WIND EFFECTS ON BUILDINGS WITH VARYING LEAKAGE CHARACTERISTICS — WIND-TUNNEL INVESTIGATION

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Summary

A wind-tunnel investigation has been conducted on a simple cubical model to see the effect of outside wall leakage on internal and external pressures. Three wind directions have been studied. The results have been extended to smoke-control problems. A method has been developed to modify the roof-vent design calculations to take wind effects into account. It is also shown that failure of vent systems may be more common than would be expected from current design methods.

1. Introduction

Effects of wind on buildings and tall structures have been investigated over the past few decades. A considerable amount of useful information has been gathered on the full-scale measurements on existing buildings [1,2] and wind-tunnel experiments conducted on models. The studies so far have been concerned largely with the estimation of wind loads that a building is likely to experience in an environment of varying turbulent-flow regimes. Such information is necessary from the structural safety point of view.

The wind-induced pressures on the sides and the roof of a building depend on the characteristics of the approaching wind, the building surroundings and on the shape and size of the building. The total wind loads acting on the walls are determined by the difference in internal and external pressures.

In the case of a simple tall building of rectangular cross-section, the external pressures vary with the magnitude and direction of the wind. If the air flows normally to one side of such a building, then the windward side is subjected to positive pressures, while other sides experience negative pressures (suction).

The internal pressures, on the other hand, depend on building-leakage characteristics. In buildings with openable windows (unsealed), an uncontrolled flow of air results between the interior and exterior, through such paths as doors and windows. This air leakage has the effect of changing the interior environmental conditions such as humidity and temperature. It also acts as the most important source of fresh air for buildings without any mechanical ventilation.

Air leakage also plays an important role in the fire safety of a building. Movement of air resulting from the inside pressure variations affects the spread of smoke within a building. It is important, therefore, in smoke-control problems, to understand the pressure variations within a building enclosure resulting from leakage. In large single-cell buildings, such as high-bay warehouses, department stores and factories, it is necessary to clear them of smoke to prevent any damage to the stock. To do this, a knowledge of the external pressure distribution is also essential for locating roof vents.

The problem of roof vent design has previously been investigated [3,4]. In these studies the wind effects have been ignored. The extraction rate through the vents has been calculated considering the buoyancy effects alone. As the majority of large buildings are situated out in the open, the wind effects become quite significant as numerous studies have shown [1,5,6] not only the suction on the roof that changes the extraction rate but the internal pressure variations resulting from leakage characteristics also have considerable effect.

The importance of wind-induced pressures is evident from the wind-tunnel studies on models [7]. The internal pressure variations are functions of both the wind direction and the relative leakage of walls.

The present experimental investigation, on a simple cubical model building with a partition, attempts to determine these effects to see how the design calculations can be modified by taking wind effects into account.

2. Description of the model

The experiments were conducted on a 25-cm cubical model manufactured out of clear acrylic plastic. The cube contained a partition wall dividing the inner space into two regions, as shown in Fig. 1 (dotted line represents partition wall).

The leakage characteristics of two walls (front and back) and the partition were varied. For this purpose ten holes were drilled on each wall with their centres lying, equally spaced, on a circle of 12.5-cm diameter with its centre at the centre of each wall (see Fig. 1). The area of each hole was 0.1 percent of the wall area (i.e. 0.625 cm^2), so that when all ten holes were open it gave total leakage on one per cent of the wall area. This choice was based on the typical measured values for buildings.

For the purpose of outside pressure measurements, each wall was provided with seventeen static pressure holes. The details of the arrangements of these holes are shown in Fig. 1. The inside pressures were simply tapped by placing the pressure measuring tubes on either side of the partition.

3. Experimental technique

The measurements were taken in the low-speed open-jet type wind tunnel at the Department of Civil Engineering and Building Science, University of Edinburgh. The open jet was 1.07 m by 1.52 m and the working table was 1.75 m by 1.53 m. A uniform section 1.75 m long was added to the outlet of the original tunnel to accommodate the elliptical wedge turbulence generators. These turbulence generators were used to produce the same wind turbulence as found in the real atmosphere. The turbulent velocity profile was as shown in Fig. 2. The model was placed at the centre of the table with measuring tubes running through a hole in the table to a 48-way pressure scanner.

The test programme was designed to investigate the effect of leakage on the inside and outside pressure distribution for the cases of three wind directions (0°, 45°, 90°), with constant wind velocity. The leakages on the front and back walls were varied in a systematic manner, keeping the partition leakage constant to its maximum value (i.e. 1%).

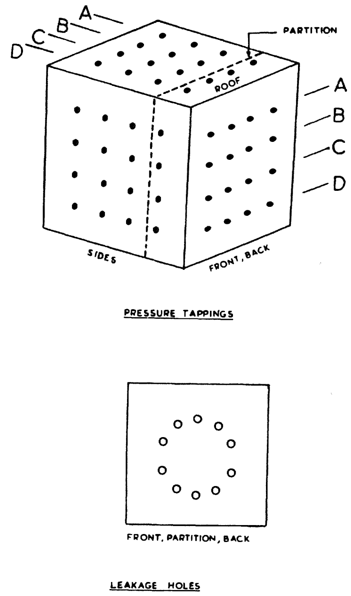

Fig. 1. Arrangement of pressure tappings and leakage holes on the box.

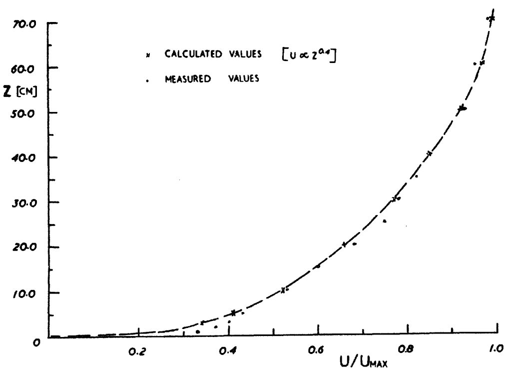

Fig. 2. Wind tunnel velocity profile.

4. Measurements

The pressure measurements were taken in order to investigate:

(a) External pressure variations with
  (i) front and back wall leakage combinations,
  (ii) wind direction.

(b) Internal pressure variations with
  (i) front and back wall leakage combinations,
  (ii) wind directions.

4.1 *Procedures*

Measurements were made for numerous lekaage combinations. Results for five such combinations, at wind directions of 0°, 45°, 90°, are presented here.

Leakage combinations were:

F	P	B	Code
0	1.0	0	+
0.4	1.0	0.4	○
0.4	1.0	1.0	□
1.0	1.0	0.4	△
1.0	1.0	1.0	●

where F = front wall; P = partition; B = back wall; "Code" refers to the points in the figures. Numbers refer to percentage leakage area on each wall.

In order to see how the pressure varied over the wall surface, graphs were plotted for four different levels (A, B, C and D) on each wall. The arrangement is shown in Fig. 3.

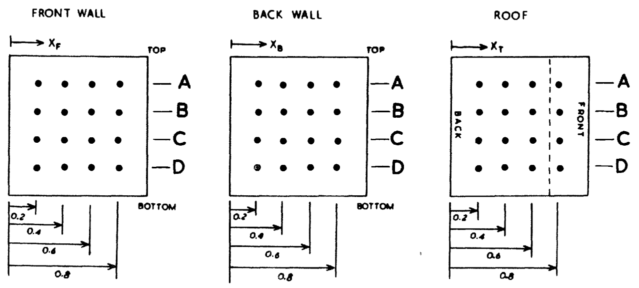

Fig. 3. Relative position of measurement levels A, B, C, D.

5. Results

Measurements for the front-wall pressures are shown in Fig. 4. It shows the pressure variations for different leakage combinations at heights marked A, B, C and D above the floor level, as indicated in Fig. 3. This is done to see if any leakage hole openings on the front wall have any appreciable effect on outside pressures in the vicinity of the hole. Figures 5 and 6 show the similar results for wind incidences 45° and 90°.

As the air which infiltrates through the openings in the front wall leaves through the back-wall openings, it is important to find out if this infiltration has any effect on the back wall pressures. Similar graphs, as for front wall, are drawn for the back wall, Figs. 7, 8 and 9. The positions A, B, C and D correspond to those in Fig. 3 for the back wall.

The pressure variations on the roof are significant for vent calculations. Figure 10 shows this variation for three wind directions investigated (0°, 45°, 90°). The similarity of contours at $\alpha = 0°$ and at $\alpha = 90°$ is noticeable. This is due to the symmetry of the model.

Figure 11 shows the actual pressure measurements on the roof for different wind direction. Again, the results are presented for lines A, B, C and D as shown in Fig. 3 for the roof. As there are no leakage holes in the roof, this figure only shows the curves for three wind directions.

The wind direction and leakage characteristics of the building have considerable effect on the internal pressures. The internal pressure variations with incidence at different leakage combinations are shown in Figs. 12 and 13 for two compartments labelled I and II.

To combine the front and back wall leakages, a parameter R, the leakage ratio, is defined as

$$R = \frac{\text{front-wall leakage area}}{\text{back-wall leakage area}}$$

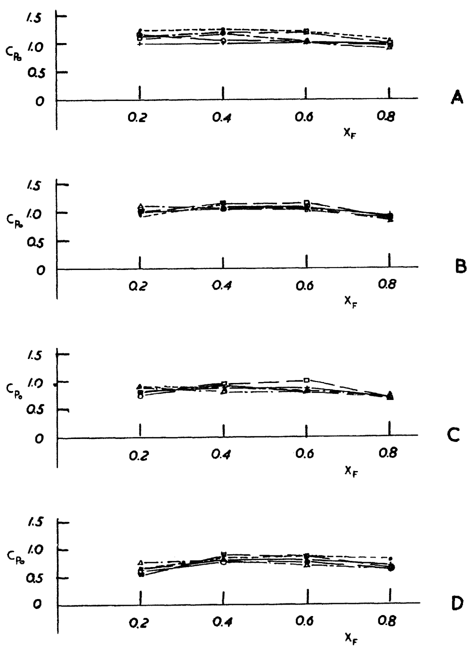

Fig. 4. Front wall outside pressure (C_{p_0}) variation with leakage α = 0°.

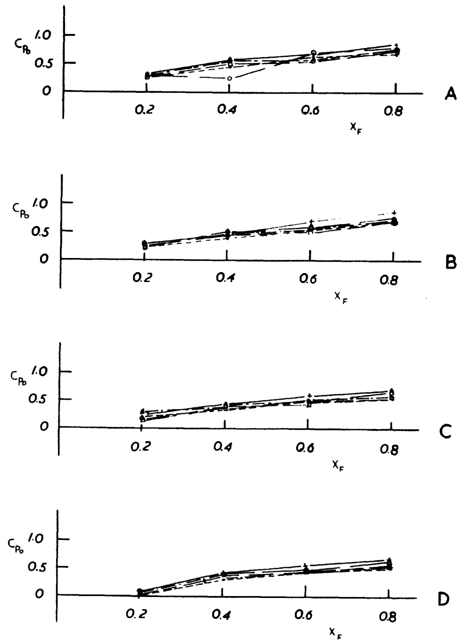

Fig. 5. Front wall outside pressure (C_{p_0}) variation with leakage α = 45°.

The variation of internal pressure with R is shown in Fig. 14 for different wind directions.

6. Analysis and calculations

When fire occurs in a large single-cell building, such as a high-bay warehouse, the hot gases and smoke rising from the fire form a layer under the ceiling. This layer grows in depth with time, unless the gases are removed. The most efficient and convenient way of removing them is by making holes (vents) in the roof. For natural ventilation (i.e. no powered extract), the shape, size and location of these vents are the important factors which determine their efficient functioning. Assuming that the layer is fully stratified (i.e. there is no mixing between the hot layer and the cold air underneath), the mass rate of flow of hot gases through the vents must be such that it is not extracting cold air under the layer. In that case the efficiency of the vents will drop.

If the temperature of the hot layer is known, and, for the safe limit of the layer thickness, the critical volume flow ($V_{\mathrm{v_{crit}}}$) through the vent is given by [4]:

$$V_{\mathrm{v_{crit}}} = \frac{2.0(gd^5 \theta_c T_0)^{\frac{1}{2}}}{(\theta_c + T_0)} \qquad (1)$$

where g = acceleration due to gravity, d = layer thickness, θ_c = excess temperature above ambient below the ceiling, T_0 = ambient air temperature. The excess temperature above ambient (θ_c) of the hot layer is determined from the knowledge of the fire size (i.e. heat output) and the application of plume theory [3].

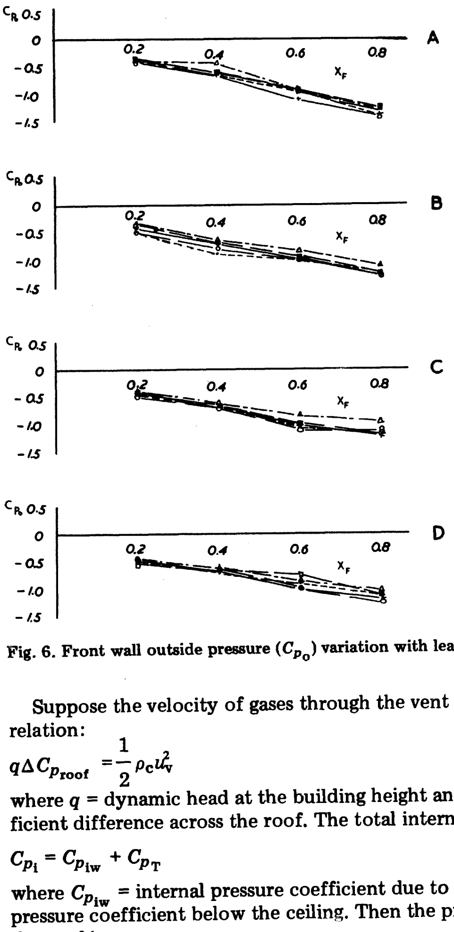

Fig. 6. Front wall outside pressure (C_{p_o}) variation with leakage α = 90°.

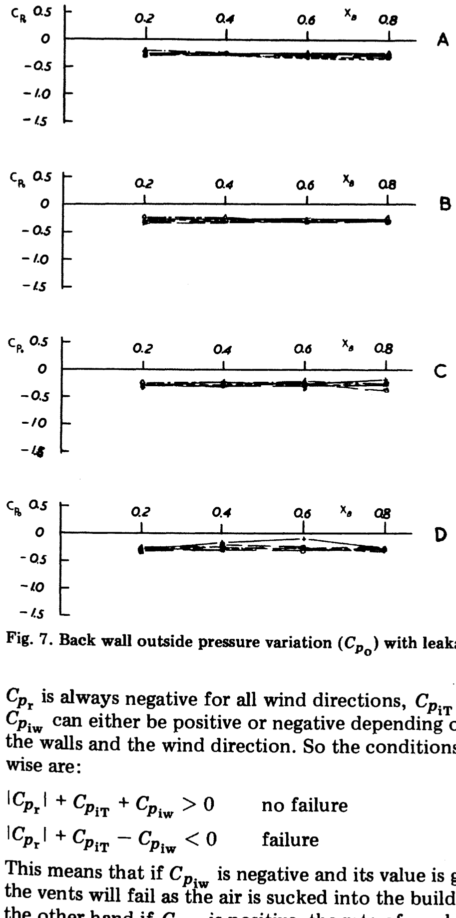

Fig. 7. Back wall outside pressure variation (C_{p_o}) with leakage α = 0°.

Suppose the velocity of gases through the vent is u_v, then from Bernoulli's relation:

$$q\Delta C_{p_{\mathrm{roof}}} = \frac{1}{2}\rho_c u_v^2 \tag{2}$$

where q = dynamic head at the building height and $\Delta C_{p_{\mathrm{roof}}}$ = pressure coefficient difference across the roof. The total internal pressure is given by:

$$C_{p_i} = C_{p_{iw}} + C_{p_T} \tag{3}$$

where $C_{p_{iw}}$ = internal pressure coefficient due to wind and $C_{p_{iT}}$ = buoyancy pressure coefficient below the ceiling. Then the pressure difference across the roof is:

$$\Delta C_{p_{\mathrm{roof}}} = C_{p_i} - C_{p_r} \tag{4}$$

where C_{p_r} = wind pressure coefficient on the roof. From eqs. (3) and (4):

$$\Delta C_{p_{\mathrm{roof}}} = C_{p_{iw}} - C_{p_r} + C_{p_{iT}} \tag{5}$$

C_{p_r} is always negative for all wind directions, $C_{p_{iT}}$ is always positive, and $C_{p_{iw}}$ can either be positive or negative depending on the relative leakage of the walls and the wind direction. So the conditions for vent failure or otherwise are:

$|C_{p_r}| + C_{p_{iT}} + C_{p_{iw}} > 0$ no failure

$|C_{p_r}| + C_{p_{iT}} - C_{p_{iw}} < 0$ failure

This means that if $C_{p_{iw}}$ is negative and its value is greater than $|C_{p_r}| + C_{p_{iT}}$, the vents will fail as the air is sucked into the building through the vents. On the other hand if $C_{p_{iw}}$ is positive, the rate of smoke flow through the vent is increased. The value of $C_{p_{iw}}$ determines the efficiency of the vent. $C_{p_{iw}}$ and C_{p_r} are known from the wind tunnel measurements, $C_{p_{iT}}$ is known from the plume theory. Thus $C_{p_{\mathrm{roof}}}$ is known.

Now, eq. (2) gives

$$u_v = (2q\Delta C_{p_{\mathrm{roof}}}/\rho_c)^{\frac{1}{2}} \tag{6}$$

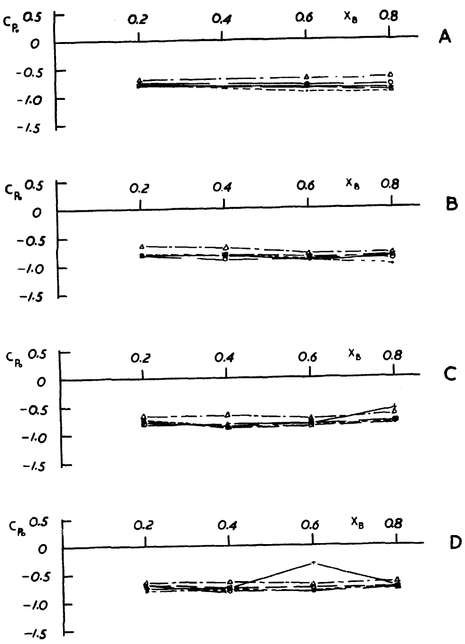

Fig. 8. Back wall outside pressure variation (C_{p_o}) with leakage α = 45°.

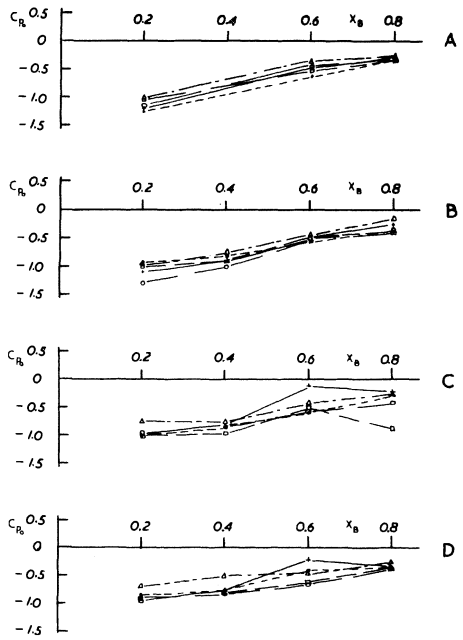

Fig. 9. Back wall outside pressure variation (C_{p_o}) with leakage α = 90°.

The critical mass flow rate of hot gases through the vent is:

$$M_{v_{crit}} = \rho_c V_{v_{crit}} \tag{7}$$

or in terms of extract velocity:

$$M_{v_{crit}} = C_v \rho_c A_{v_{crit}} u_v \tag{8}$$

where $A_{v_{crit}}$ = critical vent area, C_v = discharge coefficient for the vent, ρ_c = gas density below the ceiling. Substituting for u_v from (6), we get:

$$M_{v_{crit}} = C_v \rho_c A_{v_{crit}} (2q\Delta C_{p_{roof}}/\rho_c)^{\frac{1}{2}} \tag{9}$$

or

$$A_{v_{crit}} = \frac{M_{v_{crit}}}{C_v \rho_c} \left(\frac{\rho_c}{2q\Delta C_{p_{roof}}}\right)^{\frac{1}{2}}$$

Critical mass flow through a vent is known from eqs. (7) and (1). Therefore critical vent area required can be calculated from eqn. (10). From the knowledge of total mass to be extracted, number of such vents required can easily be worked out.

6.1 Sample calculation

Let us assume that the building is 50 m × 50 m cube, and that the wind speed at that height is 20 m/s, then

$$q = \tfrac{1}{2}\rho U^2 = \tfrac{1}{2} \times 1.22 \times 400 = 244 \text{ N/m}^2$$

For a fire of total heat output 1260 Btu/s (317.55 kcal/s), and layer depth 3 m, the initial mass flow rate is 16.88 kg/s (from Ref. [3]). Considering the building to be at wind incidence α = 0.

For leakage ratio R = 1 (from Fig. 14).

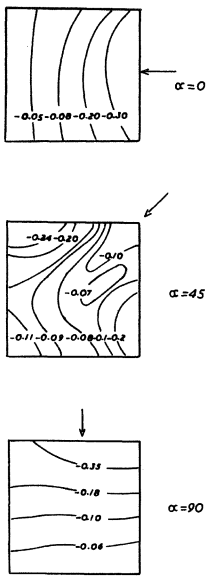

Fig. 10. Pressure contours on the roof (C_{p_o}) for wind directions α = 0°, α = 45°, and α = 90°.

$$C_{p_i} = 0.2$$

$$C_{p_{iT}} = 0.772/244 = 0.00316$$

$$C_{p_r} = -0.16$$

$$\therefore \Delta C_{p_{roof}} = 0.2 + 0.00316 + 0.16 = 0.363$$

$$\therefore A_{v_{crit}} = \frac{16.88}{0.6 \times 1.19}\left(\frac{1.19}{2 \times 244 \times 0.363}\right)^{\frac{1}{2}} = 1.937 \text{ m}^2$$

Similar calculations can be done for other leakage combinations at various incidences. The results are plotted in Fig. 15.

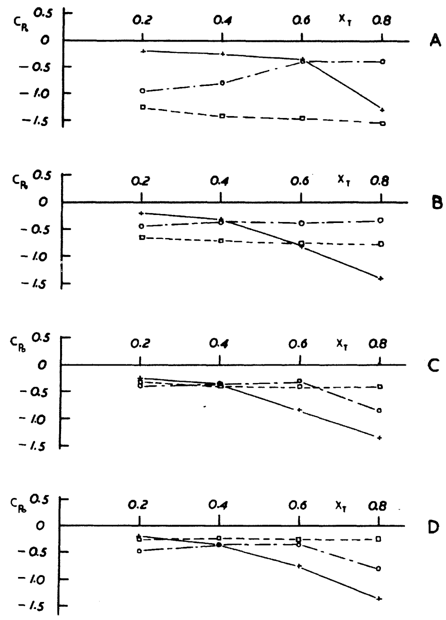

Fig. 11. Pressure distribution on the roof: (+—— +) = 0°; (o-·-·-·o) = 45°; (□-------□) = 90°.

7. Discussion

7.1. Leakage effects on outside pressures

One of the objects of this exercise was to see if any measurable changes occur in the outside pressures on the walls with variation in leakage. The leakage characteristics of the front and back walls were varied to give maximum leakage of 1 per cent on each wall. The results for three wind directions are shown in Figs. 4, 5 and 6, for the wall labelled as Front Wall. These figures (in particular Fig. 4) show that the pressures are unaffected by the leakage. The scatter can be attributed to the turbulence itself. No marked change is detectable due to opening of the holes. When the model is rotated through 90°, the front wall becomes one of the side walls, and experiences negative pressures (suction). This is clear from Fig. 6. Again, no change in pressures is detectable due to opening of the holes.

The other wall on which the leakage was varied was the Back Wall. The

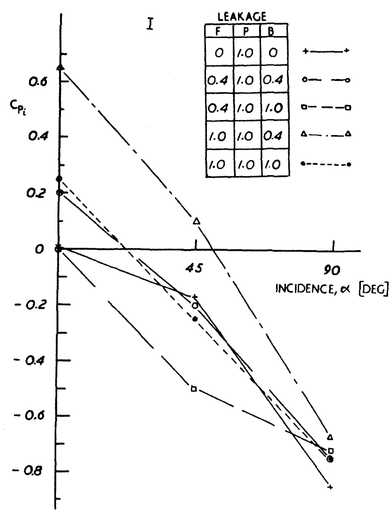

Fig. 12. Internal pressure variation (C_{p_i}) with wind direction for different leakage combinations, Region 1.

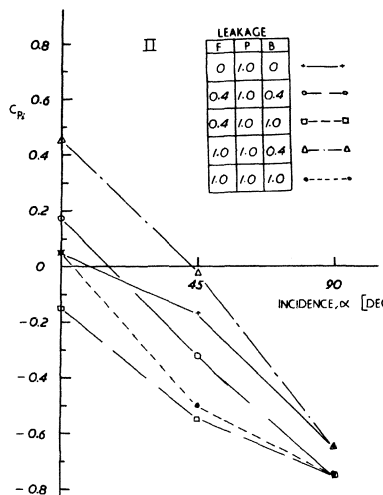

Fig. 13. Internal pressure variations (C_{p_i}) with wind direction for different leakage combinations, Region II.

results are summarised in Figs. 7, 8 and 9. As Fig. 7 shows clearly, no apparent change occurs in pressure measurements and the pressure is uniform over the whole surface ($C_{p_o} \doteqdot -0.26$). But, as the model is rotated through 45°, the suction increases (Fig. 8) and still further increase occurs when the back wall becomes one of the side walls ($\alpha = 90°$) Fig. 9. The scatter at levels C and D is very likely due to turbulence. These measurements therefore indicate that any changes in leakage characteristics of a building have no effect on the outside pressures acting on the building.

7.2 *Pressure distribution on the roof*

In case of a fire, such buildings become smoke logged easily. To clear the building of smoke, ventilation holes are required in the roof. A knowledge of the wind-induced pressure distribution on the roof is therefore necessary for better design of these holes.

Wind-induced pressure on the roof is highly dependent on the wind direction. Figure 10 shows the pressure contours for three wind directions investigated. In the regions of the roof near the windward side (when air flows normal to one of the walls), the suction increases as air is accelerated when it rounds the corner: as air slows down towards the leeward wall, the suction is decreased. This is clear from Fig. 10, for $\alpha = 0$ and 90°. The similarity of contours in these two wind directions is due to the symmetry of the model (being cubical). For any other direction the pattern is quite complex as is clear from the case of $\alpha = 45°$.

The actual measurements are shown in graphical form in Fig. 11. Here the variable parameter is only the wind direction. For $\alpha = 0°$, the outside pressure coefficient varies from -0.3 (windward wall) to -1.4 (leeward wall). The magnitude for $\alpha = 90°$ is the same.

$$-0.3 < C_{p_o} < -1.4 \qquad \text{for } \alpha = 0°$$

$$-0.3 < C_{p_o} < -1.5 \qquad \text{for } \alpha = 90°$$

7.3 *Internal pressures*

Because of the leakage, air enters the building at positive pressure areas and leaves at negative pressure areas. As a result, change in the inside pressures occurs so that inflow equals outflow. This inflow and outflow, depend on the leakage characteristics, as well as the wind direction (for a given wind profile and building shape). Any vent-design calculations must take the inside pressure variations into account, as it is the pressure difference across the roof that drives the hot gases out.

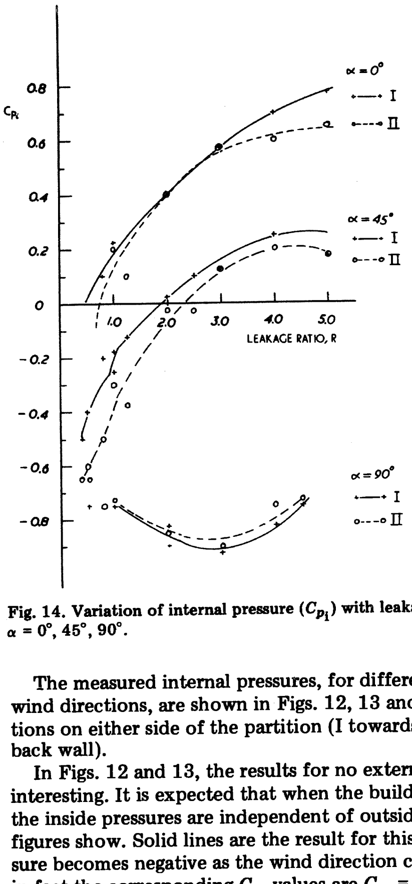

Fig. 14. Variation of internal pressure (C_{p_i}) with leakage ratio R, for wind direction α = 0°, 45°, 90°.

The measured internal pressures, for different leakage combinations and wind directions, are shown in Figs. 12, 13 and 14, where I and II are the sections on either side of the partition (I towards the front wall, II towards the back wall).

In Figs. 12 and 13, the results for no external leakage (sealed cube) are interesting. It is expected that when the building (box) is completely sealed, the inside pressures are independent of outside wind. But this is not what the figures show. Solid lines are the result for this case and they show that pressure becomes negative as the wind direction changes from α = 0° to α = 90°, in fact the corresponding C_{p_i} values are $C_{p_i} = 0$, $C_{p_i} = -0.85$, respectively. This was found to be due to the change in volume of the cube, resulting from the wind force acting on the flexible walls of the cube.

When α = 0° and the front-wall leakage is greater than the back-wall, there is a build-up of pressure inside the cube in order to adjust the back-wall pressure difference so that inflow equals outflow, and the inside pressure is lowered when the front wall leakage is less than the back wall. The comparison of the curves for △ and □ in Figs. 12 and 13 shows this clearly.

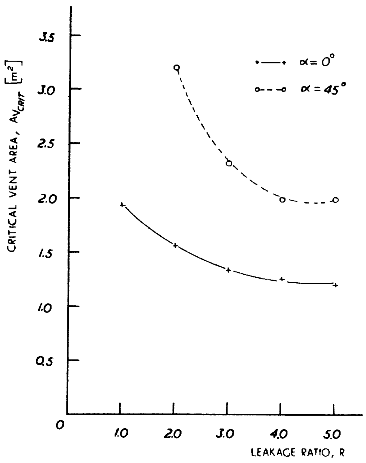

Fig. 15. Variation of critical vent area ($A_{v_{crit}}$) with leakage ratio R, for α = 0°, 45°.

When α = 90°, in this extreme case both the leaky walls are subjected to negative pressures (being now side walls). Therefore the inside pressure also drops and becomes negative as is clear from Figs. 12 and 13. This inside negative pressure will have the effect of drawing in air through the holes in the roof, and the vent failure will occur.

Figure 14 shows clearly the effect of leakage and wind direction on internal pressure. For α = 0° it is clear that internal pressure increases with R. But for $R < 1$ the curves change as shown in p. 51 of [5]. For $\alpha > 0°$, the curve shifts downwards and at 90° C_{p_i} is negative for all $R > 1$. Hence failure of vents.

Using these results, calculation for the vent sizes can be made, remembering that the negative pressures on the roof and positive pressures inside the cube add to the buoyancy pressures to increase the volume flow rate through the vent. The critical vent area for such a building is calculated and the results for different configurations are shown in Fig. 16. It shows that the critical vent size required decreases with the wind direction for any particular leakage ratio ($R > 1$). In fact, for α = 90°, all vents will fail when the wind speed (U) is significantly greater than zero. To overcome this, the building leakage characteristics must be adjusted to give positive internal pressure.

8. Conclusions

The leakage characteristics of a building do not have any appreciable effect on the outside wind-induced pressures on the building surface.

The internal pressures on the other hand are highly dependent on the leakage characteristics as well as the direction of the approaching wind. In fact the success or failure of the vents on the roof is determined by these effects. Higher leakage on the windward side improves the efficiency of the vents, and the efficiency drops if the leakage is higher on the leeward side.

For a complete solution (i.e. one solution for all wind directions) adjustment in the leakage distribution around the walls is required.

The results of this investigation are applicable directly to some existing building types if the walls of zero leakage and the internal division are regarded as fire-resisting construction and the leaky walls are regarded as curtain of glazing or light-weight metal cladding walls.

Acknowledgement

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WIND-TUNNEL-WALL CONSTRAINT ON TWO-DIMENSIONAL RECTANGULAR-SECTION PRISMS

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Summary

The effect of wall constraint on rectangular-section prisms is investigated experim in a low-turbulence wind tunnel up to a blockage ratio of 0.25. The depth to width r (d/h) of the sections varies from 0.5 to 5.0.

It is shown that the effect of confinement on the mean surface pressure on the m is not uniform in the streamwise direction and therefore cannot be regarded as an in in the effective dynamic pressure estimated from drag or base pressure measurement sumed by some investigators. The current bluff-body blockage correction formulae a found to be inadequate for correcting the drag and base pressure for these sections, ularly at large blockage ratios. A new equation, which is a modification of Maskell's tion and includes a shape factor to allow for the depth of the rectangular section, yie satisfactorily corrected drag and base pressure. Due to the large depth of the sections stream direction, corrections to the pressure distribution around them for blockage u this equation, are not very satisfactory. The correction for the Strouhal number usin new equation is valid up to d/h = 3.0.

Notation

B	cross-sectional area of wake
C	cross-sectional area of wind tunnel
C_D	drag coefficient
C_p	pressure coefficient
C_{pb}	base-pressure coefficient, average over the base
d	depth of rectangular prism in the flow direction
f	frequency of vortex shedding
H	width of wind tunnel
h	width of rectangular prism normal to flow direction
K_D	drag-blockage factor
K_p	base-pressure blockage factor
k	base-pressure parameter, $\sqrt{1 - C_{pb}}$
m	$= B/S = C_{Dc}/(k_c^2 - 1)$
n	effective dynamic pressure increase factor
Re	Reynolds number, Uh/ν