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Air Leakage Measurements of the Exterior Walls of Tall Buildings

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EVALUATION DES FUITES D'AIR DANS LES MURS EXTERIEURS D'EDIFICES ELEVES

SOMMAIRE

Le présent exposé décrit une méthode expérimentale, conçue dans le but de déterminer les caractéristiques de fuite d'air des murs extérieurs d'un édifice. Cette méthode consiste à mettre l'édifice sous pression au moyen du système d'alimentation en air et à mesurer les débits de l'air provenant de l'extérieur et les différentielles de pression qui en résultent le long des murs. L'étude des résultats obtenus permet d'établir un coefficient et un exposant de l'écoulement d'air pour les murs extérieurs. L'application de cette méthode aux débits d'air et aux différentilles de pression obtenus d'un modèle informatique simulant un édifice permet de vérifier le procédé et de constater que les résultats obtenus concordent bien avec les caractéristiques de fuite d'air utilisées dans la simulation. Les propriétés d'étanchéité à l'air des murs extérieurs de quatre édifices, évaluées au moyen de la présente méthode, sont également présentées.

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AIR LEAKAGE MEASUREMENTS OF THE EXTERIOR WALLS OF TALL BUILDINGS

Air leakage into and out of a building occurs mainly through cracks formed at the mating surfaces of the various exterior wall components. It contributes to the heating, cooling, and moisture loads of a building and is therefore of interest to the designer for calculating the energy requirements of air conditioning systems. Also, air movement inside a building resulting from air leakage through the exterior walls not only spreads odors but, in the event of fire, contributes to the spread of smoke and toxic gases.[1] The design of buildings and air handling systems to prevent undesirable air movement requires knowledge of the air leakage characteristics of exterior walls as well as those of various interior separations.

The conventional methods of estimating the rate of air infiltration are described in Chapter 25 of the ASHRAE Handbook of Fundamentals.[2] They are the air change and the crack methods, both of which depend to a great extent on the judgment and the experience of the designer. Air leakage data for windows, doors, and simple frame and brick walls are given in Ref. 2; these data are based on laboratory studies. There is no information on the air leakage characteristics of contemporary wall constructions such as curtain walls and spandrel panels with fixed glazing. It is difficult, therefore, for a designer to make a reliable estimate of the infiltration heat loss and gain, which continue to be the most uncertain component of the calculated total heating and cooling loads.

Air tightness of exterior walls depends not only on the wall design and materials used, but also on the workmanship and condition of various joints after weathering, both of which are difficult to duplicate in the laboratory. Only a relatively small section of an exterior wall can be tested in the laboratory, consequently a more realistic indication of the air tightness values of exterior walls would be obtained from tests performed on whole buildings. A test method was developed, therefore, to measure the air leakage characteristics of the exterior walls of existing buildings; four tall buildings in the Ottawa area were selected for this study. This paper describes the test method used and presents the results of air tightness measurements obtained for these buildings.

APPROACH

The air leakage characteristics of a building enclosure as a whole can be obtained by pressurizing the building with the supply air system and recording the supply air flow rate and the resultant pressure differentials across the enclosure. To obtain the air leakage characteristics of the typical wall area, however, it is necessary to isolate it from the non-typical wall areas such as those of the mechanical, ground and basement floors. This could be accomplished by sealing all leakage openings other than the exterior walls but, because of the number, size, and location of openings involved, this method of isolation is impractical for most buildings. An alternative method was developed, therefore, to determine the air leakage characteristics of a typical wall area.

Consider the idealized building enclosure shown in Fig. 1. The enclosure consists of three parts: the part enclosed

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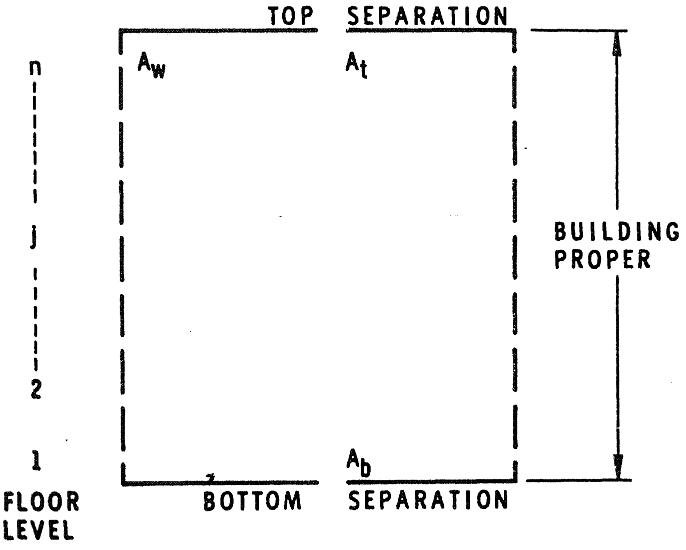

Fig. 1 Mathematical model

by the typical wall area of floors 1 to n; the top separation; and, the bottom separation. If outside air is introduced into the building proper, pressures inside are increased and hence, air flows out through the exterior walls and the bottom and top separations.

Under steady state conditions the total outside supply rate equals the air leakage rate through exterior walls plus air leakage rate through bottom separation plus air leakage rate through top separation.

thus

$$Q = A_w \left[\sum_{j=1}^{n} (\rho \Delta P_w)_j^{X_w} \right] + A_b (\rho \Delta P_b)^{X_b} + A_t (\rho \Delta P_t)^{X_t} \quad (1)$$

where

Q = the total fresh air supply rate
X = flow exponent
A = flow coefficient
ΔP = pressure difference
ρ = air density
n = the total number of floors with typical wall construction

and subscript

w = exterior wall
b = bottom separation
t = top separation

The values of Q, ΔP_w, ΔP_b and ΔP_t can be measured. By obtaining several sets of these measured values it is possible to evaluate the coefficients A_w, A_b and A_t and the exponents X_w, X_b and X_t in Eq (1).

APPLICATION

So far only a simple model of a building has been considered. The building proper, i.e., the part enclosed by the typical wall area, is usually connected to the ground, basement, and top mechanical floors by a number of vertical shafts, e.g., elevator, stair and service shafts, and air ducts. Because of these interconnections, the pressure differentials across the top and bottom separations must be defined carefully.

A typical building of about twenty-five stories is often served by an air conditioning system located on the top mechanical floor. The return and exhaust ducts are usually connected directly to the outside at the top. Elevator and service shafts may also have leakage openings connected directly to the outside at the top. Air can flow, therefore, from the building proper directly to the outside at the top through these shafts as well as into the mechanical floor and from there to outside. The pressure differential across the top separation has been defined as the difference in pressure between the top typical floor (the floor below the top mechanical floor) and the outside at mid-height of the top mechanical floor.

The basement and ground floor areas are usually served by an air conditioning system located in the basement, in which case no air ducts would connect the building proper to these areas. The only inter-connections would be the stair wells, and the elevator and service shafts that terminate either at the ground or basement floors. There is no direct connection from the building proper to the outside at the bottom. Therefore, the pressure differential across the bottom separation is defined as the difference in pressure between the first typical floor (the floor above the ground floor) and the average of the ground floor and basement pressures.

CALCULATION TECHNIQUE

Eq (1) is a nonlinear equation in six unknowns. These six unknowns can be estimated by a trial and error technique used in conjunction with the method of least squares. The calculation procedure is as follows:

1. Choose combinations of flow exponents with values between 0.5 and 1 (as this is the range of accepted values.)[2,3]
2. Use the method of least squares to obtain the flow coefficients and calculate the standard error of estimate for each combination of the flow exponents.
3. Select the values of the flow exponents and associated flow coefficients that give the lowest value of the standard error of estimate. These values are taken as the solution to Eq (1).

The rate of air leakage through the exterior wall for a given pressure differential can then be estimated by the following equations:

$$Q_w = A_w \sum_{j=1}^{n} (\rho \Delta P_w)_j^{X_w} \quad (2a)$$

or

$$q_w = \frac{A_w}{D} (\rho \Delta P_w)^{X_w} \quad (2b)$$

where,

Q_w = the total wall air leakage rate in cfm
q_w = the wall air leakage rate per unit area in cfm/sq ft
D = the total exterior wall area per story in sq ft
ρ = the air density in lb/cu ft
ΔP_w = the pressure difference across the wall in in. of water

Eq (1) shows that the division of the total air leakage rate into three components depends upon the values of pressure differentials across each separation. If those values are the same, the rate of air leakage through the exterior wall cannot be separated from the air leakage through the top and bottom. One way to ensure that they will be different is to conduct the tests when the outside temperature is lower than the inside temperature, thus producing stack action which will result in pressure differentials across the walls that will vary from the bottom to the top of the building. They can then be superimposed on those caused by the outside air supply into the building. Also, to ensure that stable pressure readings are obtained, measurements should be made during calm wind conditions.

VALIDATION OF THE METHOD

An ideal method of testing the accuracy of the proposed method would be to apply it to a building that has a known air leakage characteristic; this is not possible because air leakage characteristics are not known. A building with specified air leakage characteristics can, however, be simulated by using a digital computer.[4] Simulated test data can thus be obtained and the proposed method applied and verified.

The model selected for test is that of a twenty-story building, shown in Fig. 2, which includes a basement and a top mechanical floor. It contains three vertical shafts representing the return and exhaust air mains of the air handling system and an elevator shaft. Specific values of air leakage characteristics were used for the model and, with the aid of a digital computer, pressure differential and air leakage rate across each separation were computed.

Three conditions were considered:

Case I

The flow exponents for the exterior walls, floor and shafts were 0.5. Computations were carried out with fresh air supply rates of 0 to 70,000 cfm in 10,000 cfm increments with an outside temp of 25F and an inside temp of 75F.

Case II

Same conditions as Case I except that all leakage openings in the top separations were sealed off.

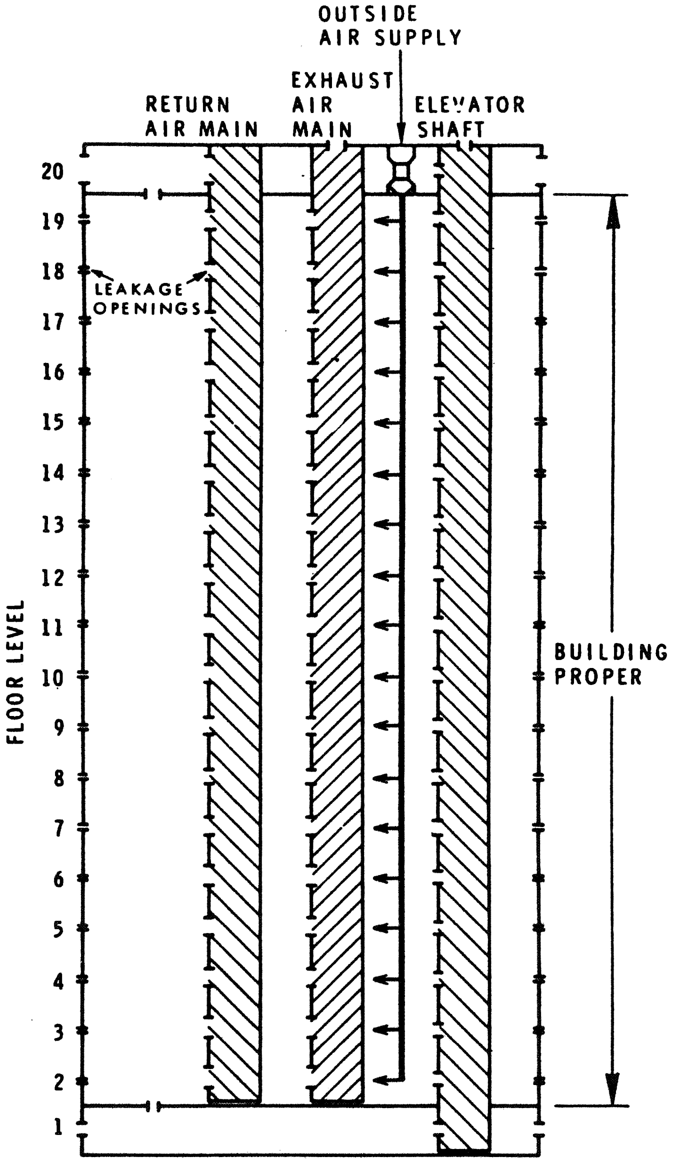

Fig. 2 Computer-simulated building

Case III

Again, same conditions as Case I except that the flow exponent for the exterior walls was 0.66.

The proposed method permits selection of the combination of flow exponents and their associated flow coefficients that give the best estimate of the overall leakage characteristics of the building enclosure as a whole. The minimum standard errors of estimates were found to be 146, 696 and 164 cfm for Cases I, II and III, respectively, indicating that the selected combination of flow exponents gave a close estimate of the specified overall leakage characteristics.

Flow exponents and coefficients of the exterior walls obtained from the proposed method were found to give a

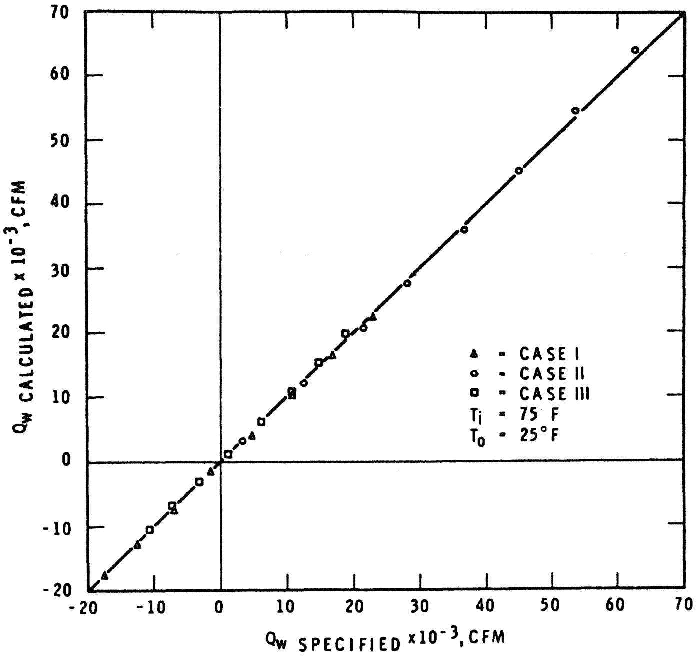

Fig. 3a Calculated exterior wall air leakage rate vs specified exterior wall air leakage rate

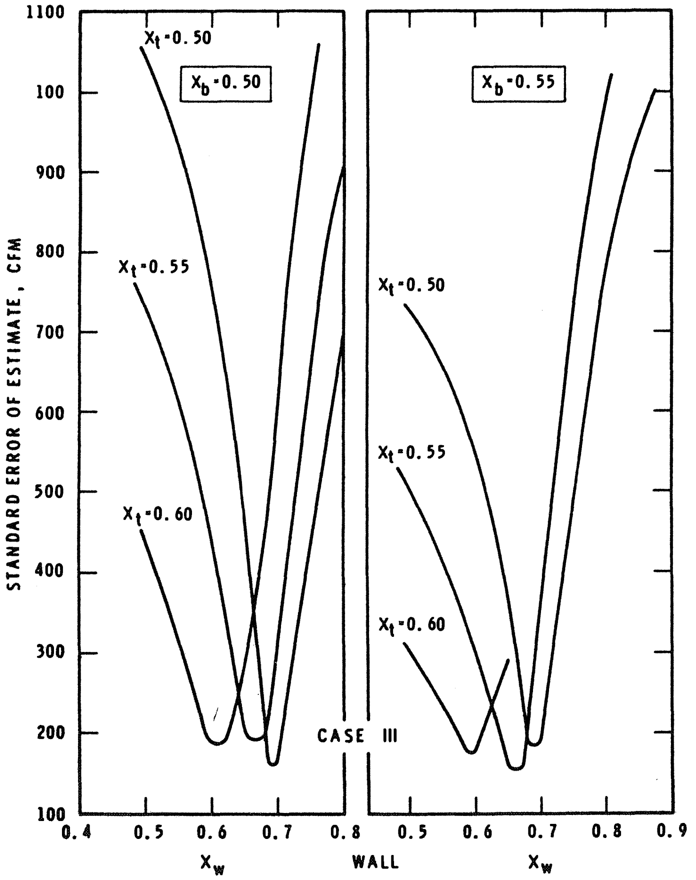

Fig. 3b Standard error of estimate vs flow exponent for wall

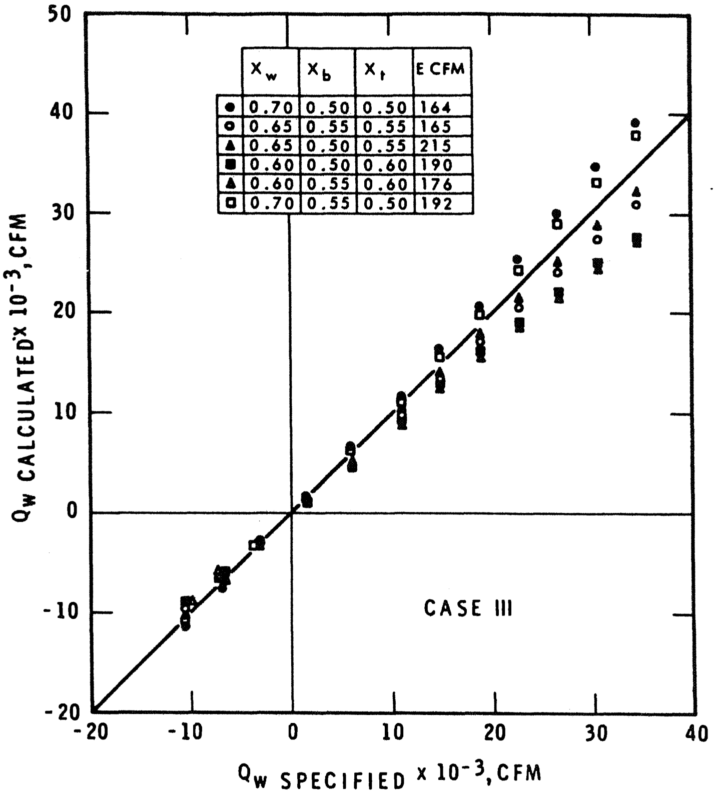

Fig. 3c Calculated exterior wall air leakage rate vs specified exterior wall air leakage rate for various standard errors of estimate

good estimate of the air leakage characteristics of the exterior walls. The calculated wall air leakage rates were plotted against the specified wall air leakage rates as shown in Fig. 3a. The results show that the calculated wall air leakage rates lie within ±10% of the specified wall air leakage rates.

Because the standard error of estimate is related to the overall air leakage rates, the minimum standard error of estimate may not necessarily give the best indication of the wall air leakage rate. To investigate this, wall exponents were plotted against the standard error of estimate for different combinations of exponents for the bottom and top separations. A graph for Case III is shown in Fig. 3b, with flow exponents in the top separation of 0.5, 0.55 and 0.60 and in the bottom separation of 0.5 and 0.55. The graph indicates that, with fixed values of flow exponents for the bottom and top separations, the standard error of estimates for different combinations of flow exponents shown in Fig. 3a varies from 164 to 215 cfm, with variation in the exterior wall flow exponent of from 0.6 to 0.7. The minimum standard error of estimate is obtained with flow exponent of 0.50 for the bottom separation, 0.50 for the top separation and 0.70 for the exterior wall. The assigned value of flow exponent for Case III is 0.66.

(c) Pressure difference across the top separation.

$$\Delta P_t = P_{in} - P_{o\,(n+1)} = \Delta P_{Min} - \Delta P_{Mon} + (\rho_o + \rho_i)\,H$$

where

H = the distance between the centers of the n^{th} and the mechanical floors ($n+1^{th}$) floor.

Subscripts

1, n = first and top typical floors,
b1 and b2 = the ground floor and basement,
M = meter reading.

RESULTS AND DISCUSSIONS

The flow coefficients and flow exponents that describe the air leakage characteristics of the various separations were obtained for the four buildings and are given in Table II. Also given in this Table are values of the standard error of estimate that indicate that the measured and estimated overall air leakage rates are in good agreement. This does not imply that the same degree of accuracy in the estimates of the exterior wall air leakage rates was obtained. It has been shown, however, that the proposed method estimates the wall air leakage rate to within ±10% for the computer-simulated building. It would be expected, therefore, that if the standard error of estimate is small, reasonable accuracy of the estimate of wall leakage characteristics would be obtained.

The total air leakage rates for the test buildings are given in Fig. 9. The total air leakage rates are expressed in

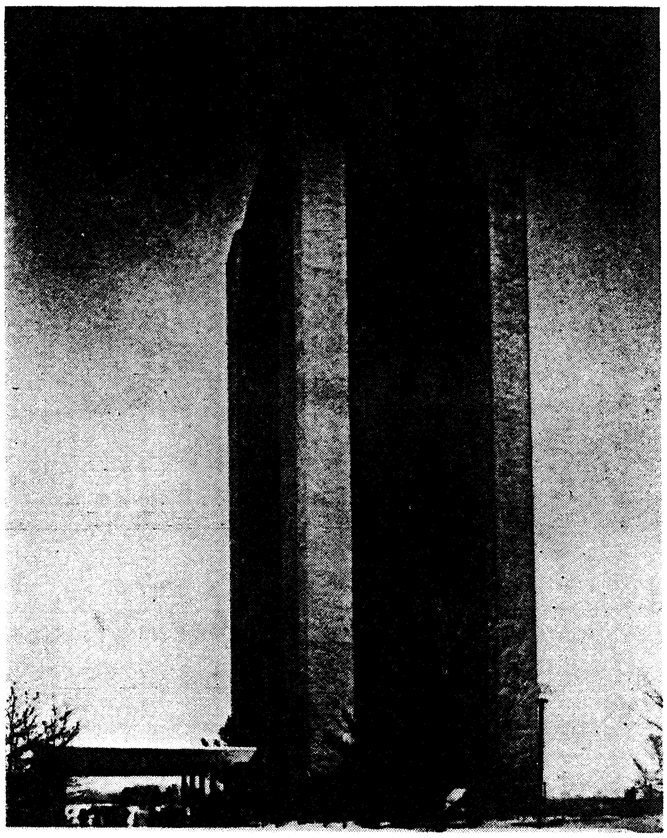

Fig. 7 Building D

TABLE II

FLOW COEFFICIENTS AND EXPONENTS

Test Buildings		A	B	C	D
Building proper	A_w	67600	12800	25200	14500
	X_w	0.70	0.5	0.75	0.65
Bottom separation	A_b	688800	33400	85900	6900
	X_b	0.7	0.7	0.5	0.5
Top separation	A_t	141300	154200	645000	184100
	X_t	0.6	0.5	0.7	0.5
Total outside wall area from ground to the roof levels (sq ft) (D_1)		112700	103700	134400	82900
Exterior wall area per typical floor (sq ft) (D)		9776	5016	5757	3920
Standard error of estimate (cfm)		8900 for 130000 $0 < Q < 130000$	1310 for 45000 $0 < Q < 45000$	1190 for 160000 $0 < Q < 160000$	1130 for 47500 $0 < Q < 47500$

Governing Equations

Over-all air leakage rate (cfm/sq ft)

$$\frac{Q}{D_1} = \frac{1}{D_1}\left\{A_w \sum_{j=1}^{n} (\rho \Delta P_w)_j^{X_w} + A_b (\rho \Delta P)^{X_b} + A_t (\rho \Delta P_t)^{X_t}\right\}$$

Wall air leakage rate (cfm/sq ft)

$$q_w = \frac{1}{D} A_w (\rho \Delta P)^{X_w}$$

Standard error of estimate (cfm)

$$E = \left\{ \sum (Q\ \text{measured} - Q\ \text{calculated})^2 / (\text{No. of samples} - 3\ ) \right\}^{1/2}$$

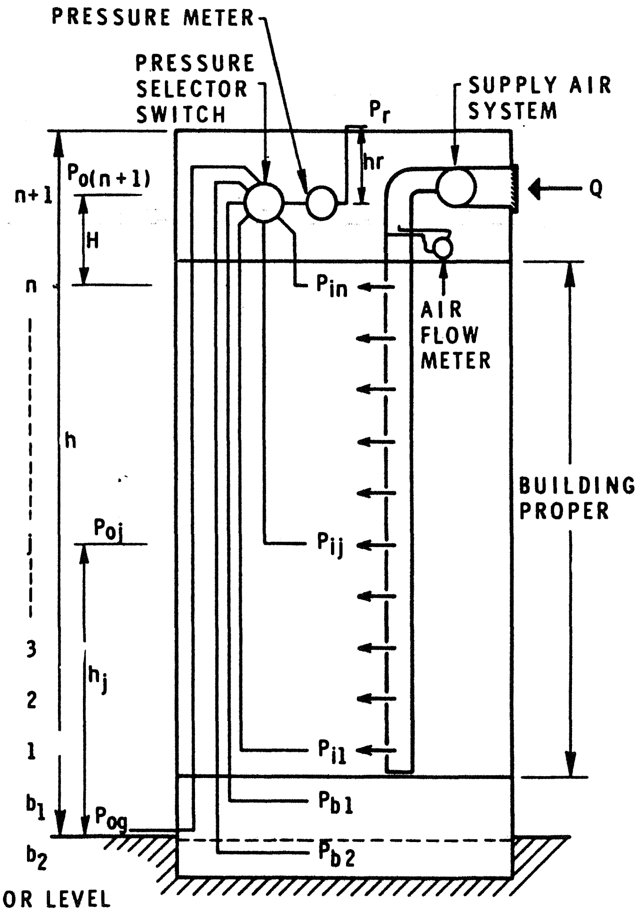

Fig. 8a Arrangement of test equipment

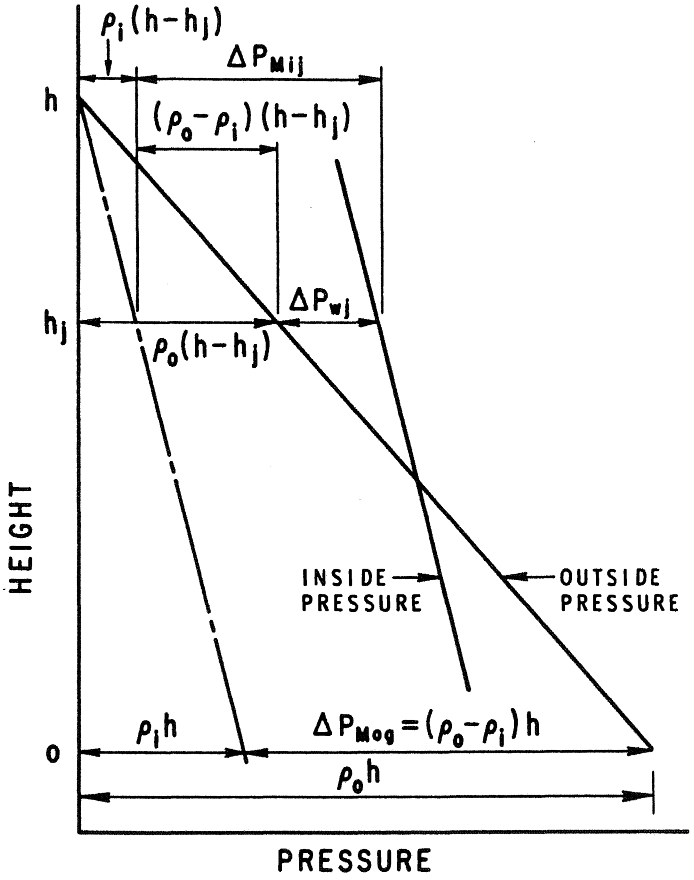

Fig. 8b Pressure difference across an exterior wall

cfm/sq ft of outside wall area above ground level and include the area of the exterior walls of the top mechanical floor. The air leakage rates for the test buildings ranged from 0.5 to 1.1 cfm/sq ft of outside wall area at pressure difference of 0.3 in. of water.

Fig. 9 shows that the overall air leakage rate of Building A is considerably higher than that of the other buildings. This building differs from the other buildings in that it has two conveyor shafts with large openings to each floor which serve as an additional interconnection between the building proper and the basement as well as the mechanical floor. Also, there is a large tunnel to a nearby building from the basement. It is to be expected that these interconnections contributed to the high value of overall leakage rate for this building.

The measurements of overall leakage characteristics for three tall buildings including Building B were reported in 1967 by Tamura and Wilson.[6] The overall air leakage rates of these buildings varied from 0.5 to 0.8 cfm/sq ft of outside wall area at 0.3 in. of water and are within the range of those given in Fig. 9. This figure also shows the overall air leakage characteristics of Building B obtained prior to 1967. During the time between the two tests, an attempt was made to improve the exterior wall tightness of Building B by sealing the cracks and openings in the corners, behind the induction units and other locations. This partly explains the lower value of air leakage rate for the recent test.

The air leakage characteristics of the exterior wall of the four test buildings are given in Fig. 10 in terms of cfm/sq ft of the total typical wall area. The exterior wall air leakage rates of these buildings varied from 0.25 to 0.48 cfm/sq ft at a pressure difference of 0.3 in. of water. The exterior wall air leakage rates of the four buildings were found to be from 30 to 55% of the overall air leakage rates. The air leakage characteristics of a 13 in. unplastered brick wall given in Ref. 2 is also plotted in Fig. 10. It appears that the exterior walls of the test buildings have about the same permeability to air as an unplastered brick wall.

It is difficult to identify all the leakage openings in the exterior wall of a building from either inspection of the wall construction or the architectural drawings. Also, air tightness of a wall section depends on the quality of workmanship as much as on the wall design and is therefore difficult to predict. The test results presented in this paper give some indication of the wall air leakage characteristics that can be expected for modern high-rise buildings.

SUMMARY

A test method was developed to determine the air leakage characteristics of the exterior walls of a building. The

TABLE I

DESCRIPTIONS OF TEST BUILDINGS

	Building A	Building B	Building C	Building D
Height	151	220	247	253
No. of floors above ground (excluding lobby and mech. floor)	9	13	20	20
Floor dimensions (ft)	166 x 210	88 x 140	126 x 146	75 x 93
Typical Floor height (ft)	13	11	10.6	10.5
Volume above ground (cu ft)	5,095,000	2,459,000	4,509,000	1,704,000
Outside wall area per typical floor (ft^2)	9,776	5,016	5,757	3,920
Typical window size (ft)	8.5 x 7.9	3.8 x 6.9	2.6 x 6.5	4.7 x 4.5
No. of windows per typical floor	56	64	104	44
Roof area/net outside wall area	.61	.25	.23	.12
Total outside wall area above ground level (including area of the exterior walls of the top mech. floor)	112,700	103.700	134.400	82,900
Windows	Fixed double glazing in aluminum	Openable double glazine in aluminum (normally locked)	Fixed double glazing	Fixed double glazing
Wall construction	5-in. PEAC panel 8-in. Tile 2-in. Rigid insulation with vapour barrier Air space 6-in. Tile 3/4-in. Plaster	Precast concrete panel backed with 2-in. rigid insulation	Precast concrete panel Air space 1-in. Rigid insulation 1/2-in. Cement rendering 6-in. Block wall 3/4-in. Plaster	(1) Wall 2-in. Hollow steel panel Air space Rigid insulation 20-in. Concrete (2) Corners 4-in. Face brick 2-in. Rigid insulation 12-in. Poured concrete

The exterior wall air leakage rates calculated with flow exponents and their associated flow coefficients corresponding to the minimum standard error of estimates given in Fig. 3b are plotted against the specified air leakage rates in Fig. 3c. The graph shows that the flow exponent and associated flow coefficient corresponding to the minimum standard error of estimate of 164 cfm does not give the best estimate of the specified wall leakage rates. The best estimate is obtained with standard error of estimate of 215 cfm. Although the flow exponents corresponding to the minimum standard error of estimate do not necessarily give the best estimate of the wall air leakage rates, as shown in Fig. 3a and 3c, they do give an adequate estimate. Also, where the wall leakage characteristics are not known, as in the case of real buildings, the use of minimum standard error of estimate serves as a criterion for the selection of the flow exponents and coefficients.

FIELD MEASUREMENTS

Air leakage characteristics of the exterior walls of four tall buildings designated as Buildings A, B, C and D (Figs. 4, 5, 6 and 7) were determined using the proposed method. These buildings all have a full basement below grade and a mechanical floor at the top. Descriptions of the building are given in Table I. Pressure differentials across the exterior walls and bottom and top separations were measured for various rates of fresh air supplied under the following conditions:

1 All auxiliary air handling systems were shut down.

2 All fans of the return and exhaust systems were shut down.

3 To obtain uniform pressurization in the building proper, stair doors were kept open except for those on the basement, ground and mechanical floors.

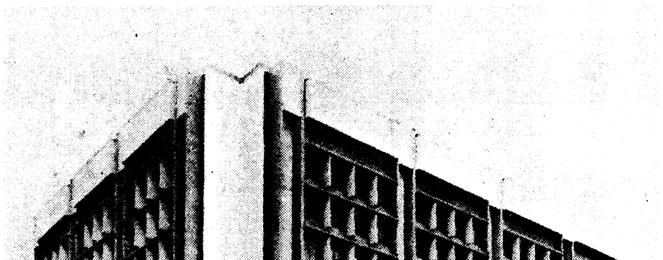

Fig. 4 Building A

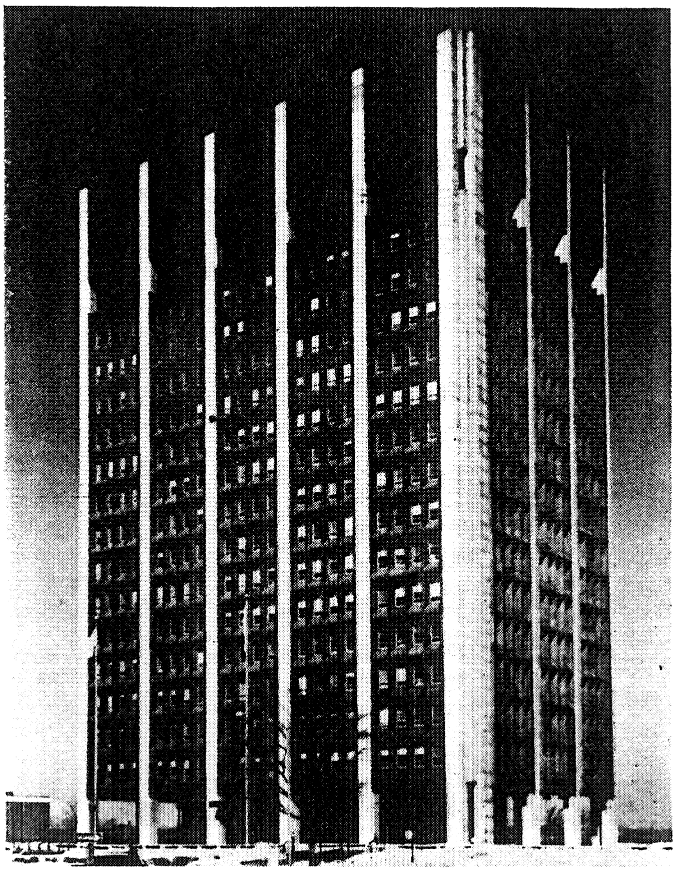

Fig. 5 Building B

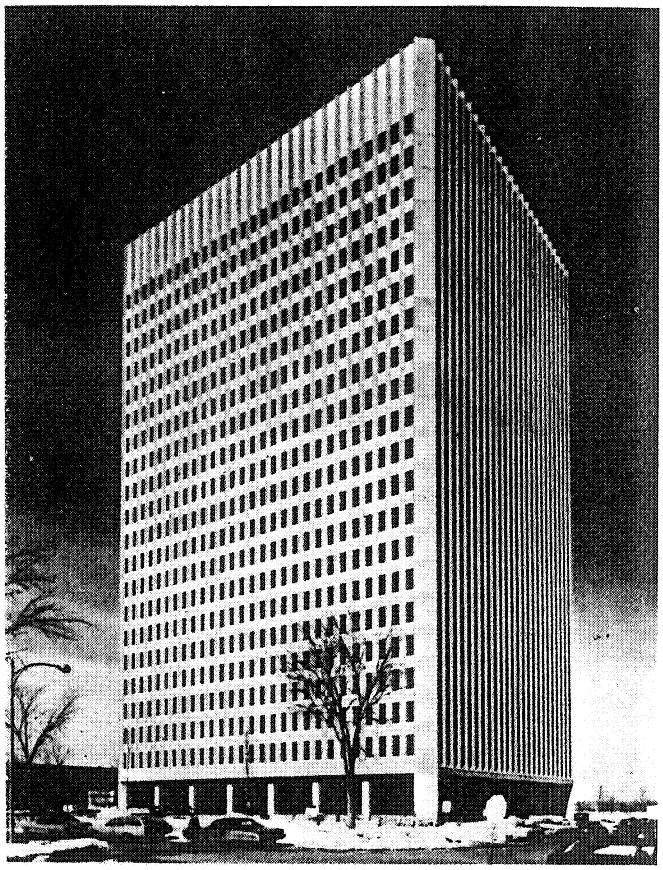

Fig. 6 Building C

4 Main entrance doors and elevator and stair doors at the basement, ground floors, and the top mechanical floors were kept closed during the test.

5 To minimize the effect of wind pressures on the buildings all tests were conducted during relatively calm conditions.

6 All tests were conducted when the outside temperature was at least 20 F below the inside temp.

7 All tests were conducted during unoccupied periods.

INSTRUMENTATION

Fresh air supply rates were measured using total pressure averaging tubes[5] and their associated static pressure taps installed in the main supply air ducts at positions as far away from the duct bends as practicable. Based on laboratory tests,[5] the accuracy of this flow rate measuring device was found to be better than ±6.5% of the actual flow rate for air velocities of from 600 to 1400 fpm. Pressure differentials were measured with a pressure recording instrument located on the top mechanical floor. One side of the meter was connected to the roof top pressure tap which served as a reference pressure; the other side of the meter was connected to a pressure selector switch. From the pressure selector switch, 3/16 in. plastic tubes were installed vertically in a stair shaft terminating at various floor spaces and also to the outside at ground level. The sensitivity of the pressure transducer is 0.002 in. of water. The schematic diagram of the installation is shown in Fig. 8a.

Pressure differences across the various separations can be calculated from the pressure meter readings as follows:

(a) Pressure difference across the exterior wall at the jth level (Fig. 8b)

$$\begin{aligned}\Delta P_{wj} &= P_{ij} - P_{oj}\\ &= \Delta P_{Mij} - (h - h_j)(\rho_o - \rho_i)\\ &= \Delta P_{Mij} - [h(\rho_o - \rho_i) - h_j(\rho_o - \rho_i)]\\ &= \Delta P_{Mij} - [\Delta P_{Mog} - h_j(\rho_o - \rho_i)]\\ &= \Delta P_{Mij} - \Delta P_{Mog}(h - h_j)/h\end{aligned}$$

where

P_i, P_o = inside and outside gauge pressures

ΔP_{Mi}, ΔP_{Mo} = meter readings associated with P_i and P_o respectively.

ΔP_{Mog} = meter reading associated with outside pressure at the ground level.

h and h_j = vertical distances as shown in Figs. 8a, 8b.

(b) Pressure difference across the bottom separation

$$\Delta P_b = P_{i1} - \left(\frac{P_{b1} + P_{b2}}{2}\right) = \Delta P_{Mi1} - \left(\frac{\Delta P_{Mb1} + \Delta P_{Mb2}}{2}\right)$$

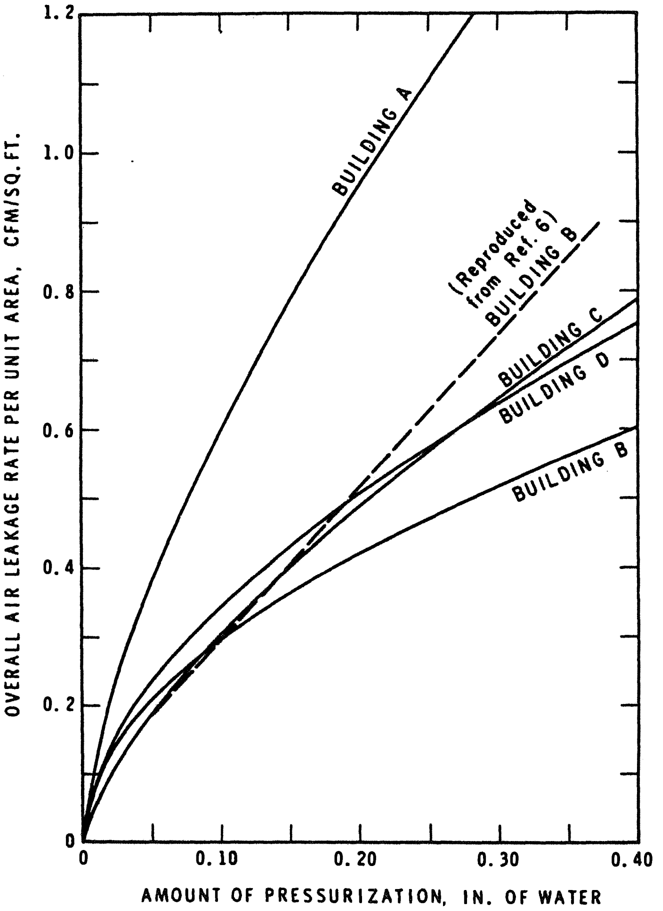

Fig. 9 Overall air leakage rate per unit area vs building pressurization

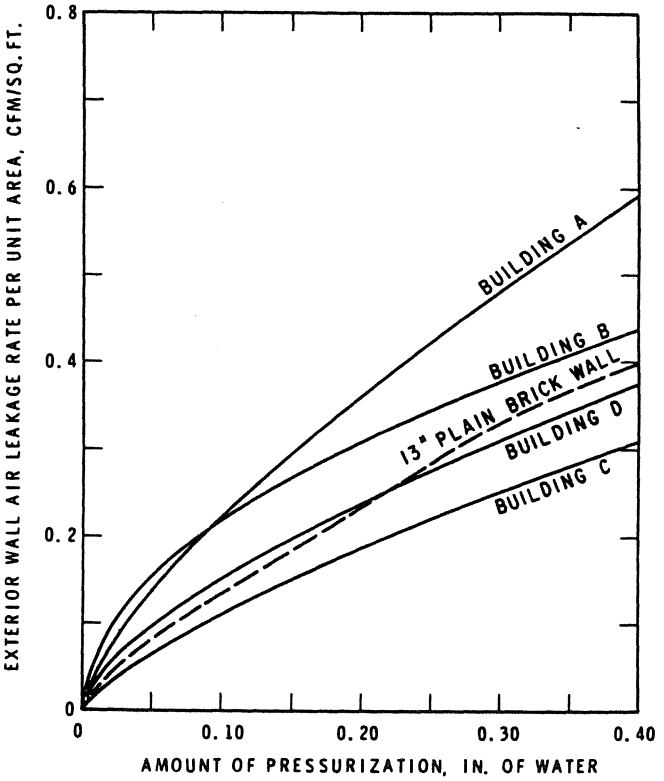

Fig. 10 Exterior wall air leakage rate per unit area vs building pressurization

validity of the method was checked using a computer-simulated building with specified air leakage characteristics. Good agreement was obtained between the calculated and specified wall air leakage rates. Using this method the exterior wall air leakage characteristics of the four test buildings were obtained. The test results indicate that the exterior walls of these buildings allow relatively high air leakage, their air leakage characteristics being similar to those obtained from laboratory tests of a 13 in. unplastered brick wall.

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REFERENCES

1. Tamura, G.T., Computer Analysis of Smoke Movement in Tall Buildings, ASHRAE TRANSACTIONS, Vol. 75, 1969.
2. ASHRAE Handbook of Fundamentals, Chapter 25, 1967.
3. Sasaki, J.R., and A.G. Wilson, Air Leakage Values for Residential Windows, ASHRAE TRANSACTIONS, Vol. 71, II, 1965.
4. Tamura, G.T., and A.G. Wilson, Building Pressures Caused by Chimney Action and Mechanical Ventilation, ASHRAE TRANSACTIONS, Vol. 73, II, 1967.
5. Ma, W.Y.L., The Averaging Pressure Tubes Flowmeter for the Measurement of the Rate of Airflow in Ventilating Ducts and for the Balancing of Airflow Circuits in Ventilating Systems, of Inst of Heating and Ventilating Engrs, Feb. 1967.
6. Tamura, G.T. and A.G. Wilson, Pressure Differences Caused by Chimney Effect in Three High Buildings, ASHRAE TRANSACTIONS, Vol. 73, II, 1967.

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