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THE APPLICATION OF DYNAMIC INSULATION IN MULTI-STOREY BUILDINGS

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ABSTRACT

A pilot study was carried out to examine the influence of fire safety requirements and external wind on the performance of naturally ventilated multi-storey buildings in which the external envelop is dynamically insulated. Fresh air was supplied to the building through the envelope by depressurisation, using a fan-driven, ducted extract system. Prototype 3, 4, 5 and 10 storey buildings, all sharing the same rectangular floor plan, were studied using a spreadsheet model. From the analysis the effects of wall porosity, depressurisation level, extract system deployment, occupant density and distribution, and building orientation have been quantified.

KEYWORDS

Building Envelop, Dynamic Insulation, Fire, Natural Ventilation, and Wind.

INTRODUCTION & BUILDING DESCRIPTION

Dynamic insulation describes a class of construction materials that provide heat insulation and which are also permeable to the passage of gas and vapour (Taylor and Imbabi, 1998a. Bartussek, 1989). The use of dynamic insulation in small buildings is relatively straightforward (Taylor and Imbabi, 2000). The practical consequences of installing dynamic insulation in larger, more complex buildings are less obvious, however. The question of ventilation analysis and design for a dynamically insulated multi-storey building, taking into consideration the extreme conditions of fire and the pressure variations on the external envelope caused by wind, is addressed in this paper. Unlike single storey, single zone low occupancy buildings (Taylor and Imbabi, 1998a), smoke control in large multi-zone buildings is a complex matter. Wind and smoke control strategies are essential factors in determining the depressurisation level of the building and the air permeance of the wall.

A simple layout of rooms arranged to either side of a central corridor that opens on to a stairwell, typical of many office buildings, is assumed - see Figure 1. A fire door leading to the stairwell at the end of the corridor defines this suite of rooms as a fire zone. The materials forming the envelop include plasterboard, thermal block, fibreboard, cellulose-based insulation, etc, and were assigned measured values of thickness, density, permeability, permeance and pressure drop reported in (Bartussek, 1989. Taylor et al, 1996). The building was assumed to have 50% glazing, and door panels were assumed to be 2.0 × 0.9 m. In assessing the influence of wind on ventilation, buildings of 3, 4, 5 and 10 storeys have been investigated. The floor to floor distance between the stories is taken to be 3.6 m and the internal floor to ceiling height is 3.0 m. The gross plan area of the building is 34.0 × 14.0 m.

With dynamically insulated buildings it should be feasible to eliminate extract ductwork by using the corridors and stairwells for venting air, provided it is not contaminated by smoke from fires or cigarettes, and toxic or unpleasant chemicals. For a speculative multi-storey building, however, it can be shown that the strategy results in an uneconomical loss of floor space. In our analysis, the following ventilation and fire safety strategy has been adopted. It will be shown that in order to ensure the minimum ventilation is achieved, each room needs be depressurised to approximately -100 Pa. The extract ducting arrangement required for this is shown superimposed in Figure 1. In order to avoid problems with the opening of doors the corridor and stair well will also be depressurised. These ducts feed ventilation shafts in the stairwell. This high level of depressurisation is also required to overcome the pressure loss in the extract ducting and wind loading.

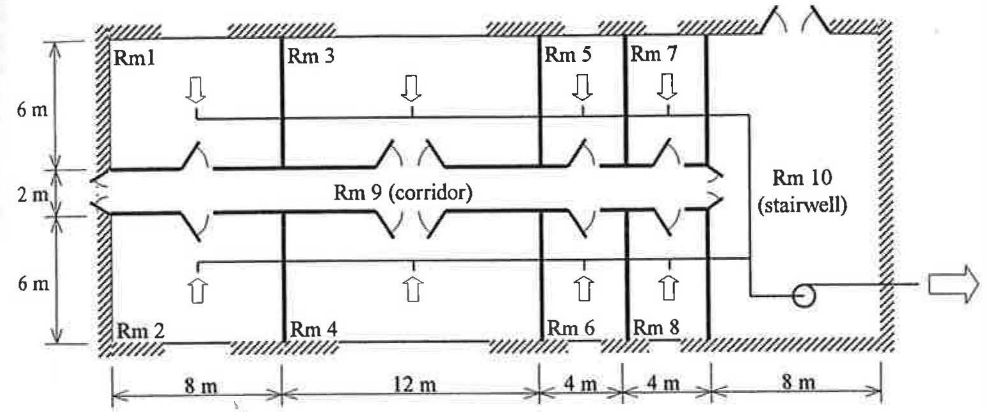

Fig. 1. Floor plan of the building.

FIRE SAFETY CONSTRAINTS

The fire authority, insurance companies, property developers, financiers and the building control authority require that measures be taken to ensure that escape routes are maintained free of smoke. In addition, insurers and owners will wish to confine the fire within specified zones, for obvious economical reasons. An important question is whether the methods of fire control and smoke venting employed significantly assist in reducing the spread of fire pending the arrival of the fire brigade. In addition, would the means of escape of persons within the building be assisted by the latter (CIBSE, 1986)? In the United Kingdom guidance is provided in Fire Precautions in the Design of Buildings, BS 5588 Part 3: Code of Practice for Office Buildings (BSI, 1983), and Part 9: Code of Practice for Ventilation and Air Conditioning Ductwork (BSI, 1989).

The rate of smoke generation, even by a small fire, is considerable. The mass flow of smoke, M, generated by flames at temperature T (K) from a fire with perimeter P (m) is (Butcher and Parnell, 1979)

$$M = 0.096 P \rho_o y^{3/2} \left(g \frac{T_o}{T} \right)^{1/2} \qquad (1)$$

where ρ_o, T_o, are the ambient air density and temperature respectively, and y the height of the bottom of the smoke layer above the floor. The volume rate of production of smoke from a fire at a temperature of 1100 K in a waste paper bucket (0.3 m diameter) in a room 3.0 m high is initially 10,000 m^3/h. For a tabletop fire, the rate of production will easily be three times greater. These rates are far in excess of what the ordinary extract vent system is designed to handle, and so its continued operation will not halt the spread of smoke to other parts of the building. The extract vent system must therefore be shut down in case of a fire. In an airtight room, the fire would soon extinguish itself. With air permeable walls, however, the fire could continue to be supplied with oxygen and burn for longer.

Any method for smoke control that is proposed must meet the basic criteria that everybody must be able to get into a protected escape route within 2½ minutes. The designer must ensure that vent air movement is away from escape routes, to prevent smoke from obstructing the exit of occupants. In a building with very high ceilings, the corridor itself could be used as a smoke reservoir (Butcher and Parnell, 1979), but if rooms are accessible only from one corridor, that corridor should not be used to vent air. The use of motorised fire dampers in ventilation ducts allows the Fire Brigade to choose whether to vent smoke or not. However, another way of ensuring stairways remain free of smoke during a fire is to maintain the stairwell at positive pressure with respect to the rest of the building (BSI, 1978). Reversing the ventilation fan direction and feeding the air only into the stairwell and corridors could be used to achieve this, provided the dampers isolating each room remain shut with no leakage.

In order for the doors to be easily opened, this positive pressure would be limited to 50 Pa. To limit the leakage of air directly to the outside the stairwell and the corridor walls would have to be of low permeability conventional construction. The air supplied to the corridors must pass easily out through the external walls so that the major pressure drop occurs across the room doors, to prevent leakage of smoke into the corridor. With a 15 Pa buoyancy pressure generated by the fire (Zickerman, 1992) a reasonable design objective would be to try and achieve a 45 Pa pressure drop across the door and the balance (5 Pa) across the external wall. In a room without a fire the flow of air around the door and through the wall is given by (Awbi, 1991)

$$Q = K_d L (P_c - P_r)^{0.6} = K_w A_w P_r \tag{2}$$

where P_c and P_r are the corridor and room pressures respectively, (K_w) the permeance, (A_w) area of wall, (K_d) leakage coefficients and (L) cumulative perimeter length for the doors. This can be re-arranged to

$$(P_c - P_r)^{0.6} - \left(\frac{K_w A_w}{K_d L}\right) P_r = 0 \tag{3}$$

which can be solved by iteration. Equation (3) has solutions for P_r of under 5 and 10 Pa for raw values of P_r of 2 Pa$^{-0.4}$ and 1 Pa$^{-0.4}$ respectively. This can be used to calculate the required leak tightness of the door for any given door size, permeable wall area and wall permeance. Thus, if the corridor is pressurised at 50 Pa, the door perimeter is 5.8 m, permeable wall area 10 m^2 and wall permeance 0.1 m^3/m^{2}hPa, the doors leakage coefficient needs to be less than 0.16 m^3/mhPa$^{0.6}$ for 10 Pa pressure drop across the wall.

Permeable internal walls would not provide acceptable fire barriers. The buoyancy pressures (15 Pa) generated by a fire in a sealed room would force hot, toxic gas through into adjacent rooms at ceiling level, increasing the ease with which fire will propagate. Although a permeable wall would filter out the relatively large particles (~10 μm diameter) which are characteristic of smoke (Taylor and Imbabi, 1998b), invisible toxic gases could still overpower occupants in adjacent rooms. It may be that even air permeable external walls would need a means of excluding external air. To do this in a practical way means bring the air into the wall at a limited number of points rather than over the whole external surface. This would increase the pressure drop of the air supply system, adding to cost and complexity.

A ducted extract system is the only feasible option in a dynamically insulated multi-storey building. Such buildings need to be depressurised to -100 Pa or higher to ensure that air flow is inwards through the wall at all points in the envelope, to meet ventilation requirements. The absolute value of the depressurisation will increase as the building height and ambient wind speed increases, and requires a ducted system, since using corridors would make airflows and pressures difficult to control as people use the building. The choice of air permeance for the walls is confined to a narrow range. It transpires that the materials that could be used in a permeable wall (Bartussek, 1989. Taylor et al, 1996) will result in an overall wall permeance of between 0.1 m^3/m^{2}hPa and 1 m^3/m^{2}hPa. For simplicity and economy of construction, the permeance of the envelope needs to be uniform, and this has been assumed in the current model.

THE EFFECTS OF WIND

Changes in wind direction will naturally affect performance. To quantify the effects of wind speed, building height and the air permeance of the walls on depressurisation and occupancy pattern within the building, the pressure coefficients were calculated using the Swami and Chand a (1988) correlation for tall buildings. The pressure coefficient was calculated at the midpoint of each external wall for every room. The external pressure P_o at that point is readily calculated from the wind speed at roof height V_h using

$$P_o = C_p\left(\frac{1}{2}\rho V_h^2\right) \tag{4}$$

with V_h estimated from standard expressions (Awbi, 1991) for wind speed as function of height and local terrain - assumed to be urban in this case. The wind speed at the reference site, V_{ref}, is measured in flat open country. Thus, for a building of roof height z_h

$$V = \frac{1}{0.67}\left(\frac{z_h}{10}\right)^{0.25} V_{ref} \tag{5}$$

The airflow through the wall varies in direct proportion to the pressure difference across the wall, and the internal pressure P_i is arranged to be the same in every room.

RESULTS

CIBSE recommend a minimum ventilation rate of 8 l/s/person. The spreadsheet model used assumes single occupancy offices are located on the leeward side of the building. Pressure at the centre of an external wall panel is assumed representative of the external pressure for that room for airflow calculations. The maximum number of occupants is given by the airflow rate through the wall divided by ventilation rate per person. The maximum number of occupants for each location is summed to give the total number of occupants for the whole building. Wind speed at Aberdeen that is likely to be exceeded 50% of the time is 5.5 m/s. For design purposes, it is necessary to calculate the required depressurisation at the higher wind speed of 10 m/s to ensure surplus capacity. The results of such calculations are shown in Table 1. At lower wind speeds both occupant density and depressurisation levels are reduced, more so for higher permeance construction. Dynamically insulated buildings in excess of 10 storeys are not likely to be a practical proposition because of the very excessive depressurisation required.

Table 1. Occupant densities and depressurisations for a wind speed of 10 m/s.

Building height (m)		Permeance (m^3/m^{2}hPa)	Maximum no of occupants	Depressurisation (Pa)
36.0	(10 storeys)	1.0	2862	-98.7
		0.1	332	-121.3
18.0	(5 storeys)	1.0	1030	-66.2
		0.1	142	-99.3
14.4	(4 storeys)	1.0	722	-57.5
		0.1	110	-95.0
10.8	(3 storeys)	1.0	454	-47.5
		0.1	82	-90.0

Table 2 shows the number of occupants in each room of a 10-storey building with 0.1 m^3/m^{2}hPa wall permeance at a wind speed of 5.5 m/s. Note that room 2 on the 9th and 10th floors can only support 4 occupants in this configuration, and the total number of occupants is thus reduced to 188. The average space allocation is 18 m^2 per occupant, which is generous by office standards. The extravagant space allocation of 72 m^2 per occupant for the largest rooms is clearly uneconomical.

Table 2. Pattern of occupancy in 10-storey building.

Room	1	2	3	4	5	6	7	8
No of occupants	4	5	1	1	3	3	1	1
m^2/occupant	12	10	72	72	8	8	24	24

The ventilation per occupant supplied to each room can be determined in a similar manner. For a 10 storey building with a wall permeance of 0.1 m^3/m^2hPa the depressurisation required at 10 m/s for minimum ventilation is -121 Pa. At the same time, the maximum ventilation rate per person increases from 14.9 to 30.9 l/s/person, and the average air change rate for the entire building increases from 0.39 to 0.62 ach. Even for a modest 4 storey building the depressurisation required for the same conditions is -95 Pa. A lesser depressurisation could be achieved by employing an external wall of permeance 1 m^3/m^2hPa. Masonry blocks with the permeance of insulation would provide the perfect solution in this case.

The depressurisation that can be practically achieved depends on the design of the extract ventilation system. Assuming a duct air speed of 1.5 m/s for the cases under consideration, the duct sizes on each floor would be 0.4 and 0.3 m diameter on the windward and leeward sides respectively. The entire network could be driven by a single extract fan, but the duct supplying such a fan would be of the order of 1.6 m diameter. Duct pressure losses remain at less than 0.08 Pa/m, providing good flexibility in design and the option of working at higher air speeds and therefore smaller duct sizes.

To recap, the design issues highlighted when designing a dynamically insulated multi-storey building are:

- With large depressurisation the envelope needs to be exceptionally air and watertight. At such pressures, water penetrating the envelope will be blown indoors.
- Occupancy and usage of space within the building will be constrained by the available ventilation through the walls, which in turn depend on building geometry and prevailing wind conditions.
- The ventilation provided through the wall is only an exact match to the ventilation required in a room at the design wind speed and direction. At other conditions, the majority of rooms will be over-ventilated.
- The depressurisation within each room needs to vary with wind speed and direction. This is relatively easy to achieve when the building is small and encloses a single open space. In compartmentalised buildings, it will require the dampers in the extract ducts to be controlled by a transducer measuring the differential pressure across the external wall(s) of the room.

Some of the limitations can be overcome. Enclosing the building within a wind barrier would eliminate the small pressure differences that occur over the envelope, and stop rain penetrating the envelope. Channels could be provided through the building, for example in the floor, to equalise the pressures on windward and leeward sides of the building. Such measures invariably lead to increased complexity of design and cost, and need to be assessed individually.

DISCUSSION AND CONCLUSIONS

Fire safety considerations suggest that a ducted extract ventilation system would be more appropriate than using the corridors for most building types. In case of a fire, the damper in the ventilation extract from each room should automatically shut. Although the ventilation extract plays no part in smoke control, the extract grille in a room cannot be placed in the optimum position for ventilation, which is opposite the external wall, since one must consider the implications for human safety. Therefore, a compromise position for the extract grille would be in the centre of the room. Air permeable internal walls are unsafe because they will not prevent the spread of hot, toxic gases during a fire.

For simplicity of construction, the permeance of the external wall should be the same over the whole envelope and in the range 0.1 to 1.0 m^3/m^2hPa. Windows must always remain shut. This is essential for the correct operation of dynamic insulation and desirable in buildings where physical security is important. The ventilation in a room could be controlled manually if required, by adjusting the extract duct damper, but the urge to do so should be minimal in a building which inherently provides a high quality indoor environment. Main access doors to the building need also to be leak-tight, so short of using an airlock, revolving doors provide a practical solution. There are other important benefits in using dynamic insulation. Air permeable walls have the potential to filter particulate pollution and reduce outdoor noise (Taylor and Imbabi, 1998b). In today's urban environments windows can be kept closed in summer without compromising ventilation quality, to provide a quiet and clean work environment for occupants and sensitive office equipment.

Dynamic insulation also provides outside air without draughts. This is useful in winter, but its efficacy in providing a fresh atmosphere in summer remains to be established.

The narrow building form examined in this paper could be easily ventilated by opening windows. In a deep plan building using dynamic insulation, air would need to be ducted from rooms at the periphery to those at the centre. Thus, rooms at the periphery must be pollution free and with low occupation density. An arrangement that overcomes these restrictions is use of a porous ceiling, with air distributed through floor or ceiling voids. The ventilation systems described are 100% fresh air systems. There is no opportunity to recycle a proportion of the warm air around the building to reduce ventilation heat loss and remove internally generated particulates from the air. These desirable features could be incorporated if the building were fitted with a cavity, requiring additional outer cladding. This would not be as efficient as an internal ducted re-circulation system, since the warm air would lose heat to the outside via the uninsulated cladding.

The findings show how dynamic insulation could be applied in a cellular multi-storey office block and highlight the design considerations of fire safety and wind loading. The building height is limited by the depressurisation to around 10 storeys, depending on the local climate and topography. The location of occupants and work processes is also determined by these external factors, which constrain how space within the building is used. Also, ventilation performance could be adversely affected by developments on adjacent sites, over which the building user and owner often have little or no control. However, there are a number of advantages. In city centre environments, chemical pollution and noise from motor vehicles and other sources require buildings to be sealed, and air to be supplied and filtered by mechanical systems. Air permeable walls can fulfil both of these requirements with less plant and lower energy requirements when compared to air conditioned buildings, reducing the initial and running costs.

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