and pressures, power spectral densities and cross-correlation spectral densities.

The five runs can be described briefly as follows:

RUN	DATE	WIND DIRECTION REL. TO BLDG.	8-MINUTE MEAN WIND SPEED, f.p.s.
1	5 March 1964	(west)	(65-70)
2	9 May 1964	(west)	(60-65)
3	18 March 1965	S-39°W	45
4	4 November 1965	N-07°W	56
5	2 March 1966	N-60°W	49

Wind information for Runs 1 and 2 as estimated from airport records.

3. Measurements in a boundary-layer wind tunnel

With the co-operation of Prof. A.G. Davenport, Director of the University of Western Ontario Boundary Layer Wind Tunnel, and his staff, preliminary measurements were made in December 1966 on a 1:400 scale model of the 34-storey building for comparison with the full-scale measurements.

The walls of the model were machined from plastic, including the mullion detail. In addition to the 49 taps located as on the full-scale building, several taps on other levels were prepared, complete with tubing through the base for connection to a multiple-port scanivalve pressure transducer.

All other buildings within a 1600 foot radius were modelled to scale, and a topographic model of the land contours for about 2 miles in the upwind direction appropriate to Run 4 was prepared. A turbulent boundary layer flow is built up in the boundary layer wind tunnel by covering the upstream portion of the tunnel bottom (in this case the topographic model) with small blocks and packing wool to represent houses and trees respectively, as shown in Figure 4.

The modelling of land contours in the upwind direction was considered necessary because of the prominence of the eastern portion of Mount Royal about a mile to the north. Run 4 was selected for the first comparison between full-scale and model approaches because it was the only run for which the wind direction was nearly normal to one wall.

4. Zero-wind reference pressure

The pressure transducers measure the difference in pressure between the external pressure at the tapping point and the barometric pressure in the false ceiling space of the ninth floor, near the centre of the building. All twelve transducers were connected by plastic tubing to this same reference pressure. A correction for chimney action was made for the eight transducers on the 33rd floor relative to those on the 10th floor.

The ninth is a typical office floor with fixed windows, and the internal pressure was considered relatively free from disturbance by wind effects over a short term such as 10 to 15 minutes. The tenth floor, on the other hand, is open to the outside through exhaust and inlet ducts used for the mechanical equipment located there and so was not considered satisfactory as a reference level.

The ideal reference pressure would give a zero reading for each transducer when the wind speed was zero. It is unfortunately impractical either to establish such a pressure or to determine the static off-set by taking zero readings for a given run by waiting around to get a zero wind speed condition. Static off-sets of the reference pressure are caused by the operation of the mechanical services of the building and by the pressure differences due to chimney action when inside and outside air temperatures differ (Tamura and Wilson, 1967).

The static off-sets of the reference pressure were in some cases so great that all pressures recorded in a strong wind, even those on the windward wall, were negative. It was found by comparison of Run 4 with the preliminary model test that the best correlation could be achieved if the reference level was shifted enough to make the ratio of wake pressure to windward pressure -0.22. Most conventional wind tunnel test results would suggest a much greater shift, to give a ratio ranging from -0.5 to as great as -1.0. On the other hand, model tests in a boundary layer tunnel simulating flow over rough terrain tend to support the use of the smaller ratio (Jensen and Franck, 1965). The mean pressures for all runs were therefore shifted a constant amount appropriate to each run to make the ratio of wake to average windward pressure -0.25.

RESULTS OF FULL-SCALE MEASUREMENTS

1. Mean and root-mean-square pressure coefficients

The results of the full-scale measurements are expressed in non-dimensional form as pressure coefficients giving the ratio of the 8-minute mean pressure to the 8-minute mean dynamic pressure of the wind:

$$C_p = \frac{\frac{1}{N}\sum(P_i - P_o)}{\frac{1}{2}\rho V^2} \qquad \text{Equation 1a}$$

C_p	full-scale mean pressure coefficient
P_i	the "i"th of N samples of differential pressure taken over an 8-minute period, p.s.f.
P_o	reference pressure corrected for static offset as described in the previous section, p.s.f.
ρ	mass density of air, lb-sec.^{2}/ft.^{4}
V	8-minute mean wind speed, ft./sec.

As a measure of the fluctuating component of pressure, the root-mean-square of deviations from the mean pressure was computed and also expressed as a pressure coefficient:

$$C_F = \frac{\left[\frac{1}{N}\sum_{i=1}^{N}(P_i - \overline{P})^2\right]^{\frac{1}{2}}}{\frac{1}{2}\rho V^2} \qquad \text{Equation 1b}$$

C_F full-scale root-mean-square pressure coefficient

$\overline{P}$ 8-minute mean pressure, p.s.f.

The mean dynamic pressure of the wind that was used to form pressure coefficients was based on the 8-minute mean wind speed at the 800 foot height of the anemometer.

Tables 1 through 4 present mean pressure coefficients and root-mean-square pressure coefficients for each of the transducer locations in use during the different runs. Each transducer location is identified by a two-digit number prefixed by N, S, E or W according to its position on the north, south, east or west wall respectively. The units digit refers to the numbering order:

(a) from the west end for positions on the north and south walls or

(b) from the north end for positions on the east and west walls.

The tens digit is 1 for the tenth floor or 3 for the 33rd floor. Figs. 2 and 3 show the numbering scheme and the 49 possible transducer locations.

2. Spectral representation of fluctuating pressures

The general turbulence in the free air-stream is considered to be one of the main causes for the fluctuations in pressure on a building. Although it is not usually possible to relate individual gusts to the pressure fluctuations that they cause, the transformation from wind speed variance to pressure variance can be investigated by means of spectral representations. The object of computing power spectral density estimates from the complicated waveform produced by the random fluctuations in the wind is to give a statistical picture of the average contribution made by each size of gust to the total variance of the record (general reference, Bendat and Piersol, 1966).

Power spectral density estimates were computed for wind pressures measured on the building and for wind speed measured by the anemometer using the method of Blackman and Tukey (1958). Wind speed was converted to dynamic pressure for greater convenience in making comparisons with the pressure spectra. This had the effect of increasing the ordinate scale (and the total variance) by a factor of 4, but in comparing spectral shapes the ordinate scale was normalized by dividing by the total variance. The spectral shapes for wind speed and dynamic pressure were not found to be appreciably different.

Davenport (1961) suggested an empirically derived spectral shape for strong wind, normalized by the product of the surface drag coefficient and the velocity squared. In this form it was proposed that the empirical spectrum would be applicable to strong winds in stable weather systems over all types of terrain:

$$\frac{S(n)}{kV^2} = \frac{4\xi}{(1+\xi^2)^{4/3}} \qquad \text{Equation 2}$$

$S(n)$	spectral density of wind speed, (ft./sec.)^2/(cycle/sec)
V	mean wind speed in ft./sec.
k	surface drag coefficient evaluated at the same height as the mean velocity, V.
n	frequency in cycles/sec.
$\xi = 4000\ n/V$	frequency made non-dimensional by V and a length scale factor, 4000 feet

The above "universal" spectral curve for strong wind speed normalized by total variance instead of kV^2 is compared to dynamic pressure spectra (Fig. 5) and building pressure spectra (Figs. 6, 7, 8 and 9). Total variance of the universal spectrum is given by:

$$\sigma_v^2 = 6\ k\ V_h^2 \left(\frac{33}{h}\right)^{2\alpha} \qquad \text{Equation 3}$$

σ_v^2	total variance of wind speed
k	surface drag coefficient evaluated at 10 meters.
V_h	mean wind velocity at height h, ft./sec.
h	height of measurement in ft.
α	exponent of mean wind speed profile.

Figure 5 shows reasonable agreement of the computed spectra for Runs 3, 4 and 5 with Davenport's empirical spectrum. The ordinate scale can be compared by using the total variance to compute k in Equation 3, assuming some reasonable value for α.

Mean velocity profiles in the preliminary model test gave a value of α = 0.35 for a north wind. Using α = 0.35, Runs 4 and 5 indicate that k = 0.05, in good agreement with Davenport's recommendation for urban environments. If the same value for α is used in Run 3, however, k = 0.012. Now, the terrain to the southwest (Run 3) is definitely much smoother than to the north or west, but it seems doubtful that it is smooth enough to completely explain so low a value for the surface drag coefficient. If a smaller value of α more appropriate to a smoother terrain is used in Equation 6, k becomes even smaller.

The spectral shapes of pressures on the 33rd floor (Figs. 6 and 7) also agree in overall shape with Davenport's spectrum except that the position of the peak appears to be shifted toward higher frequencies.

The spectra for windward pressures at the 10th floor show in general little resemblance to the wind speed spectrum. One possible explanation is that eddies shed from the surrounding buildings are the main cause of the pressure fluctuations at that level, rather than the turbulence of the general wind flow. The highest frequency that was analyzed was 0.5 cycle/second, but it appears from Figs. 8 and 9 that appreciable variance should be attributed to higher frequencies. Proper analysis requires re-sampling at more frequent intervals than once per second, and the present estimates at higher frequencies are in error (too large) because of aliasing (Blackman and Tukey, 1958). The apparent existence of power at higher frequencies will be investigated when the present laborious manual method of digitizing analogue records can be replaced by a new digital data sampling and recording system.

All the records gathered up to the present have been taken during the passage of large-scale weather systems, for which the assumption of stable conditions is probably valid. The predominant cause of turbulence is the generation of eddies by the friction of the wind flow over the rough surface of the ground. A significant portion of the strong winds for which buildings must be designed occurs during local squalls and thunderstorms, and the spectral characteristics of strong wind under these circumstances may not fit the empirical strong-wind spectrum (Davenport, 1961). Unexpected storms cannot usually be recorded because it takes 3 or 4 hours to drive from Ottawa and set up the transducers for recording.

3. Comparison with model test results

The difficulties encountered in making measurements in so complicated an environment make concurrent model studies almost essential for effective application of the full-scale measurements. The primary value of going to the considerable expense of collecting limited full-scale pressure measurements applicable to the centre of a large city is to enable model simulation techniques to be developed and (if possible) verified by agreement with the pressures on actual buildings.

To obtain an objective measure of the extent to which the model scale results agree with the full-scale measurements, a linear regression was done of the twelve pairs of readings, model and full-scale, for the twelve different transducer locations used in Run 4. The following regression equations were obtained for the mean and r.m.s. pressure coefficients:

	r^2
$C_P = 1.14\, C_p + 0.04$	0.92
$C_F = 0.88\, C_f + 0.05$	0.71

C_P, C_p full-scale and model mean pressure coefficients, respectively

C_F, C_f full-scale and model r.m.s. pressure coefficients, respectively

r^2 square of correlation coefficient

Ideally, the model and full-scale coefficients should be equal, indicating the perfect agreement of model and full-scale pressures. In fact, however, the square of the correlation coefficients indicate that about 90% of the variation in the mean pressures, and about 70% of the variation in the r.m.s. pressures can be explained by the model scale results.

Pressure spectra from model results should also be in agreement with full-scale pressure spectra if the proper flow simulation has been achieved. Fig. 10 is a sample comparison, showing model and full-scale spectra for point N33 from Run 4, and from this it appears that the flow simulation was adequate in at least some fundamental respects.

4. Aerodynamic admittance

The transformation from speed to pressure can be examined on the basis of the average effect of all sizes of gusts rather than just some individual gust by spectral representations of the fluctuating components of wind speed and pressure. Spectral representation, giving the distribution of gustiness according to frequency, makes it possible to account for the reduced effectiveness of smaller gusts as a function of their size. The relation between velocity and pressure spectra is given (following Davenport, 1963a) as:

$$\frac{S_{P_{ave}}(n)}{\overline{P}_{ave}^{2}} = \left|X_a(n)\right|^2 \frac{4\, S_v(n)}{V^2} \qquad \text{Equation 4}$$

$S_{P_{ave}}(n)$	spectrum of pressure fluctuations averaged over a given area in $(\text{p.s.f.})^2/(\text{cycle/sec.})$
$\left\|X_a(n)\right\|^2$	aerodynamic admittance function
$S_v(n)$	spectrum of speed fluctuations measured at a single point in space, in $(\text{ft./sec.})^2/(\text{cycle/sec.})$
V	time average of wind speed, ft./sec.
$\overline{P}_{ave}$	pressure averaged with respect to time (bar indicates time average) and averaged spacially over a given area (p.s.f.)
n	frequency in cycles/sec.

The pressure spectrum and the mean pressure in Equation 4 apply to the pressure averaged over a given area on the building.

In this case the aerodynamic admittance function fulfills two roles: it is the ratio of the fluctuating flow pressure coefficient to the mean flow pressure coefficient as a function of frequency, and it expresses the reduction in spatial correlation of gust pressures as a function of frequency.

In view of the scanty knowledge about wind speed right at the building it does not seem worthwhile to attempt an evaluation of the aerodynamic admittance function in its capacity as a normalized fluctuating flow pressure coefficient. The spectral peaks of pressures cannot be positioned relative to the wind speed spectrum with sufficient accuracy go give a meaningful result.

A more meaningful comparison can be made of the average of spectra of individual point pressures and the spectrum of pressures averaged along a horizontal line. This relates to the role of the aerodynamic admittance function as a "size reduction factor" for taking account of the reduced effectiveness of small gusts in causing pressures over a large area:

$$\frac{S_{P_{ave}}(n)}{P_{ave}^{2}} = R_h(n) \frac{{}_{ave}S_P(n)}{{}_{ave}P^2} \qquad \text{Equation 5}$$

$S_{P_{ave}}(n)$ spectrum of pressure fluctuations averaged along a horizontal line in $(p.s.f.)^2/(cycle/sec.)$

$R_h(n)$ horizontal cross-correlation function

P_{ave}) pressure averaged along the horizontal
$_{ave}P$) line and with respect to time, (p.s.f.)

$S_{ave}p(n)$ average of spectra of individual point pressure fluctuations measured along the horizontal line, $(p.s.f.)^2$/(cycle/sec.)

The horizontal cross-correlation function is in this relation equivalent to the aerodynamic admittance, and enters as a constituent part of same in Equation 4.

The results of evaluating the horizontal cross-correlation as defined in Equation 5 are given in Figure 11. In the reduced frequency "C", D is the length of the line and V is the mean wind speed at the anemometer site. The factor, "K" is defined in the following section.

5. Horizontal scales of wind pressure turbulence

The reduced frequency, $C = \frac{KnD}{V}$ is the ratio of the length of the line along which pressures are averaged to the horizontal semi-scale of the gust pressure turbulence. The latter is therefore V/Kn, expressed by the K factor and the gust wavelength V/n. Following Davenport (1963b) this K-factor was evaluated from a consideration of the cross-correlation between pairs of simultaneously recorded pressures at various separation distances. The modulus of the cross-correlation spectrum (a complex quantity) was normalized by the spectra of the individual pressures that were correlated, and an exponential decay curve was fitted by a least-squares method to the resulting coherence function:

$$\sqrt{COH} = \frac{|S_{12}(n)|}{\sqrt{S_{11}(n) \cdot S_{22}(n)}} \quad \text{Equation 6}$$

$$\sqrt{COH} \doteq \exp\left[-\frac{KnD}{V}\right] \quad \text{Equation 7}$$

$\sqrt{COH}$ square root of coherence

$|S_{12}(n)|$ modulus of cross-correlation spectrum of pressures at points 1 and 2 respectively $(p.s.f.)^2/(cycle/sec.)$

$S_{11}(n)$, $S_{22}(n)$ power spectra of pressures at points 1 and 2 respectively in $(p.s.f.)^2/(cycle/sec.)$

D distance in feet between points 1 and 2

K exponential decay factor determined by least squares fit of coherence data to function of reduced frequency.

The results of the evaluation of the K factor are given in Table 5, along with the overall correlation between the pairs of points (square of correlation coefficient, r^2) and the separation D in feet. The mean value for K is 7.7, standard deviation is 2.6, and the range is 3.8 to 15.8.

The square root of coherence represents the correlation between two points as a function of gust frequency. If the correlation can be adequately expressed by the approximate form of equation 7, then the average correlation, i.e., the horizontal cross-correlation function over the length of the line along which pressures are averaged should be given by the double integral (Davenport, 1967):

$$R_h(n) = \int_0^1\int_0^1 \exp\left[-C\left|x-x'\right|\right] dx \cdot dx' \qquad \text{Equation 8}$$

$$= \frac{2}{C^2}\left(e^{-C} + C - 1\right)$$

$C = \frac{KnD}{V}$ Ratio of separation to horizontal semi-scale of pressure turbulence.

Equation 8 is plotted as a solid line through the experimentally determined points for the horizontal cross-correlation function in Fig. 11. In defining a dynamic gust loading factor, Davenport (1967) makes use of a horizontal joint acceptance function which is a simplifed approximation of Equation 8:

$$\left|J_h(n)\right|^2 \cong \frac{1}{1 + \frac{KDn}{2V}} \qquad \text{Equation 9}$$

$\left|J_h(n)\right|^2$ Horizontal joint acceptance function.

As an example of how the full-scale determinations of the horizontal semi-scale of gust pressures on the building might be used, Figure 12 was prepared to show the application of Equation 9 to the problem of obtaining the variance of the average pressure along a line. Known quantities are the point pressure spectrum, $S_p(n)$ normalized by the total variance σ_p^2, length of line D, K-factor, and Equation 9. The quantity to be derived is the area under the spectrum of averaged pressure. When the correct K-factor of 8 (average from Table 5) is used, the derived spectrum (solid line through open square points) is in good agreement with the measured spectrum of averaged pressure (open circles). If, on the other hand, a value of K = 20 (appropriate to the horizontal semi-scale of gusts in the free air-stream) is used, the area under the derived spectrum of averaged pressure is somewhat smaller than the area under the actual spectrum.

CONCLUSIONS

1. Detailed and accurate wind load information applicable to actual buildings in the centre of a large city can best be obtained from model studies in which the immediate surrounding structures of comparable size and the general turbulence of the free wind and other relevant flow characteristics are correctly modelled. The limited comparisons between full-scale measurements and a preliminary model test in the boundary layer wind tunnel at the University of Western Ontario indicate that reasonable agreement can in fact be achieved. Further full-scale measurements on other buildings and correlation with models are essential to the further development and verification of the modelling techniques.

2. The relevant flow characteristics, notably the mean wind profile, surface drag coefficient and the spectral distribution of variance, will have to be determined with greater reliability for large city conditions before it will be possible to perform accurate model tests. In particular, possible variations in strong-wind characteristics for thunderstorms should be investigated.

3. The horizontal semi-scale of gust pressure on the building appears to be at least twice as large, on the average, as the same scale for gusts in the free air-stream. This presents a "picture" of the average gust after contact with the building as being roughly cubical in shape, whereas in the free air-stream it seems to be more than twice as high as it is wide and long. The average correlation of gust pressure averaged in the horizontal direction on the face of the building is in fair agreement with the theoretical expressions (Equation 8) and with the simplified form (Equation 9), both suggested by Davenport, provided the correct semi-scale of turbulence is used. The average horizontal semi-scale determined from the fluctuating pressure on the building was approximately V/8n. It seems probable that this increased correlation of gust pressures, i.e. a broadening of the gust front upon striking the building, is a general occurrence, but further investigations on other buildings is needed to determine it quantitatively.

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TABLE 1

WINDWARD PRESSURE COEFFICIENTS AT 33rd FLOOR - MEAN & RMS VALUES

Run	Wind	Pressure Coefficients at Various Locations				
1	Dir: West Mean: 65-70 fps* RMS:	W32 0.53 0.40	W33 0.56 0.35			
2	Dir: West Mean: 60-65 fps* RMS:	W32 0.51 0.31	W33 0.34 0.30			
3	Dir: S-39°W Mean: 45 fps RMS: 4 fps	S33 0.40 0.17	S35 0.34 0.16	S36A 0.21 0.15	S38 -0.05 0.10	W33 -0.11 0.11
4	Dir: N-7°W Mean: 56 fps RMS: 11 fps	N33 0.84 0.24	N36A 0.74 0.24	N38 0.36 0.22		
5	Dir: N-60oW Mean: 49 fps RMS: 8 fps	N33 0.32 0.12	N36 0.20 0.16	N38 0.28 0.13	W32 0.02 0.14	W33 0.08 0.12

* Estimated from Airport Records

TABLE 2

WAKE PRESSURE COEFFICIENTS AT 33rd FLOOR - MEAN & RMS VALUES

Run	Wind	Pressure Coefficients at Various Locations					
1	Dir: West Mean: 65-70 fps* RMS:	N33 -0.10 0.11	N38 -0.14 0.10	S33 -0.13 0.17	S38 -0.17 0.16	E30 -0.07 0.09	E35 -0.20 0.10
2	Dir: West Mean: 60-65 fps* RMS:	N33 -0.23 0.22	N35 -0.06 0.14	N36A -0.07 0.12	N38 -0.04 0.04	S33 -0.08 0.11	S35
3	Dir: S-39°W Mean: 45 fps RMS: 4 fps	N33 -0.08 0.06	N35 0.19 0.07	W33 -0.11 0.11	E34 -0.36 0.07		
4	Dir: N-7°W Mean: 56 fps RMS: 11 fps	E30 -0.44 0.24	E32 -0.44 0.29	W32 -0.38 0.34	S33 -0.18 0.16	S36A -0.22 0.18	
5	Dir: N-60oW Mean: 49 fps RMS: 8 fps	E30 -0.09 0.09	E33 -0.04 0.09	S33 -0.07 0.07			

* Estimated from Airport Records

TABLE 3

WINDWARD PRESSURE COEFFICIENTS AT 10th FLOOR - MEAN & RMS VALUES

Run	Wind	Pressure Coefficients at Various Locations		
1	Dir: West Mean: 65-70 fps* RMS:	W12 0.21 0.14	W13 0.16 0.14	
2	Dir: West Mean: 60-65 fps* RMS:	W10 0.20 0.10	W14 0.18 0.07	
3	Dir: S-39°W Mean: 45 fps RMS: 4 fps	S13 0.22 0.11	S16 0.06 0.07	
4	Dir: N-7°W Mean: 56 fps RMS: 11 fps	N13 0.65 0.10		
5	Dir: N-60°W Mean: 49 fps RMS: 8 fps	N16 0.50 0.06	W12 0.32 0.10	

* Estimated from Airport records

TABLE 4

WAKE PRESSURE COEFFICIENTS AT 10th FLOOR - MEAN & RMS VALUES

Run	Wind	Pressure Coefficients at Various Locations		
1	Dir: West Mean: 65-60 fps* RMS:	N11 0.11 0.33	S11 -0.14 0.17	
2	Dir: West Mean: 60-65 fps* RMS:	N14 0.13 0.02	S14 0.02 0.06	
3	Dir: S-39°W Mean: 45 fps RMS: 4 fps	W14 -0.10 0.23	E14 -0.43 0.07	
4	Dir: N-7°W Mean: 56 fps RMS: 11 fps	E12 -0.04 0.24	W12 -0.08 0.30	S13 0.11 0.17
5	Dir: N-60° Mean: 49 fps RMS: 8 fps	E13 0.24 0.08	S13 0.20 0.05	

* Estimated from Airport records

TABLE 5

K-FACTORS OBTAINED FROM $\sqrt{COH}$ BY LEAST SQUARES ANALYSIS

Run	Wind	Locations Correlated	D, ft.	r^2	K
1	Dir: West	W33/W32	24	0.7	5.5
	Mean: 65-70 fps*	W13/W12	24	0.6	9.0
2	Dir: West	W33/W32	24	0.6	7.0
	Mean: 60-65 fps*	N35/N36A	42	0.4	7.5
		N33/N35	47	0.3	7.9
		N33/N36A	89	0.2	7.2
3	Dir: S-39°W	S36A/S38	38	0.4	8.2
	Mean: 45 fps	S33/S35	42	0.6	7.3
	RMS: 4 fps	S35/S36A	46	0.6	5.2
		N33/N35	47	0.1	8.3
		S13/S16	61	0.4	7.3
		S35/S38	84	0.3	6.3
		S33/S36A	87	0.4	8.4
4	Dir: N-07°W	N36A/N38	37	0.4	6.0
	Mean: 56 fps	E30/E32	42	0.9	3.8
	RMS: 11 fps	"	"	0.9	5.2
		"	"	0.9	4.3
		"	"	0.8	4.7
		S36A/S33	87	0.5	6.9
		"	"	0.5	8.7
		N36A/N33	89	0.3	9.9
5	Dir: N-60°W	W32/W33	24	0.5	15.8
	Mean: 49 fps	N36/N38	56	0.3	11.1
	RMS: 8 fps	"	"	0.4	12.7
		N33/N36	70	0.3	5.7
		"	"	0.3	5.8
		N33/N38	125	0.1	11.0
		"	"	0.4	7.7

* Estimated from Airport Records

FIGURE 1

34-STOREY OFFICE BUILDING LOOKING SOUTH-EAST
DARK BANDS ARE AT 10th AND 33rd FLOORS, WHERE
THE MECHANICAL SERVICES ARE LOCATED AND WIND
PRESSURE MEASUREMENTS WERE TAKEN.

BR 4023-1

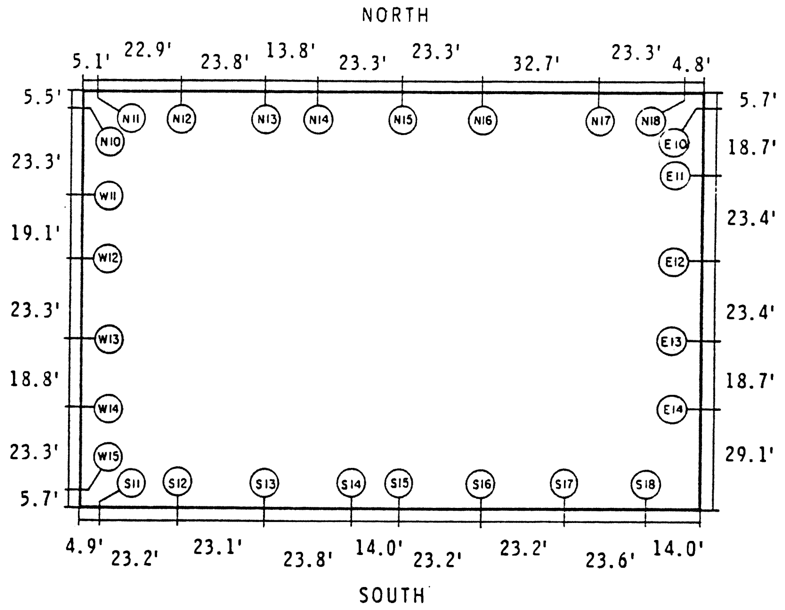

FIGURE 2

27 TAPPING POINTS FOR PRESSURE TRANSDUCERS ON THE 10th FLOOR OF 34-STOREY OFFICE BUILDING.

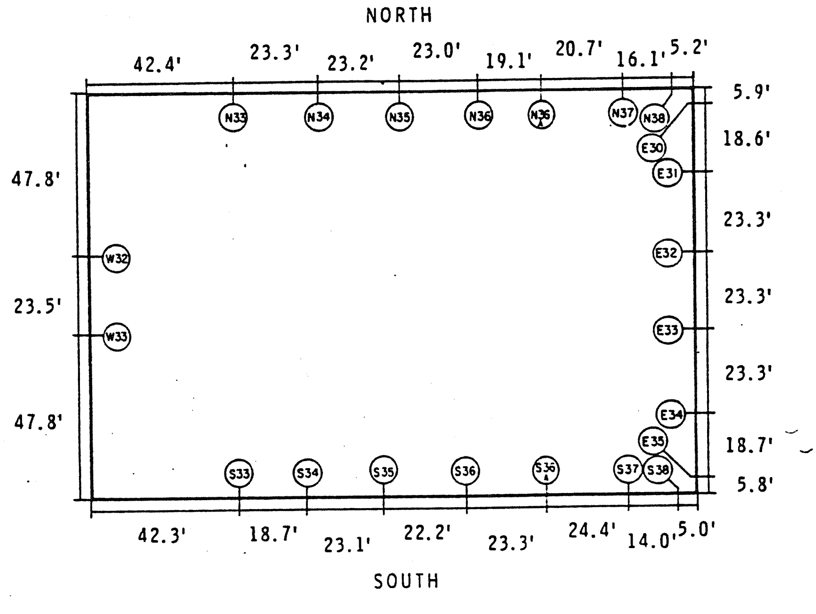

FIGURE 3

22 TAPPING POINTS FOR PRESSURE TRANSDUCERS ON THE 33rd FLOOR OF 34-STOREY OFFICE BUILDING

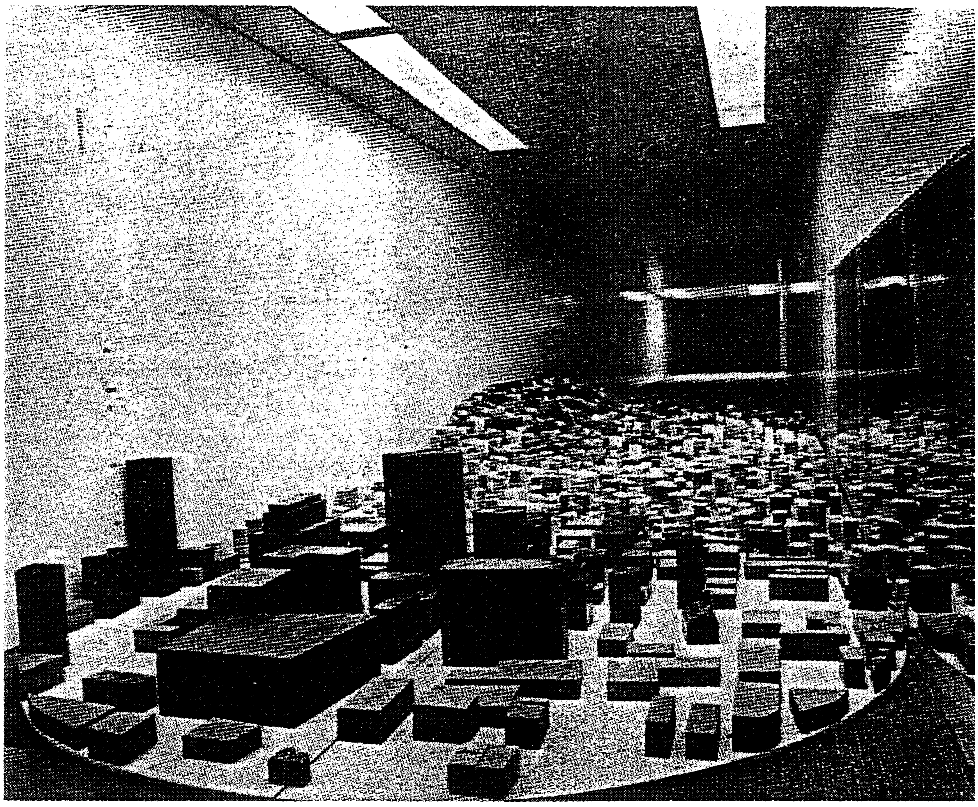

FIGURE 4

MODEL OF DOWNTOWN MONTREAL WITH MAJOR TOPOGRAPHICAL FEATURES IN THE BOUNDARY LAYER WIND TUNNEL AT THE UNIVERSITY OF WESTERN ONTARIO FOR COMPARISON WITH FULL-SCALE MEASUREMENTS.
(Photograph by Ron Nelson, London, Ont.)

BR 1023-2

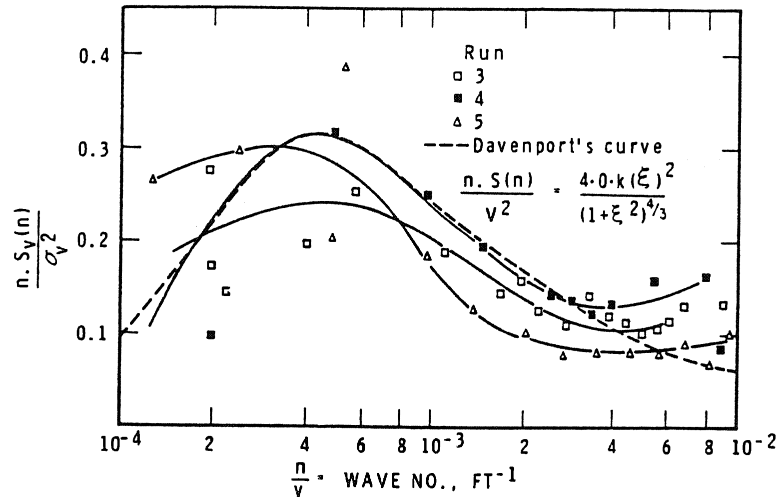

FIGURE 5

LOGARITHMIC POWER SPECTRAL DENSITY OF THE DYNAMIC PRESSURE OF THE WIND SPEED AT 800 FEET ABOVE THE STREET LEVEL.- COMPARED WITH DAVENPORT'S UNIVERSAL SPECTRUM FOR STRONG WIND SPEED.

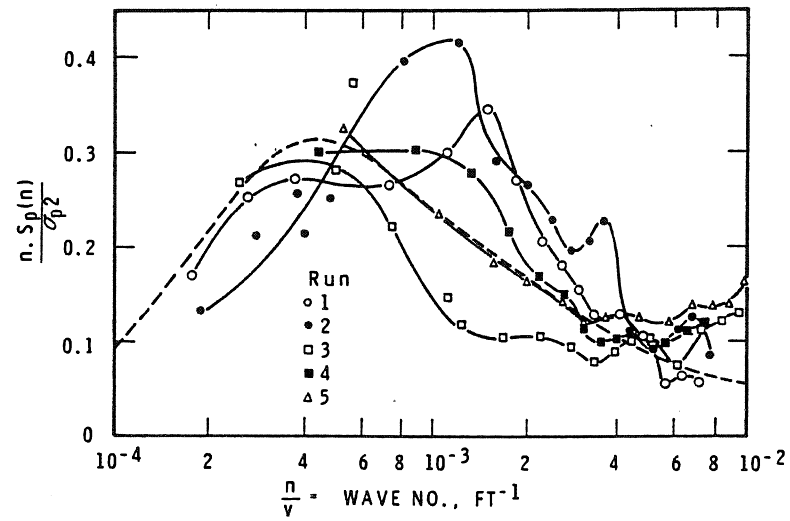

FIGURE 6

LOGARITHMIC POWER SPECTRAL DENSITY OF WINDWARD PRESSURES AT 33rd FLOOR.

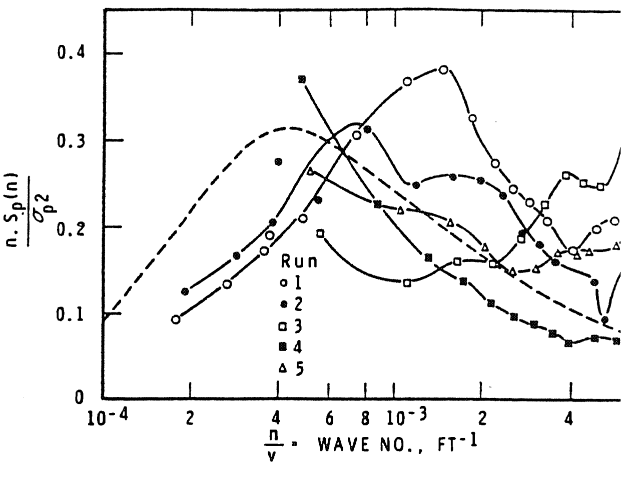

FIGURE 7

LOGARITHMIC POWER SPECTRAL DENSITY OF W
PRESSURES AT 33rd FLOOR.

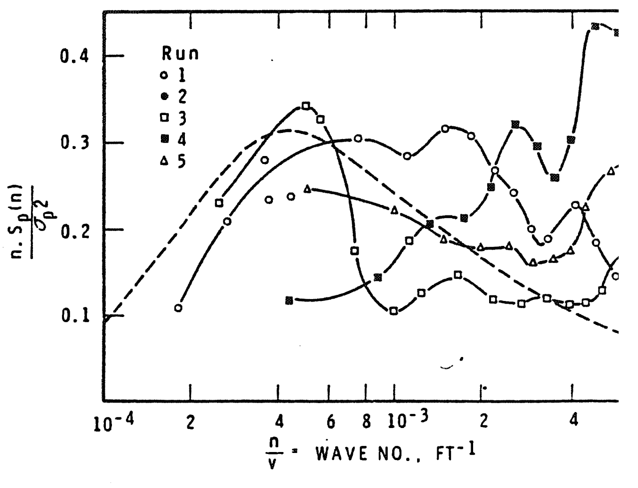

FIGURE 8

LOGARITHMIC POWER SPECTRAL DENSITY OF WIN
PRESSURES AT 10th FLOOR.

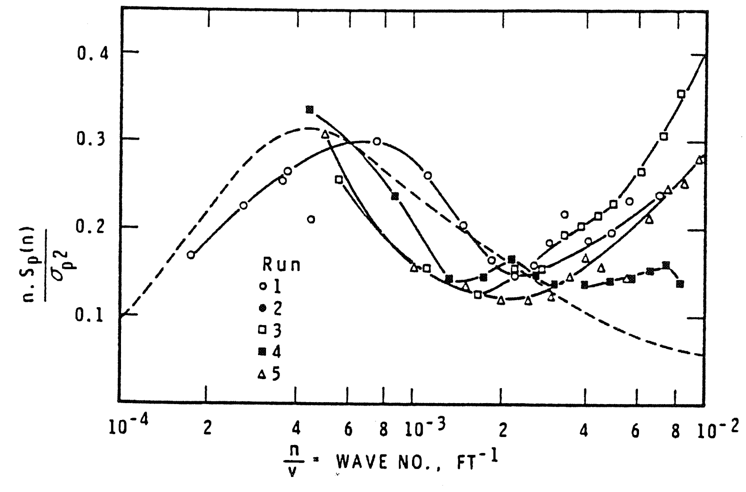

FIGURE 9

LOGARITHMIC POWER SPECTRAL DENSITY OF WAKE PRESSURES AT 10th FLOOR.

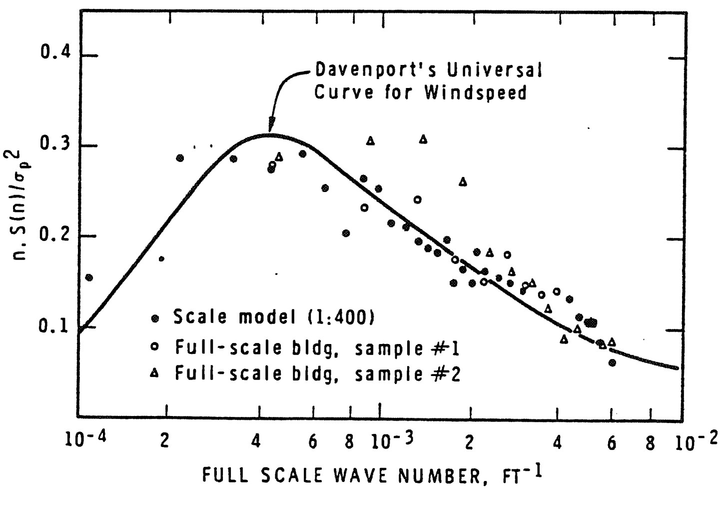

FIGURE 10

SAMPLE POWER SPECTRAL DENSITY CURVES OBTAINED FROM BOTH MODEL AND FULL-SCALE EXPERIMENTS ON AN OFFICE BUILDING IN MONTREAL.

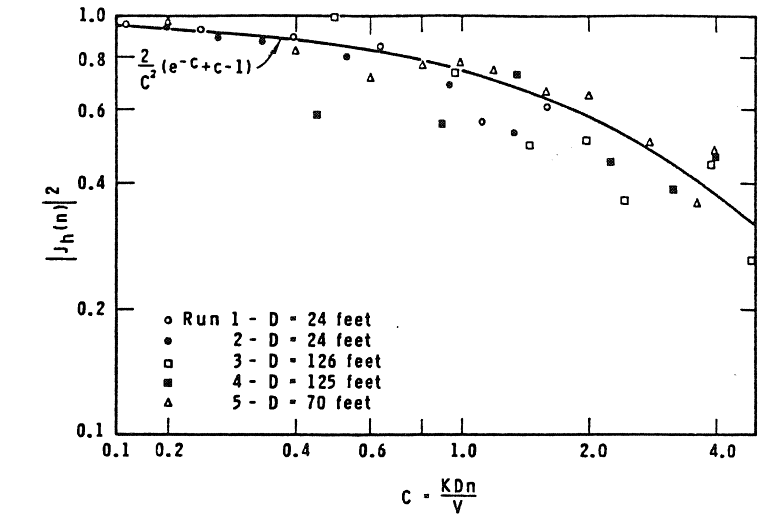

FIGURE 11
HORIZONTAL CROSS-CORRELATION

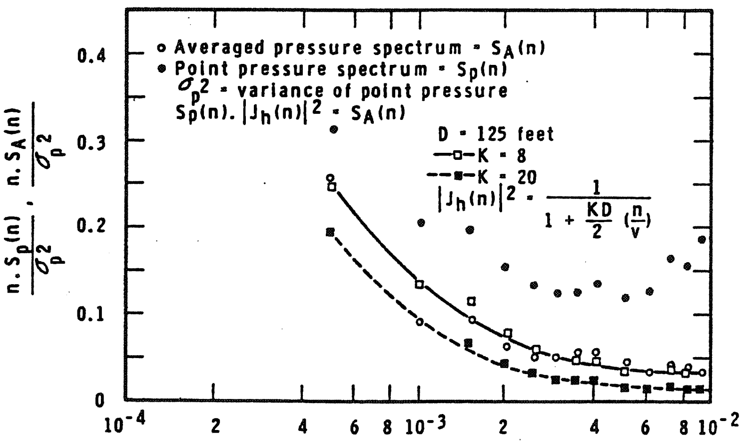

FIGURE 12

POINT PRESSURE SPECTRUM MULTIPLIED BY JOINT ACCEPTANCE FUNCTION COMPARED TO AVERAGED PRESSURE SPECTRUM - RUN 5