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Pressure Differences Caused by Wind on Two Tall Buildings

Estimating the quantity of air leakage for a building requires a knowledge of the pressure difference pattern over the exterior wall, as well as the air leakage characteristics of the exterior wall components. Wind is one of the major forces causing the pressure differences which result in air leakages. The other forces are chimney action and the imbalance of supply and exhaust air of the mechanical ventilation system.

Information on the pressure patterns resulting from wind, as a function of building configuration, can be found in many references dealing with model studies in wind tunnels[1]. Velocity conditions in such studies are usually idealized. In reality, wind conditions are affected by the surrounding terrain and adjacent buildings. Because of the complex nature of the wind, and the difficulties of measuring it under the non-steady conditions that occur in nature, there is little information on pressure patterns for actual buildings.

As part of a study on the pressure differences that occur across building enclosures, pressure measurements were conducted on two tall buildings (44 and 34 stories) located in Montreal. The first phase of this investigation dealt with the exterior wall pressure differences caused by chimney action and mechanical ventilation system operation. Pressure differences across the exterior wall and interior separations were measured during calm periods at various outside temperatures. The results of these measurements have been reported[2].

The second phase dealt with the pressure differences across the exterior wall which were caused by wind. For this study, continuous wind and pressure records were obtained and a regression analysis was carried out with the aid of a digital computer to determine wind pressure coefficients for both buildings. The results of the analysis are given in this paper.

DESCRIPTION OF THE TEST BUILDINGS

Buildings A and B, shown in Figs. 1 and 2, are commercial office buildings located in downtown Montreal. A contour map describing the characteristics of the terrain in which Buildings A and B are located is given in Fig. 3.

Building A has 44 stories and is 607 ft above street level to the top of the architectural fence on the roof. Rectangular in shape, it has dimensions of 100 by 140 ft. The 34-story Building B is 436 ft high and has floor dimensions of 117 by 173 ft. A more complete description of the buildings is given in Reference 2.

Fig. 4 shows the location and size of buildings in the immediate vicinity of the two test buildings

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Fig. 1 Building A

ınd gives an indication of the extent to which they ıre shielded.

For convenience the cardinal directions were ırbitrarily chosen at right angles to the building :aces. Unless otherwise stated, the cardinal direc- :ions are as indicated in Fig. 3.

:NSTRUMENTATION

The outside pressure taps were located in the middle ɔf each wall of the two mechanical equipment floors: :or Building A at heights of 195 and 545 ft, and for Building B at heights of 135 and 410 ft above street level. The exterior wall pressures were referenced

Fig. 2 Building B

to inside pressure taps located two floors away from the corresponding mechanical equipment floor. In addition to the pressure taps at the two upper levels, outside taps were installed on each of the four walls of Building B at the ground floor level.

The outside and inside taps were connected to a strain gauge diaphragm-type pressure transducer (sensitivity 0.002 in. of water) of the pressure recording system located in one of the mechanical equipment floors. The connection between the pressure tap and the pressure transducer was made with ¼-in. plastic tubing which contributed to the lag of the recording system. With 400 ft of ¼-in. plastic tubing (the longest connection used) the time constant of the recording system for a step input was 2.7 sec. The time constant of each pressure tap was different because of the varying lengths of the tube connections.

The outside air temperature was measured with a thermistor located in a sheltered area on the roof of

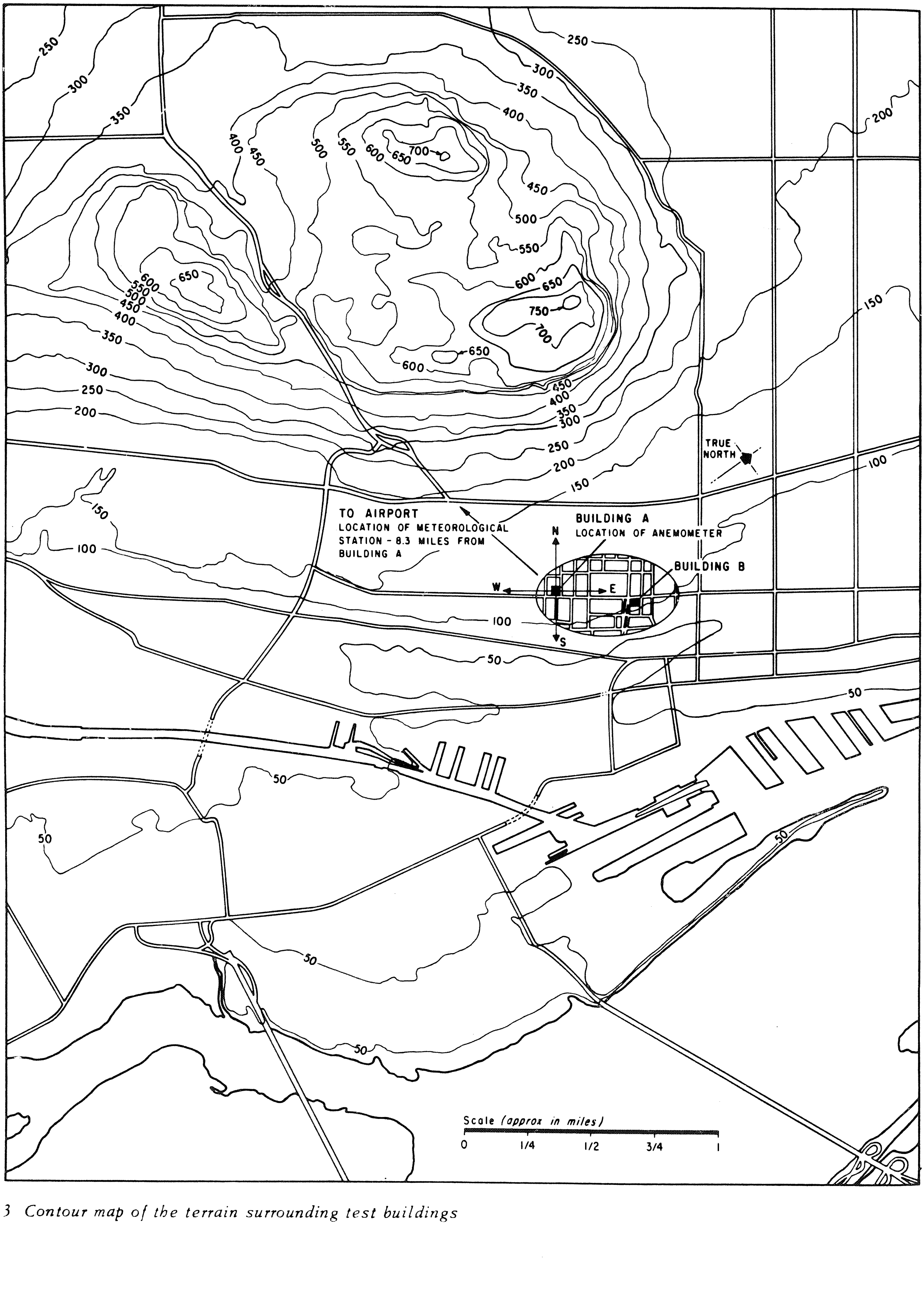


Fig. 3 Contour map of the terrain surrounding test buildings

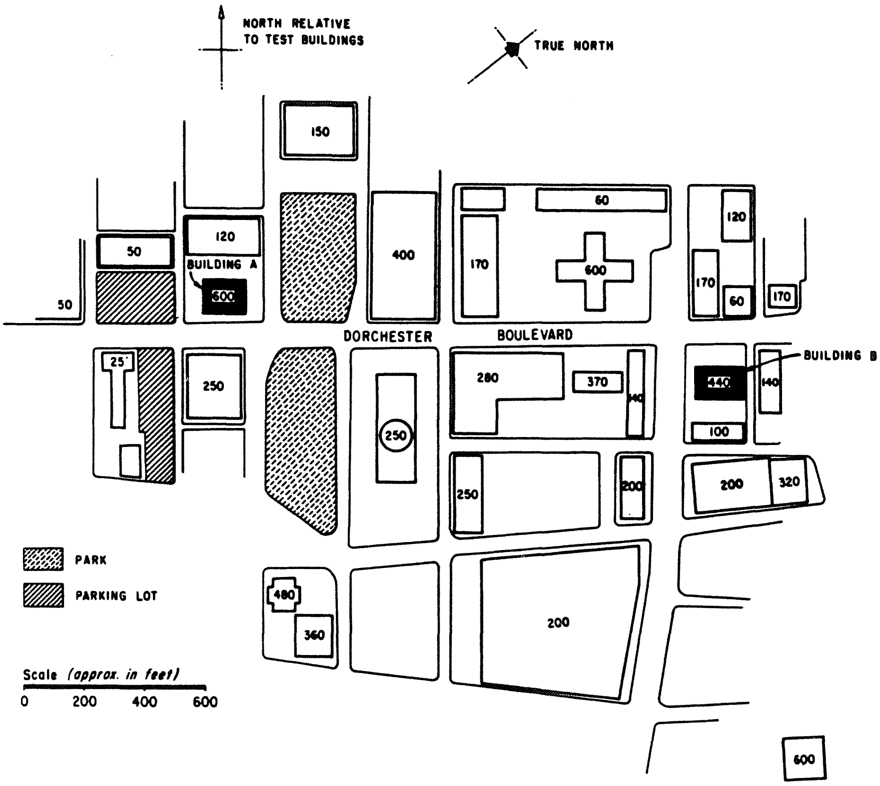


Fig. 4 Plan showing heights of adjacent buildings

: building. The wind speed and direction were asured with a cup-type anemometer that had a chanism to indicate one of eight wind directions. ch wind direction, therefore, covers a 45-deg gment. The anemometer was located on a radio st on top of Building A, 200 ft above roof level or proximately 800 ft above street level. The wind ormation from this anemometer was transmitted by ephone connection and recorded on the pressure :ording system of Building B, located 0.3 mile st of Building A.

To compare on-site and meteorological station nd velocities, an additional record of wind information was obtained on an operational recorder. The teorological station is located 8.3 miles northwest Building A.

Pressure differences at each pressure tap location, nd speed and direction, and outside air temperature re recorded every 4 mins. on a 16-point millivolt :order. Wind speed readings, which always followed) pressure readings, were an average speed over a sec interval. The readings were recorded on a ip chart for visual checking. A digital encoder athed to the slider arm shaft of the recording potentiometer was used to record each reading on either magnetic tape or punched paper tape in 3 digit binary numbers. The pressure records were processed and analyzed using an IBM 360 digital computer.

METHOD OF ANALYSIS

The values of the pressure differences across the exterior walls of a building are the net result of the combined action of various forces. It was assumed in this analysis that these pressure differences at any location could be adequately represented by the sum of the pressure differences due to the individual forces at that location.

At any height, the actual pressure difference across an exterior wall caused by chimney effect[3] alone, expressed as a function of the inside and outside air temperature, is

$$\Delta p_c = \beta\left(\frac{1}{T} - \frac{1}{t}\right) \qquad (1)$$

where

Δp_c = pressure difference across exterior wall caused by chimney action

T = absolute temperature outside
t = absolute temperature inside
β = constant (either positive or negative)

The pressure difference across one face of the exterior wall caused by wind velocity alone can be expressed as a function of the velocity head.

The equation for the velocity head is

$$P_v = \rho \frac{V^2}{2}$$

where

P_v = velocity head
V = wind velocity
ρ = air density.

The actual pressure difference across one face of the exterior wall caused by wind can be expressed as

$$\Delta p_v = \gamma P_v \qquad (2)$$

where

Δp_v = pressure difference across an exterior wall caused by wind
γ = wind pressure coefficient
a positive value indicates a higher pressure outside than inside
a negative value indicates a lower pressure outside than inside

The net effect of chimney and wind action and the ventilation system operation on the exterior wall pressure difference is then expressed by the following:

$$\Delta P = \lambda + \beta\left(\frac{1}{T} - \frac{1}{t}\right) + \gamma P_v \qquad (3)$$

where

ΔP = the resultant pressure difference across one face of an exterior wall
λ = pressure difference caused by the ventilation system.

If there is little change in the outside temperature during the period under consideration, variations in ΔP are due mainly to the variations in wind speed. The first two terms on the right hand side of Eq 3 are then combined to give the following simple linear relationship:

$$\Delta P = \alpha + \gamma P_v \qquad (4)$$

Each section of the record selected for analysis covered an extended period during which there was a constant outside air temperature (within 10 degs F) and constant wind direction. The mode of operation of the ventilation system also remained constant. The range of wind velocity in each of the selected pressure records was usually not greater than 10 to 15 mph. In order to compute wind pressure coefficients that would be applicable over a wider range, two sections of record with the same wind direction but with different absolute wind speeds were combined for purposes of analysis. The α values were usually not the same, since the outside temperatures for the two sections of records were in most instances different. A dummy variable[4], Z, was therefore added to Eq 5 to account for the two values of α as follows:

$$\Delta P = \alpha + \alpha_1 Z_1 + \gamma P_v \qquad (5)$$

where

Z_1 = 0 when the pressure reading is from the first selected record
Z_1 = 1 when the pressure reading is from the second selected record
α = constant for the first selected record
$\alpha + \alpha_1$ = constant for the second selected record

The use of Eq 5 for the determination of the γ values for the four walls at any specific level would also yield 4 values of both α and $\alpha + \alpha_1$ which should be the same for each level. By extending the use of dummy variables, the method of analysis can be further modified so as to yield single values of α and $\alpha + \alpha_1$ for each level for the two sections of record in combination. This technique leads to a better determination of the values of α and $\alpha + \alpha_1$ and should therefore provide better values of wind pressure coefficients, γ.

The equation incorporating the dummy variables is as follows:

$$\Delta P = \alpha + \alpha_1 Z_1 + \gamma_1 P_v + \gamma_2 Z_2 P_v + \gamma_3 Z_3 P_v + \gamma_4 Z_4 P_v \qquad (6)$$

where

Z_i = 0 if pressure reading is not associated with the i-th wall
Z_i = 1 if pressure reading is associated with the i-th wall

and

i = 2, 3, 4

pressure coefficient for each wall for a given d direction is then

$$\gamma'_1 = \gamma_1$$
$$\gamma'_2 = \gamma_1 + \gamma_2$$
$$\gamma'_3 = \gamma_1 + \gamma_3$$
$$\gamma'_4 = \gamma_1 + \gamma_4$$

The wind pressure coefficients were obtained by ılyzing each set of selected records to obtain the ;t fit with Eq 6. In this analysis the values of P_v re based on the velocity head of on-site wind :ained from the anemometer on the radio mast ɔve Building A.

In order to relate the wind pressure coefficients the wind velocity at the meteorological station, ɜ on-site wind records were correlated with the :teorological wind records. The latter were usually ailable as hourly average wind speeds. The ratio on-site hourly average wind velocity and the ɜteorological wind velocity was determined for ch wind direction.

The wind pressure coefficient related to the ɜteorological wind velocity is then given by

$$\gamma_m = R_v{}^2 \gamma' \tag{7}$$

ıere

R_v = ratio of on-site wind velocity to meteorological wind velocity

γ_m = pressure coefficient based on meteorological wind velocity

γ' = pressure coefficient based on on-site wind velocity.

ˡESULTS AND DISCUSSION

ᶠig. 5 is an example of the wind and pressure ecords obtained on-site and their correlation with Ǝq 6. Results in Fig. 5 are for the west wall of Building A at the 545-ft level with wind from the vest direction. These pressures obtained from two selected pressure records with outside air temperatures of 42 F and 10 F are plotted against on-site wind speed. The two curves were determined from the results of the regression analysis.

The pressure differences caused by chimney action and the ventilation system operation (the α values) are the pressure differences corresponding to zero wind velocity. The pressure differences are −0.40 and −0.74 in. of water for outside temperatures

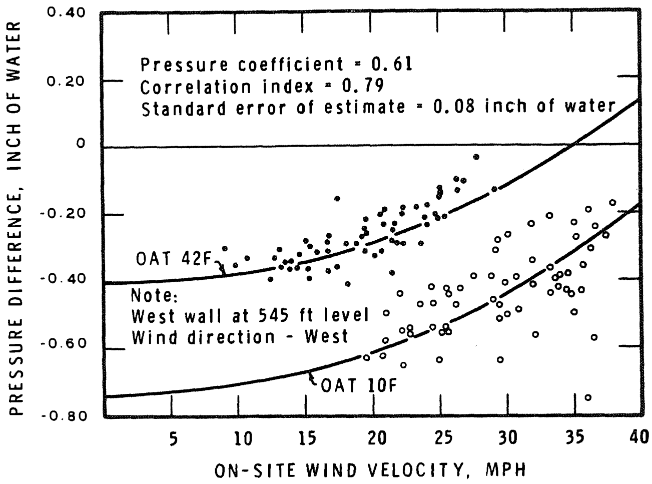


Fig. 5 Pressure differences across windward wall of Building A

of 42 and 10 F respectively. With increase in wind velocity there is a corresponding increase in the pressure differences across the windward wall. For the whole range of on-site wind speeds shown on the graph, however, the pressure differences are negative, with air exfilitration across the windward wall at the 545-ft level, indicating that the pressure difference caused by chimney action constituted a significant portion of the total.

An analysis similar to that represented by Fig. 5 was carried out for each exterior wall pressure tap location and in the process the wind pressure coefficients based on on-site wind were determined. For each wind direction the correlation index and the standard error of estimate, based on on-site wind velocity, were computed for each measuring level.

The correlation index indicates the proportion of the variance in the values of the exterior wall pressure differences explained by the concomitant variation in the wind velocity. A value of unity for the correlation index indicates a perfect correlation, whereas a value of zero would indicate no correlation. The degree of correlation depends on the (1) variation in the wind pattern on a building caused by local obstructions, (2) size of wind gust, (3) variation in wind direction (a given wind direction covers a 45-deg segment), (4) variation in pressure caused by projections on the exterior wall, (5) variation in inside pressure caused by elevators and doors and the operation of the ventilation system, and (6) the accuracy of the wind and pressure measuring equipment. For Building A the correlation index varied from 0.65 to 0.90 at the upper level and 0.33 to 0.87 at the intermediate level; for Building B it varied from 0.43 to 0.82 at the upper level, from 0.11 to 0.61 at the intermediate level and from 0.03 to 0.65 at the ground level. The degree of correlation between concomitant values of on-site wind and wall pressure differences was thus better for higher levels than for lower ones; and was better for Building A than Building B. As would be expected, the better correlations were obtained for pressure tap locations closest to the point of wind velocity measurement and where there was the least shielding.

The standard error of estimate indicates the degree of agreement between the observed pressure differences and those estimated from Eq 6. With reference to Fig. 5, it is a measure of the scatter of the data points around the regression curves. For Building A, values varied from 0.038 to 0.077 in. of water at the upper level, and from 0.013 to 0.079 in. of water at the intermediate level. For Building B, values varied from 0.023 to 0.097 in. of water at the upper level, from 0.017 to 0.064 in. of water at the intermediate level, and from 0.013 to 0.048 in. of water at the lower level.

The method of analysis, utilizing Eq 6, separates the pressure difference due to wind action from that due to chimney action and the ventilation system operation. These pressure difference effects can also be isolated by examining the records obtained during calm periods. This has been done for Building B in Fig. 6, which shows the pressure differences at the 410 and 135-ft levels plotted against outside air temperature. At the 410-ft level the negative pressure difference across the exterior wall increases with decreasing outside air temperature. Because the 135-ft level is close to the neutral zone level of the building the change in the pressure difference with outside air temperature is small.

Fig. 6 also shows the effect of the office-hour and after-hour operation of the ventilation system. After office hours, several ventilation fans were shut down, altering the balance of outside supply and exhaust air. Comparison of the measured wall pressure differences with the line showing pressure differences caused by chimney action alone[2] in-

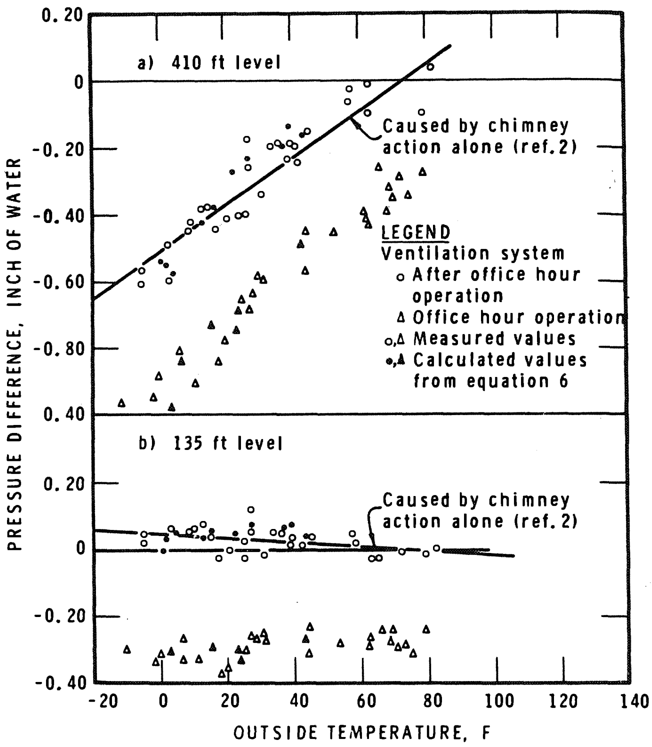


Fig. 6 Exterior wall pressure differences for Building B during calm periods

dicates that supply and exhaust air were essentially balanced under the after-hour conditions. When the ventilation system was operating fully there was an imbalance of supply over exhaust, causing a pressurization of approximately 0.2 to 0.3 in. of water at both levels.

The pressure differences due to the combined effects of chimney action and the ventilation system obtained from Eq 6 are also plotted in Fig. 6. The calculated values agree reasonably well with the values measured directly, indicating the validity of Eq 6. It would appear, therefore, that the pressure difference across the exterior wall due to the combined forces can be adequately approximated by summing the pressure differences due to the individual forces.

Wind pressure coefficients computed from Eq 6, referenced to on-site wind measurements, are given in Tables I and II for both buildings. For a given wind direction each pressure coefficient is based on an average of 130 readings for Building A and 180 readings for Building B. The coefficients apply to conditions at the mid-point of the walls where the pressure taps were located.

TABLE I

WIND PRESSURE COEFFICIENTS FOR BUILDING A BASED ON ON-SITE WIND VELOCITY

WIND DIRECTION	HEIGHT FT	EXTERIOR WALL			
		N	E	S	W
N	545	1.06	-0.46	-0.35	-0.45
	195	0.40	-0.55	-0.52	-0.17
NE	545	0.42	0.39	-0.20	-0.17
	195	0.36	0.13	-0.23	-0.11
E	545	-0.15	0.65	0.10	0.02
	195	0.06	0.23	0.10	0.04
SE	545	-0.30	0.60	0.04	-0.18
	195	-0.08	0.64	0.08	-0.05
S	545	-0.08	0.13	0.79	-0.08
	195	-0.22	0.09	0.08	-0.18
SW	545	-0.32	-0.29	0.24	0.26
	195	-0.44	-0.36	0.10	0.09
W	545	-0.06	-0.21	-0.35	0.61
	195	-0.21	-0.34	-0.49	0.25
NW	545	0.38	-0.29	-0.28	0.16
	195	0.21	-0.30	-0.35	0.16

TABLE II

WIND PRESSURE COEFFICIENTS FOR BUILDING B BASED ON ON-SITE WIND VELOCITY

WIND DIRECTION	HEIGHT FT	EXTERIOR WALL			
		N	E	S	W
N	410	0.80	-0.35	-0.11	-0.45
	135	0.33	-0.20	-0.08	-0.07
	6	0.09	-0.17	-0.28	-0.12
NE	410	0.44	0.36	-0.08	-0.07
	135	0.42	0.07	-0.10	-0.18
E	410	-0.13	0.41	-0.18	-0.05
	135	0.10	0.05	0.03	-0.01
	6	0.24	0.17	0.08	0.05
SE	410	-0.23	0.03	-0.04	-0.15
	135	-0.03	-0.03	0	-0.04
S	410	-0.11	-0.16	0.32	-0.14
	135	-0.10	-0.18	0.14	0
SW	410	-0.15	-0.19	0.09	0.10
	135	-0.14	-0.19	0.10	0.03
	6	-0.24	0	0.17	-0.01
W	410	-0.08	-0.06	-0.07	0.17
	135	-0.02	-0.07	0	-0.01
	6	0.03	0.03	0.03	0.03
NW	410	0.29	-0.18	-0.11	-0.05
	135	0.21	-0.17	-0.07	0
	6	0.05	-0.10	-0.13	-0.05

TABLE III

SUMMATIONS OF PRESSURE COEFFICIENTS FOR WINDWARD AND LEEWARD WALLS OF BUILDINGS A AND B

BUILDING A WIND DIRECTION	545 FT LEVEL	195 FT LEVEL
North	1.40	0.92
East	0.63	0.19
South	0.71	0.30
West	0.82	0.59

BUILDING B WIND DIRECTION	410 FT LEVEL	135 FT LEVEL	6 FT LEVEL
North	0.92	0.41	0.37
East	0.46	0.06	0.12
South	0.42	0.24	–
West	0.23	0.06	0

In general, the pressure coefficients are positive on windward sides and negative on leeward sides. The values of the coefficients are affected by elevation (generally being higher at upper levels) and vary also with wind direction. These effects relate to variations with direction of the vertical profile or gradient of the wind and to the shielding effect of adjacent buildings. In wind tunnel studies[5] a significant reduction of wind pressure on a model of a 100-ft high building was noted when a shielding building of equal height was as far away as 15 times the building width.

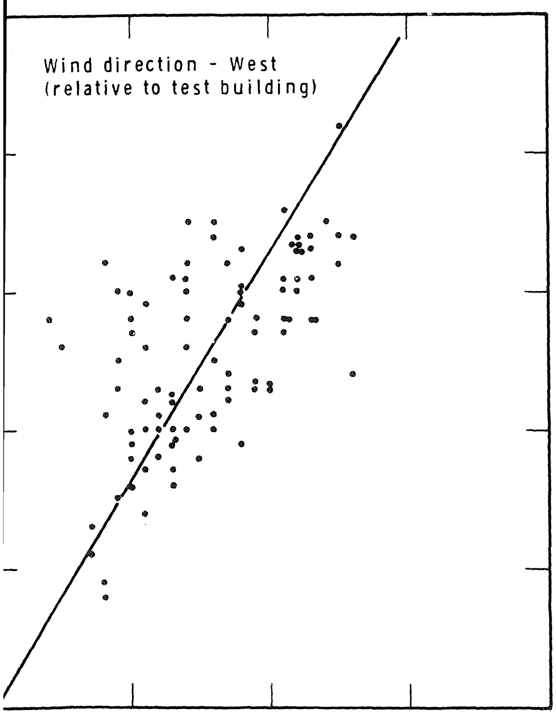
Differences in wind effect can best be seen by summing the pressure coefficients on windward and leeward sides, as shown in Table III. These coefficients are indicative of the total pressure difference acting across the building. It will be noted that there is some directional effect on the pressure coefficients for the upper level of Building A. Values for winds from the east are lowest, due to the shielding effect of high buildings in that direction (see Fig. 4). There is no direct shielding from the other directions and differences are related to variations in the wind profile. The high values for north winds are probably associated in some way with the small mountain to the north. At the intermediate level of Building A, east and south walls are shielded while the north and south are relatively exposed.

The coefficients for Building B are generally lower than those for Building A at the upper level, mainly because of B's lower height. The value in Table III for the north direction is greatest (as it is in Building A); whereas that for the west is smallest because of high buildings to the west and northwest. At the intermediate level there is some shielding in all directions, the effect being greatest for east and west winds. At the street level, the pressure differences are unpredictable; significant pressure differences occur with winds from the north and also from the southwest (see Table II), whereas values are smaller for the other directions.

It will be noted, using values from Tables I and II, that the ratio of pressure coefficients for windward sides to corresponding ones for the leeward sides is quite variable with elevation and direction. This implies differences in the ratio of infiltration and exfiltration. For example, if it is assumed that the effective area of leakage openings in the exterior wall is uniformly distributed at the perimeter of Building A, a simple calculation utilizing the wind pressure coefficients indicates an approximate balance of infiltration and exfiltration at the 545-ft level with wind from the north or west. A similar calculation for the intermediate level indicates greater exfiltration than infiltration. This suggests that there may be a vertical flow of air within the building induced by wind action; or that the single pressure tap in each wall does not provide a good indication of the average pressure difference. There is also the possibility that this apparent effect is due to limitations in the method of analysis; for the assumption that the pressure :es due to the ventilation system are con- a particular mode of operation may not be valid.

: VS METEOROLOGICAL ELOCITY

ıd pressure coefficients in Tables I and II renced to the wind velocity measured on site. ıd data generally available, however, is that d at the local meteorological station. ratios of the wind velocity at the site (800 ft street level on top of Building A) and at the ological station (33 ft above ground) were cal- l for each wind direction from the hourly aver- lues. As an example, a plot of the records for om the west direction is shown in Fig. 7. lculated ratio for this direction is 1.60. . 8 shows the variation of the ratio of on-site eorological wind speed (R_v) with wind direc- Vind velocities varied from 0 to 30 mph at the ological station in the records selected for is. The on-site anemometer was located well



7 *Comparison of on-site and meteorological wind velocity*

above adjacent buildings; the variation in the ratio with direction is therefore caused by differences in the general characteristics of the surroundings at the two locations. Relatively high values of R_v were obtained for the west, southwest and northeast direction. The lower values of R_v for the north and northwest directions are caused by the low mountain to the north of Building A (see Fig. 1). The lower values of R_v for the east and southeast directions can possibly be attributed to the effect of the cluster of tall buildings located east of Building A. The low value of R_v for the south direction may be due to some shielding of the anemometer by the 10-in. diameter radio mast. The anemometer was located on a 5-ft arm attached to the north side of the mast.

The wind velocity profile in the vertical direction can be approximated by the following equation[5]:

$$\frac{V}{V_r} = \left(\frac{h}{h_r}\right)^k \qquad (8)$$

where

V = mean wind speed at height h above ground
V_r = mean wind speed at the reference height h_r above ground
k = exponent.

The value of the exponent can be taken as 1/7 for flat open country[1]. The ratio of mean wind velocity at 800 ft and that at 33 ft, for an exponent of 1/7 is also shown in Fig. 8. If the exponent of 1/7 applies to the terrain at the meteorological station, the mean wind velocities 800 ft above ground at the two locations are approximately the same with wind from the northeast, west and southwest directions.

Wind pressure coefficients in Tables I and II can be computed in terms of meteorological wind records using Eq 7 and the information in Fig. 8. This will obviously alter the relative value of the coefficients because of variations in the ratio of on-site to meteorological wind speed.

SUMMARY

Coefficients describing the pressure differences due to wind action have been obtained for selected points across the walls of two tall buildings in the center of a large city. The coefficients were quite

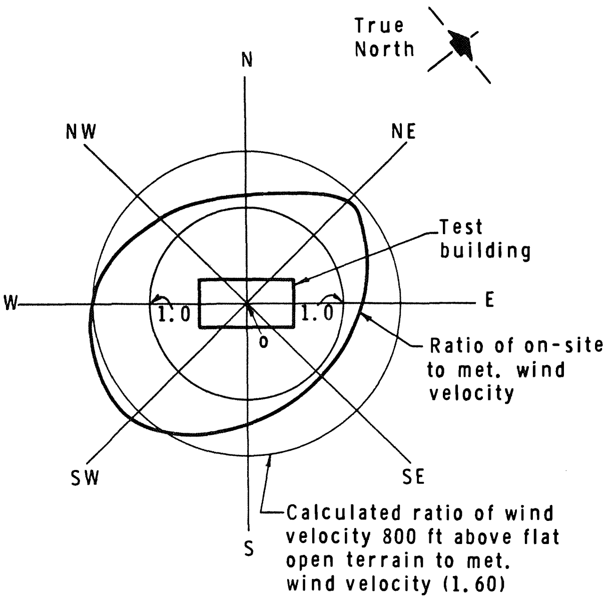


Fig. 8 Ratio of on-site wind velocity to meteorological velocity

variable with location, because of variations with direction of the vertical wind velocity gradient and the shielding effect of adjacent buildings.

The pressure coefficients were based on wind speeds measured at the site. These velocities in turn were related to the wind velocities measured at the meteorological station 8 miles away. This relationship is variable with direction and depends upon the general characteristics of the terrain, including buildings, at the two locations.

The results emphasize the difficulty of predicting the specific values of pressure differences due to wind to be expected with a particular building; and the difficulty, therefore, of making accurate predictions of corresponding air infiltration and exfiltration.

In the analysis of the pressure records, pressure differences due to wind action were isolated from those caused by the combined effect of chimney action and the effect of the mechanical ventilation system operation. These latter values agreed reasonably well with the values of pressure differences measured during calm periods. This suggests that the resultant pressure difference across the exterior wall can be approximated by the summing of the pressure differences caused by the various forces.

During periods of moderate wind velocity and low outside temperature, the pressure differences caused by chimney action constitute a significant part of the resultant pressure differences across the upper and lower levels of a tall building.

ACKNOWLEDGEMENT

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DISCUSSION

:HARD E. BARRETT (Columbus, Ohio): It would .nteresting if the authors could build a scale lel of this and surrounding buildings and conduct tudy of wind pressures as measured in a wind nel. Although wind tunnel studies are becoming :e common for large buildings, there has been le effort to correlate wind tunnel data to actual asurements on large buildings because measurents are not generally made after the building is ıstructed. Measurements on buildings are diffilt enough to obtain and further problems are enuntered in identifying the pressure components lely associated with wind.

The authors of this paper have already accomished the difficult task of making pressure measements on the buildings and factoring out the ind pressures. It seems that, if these results are be of maximum usefulness in the engineering of ture buildings, a corresponding wind tunnel study desirable.

. T. TAMURA: Wind pressure patterns for the two est buildings reported in this paper are in general greement with those reported in many publications ealing with model studies in wind tunnels. A comarison of the values of wind pressure coefficients, owever, is difficult because of the variation in he wind velocity profile, location of reference ressure, building height and shape and the type of wind tunnel used in the various studies.

A paper entitled "Wind Pressure Measurements on a Full-Scale High-Rise Office Building" by W. A. Dalgleish et al (International Research Seminar on Wind Effects on Buildings and Structures held at the National Research Council, Ottawa, September, 1967) describes the results of pressure measurements on Building B of this paper. Because of their interest in wind pressure from the structural load aspect of a building, the number and location of pressure taps, method of recording and analysis of wind pressure records were different from the ones described in this paper. Where the pressure taps were located in the same region of the exterior wall, the comparison of the two values of wind pressure coefficients indicated reasonable agreement.

The paper by A. Dalgleish et al also describes the results of model studies of the same building in a boundary layer type wind tunnel in which the surrounding terrain including buildings as well as the test building were modeled. The results of the wind tunnel measurements indicated good correlation with those of the field measurements. For further studies on wind effect related to air leakage of buildings, we are also exploring the possibilities of model tests in a boundary layer type wind tunnel.