Permeability Measurements on a Typical Hong Kong Apartment

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1. Introduction

Permeability describes the connectivity provided by a pathway between spaces. The effect of permeability on the fluctuation of internal pressure induced by wind was mentioned by Holmes [1] in his comparison of wind tunnel model data with computational simulation. Holdø et al. [2] have detailed the influence of permeability on the mean and fluctuation of internal and external pressures on pitched-roof buildings in wind tunnel model tests. Vickery [3] has detailed the effects of leakage and openings on internal pressure by using the gust factor approach and the interaction of internal pressures with the building envelope under different leakage configurations [4]. The aforementioned studies demonstrated that permeability measurement is an indispensable part of an internal pressure study for all types of buildings.

2. The Test Site

While most research on internal pressure has focused on wind loads on individual façade elements of low rise buildings in hurricane prone regions, the same phenomena may also cause substantial damage to façades and windows in typical high-rise buildings. The risk of damage is perhaps greater owing to the low permeability of typical apartments in Hong Kong and the possibility of sudden penetration of a building envelope by wind borne debris. A recent study at The Hong Kong University of Science and Technology (HKUST) revisited the effect of wind-induced internal pressure in well-compartmentalised high-rise buildings. A corner apartment in the Visitor Center on the campus of HKUST, with a relatively uninterrupted exposure for the predominant windward direction, was chosen as the test site (Figure-1). The test apartment reflects the configuration of a typical apartment in Hong Kong featuring rooms separated by brickwork or concrete partitions. Each room is fitted with a solid timber door and ventilation is either provided by windows mounted on an aluminum frame or independent air conditioning unit. The partitions, doors and windows effectively isolate each room into an individual space with low background permeability and interconnectivity. This type of apartment provides a chance to investigate the effect of permeability on internal pressure over a range of configurations of opened and closed windows and doors.

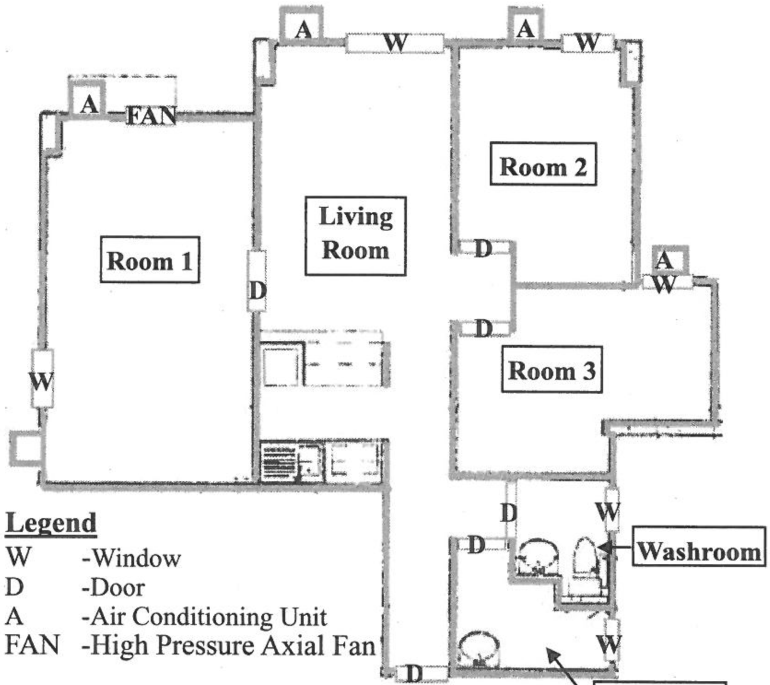

Figure 1- The Test Apartment

3. Methodology

The permeability test method stated in ASTM E779-03 [5] has been widely adopted by the industry and researchers to study the permeability of a single compartment unit [6]. The authors intended to extend the method to measure the permeability and interconnectivity by creating different configurations in the test apartment. Windows and doors are opened, closed or sealed in different configurations to create different leakage paths. The bulk permeability of each configuration was measured and the permeability of each path is then found by regression analysis. This analysis resolves the bulk permeability of each configuration as a linear combination of the leakage of individual components in a leakage model.

A high pressure axial fan which could deliver a pressure difference up to 600Pa was mounted directly onto a window frame. The fan power was controlled by a stepless 3-phase frequency inverter.

Flow entering the fan was first accelerated by a contraction unit made with polystyrene fitted into a 500mm diameter reinforced PVC pipe. The velocity of the flow across the neck of the contraction unit was recorded with a handheld anemometer. The velocity profile across the radius of the contraction unit was then normalized against the velocity at the reference point as illustrated in Figure 2. The result illustrates that the normalized velocity profile is fairly consistent at different fan power and settings. The flow rate across the fan, which is also the sum of the flow rate entering the space confined in a particular configuration, was deduced from Equation 1.

$$Q = \int_0^R 2\pi r v_{ref} f(r) dr \qquad (1)$$

Q = *Flow Rate (m^3/s)*
r = *Distance from Centre (m)*
R = *Internal Radius at the Neck of Contraction*
v_{ref} = *Reference Velocity (m/s)*
$f(r)$ = *Normalized Velocity Profile*

A vented acrylic disk of 50mm diameter was connected with a 1.5m tubing system to give a flat response on dynamic pressure signals up to 30Hz. Each pair of taps across the building envelope is subsequently connected to ports on a differential pressure sensor (Honeywell type 163PC01D36). For external pressure taps, the section of tubing from the hole drilled across the building envelope to the sensor end was shielded with a 6mm tube fitted with an air tight plug to avoid leakage. The whole pressure measurement system is illustrated in Figure 3.

The DC signal from the pressure sensor was first amplified with a signal conditioning unit with a 30Hz low pass filter to filter out system noise with a characteristic frequency of 50Hz. The signal was subsequently digitized with a 16-bit A/D acquisition system at a sampling frequency of 200Hz before being stored.

During the permeability test, a particular configuration with different opened and closed windows and doors was first set up and the fan was turned on to its full power for setting a suitable gain on the amplifier. Measurements for each configuration were taken with respect to fan power, for the range 0% to 100%, in 10% increments. During the tests, the reference velocity across the fan was recorded with a hand held anemometer. The external wind speed was monitored with an anemometer on top of the roof throughout the experiment.

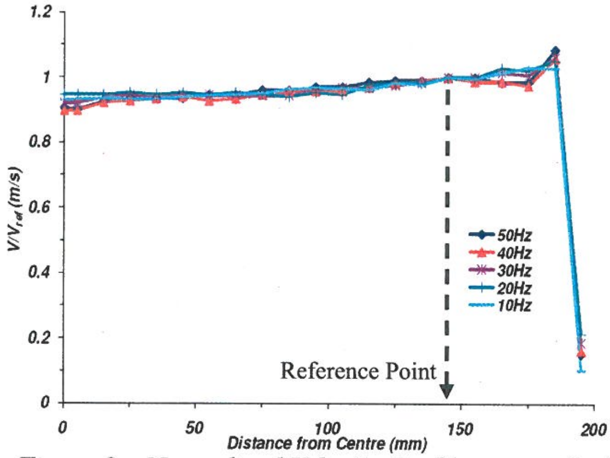

Figure 2 – Normalized Velocity Profile across the Fan

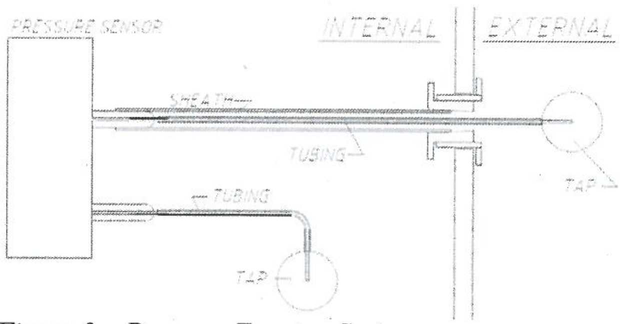

Figure 3 – Pressure Tapping System

4. Test Configurations and Results

Ten test configurations have been designed to identify the bulk permeability and permeability of individual components by means of plotting the flow rates against pressure difference across the isolated space. The arrangements of doors and windows for different configurations are stated in Table 1.

The sealing of doors was achieved by plugging gaps around the frame with modelling clay. The key hole and knob were sealed in a similar manner. Workmanship was then confirmed by the application of a leak detecting agent while the fan was turned on.

The bulk permeability of the test configurations are presented as flow rate-pressure difference curves in Figure 4a (Configurations 1 - 5) and 4b (Configurations 7 - 11). It was determined that the flow rate – pressure difference relationship of an individual component in a particular configuration generally follows a power law model.

Table 1 – Permeability Configurations

Configuration No.	Room 1 Window	Room 1 Door	Room 2 Window	Room 2 Door	Room 3 Window	Room 3 Door	Washroom Window	Washroom Door	Bathroom Window	Bathroom Door	Living Room Window	Main Door
1	Closed	Closed	Open	Open	Open	Open	Open	Open	Open	Open	Open	Open
2	Closed	Open	Open	Closed	Open	Closed	Open	Closed	Open	Closed	Closed	Closed
3	Closed	Open	Closed	Open	Closed	Open	Open	Closed	Open	Closed	Closed	Closed
4	Closed	Open	Closed	Open	Closed	Open	Closed	Open	Open	Closed	Closed	Closed
5	Closed	Open	Closed	Open	Closed	Open	Closed	Open	Closed	Open	Closed	Closed
7	Closed	Open	Open	Sealed	Open	Sealed	Open	Sealed	Open	Sealed	Closed	Sealed
8	Closed	Open	Close	Open	Open	Sealed	Open	Sealed	Open	Sealed	Closed	Sealed
9	Closed	Open	Open	Open	Closed	Open	Open	Sealed	Open	Sealed	Closed	Sealed
10	Closed	Open	Open	Open	Closed	Open	Closed	Open	Open	Sealed	Closed	Sealed
11	Closed	Open	Open	Open	Closed	Open	Closed	Open	Closed	Open	Closed	Sealed

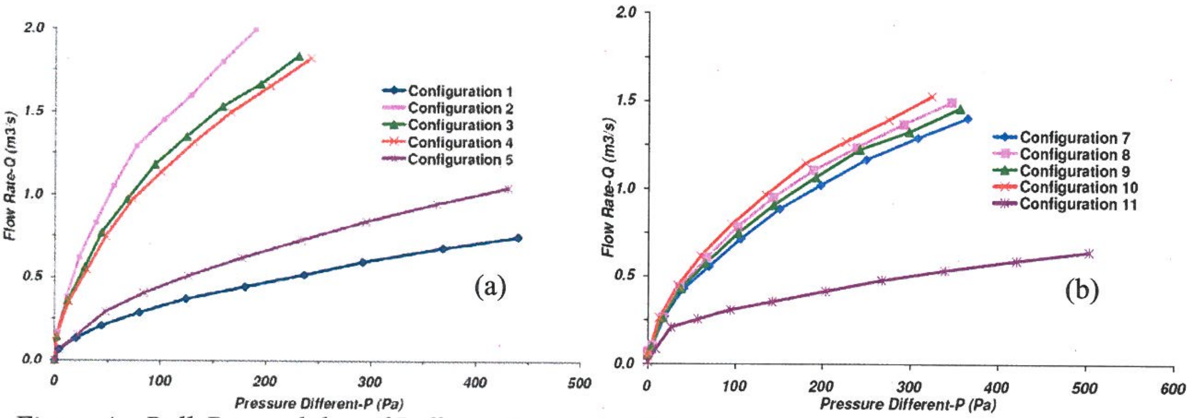

Figure 4 – Bulk Permeability of Different Testing Configurations

5. Leakage Model

In order to identify the permeability of individual components, a permeability model which consists of 7 independent variables was established. The flow rate-pressure difference curves obtained from each configuration were first interpolated within the range of 0-180Pa at 10Pa intervals to generate the Bulk Permeability Matrix (***Q***) in Equation 2.

The following individual leakage components in the testing apartment were subsequently identified:

a. Bedroom Background Permeability (q_A) – Each bedroom is fitted with one air conditioning unit and a window, the second window in Room 1 has been demounted and fitted with the fan unit and hence Room 1 was assumed to share the same configuration as other bedrooms.

b. Living Room Background Permeability (q_B) – The windows and air conditioning unit in the living room is different from the bedroom and hence distinguished as another variable.

c. Washroom/Bathroom Background Permeability (q_C) – The washroom and bathroom in the testing apartment is fitted with identical windows with an exhaust fan mounted on the glass and hence they are grouped under the same variable.

d. Living Room-Bathroom Interconnectivity (q_D) – During site survey of the testing apartment, a major leakage path was found above the false ceiling between the bathroom and the living room for passage of ducting and pipe works. The permeability of this path is specifically addressed with this variable.

e. Door Permeability - Door permeability in the testing apartment was classified into 3 categories owing to the significant variation of gap width and arrangement: Bedroom Door Permeability (q_E); Washroom/ Bathroom Door Permeability (q_F) and Main Door Permeability (q_G).

Room 2 and 3 are separated by a wooden closet which presents a possible interconnectivity between Room 2, Room 3 and the Living Room. Hence Configurations 2, 7 and 8 were not considered to remove these unknowns during the analysis.

The participation of individual elements in each configuration is presented in the participation matrix (***P***) in equation 2. By fitting ***q*** with regression analysis at each pressure interval the permeability of individual elements could be found and the result is presented in Figure 5

$$Q = P\,q \qquad (2)$$

where:

Q = Bulk permeability matrix
P = Participation matrix
q = Permeability matrix of individual component

Expand Equation 2 to get Equation 3 below.

$$\begin{pmatrix} Q_{1-1} & Q_{1-i} & Q_{1-n} \\ Q_{3-1} & Q_{3-i} & Q_{3-n} \\ Q_{4-1} & Q_{4-i} & Q_{4-n} \\ Q_{5-1}\cdots & Q_{5-i}\cdots & Q_{5-n} \\ Q_{9-1} & Q_{9-i} & Q_{9-n} \\ Q_{10-1} & Q_{10-i} & Q_{10-n} \\ Q_{11-1} & Q_{11-i} & Q_{11-n} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 3 & 1 & 0 & 1 & 0 & 2 & 1 \\ 3 & 1 & 1 & 1 & 0 & 1 & 1 \\ 3 & 1 & 2 & 0 & 0 & 0 & 1 \\ 3 & 1 & 0 & 1 & 0 & 0 & 0 \\ 3 & 1 & 1 & 1 & 0 & 0 & 0 \\ 3 & 1 & 2 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} q_{A-1} & q_{A-i} & q_{A-n} \\ q_{B-1} & q_{B-i} & q_{B-n} \\ q_{C-1} & q_{C-i} & q_{C-n} \\ q_{D-1}\cdots & q_{D-i}\cdots & q_{D-n} \\ q_{E-1} & q_{E-i} & q_{E-n} \\ q_{F-1} & q_{F-i} & q_{F-n} \\ q_{G-1} & q_{G-i} & q_{G-n} \end{pmatrix} \qquad (3)$$

where:

$Q_{k\text{-}i}$ = Flow measured in configuration k at pressure interval i (m^3/s)
$q_{A\text{-}i}$ = Flow contributed by component A at pressure interval i (m^3/s)

6. Conclusions

The permeability of a typical Hong Kong apartment building was determined for different configurations of opened and closed doors and windows. It was determined that the flow rate – pressure difference relationship of an individual element and a particular configuration generally follows a power law model.

These findings will be applied to a numerical model of the test apartment to investigate the effect of permeability of single chamber and multi-chamber internal pressure fluctuations induced by wind. Work on testing the permeability of the apartment under positive pressure is now in progress and we are expecting the whole picture of the permeability in the test apartment once completed.

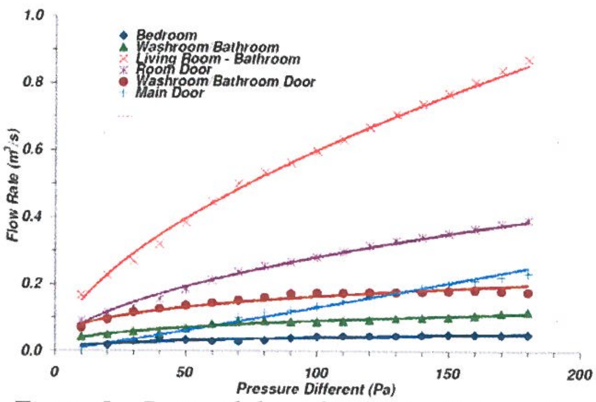

Figure 5 – Permeability of Individual Elements

7. Acknowledgements

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8. References

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