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SCALE MODEL VERIFICATION OF PRESSURE DIFFERENTIALS AND INFILTRATION INDUCED ACROSS THE WALLS OF A HIGH-RISE BUILDING

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Summary

Predicting the energy requirement due to air infiltration through a building envelope is still very difficult. Considerable disagreement has been observed between the measured air leakage of multi-storey buildings and that calculated by ASHRAE recommendations.

Air infiltration for a high-rise building is mainly attributed to the characteristics of the wind environment around the structure, the thermal gradient across the building envelope and the mechanical ventilation of the building. The first two causes were found to be predominant in a full-scale observation of a twenty-storey apartment building reported previously.

Following this measurement, the verification of both wind and thermal effects on the pressure differentials was attempted using a wind-tunnel simulation for the former and a heated vertical duct for the latter.

The problem of the combined effect, or interaction, of various causes on the total pressure was encountered during data reduction. While it was assumed in the above analysis that the differential pressures were given by a linear summation of those caused by the individual actions, this may not be true in reality. The case of wind and mechanical ventilation acting together was extensively investigated and the non-linearity of both induced pressure differentials and air infiltration/exfiltration was discussed.

1. Introduction

Predicting the energy requirement due to air infiltration through a building envelope is still very difficult. It has been shown, for example [1], that there is a considerable discrepancy between the measured air leakage of multi-storey buildings and that calculated by the ASHRAE recommendations.

A full-scale measurement of pressure differences across the exterior walls of a twenty-storey apartment building (a student dormitory) was carried out at the University of Ottawa and the results of the study were previously reported in ref. 2. To verify both wind and thermal effects on the measured pressure differentials, a wind-tunnel test on a scale model of the building to investigate the wind-induced pressure components and a simulation of stack effect using a heated vertical duct of about 18 m in length were carried out.

The specific problem of the combined effect of various causes on the induced total pressure differentials was encountered during data reduction of pressure measurements on the building.

Analysis of the pressure data measured on the building was carried out on the assumption that the total pressure difference, Δp, is given by linear summation of three kinds of pressure differentials caused by wind action, the stack effect and mechanical ventilation, i.e.,

$$\Delta p = (\Delta p)_w + (\Delta p)_s + (\Delta p)_v \quad (1)$$

where: Δp = the total pressure difference across the wall, $(\Delta p)_w$ = the pressure difference caused by wind action, $(\Delta p)_s$ = the pressure difference caused by stack effect, and $(\Delta p)_v$ = the pressure difference caused by the operation of a mechanical ventilation system. This assumption seems to be generally accepted [3], though it is not physically justifiable. When the infiltration flow is the result of multiple inputs, stack effect and mechanical ventilation, for example, the total pressure differential due to combined action cannot be given by simple linear summation of the individual pressure differentials due to each effect. Since the flow due to infiltration is the direct result of the pressure differential, the assumption above is not logically consistent. The topic discussed in the third part of the present report is this non-linearity of pressure differentials under combined action. Non-linear characteristics of both pressure differentials and air infiltration rate are examined under wind action and ventilation operation.

2. Verification of the wind effect

A wind-tunnel test was carried out to verify the measured wind-induced pressure component. The facility used is an open-circuit wind tunnel with a test section of 0.91 × 0.61 m and approximately 4.5 m long, located at the University of Ottawa. The tunnel has a maximum mean speed of 45 m s^{-1} in the test section with less than ± 1.5% wind speed deviation in the middle 85% of the tunnel width. A set of three triangular spires and a 20 m long plate with 13—19 mm high roughness cubes were installed on the upstream side of the tunnel floor to produce a simulated atmospheric boundary layer flow. The model building is shown in Fig. 1.

The vertical profiles of mean wind speed as well as the intensity of the along-wind tubulence component at the model location are summarized in Fig. 2. The power law exponent for the mean speed profile was found to be approximately 0.28, which is comparable with the full-scale observation above. The boundary-layer flow at the test section was about 38 cm deep. Considering the scale of turbulence produced in the test section, the appropriate linear scale of the model was chosen to be 1 : 1000 of full scale. The turbulent boundary layer produced at this scale represents a typical wind flow condition over urban terrain [4]. Figure 3 depicts the spectrum of the along-wind velocity component at a height corresponding to the elevation of the tower-top anemometer, or the reference height.

The model building is made of plexiglass and is equipped with exactly the same arrangement of pressure taps and pneumatic averaging system as the test building. The model was installed in the test section of the wind tunnel together with its local surroundings, modelled to the same linear scale as the building. The measured pressure reading was normalized by the dynamic pressure at the height of the anemometer. The model is rigid and airtight and no attempt was made to simulate the actual wind-induced

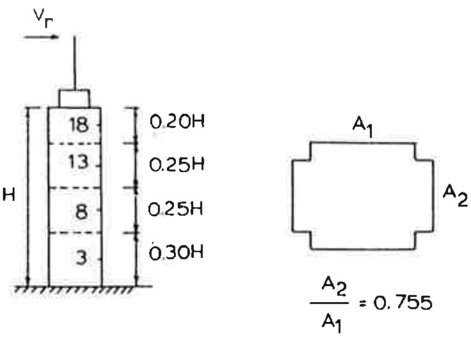
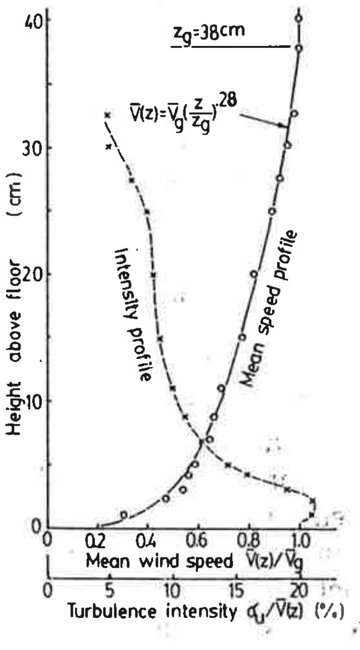


Fig. 1. Building model.



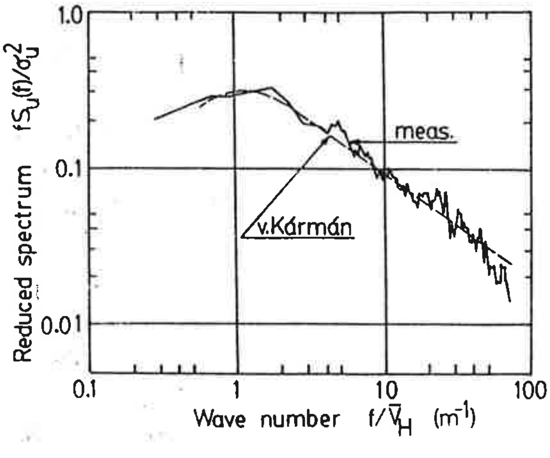


Fig. 2. Profiles of mean windspeed and longitudinal turbulence intensity.

Fig. 3. Dimensionless spectral density of the longitudinal component of turbulence.

air infiltration through the walls. The reference pressure was taken with a Pitot-static pressure gauge at the gradient height.

Calculation of the wind-induced pressure differential across the building walls was carried out under the following assumptions:

(1) The cracks and openings of the building are uniformly distributed over all four walls but not on the roof;

(2) The external pressure coefficients are distributed in stepwise profiles and the measured values at the pressure tap locations can be used as representative of each layer; and

(3) The internal pressure of the building is spatially constant and its magnitude can be decided from the total air-flow balance through wall cracks.

The internal pressure coefficient calculated via this procedure is given in Fig. 4 versus wind azimuth. Estimation of the internal pressure can vary, depending the assumed air flow characteristics through the openings; i.e., the pressure drop, Δp, across the building envelope can be expressed as two terms as follows:

$$\Delta p = a_1 V + a_2 V^2 \qquad (2)$$

in which V represents the air flow rate through openings and the two constants a_1, a_2 largely depend upon the shape and dimensions of the openings. These terms correspond to the standard friction loss and other losses, respectively. For comparison, two cases of $\Delta p = a_1 V$ and $\Delta p = a_2 V^2$ are given in Fig. 4, and the pressure differentials across the building envelope at four different evaluations are summarized in Fig. 5. The results of full-scale measurements are given in the shaded area in Fig. 5. Agreement between

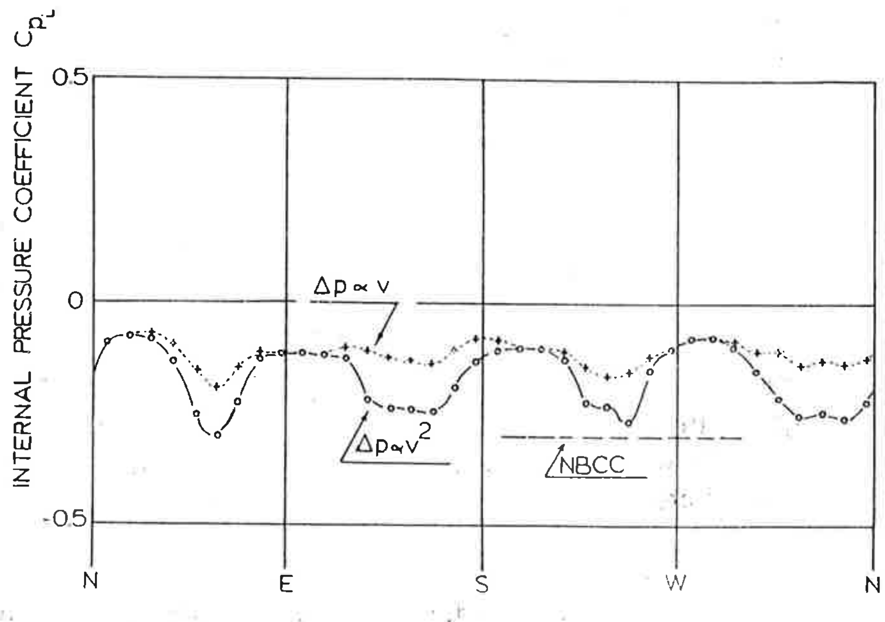


Fig. 4. Calculated internal pressure coefficients for linear and quadratic assumptions.

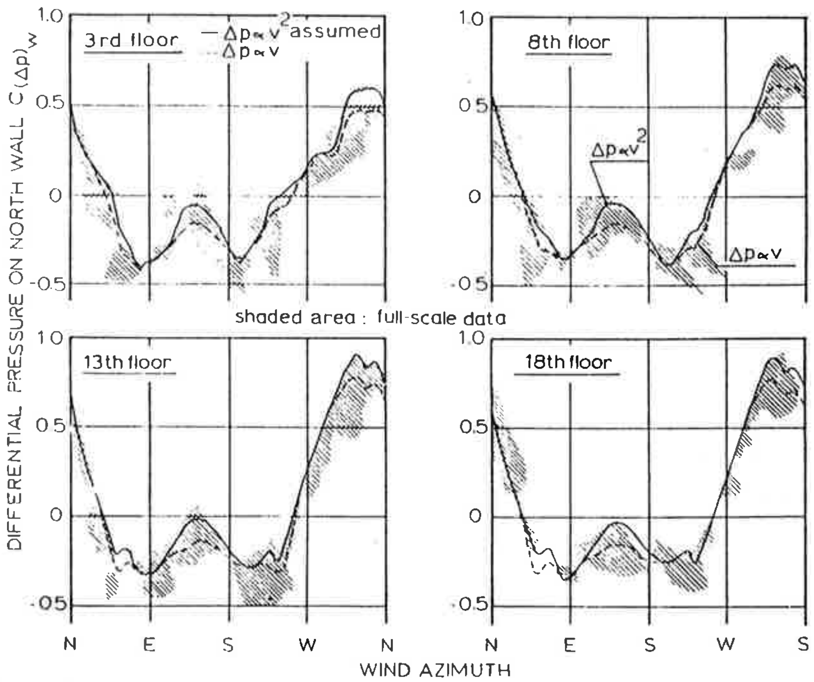


Fig. 5. Comparison of model and full-scale differential pressures of the north wall.

model test results and full-scale observations is generally satisfactory. It is of interest to note that $\Delta p = a_1 V$ leads to better agreement than the alternative relationship.

3. Verification of thermal effect

The pressure due to the stack effect can be approximately given by the following equation;

$$(\Delta p)_s = C_1 \left(\frac{1}{T_0} - \frac{1}{T_i}\right)(C_2 - z) \qquad (3)$$

where: $(\Delta p)_s$ = the pressure differential caused by the stack effect at the elevation z (m) above the ground, T_0 = the outside temperature (K), T_i = the inside temperature (K), and C_1 and C_2 are constants. C_2 corresponds to the height of the neutral pressure level (NPL), at which the inside and outside pressures are equal. Equation (3) is derived simply from the pressure equilibrium and the equation of state for a perfect gas assuming that the variation of temperature with height is small and negligible, both in the atmosphere and inside the building. A theoretical estimate of C_1 is 3.44×10^3 Pa K m^{-1}, which compares favourably with the measured value, $C_1 = 3.70 \times 10^3$ Pa K m^{-1} [2].

Equation (3) can predict the actual distribution of the pressure differential caused by the stack effect, provided that the neutral pressure level,

C_2, is accurately known. The ASHRAE [5] recommended calculation of NPL as follows:

$$\frac{C_2}{H} = \frac{1}{1 + \frac{T_0}{T_i}\left(\frac{A_0}{A_H}\right)^2} \tag{4}$$

where: A_0 = the cross-sectional area of lower opening, and A_H = the cross-sectional area of upper opening. Application of this equation is limited to the case of a building having only two sufficiently large openings, one upper and one lower, and the recommended equation is based on Bernoulli's principle and the continuity equation. Neither the resistance along the flow path, including cracks and openings, nor the actual distribution of openings along the building height is taken into account for the derivation of eqn. (4). It is, therefore, quite legitimate to doubt the accuracy of predictions of NPL by this method.

The results of an experimental study on the stack effect are reported here using a simple model, simulating a high-rise building without any internal partition, for various thermal conditions and crack distributions. Needless to say, this model test is not meant to simulate any particular building but to clarify the stack effect mechanism in high-rise structures.

The test section is made of 18.3 m long copper pipe (50.8 mm ID) and divided into 20 heating units. Each heating unit is about 0.90 m in length and has an independent heating element which can be controlled individually. The copper pipe is thermally insulated from the ambient air. Thus, the internal temperature distribution can be set to any designed profile. One K-type thermocouple was spot-welded on the outer wall of the tube at the centre of each unit. Seven pressure taps and six holes to represent the wall cracks, as shown in Fig. 6, are also provided.

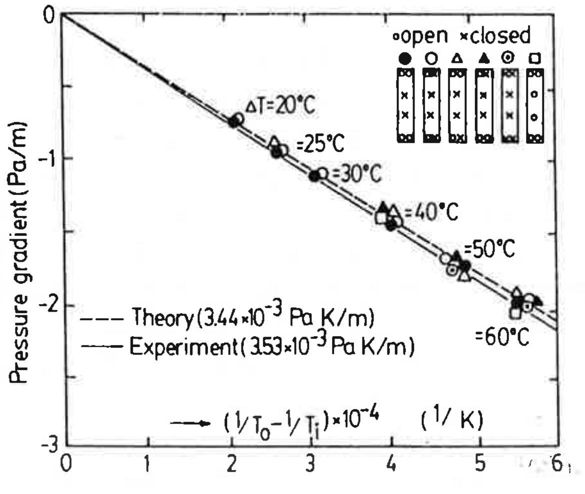


Fig. 6. Vertical pressure gradient.

In order to test the validity of eqn. (3), the coefficient C_1 is plotted against temperature change in Fig. 6, which exhibits a linear relationship. The values of C_1 were obtained from the vertical profiles of pressure differential, such as those shown in Fig. 7. As it can be observed in Fig. 6, the agreement between the values of C_1 obtained from experiment and the theoretically predicted value is excellent. This confirms the finding from full-scale measurements reported in the previous section. The values of NPL based on the ASHRAE recommendations, eqn. (4), and those obtained from the present experiment are compared in Fig. 8. The deviation between the two is significant. This deviation can probably be attributed to the flow resistance along its path as these results are all from the cases of only two openings, upper and lower. While the ASHRAE equation shows the effect of the difference in inside and outside air tempera-

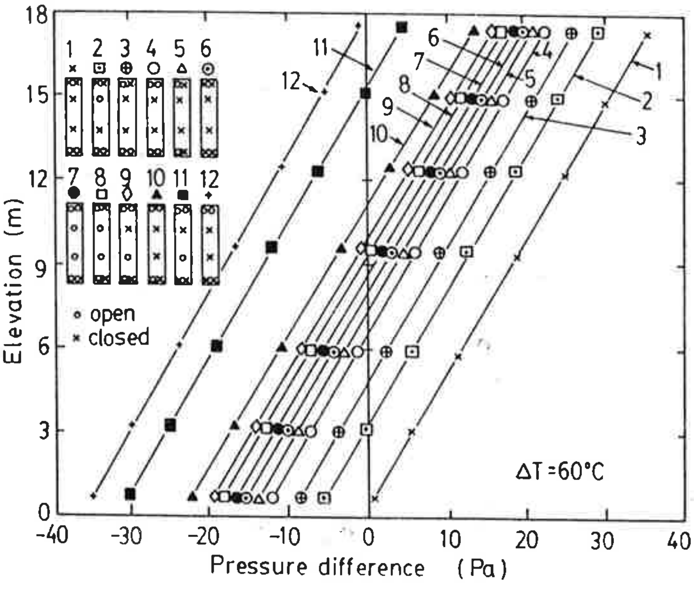


Fig. 7. Thermally induced pressure differential profiles.

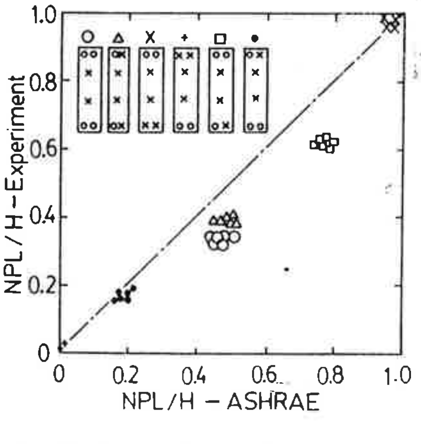


Fig. 8. Comparison of experimental and ASHRAE predictions of NPL.

tures, the experimental results indicate that NPL is hardly affected by the temperature difference for a given crack distribution.

4. Non-linearity of pressure differentials under combined effects

As mentioned in the earlier sections, the non-linear characteristics of differential pressure and air infiltration under combined effects of wind action, stack action and forced ventilation can cause inaccurate estimates of the thermal performance of the building, and yet this problem does not seem to have been given any serious consideration so far. To verify this anomaly in the calculation of air infiltration, the non-linearity of combined wind action and mechanical ventilation on the pressure differential and air infiltration across the building envelope was investigated via a wind-tunnel test [6]. A study of the combined action of the stack effect and mechanical ventilation is also under progress by the authors. The linear summation of stack and wind effects is also likely to be controversial.

4.1. Experimental set-up

The test model simulating a building in this case is a rigid acrylic box having a square section of 15.2 × 15.2 cm and 30.4 cm high. Each wall of the model is divided into three levels, each level having four holes 2 mm in diameter, giving a total of 48 holes as shown in Fig. 9. Each hole represents a wall crack. One external pressure tap is provided at the centre of each pair of holes, making a total of 36 available taps. Four additional internal pressure taps are also provided. The model has a plain flat roof, while the floor has a 25 mm diameter hole in its centre, which is connected to an air pump of 0.41 m^3 min^{-1} capacity to simulate mechanical ventilation. The model is installed in the test section of the wind tunnel, which is described in the previous section.

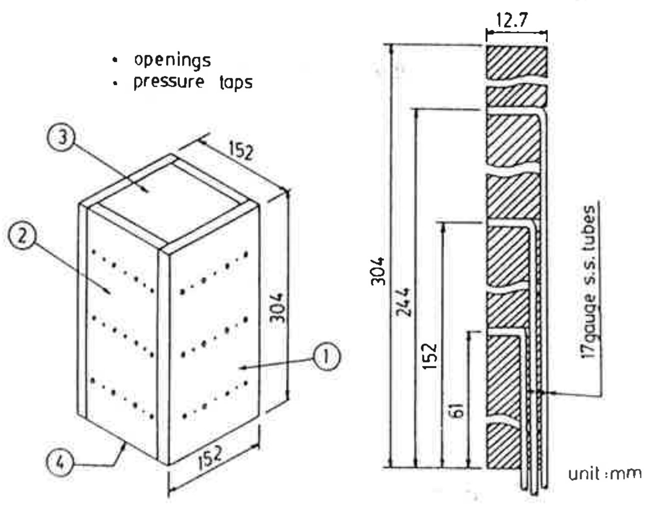


Fig. 9. Model building for study of non-linearities.

The test was carried out with various combinations of mean wind speed and azimuth angle. The ventilation rate was also changed in the range of ± 35% of the building internal capacity per second. As the only significant issue of this part of the study is the interaction problem of ventilation-induced and wind-induced pressures and the actual pattern of pressure distribution over this particular building is not a problem not much attention was paid to blockage or to the simulation of wind conditions. However, for the purpose of qualitative discussion, the model was tested in a uniform smooth flow as well as in turbulent shear flow produced by the upstream roughness.

4.2. Results and discussion

First, the pressure distribution was measured under wind action only. Since the shape of the building is square, a symmetrical pressure distribution was observed. Internal and external pressure readings are normalized by the dynamic head at the gradient level and are summarized in Figs. 10 and 11 together with the resulting pressure differentials. Knowing both the external and internal pressure distributions, the infiltration rate can be calculated by applying the standard friction and form losses across the openings.

Second, the ventilation pump was operated without wind. When the model building is not internally partitioned, a negative internal pressure is uniformly observed if the air is extracted from the building with the pump. Similarly, the internal pressure becomes positive and uniform when the building is pressurized. The external pressure of the building walls is hardly affected by these operations. The air infiltration due to mechanical ventilation can again be calculated from the pressure differentials across the walls. The calculated flow rate was found to be 7—8% greater than

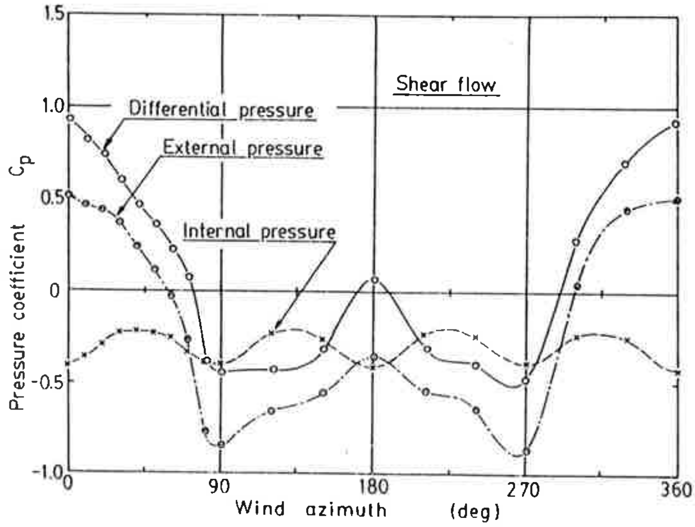


Fig. 10. Differential wall pressures in shear flow.

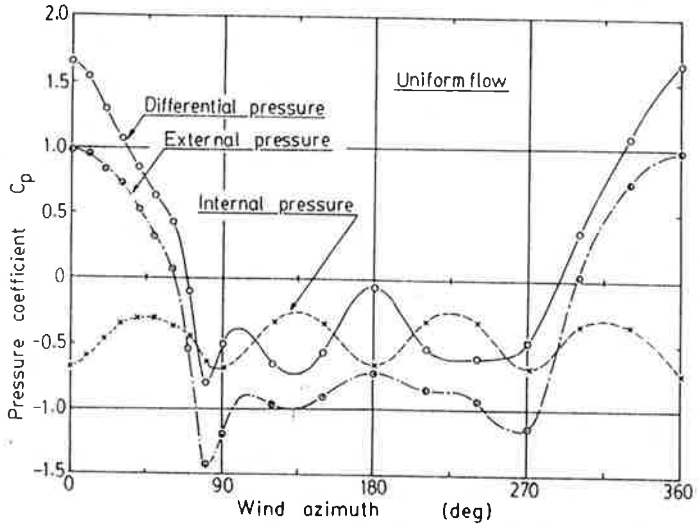


Fig. 11. Differential wall pressures in uniform flow.

the actual flow rate measured at the bottom plate of the building with a rotameter. This may be due to the use of a friction factor applicable to fully developed flow. This illustrates the accuracy of the flow calculation compared to the known pressure distribution.

Finally, the pressure induced by the combined action of wind and mechanical ventilation was examined. The external pressure distribution of the model building under combined action is very similar to that induced by the action of wind only. However, the internal pressure distribution is markedly changed.

A representative comparison is made in Fig. 12 between the pressure differential due to the effects of combined wind action and mechanical suction and the linear summation of the pressure differentials induced by

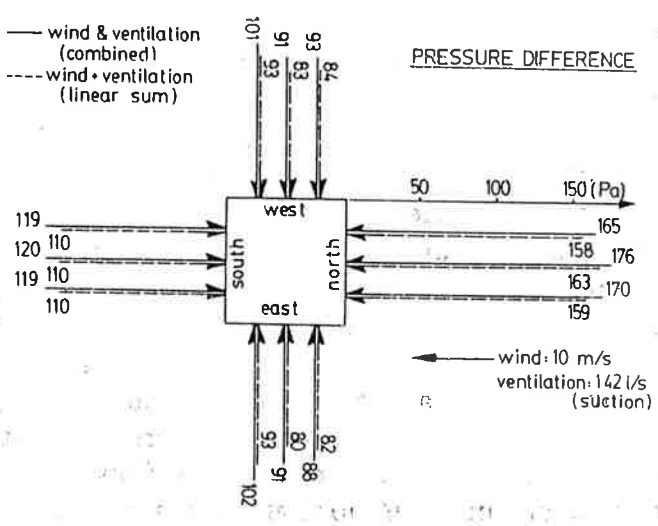


Fig. 12. Non-linearity of pressure differential (building with suction).

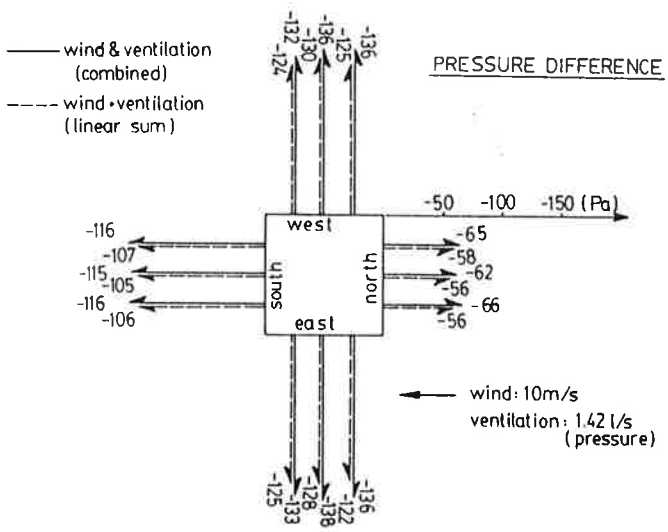


Fig. 13. Non-linearity of pressure differential (building pressurized).

the individual actions. The solid lines represent the former, while the broken lines the latter. Figure 13 is a similar diagram but of the case in which there is a combined action of wind and mechanical pressurization. In both figures the non-linearity of the pressure differential induced by wind and forced ventilation is clearly demonstrated. The linear summation of the pressure differentials due to each individual action cannot be taken as equivalent to the pressure differential from the combined action. It is interesting to note that the linear summation of independent actions leads to a slightly smaller magnitude pressure drop across the wall than the actual differential pressure in both infiltration and exfiltration cases. The percentage variations due to the non-linearity were found to be between 5 and 30%, depending on the test conditions, but it is generally observed that the deviation:

(i) was greater with the shear flow,
(ii) increased in magnitude with a decrease in the mechanical ventilation rate,
(iii) increased for wind normal to one wall of the building, and
(iv) was almost independent of wind speed.

The non-linearity in the summation of the pressure differentials induced by wind and mechanical ventilation may be due to the fact that when the ventilation is by suction, for example, the suction in the building through the openings decreases the relative size of the wakes and hence, results in a decrease in the negative pressure at the sides and rear walls of the building. The changes in the distribution of pressure in the wake also lead to the readjustment of the internal pressure and the external pressure at the frontal face. For the same flow of mass, a greater external pressure occurs at the wall normal to the wind. Therefore, the pressure differential across the four walls of the building due to the combined action of the wind and mechanical ventilation is always greater than the linear summation of the individual pressure differentials.

4.3. Non-linearity of air infiltration/exfiltration

The non-linearity of the pressure differential induced by wind and mechanical ventilation implies the non-linearity of air infiltration or exfiltration of a building due to those two separate actions, and this is clearly seen in Figs. 14 and 15. These figures distinctly show the increased percentage deviation of the air infiltration rate or exfiltration rate compared with the deviation in pressure. The deviation is between 5 and 50% with greater deviations observed over the front and side walls of buildings.

From this part of the study, it may be concluded that:

(i) The linear summation of pressure differentials due to the action

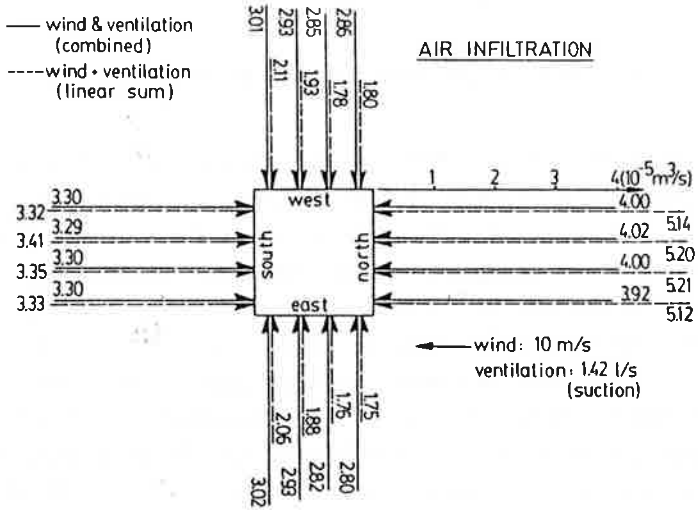


Fig. 14. Non-linearity of air infiltration rates.

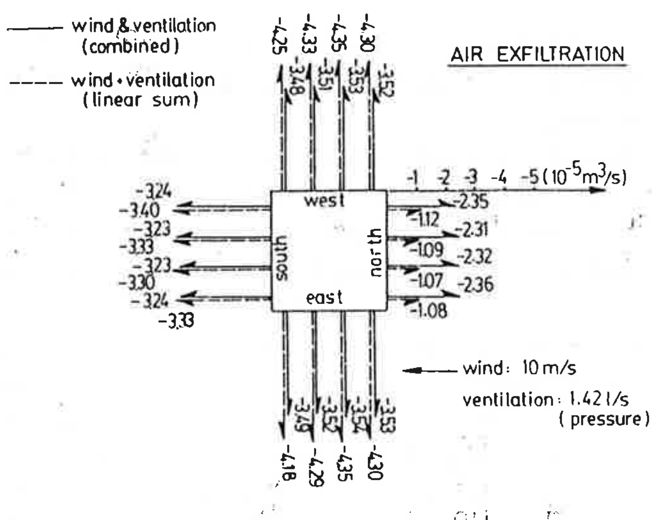


Fig. 15. Non-linearity of air exfiltration rates.

of the wind and the operation of a forced ventilation system cannot be taken to be the equivalent of the pressure differential due to the combined action of the two,

(ii) From (i) above, it is evident that the linear summation of air infiltrations or exfiltrations due to individual actions is also not equivalent to the air infiltration or exfiltration due to the combined action of the two, and

(iii) Knowing the pressure differentials across the building envelope, a fairly accurate estimation of the infiltration rate can be made by applying the standard friction and form losses across the openings in the walls.

5. Concluding remarks

The effects of wind, temperature and mechanical ventilation on pressure differentials and pressure-induced air infiltration or exfiltration rate across the exterior walls of high-rise buildings were extensively investigated through full-scale measurements, laboratory experiments and theoretical considerations. The main findings of the study may be summarized as follows:

(1) The full-scale measurements on a twenty-storey building and the data analysis lead to the following findings [2]:

(i) Pressure differences are caused by the stack effect, the wind and the operation of the mechanical ventilation system. The first two causes are predominant for this particular building during the winter season.

(ii) The stack effect, for buildings having an open floor layout, is linearly proportional to the difference of the reciprocal outer and inner absolute temperatures, and varies almost linearly with height. The neutral pressure level occurs at approximately 70% of the total building height.

(iii) The pressure distribution is also affected by the occupancy conditions of the building.

(iv) The wind-induced pressure distribution under relatively strong wind shows good conformity with previous knowledge for typical bluff sections, such as a square.

(v) The pressure differences caused by the heating and ventilation systems are much smaller than those caused by the stack effect and by wind action. Evaluation of the former was found to be difficult and this uncertainty was attributed to the assumption that a linear summation of three pressure components was valid.

From the present scale model study, it may be concluded that:

(2) The wind tunnel study verified the wind-induced component of the measured pressure differential above. The calculation of pressure differentials from the measured external pressure distribution gave reasonably accurate results assuming the standard friction losses across openings.

(3) The verification study of the stack effect confirmed that the ther-

mally induced pressure differentials can be accurately predicted with the correct value of the neutral pressure level. The calculation of NPL must recognize flow resistance and the distribution of openings on the building.

(4) The pressure differentials and induced air infiltration or exfiltration rate under combined action of wind, stack and forced ventilation cannot be correctly given by a linear summation of the results under each independent action. This non-linearity seems to be particularly pronounced when wind-induced ventilation is involved. The study of the combined action of wind and mechanical ventilation leads to the following remarks:

(i) The linear summation of pressure differentials due to the action of wind and forced ventilation is found not to be the equivalent of that under combined action.

(ii) The linear summation of air leakage rates was found to deviate even further from the actual values under combined action.

(iii) Knowing the pressure differentials across the building walls, an accurate estimation of the air leakage rate can be made by applying the standard friction and form losses across the openings in the walls.

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