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The Effect of Varying Opening Areas in a Windward Wall on the Internal to External Pressure Coefficient Ratio of a High-Rise Apartment

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Abstract

A scale model wind tunnel test of the apartments of a proposed high-rise building in Melbourne, Victoria has been carried out to obtain predictions for the internal pressure fluctuations when windows in the external building envelope are open. The effect of varying the window type and opening area in both central and corner apartments were investigated and compared to the values predicted in AS/NZ1170.2:2011. Results indicated that the standard predicts the positive internal pressure well, with measured values being within 9% of the standard based predictions. However, large differences between the measured results and the standard were found for peak negative internal pressure coefficient ratios, with measured pressure ratios being approximately 30-50% less than those predicted using AS/NZS1170.2. The study suggests that negative internal pressure may be overestimated in the standard.

Introduction

An opening in a building envelope, is considered as a “dominant opening” if its area is greater than the sum of the leakage areas of the other faces (AS/NZS1170.2:2011). In such a case, the internal pressure may approach or even equal the external pressure experienced on that face. The effect of varying dominant opening size on the internal pressure has been studied before by Woods and Blackmore (1995) and Guha et. al. (2012) who conducted experimental wind tunnel testing in order to determine the change in internal to external pressure ratio as the opening size was varied. These studies consider the dominant openings as circular holes in the windward face. As such, the effect of different window types on the wind induced internal pressure (ie. Casement and awning windows) has not been investigated.

Experimental scale model wind tunnel testing of the internal pressure of buildings has been studied for a number of years. Holmes and Ginger (2012) summarised the previous work in this area, focusing specifically on the case of a dominant windward opening, as this is considered the critical design case in most instances. In order to accurately account for the scaling of the frequencies related to internal pressure in buildings there are scaling requirements that must be fulfilled. The study also suggested that in addition to the approaching flow, the wake turbulence influenced the behaviour of the Helmholtz resonance and that using realistic turbulence intensities was important when measuring internal pressure. Most studies conducted in this area consider only low-lying buildings.

The Australian Standard that establishes the design pressures applicable to internal partitions as a result of wind actions on the building façade is AS/NZS 1170.2:2011. Table 5.1(B) from this standard indicates that for openings in the external façade that exceed openings in internal partitions by a factor of 6 or more, internal partitions must resist the full external pressure. However, standard based internal pressure coefficients are determined using simplified quasi-static theoretical analysis, for a limited number of cases (Holmes and Ginger, 2012).

The objective of this study was to determine by experimental methods the internal pressure of a high-rise apartment and the change in internal pressure experienced as the dominant opening size was varied, using two different types of window and apartment configurations. These results were then compared to those predicted using AS/NZS1170.2:2011.

Methodology

The tests were carried out using a simplified model of a subject apartment at a scale of 1:20. The full scale apartment has a floor area of 39.4 m^2 and was approximated as a 6 m x 6.5 m rectangular plan, which was then scaled by a factor of 1:20. The wind pressures were measured on the surfaces simulating the exterior facade of the proposed building model. The internal pressure was also measured. Pressure measurements were taken with a multi-channel pressure transducer array. The model was tested at the Vipac Melbourne Boundary Layer Wind Tunnel.

Model Requirements

Dynamic similarity between the model and full scale necessary for internal pressure measurement was achieved using volume scaling. This is critical for obtaining the correct natural frequency for Helmholtz resonators and ensured that the full-scale apartments were accurately approximated by the scaled model. This scaling requires that:

$$V_m = V_F \frac{(L_m / L_F)^3}{(U_m / U_F)^2} \tag{1}$$

where V is the volume, L is the length, U is the velocity and subscript *m* denotes model scale and subscript *F* denotes full scale. To produce this effect, the volume of the scaled model needs to be augmented by a factor of $1/[U_r]^2$, where U_r is the full scale to test scale velocity ratio (Holmes and Ginger, 2012). As such, with the U_r of 1/3 used in this test, the volume was increased by a factor of 9.

The background leakage was simulated using a circular lumped leakage opening with an area of 0.5 cm^2, corresponding to a full-scale leakage area of 0.019m^2. Guha et al. (2011) has shown that a lumped leakage configuration resulted in 2-5% higher internal pressure fluctuations than the equivalent uniformly distributed porosity. The model was sealed thoroughly to ensure that there was no additional leakage via openings other than the lumped leakage area specified.

In order to approximate the “worst case” scenario, the apartment with the smallest floor area was chosen as the subject apartment.

Approach Wind Simulation

The tests were carried out in the 3 m wide × 2 m tall, 16 m long Boundary Layer Wind Tunnel owned and operated by Vipac Engineers & Scientists Ltd at Port Melbourne. The proposed development is in the centre of the Melbourne CBD. As per AS/NZS 1170.2:2011 the surrounding Terrain Category between 3 and 4 (Cat 3.5) was used in this study to determine the expected velocity and turbulence at the full scale height of the apartment. The wind tunnel V/V_{ref} at the height of the opening was 0.884 to simulate the full scale velocity at the top of the building and the turbulence intensity was 14.4%. The mean velocity and turbulence intensity profiles used in the study are shown in Figure 1. During the testing these profiles were monitored at two points – one at 1.25 m height and one at 0.55 m height.

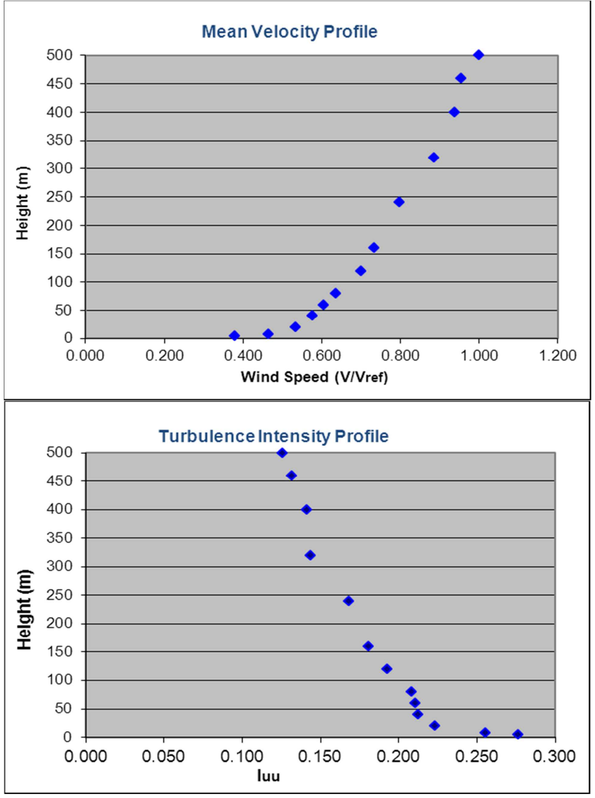

Figure 1. Mean velocity and turbulence intensity profiles.

Pressure Measurements

Four scenarios were investigated:

1. Apartment situated on the **centre** of the façade, with **casement windows**
2. Apartment situated on the **corner** of the façade, with **casement windows**
3. Apartment situated on the **centre** of the façade, with **awning windows**
4. Apartment situated on the **corner** of the façade, with **awning windows**

In each of these configurations, the windows were opened in increments of ~1.2mm to a maximum of 6.25mm (125mm full scale) to investigate the variation in internal pressure as the opening area was increased. The physical detail of the building model is shown in Figure 2.

Pressure measurements were taken over all surfaces simulating external facades of the rigid model representing an apartment of the high-rise development. The internal pressure was measured on the four inner walls of the apartment model. Measuring at four locations was thought to be sufficient to determine the internal pressure, as indicated by Guha et al (2012). PVC tubes with 1.5 mm internal diameter linked the taps to a pressure transducer array using a digital correction to remove the effects harmonic fluctuations in the connection tube. Pressure measurements were obtained for 36 wind directions for a full 360° circle. For each tap, the pressure fluctuations were measured for a duration of 60 seconds. Statistical analysis was carried out on the signals and the mean, standard deviation, and peak (i.e. maximum and minimum) values were obtained.

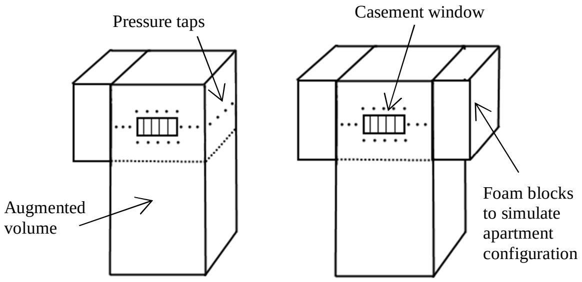

Figure 2. Test set up - casement window in corner configuration (left) and centre configuration (right)

Coordinates and Measured Parameters

Figure 3 is a test set up showing the plan coordinates. The reference axis for the wind direction is the direction normal to the facade containing the window. The wind attack angles were described by 0°, ±10°, ±20°, ±30°, ±40°, ±50°, ±60°, … ±170°, and 180° corresponding to a full rotation from 0° to 360° in 10° increments.

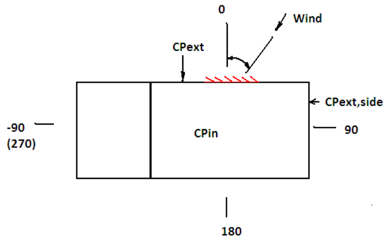

Figure 3. Test set up of the model, showing the coordinate and measurement parameters (casement window on corner apartment)

Four pressure taps were installed on the four inner walls of the models for the internal pressure measurements, as a constant pressure was expected for the entire internal volume. For the external pressures, 16 pressure taps were installed on the front façade of the test apartment. For the corner configuration, an additional 11 taps were installed on the side façade.

The pressure coefficients C_{Pext}, $C_{Pext,side}$ and C_{Pin} shown in Figure 3 are the average values from these taps.

Results

For each of the configurations of apartment position, window type and opening size, the peak positive and negative pressure coefficients were measured at each tap location. The average of the external and internal taps were taken and a ratio of internal to external pressures was calculated. The ratios at maximum pressure and maximum suction are presented.

Awning Wind Pressure Ratios

In terms of the ratio between the internal and external pressure coefficients, the ratio R_{pos} and R_{neg} corresponding to the pressures with the largest magnitude are the most important for design purposes. These ratios, as they vary with opening area, are listed in Table 1 and are also depicted in graphical form in Figure 4.

	Centre Configuration		Corner Configuration	
Opening Area (m^2)	**R_{pos}**	**R_{neg}**	**R_{pos}**	**R_{neg}**
0.79	0.97	0.71	1.02	0.71
0.64	0.98	0.59	1.01	0.66
0.46	0.92	0.53	0.96	0.72
0.28	0.92	0.56	0.99	0.59
0.12	0.84	0.40	0.82	0.65
0.03	0.52	0.42	0.48	0.52

Table 1. Internal to external pressure coefficient ratios (at maximum pressure or suction) for the awning windows in the windward wall for both apartment configurations

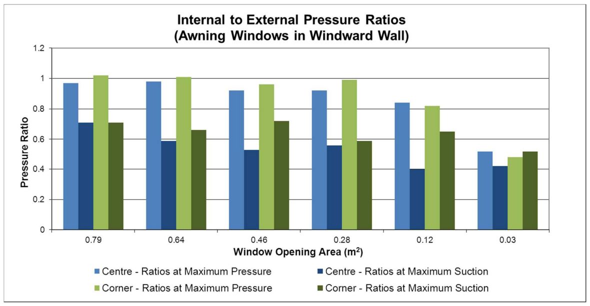

Figure 4. Internal to external pressure coefficient ratios (at maximum pressure or suction) for awning windows in the windward wall for both apartment configurations

It can be seen that for both apartment configurations, the positive pressure coefficient ratios remain fairly constant at values around 0.9-1 for windows with opening area 0.79-0.28 m^2. There is a slight decrease in ratio to 0.8 for opening area 0.12 m^2 and a more dramatic reduction for 0.03 m^2 to a ratio of around 0.5-0.6. For the centre apartment configuration, the negative pressure ratios remain within approximately 0.55-0.7 for window opening areas from 0.28-0.79 m^2, and decrease to 0.4 for windows with opening area 0.12 m^2 and below. For the corner apartment configuration, the negative pressure ratios remain relatively constant within approximately 0.5-0.7 with varying window opening area.

These results generally indicate that there is only minor variation of the internal to external positive pressure ratios until the opening area is reduced to 0.03 m^2.

Casement Window Pressure Ratios

In terms of the ratio between the internal and external pressure coefficients, the ratio R_{pos} and R_{neg} corresponding to the pressures with the largest magnitude are the most important for design purposes. These ratios, as they vary with opening area, are listed in Table 2. The internal to external ratios at maximum pressure and maximum suction are also shown in graphical form in Figure 5.

It can be seen that for both apartment configurations, the positive pressure coefficient ratios remain fairly constant at values around 1 for windows with opening area 1.35-0.09 m^2. There is a slight decrease in ratio to 0.8 for opening area 0.05 m^2, then 0.65-0.7 for 0.03 m^2 and a more dramatic reduction for 0.02 m^2 to a ratio of around 0.3. For the centre apartment configuration, the negative pressure ratios remain within approximately 0.5-0.65 for window opening areas from 0.29-1.35 m^2, and decrease to 0.4 for windows with opening area 0.02 m^2. For the corner apartment configuration, the negative pressure ratios remain within approximately 0.65-0.75 for window opening areas from 0.05-1.35 m^2 and decrease to 0.5-0.55 for windows with opening area 0.03 m^2 and below.

	Centre Configuration		Corner Configuration	
Opening Area (m^2)	**R_{pos}**	**R_{neg}**	**R_{pos}**	**R_{neg}**
1.35	1.04	0.55	1.02	0.74
1.09	1.03	0.61	1.03	0.70
0.83	0.95	0.62	1.09	0.63
0.56	1.05	0.51	1.12	0.73
0.29	1.05	0.51	1.08	0.73
0.09	1.00	0.66	1.00	0.66
0.05	0.78	0.51	0.75	0.64
0.03	0.66	0.48	0.69	0.53
0.02	0.33	0.41	0.30	0.49

Table 2. Internal to external pressure coefficient ratios (at maximum pressure or suction) for the casement windows in the windward wall for both apartment configurations

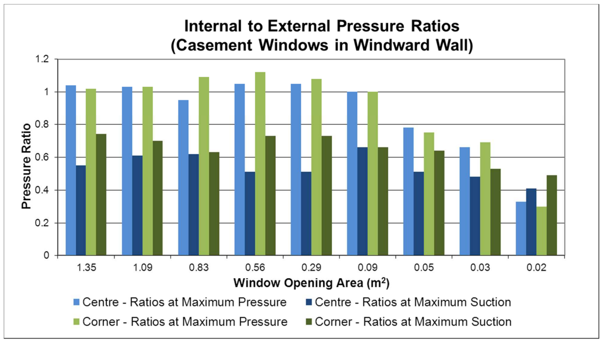

Figure 5. Internal to external pressure coefficient ratios (at maximum pressure or suction) for casement windows in the windward wall for both apartment configurations

These results indicate that there is only minor variation of the internal to external positive pressure ratios until the opening area is reduced to 0.05 m^2.

Comparison With AS/NZ1170.2

According to AS/NZS 1170.2:2011 (Table 5.1(B)) the internal pressure is determined by the ratio of the dominant opening to the total open area of the other surfaces. For the windward case, the standard states that if this ratio is 6 or more, then the entire external pressure is transmitted to the internal partitions. With the effective leakage area of 0.019 m^2 assumed in this test, this corresponds to a window opening area of 0.12 m^2. Table 3 and Table 4 present a comparison between the internal to external pressure ratios (peak positive pressure) predicted by the standard for each area ratio and those measured in the study.

It can be seen that the awning windows resulted in positive pressure ratios less than those predicted in the standard, whereas the casement windows generally resulted in values higher than in the standard. For both window types, as the area ratio decreased, the difference between the measured and standard-predicted values increased. Most of the measured pressure ratios were within 9% of the standard predicted values. The noticeable exception is the casement window with an area ratio of 6. This window resulted in a measured pressure ratio 17% less than that predicted using AS/NZS1170.2.

Area Ratio	Pressure Ratio (Centre config.)	Pressure Ratio (Corner config.)	Average Pressure Ratio	Standard Predicted Pressure Ratio	Difference (%)
39.5	0.97	1.02	0.995	1	-0.5
32	0.98	1.01	0.995	1	-0.5
23	0.92	0.96	0.94	1	-6
14	0.92	0.99	0.955	1	-4.5
6	0.84	0.82	0.83	1	-17

Table 3. Awning Windows - Comparison with the internal to external pressure ratios predicted with AS/NZS1170.2:2011 - Table5.1(B)

Area Ratio	Pressure Ratio (Centre config.)	Pressure Ratio (Corner config.)	Average Pressure Ratio	Standard Predicted Pressure Ratio	Difference (%)
68	1.04	1.02	1.03	1	3
54.5	1.03	1.03	1.03	1	3
41.5	0.95	1.09	1.02	1	2
28	1.05	1.12	1.085	1	8.5
14.5	1.05	1.08	1.065	1	6.5
4.5	1	1	1	0.925	8.1
2.5	0.78	0.75	0.765	0.8	-4.4
1.5	0.66	0.69	0.675	0.7	-3.6

Table 4. Casement Windows - Comparison with the internal to external pressure ratios predicted with AS/NZS1170.2:2011 - Table5.1(B)

Table 5 and Table 6 present a comparison between the internal to external pressure ratios (peak negative pressure) predicted by the standard for each area ratio and those measured in the study.

Area Ratio	Pressure Ratio (Centre config.)	Pressure Ratio (Corner config.)	Average Pressure Ratio	Standard Predicted Pressure Ratio	Difference (%)
39.5	0.71	0.71	0.71	1	-29
32	0.59	0.66	0.625	1	-37.5
23	0.53	0.72	0.625	1	-37.5
14	0.56	0.59	0.575	1	-42.5
6	0.4	0.65	0.525	1	-47.5

Table 5. Awning Windows - Comparison with the internal to external pressure ratios predicted with AS/NZS1170.2:2011 - Table5.1(B)

Area Ratio	Pressure Ratio (Centre config.)	Pressure Ratio (Corner config.)	Average Pressure Ratio	Standard Predicted Pressure Ratio	Difference (%)
68	0.55	0.74	0.645	1	-35.5
54.5	0.61	0.7	0.655	1	-34.5
41.5	0.62	0.63	0.625	1	-37.5
28	0.51	0.73	0.62	1	-38
14.5	0.51	0.73	0.62	1	-38
4.5	0.66	0.66	0.66	0.925	-28.6
2.5	0.51	0.64	0.575	0.8	-28.1
1.5	0.48	0.53	0.505	0.7	-27.9

Table 6. Casement Windows - Comparison with the internal to external pressure ratios predicted with AS/NZS1170.2:2011 - Table5.1(B)

It can be seen that the both the awning and casement windows resulted in negative pressure ratios less than those predicted in the standard. This difference was significant; with the measured pressure ratios being approximately 30-50% less than those predicted using AS/NZS1170.2.

Discussion

The results showed that in some instances, the internal pressures predicted by the standard may be conservative.

Considering positive internal pressure, the differences between the standard and the measured values was generally within 9%. For awning windows, it was found that at an opening area to background leakage ratio of 6, the measured values were 17% less than the standard prediction. According to the standard, at this ratio, the entire external pressure coefficient should transmit to the internal walls. The results suggest that this may occur at a higher area ratio. However, this was not repeated for the casement window configuration measurements, which remained within 9% for all area ratios, indicating that there may be differences between window type. Further investigation is required to determine the impact of different window types on the internal to external pressure ratios.

When the negative internal pressure is considered, it can be seen that all results indicate that the standard based predictions are conservative. Measured internal to external pressure coefficient ratios were between 30-50% lower than those predicted using AS/NZS1170.2:2011.

Conclusions

A scale model wind tunnel test of the apartments of a proposed high-rise building in Melbourne, Victoria has been carried out to obtain predictions for the internal pressure fluctuations when windows in the external building envelope are open. The effect of varying the window type and opening area in both central and corner apartments were investigated and compared to the values predicted in AS/NZ1170.2:2011. Differences between measured positive pressure values and standard -based predictions were within 9% for casement windows. For awning windows, this difference was within 6%, except for an opening area of 6 times that of the background leakage which resulted in measured values 17% less than the predicted value. However, large discrepancies were found for peak negative internal pressure ratios for both window types, with measured pressure ratios being approximately 30-50% less than those predicted using AS/NZS1170.2:2011.

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