Air infiltration and internal pressures in tall buildings

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ABSTRACT

Wind increases the external pressure on windward walls, and decreases it on side and leeward walls. The walls have leakage paths through which air flows either in or out, depending on whether the internal pressure is lower or higher than the external pressure. Internal pressure adjusts to make inflow equal outflow, and depends on the size and location of large openings as well as the "background" leakage and the external pressure distribution. A program, originally written to compute air infiltration, was used to predict the internal pressure for a 56-story building. The analysis showed that the addition of a single opening the size of a typical window may cause as much as a 60 percent increase in the time-averaged maximum cladding pressure, by transferring load from the leeward and side walls to the windward wall.

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Air Infiltration and Internal Pressures in Tall Buildings

W. Alan Dalgliesh

Wind forces air through walls via leakage paths and larger openings, and the resulting air movement alters pressures inside buildings. Leakage paths can occur as narrow cracks and other small defects in the seals joining windows and wall panels. Whatever the situation with regard to larger openings, all buildings have some degree of uniformly distributed leakage through which wind can influence internal pressures.

This paper explores how wind loads are affected by air flow through the walls. The wind load on a wall is the external pressure minus the internal pressure, and even for uniformly distributed leakage, the internal pressure contribution can be substantial. Moreover, one window-size opening may lead to a transfer of most of the wind load from the windward wall to the leeward and side walls or vice versa, depending on the location of the opening. How much load is transferred depends on the flow resistance of the opening relative to the flow resistance of the distributed leakage; the tighter the building envelope, the greater the wind load transfer for a given opening.

The flow resistances of distributed leakage through exterior walls have been measured and related to the pressure differences causing flow in several tall buildings in Canada (Shaw et al., 1973; Shaw, 1979). With this information, one can deal quantitatively with the effects of large openings on cladding pressures for any given building. Cladding pressures across each wall of a typical tall building were calculated using a computer program originally developed to assess air infiltration (Sander, 1974). Results of ten cases are examined, five for each of two wind directions. Two cases are for distributed leakage alone while the other eight include one opening, small or large.

FLOW RESISTANCE OF DISTRIBUTED LEAKAGE

Distributed leakage is evaluated in terms of a flow coefficient C and a flow exponent n. Air flow Q in m^3/s for a pressure difference P in Pa and "tributary" area A in m^2 is

$$Q = C\,A\,P^n \tag{1}$$

The exponent n varies from 0.5 for turbulent flow through a sharp-edged orifice to 1.0 for laminar flow through very narrow passages, and is found to averge about 0.65 for exterior walls.

Experiments on eight buildings ranging from 9 to 25 floors in height are consistent with the following value of C for average exterior wall construction: 0.9×10^{-4} $m^3/(s \cdot m^2 \cdot Pa^{0.65})$. Typical values for "tight" and "loose" construction are one third and double this value, respectively.

COMPUTER INPUT: MODEL OF A 56-STORY BUILDING

The example building, 30.5 m × 61 m in plan, has a story height of 3.8 m and an overall height of 221 m. For purposes of calculation, it is considered sufficiently accurate to divide the building into compartments of six floors except for the 45th, where an opening was assumed to occur for eight of the ten cases studied. The opening is represented by a shaft with an external vent. Floor-to-floor leakage, with flow exponent 0.5, occurs through stairwells and

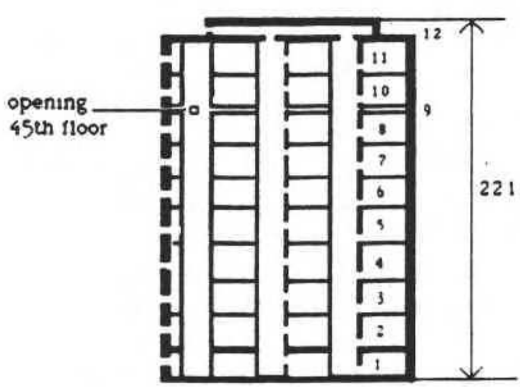

Fig. 1 Schematic of 56-story building showing the 12 compartments and the 3 vertical shafts used in the computer analysis

service shafts, represented by a second shaft, and through elevator doors, represented by a third shaft (Fig. 1). Distributed leakage for average exterior wall construction is used for all cases. Four cases have an opening of 1.5 m^2 added, and four more have an opening of 3.0 m^2. Other details of the computer input are similar to the example given by Sander (1974).

COMPUTER OUTPUT: NET PRESSURES ACROSS EXTERIOR WALLS

The net pressures across each wall for each of the ten leakage conditions are listed in Table 1. Figures 2 and 3 show that each of the ten cases results in an internal pressure different from the rest. Increasing the internal pressure transfers some of the cladding load from the windward wall to the other three walls. Similarly, decreasing the internal pressure transfers load from the three walls (under negative external pressure) to the windward wall. Note that the differences in net pressures between wind on the long wall (Fig. 2) and wind on the short wall (Fig. 3) tend to disappear for cases with the larger opening.

INTERNAL PRESSURE COEFFICIENTS

Internal pressure coefficients are derived by dividing the net pressure for any wall (windward, side, or leeward) in Table 1 by the reference wind pressure (1.33 kPa), and subtracting the resulting net pressure coefficient from the external one (windward, 0.78; side, −0.65; leeward, −0.26).

Simple approximations to internal pressure have been proposed. Davenport and Surry (1983) suggest a linear average of external pressure coefficients, C_{pe} for all surface areas, weighted by the corresponding "equivalent orifice areas," described below. Newberry and Eaton (1974) used the orifice equation in which flow is proportional to the square root of pressure difference, requiring an iterative solution to balance inflow and outflow.

Table 1 Net pressures across walls at the 45th floor

	Wind Normal to Wall	Long Wall Windward kPa	Long Wall Sides kPa	Long Wall Leeward kPa	Short Wall Windward kPa	Short Wall Sides kPa	Short Wall Leeward kPa
Opening Area (m^2)	Location						
3.0	Windward	0.16	−1.74	−1.22	0.21	−1.68	−1.17
1.5	Windward	0.43	−1.46	−0.95	0.58	−1.32	−0.80
No opening		1.15	−0.74	−0.23	1.46	−0.44	0.08
1.5	One Side	1.62	−0.28	0.24	1.75	−0.14	0.37
3.0	One Side	1.80	−0.10	0.42	1.84	−0.05	0.46

The equivalent orifice area *(A_{eo})* for the distributed leakage of a wall is

$$A_{eo} = \frac{A\ C\,(r/2)^{0.5}\ P^{0.65-0.5}}{C_d} \tag{2}$$

Air density $r = 1.3\ kg/m^3$ and discharge coefficient $C_d = 0.60$ were used to make the linear and square root approximations for comparison with results from the more detailed computer model (see Table 2). The three estimates of

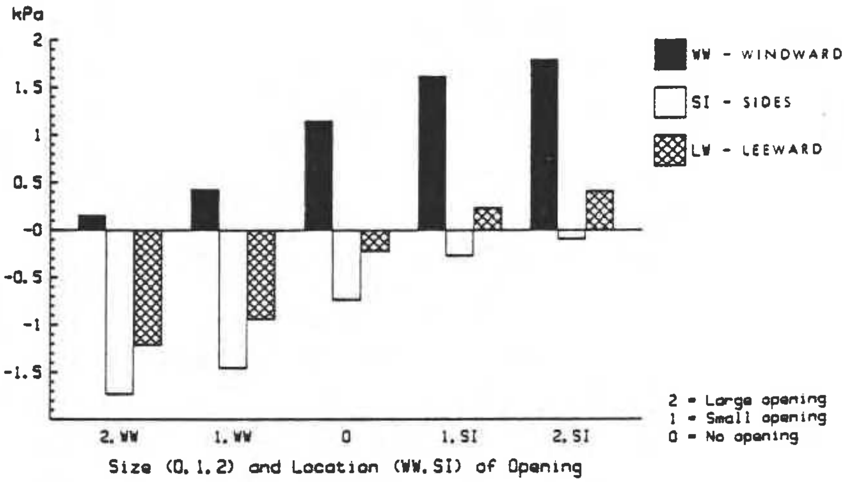

Fig. 2 Effect of an opening on wall pressures; wind normal to long face of building

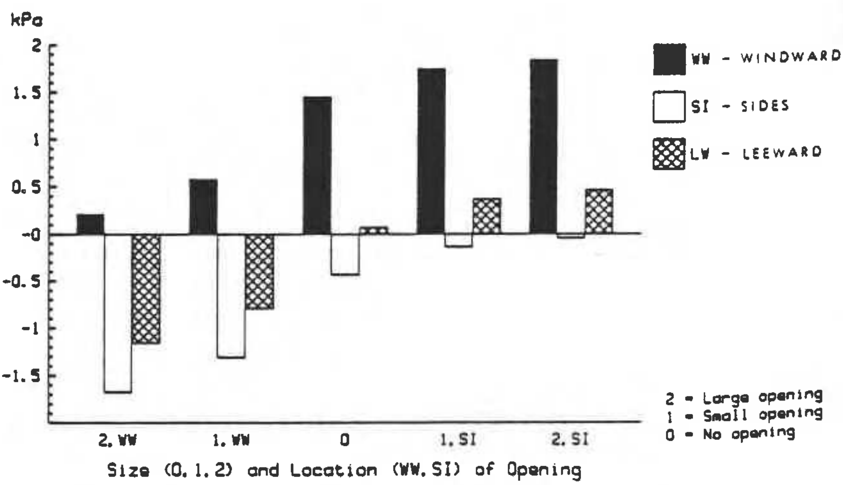

Fig. 3 Effect of an opening on wall pressures; wind normal to short face of building

internal pressure coefficient. C_{pn} are reasonably similar for the cases of no opening and large opening. However, both simple approximations overestimate the effects of the small opening, a feature emphasized by the line chart of Fig. 4 in which each case is labelled with the internal pressure coefficient of the computer model result. The simpler linear approximation is closer to the computer model result in all but one case.

EFFECT OF OPENING AREA

The area of the opening ranged from 1.3% to 5.2% of the area of the 45th floor wall in which it was located. However, the effectiveness of the opening

Table 2 Approximate and Detailed Estimates of C_{pi}

Wind Normal to Wall		Long Wall			Short Wall		
		Sq. Root	Linear	Detailed	Sq. Root	Linear	Detailed
Opening							
Area (m²)	Location						
3.0	Windward	0.78	0.72	0.66	0.77	0.69	0.62
1.5	Windward	0.77	0.66	0.46	0.76	0.62	0.34
No opening		−0.13	−0.01	−0.09	−0.47	−0.31	−0.32
1.5	One Side	−0.64	−0.56	−0.44	−0.65	−0.61	−0.54
3.0	One Side	−0.65	−0.60	−0.57	−0.65	−0.63	−0.61

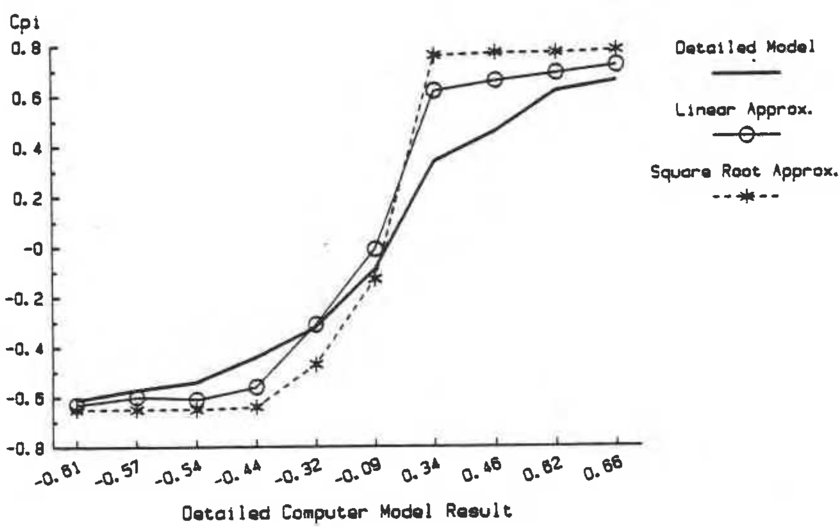

Fig. 4 Mean internal pressure coefficient calculated for 45th floor of 56-story building

depends more directly on its area relative to the equivalent orifice area of the distributed leakage. The sum of the A_{eo} for all four walls of the 45th floor is only about 0.25 m^2.

The effect of relative area for wind normal to the long wall can be seen in the third column of Table 2. The small opening is six times the total A_{eo} and changed the internal pressure coefficient C_{pi} from −0.09 to −0.44 when the external pressure coefficient C_{pe} outside the opening was −0.65, and to 0.46 when C_{pe} was 0.78. The large opening is 12 times the total A_{eo} and brought C_{pi} from −0.09 to −0.57 when C_{pe} was −0.65, and to 0.66 when C_{pe} was 0.78.

Similar trends can be followed for the five cases of wind normal to the short wall (see last column, Table 2). A surprisingly small opening is sufficient to cause significant shifts of wind load between the windward wall and the other three walls.

CONCLUSION

A single opening the size of a large window may well have the effect of increasing the maximum cladding pressure by 60% over the case in which uniformly distributed leakage is assumed. The transfer of cladding load from the windward wall to the other three walls (or vice versa) is mainly the result of the wind itself altering the internal pressure, acting through the overall leakage of the building.

A computer program of the sort used in this study could be used in design to alert both the mechanical and the structural consultants to the consequences of deviating from a uniform distribution of leakage. The same computer model will predict air infiltration effects under calm or moderate wind conditions and cladding pressures for design wind speeds.

Pooling of information available to mechanical and structural consultants could benefit both contributions to design by making possible a more realistic assessment of internal pressure. For example, use could be made of the more detailed patterns of external pressure coefficients available to the structural designer. The program would have to be modified to allow compartments in both the horizontal and the vertical directions because the flow around a building produces large horizontal gradients in external pressure. The model used in this study gives only mean pressures, and should be extended to deal with fluctuating external pressures.

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