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Correlation of internal and external pressures on building cladding elements

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ABSTRACT

Internal pressure in a building depends on the size and location of openings, porosity, building volume and flexibility. The combination of internal and external pressures generate net wind loads on structural elements based on the correlation of the internal and external pressures. The correlation of internal and external pressures depends on the location of cladding elements and openings in the envelope with respect to the wind direction. The correlations of pressures on the roof and wall structural elements obtained from 1:200 scale model building study showed that external and internal pressures near the dominant opening are well correlated and different correlations of external and internal pressures were identified on the building wall and roof claddings.

1. Introduction

Typical open plan, nominally sealed industrial buildings have a porous envelope. Airflow on and around the envelope generates smaller internal pressures than the external pressures on these buildings, which depends on the level of porosity. If a door/window is kept open or door/window fails the large opening increases the internal pressure in the building. Large windward openings produce high positive internal pressures, while sidewall openings create high negative internal pressure. The study of internal pressure is important for building design, as it is often the critical load case.

Net loads on the structural elements are highly dependent on the correlation of external and internal pressures. Combination of positive external pressure with negative internal pressure produces positive net pressure on cladding elements. In contrast, negative net pressure is produced by the combination of negative external and positive internal pressures. Peak external and peak internal pressures may not occur concurrently. Therefore, Action Combination Factors ($K_{c,e}$ and $K_{c,i}$) are defined in the AS/NZS 1170.2,2011 to lesser conservative building design. These are developed based on studies conducted since in 1979. This paper presents a wind tunnel model study of the correlation of external and internal pressures on walls and roof cladding elements and defines reduction factors based on net peak coefficients of external to internal pressures.

2. Wind Tunnel Experiment

The test was carried out in the boundary layer wind tunnel at the Cyclone Testing Station, at James Cook University, in an approach terrain category 2 as defined by AS/NZS 1170.2,2011. Figure 1 shows 3D view of the 1:200 scale-building model with the dimensions of 400 mm X 200 mm X 100 mm. The volume ratio between full scale to model scale can be defined by $[V]_r = [L]_r^3/[U]_r^2$, where $[L]_r$ is the length scale ratio and $[U]_r$ is the velocity scale ratio of the full scale to model scale (Holmes, 1979). Accordingly, internal volume was distorted by an additional depth of 600 mm under the turntable of the wind tunnel. In addition, total porous area to wall area ratio was maintained uniformly by the evenly distributed, 3 mm and 1.5 mm diameter porous holes along the four walls to achieve maximum of 0.6% porosity level on each wall.

A large opening (LO) was located on the wall 1 has an area of 120 mm X 80 mm. External pressures were measured on four taps on Wall 1, two taps on Wall 2 and two taps on Roof as shown in Figure 1. Tests were carried out for a range of wind directions, θ =0° to 360° in 10° intervals for 16 seconds at a frequency of 625 Hz. Tests were repeated five times for each wind directions and Wall 1 was the windward wall for all tests at the θ = 0 °. Four different configurations of openings and porosities described in Table 1 were studied.

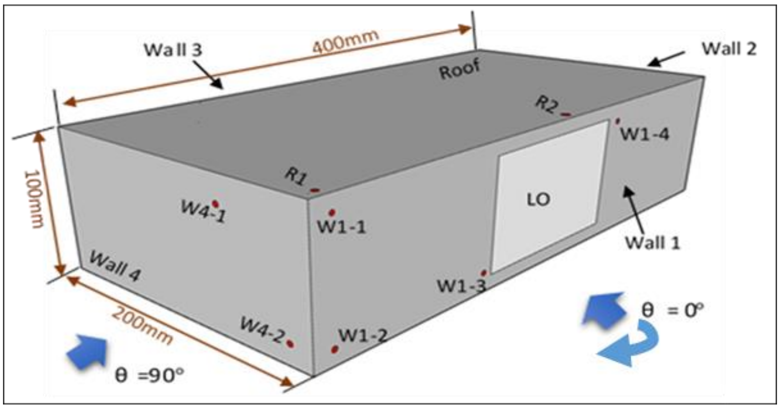

Fig. 1. Wind Tunnel Model with Opening, Selected External pressure taps on wall 1, wall 4 and roof

Table 1. List of Configurations

Case #	Description	$\frac{\textbf{Total Porous Area}}{\textbf{Total Wall Area}}$ (%)			
		W1	**W2**	**W3**	**W4**
1	Nominally Sealed	0.6	0.6	0.6	0.6
2	Large Open (LO)	0	0	0	0
3	Large Open (LO)	0	0.3	0.3	0.3
4	Large Open (LO)	0	0.6	0.6	0.6

The time (t) varying external pressure, $(p_e(t))$ and internal pressure,$(p_i(t))$ were converted into pressure coefficients $(C_p(t))$ to give mean, standard deviation, maximum and minimum coefficients as defined follows;

$$C_{\bar{p}} = \frac{\bar{p}}{(1/2)\ \rho_a \bar{U}_h^2}\ ,\quad C_{\sigma p} = \frac{\sigma_p}{(1/2)\ \rho_a \bar{U}_h^2}\ ,\quad C_{\hat{p}} = \frac{\hat{p}}{(1/2)\ \rho_a \bar{U}_h^2}\ ,\quad C_{\check{p}} = \frac{\check{p}}{(1/2)\ \rho_a \bar{U}_h^2}$$

where, $\bar{p}$, σ_p, $\hat{p}$ and $\check{p}$ are the mean, standard deviation, maximum and minimum pressures ;

$\bar{U}_h$ is the mean wind speed at the mid-roof height (h) and ρ_a is the density of air.

2.1. Correlation of internal and external pressures

Correlation coefficient is defined as the function of the lag time (τ) of one time history relative to the other. Accordingly, correlation coefficient of external and internal pressure time histories, r_{pipe} was defined by Eq.(1) at the zero lag time $(\tau = 0)$; where, C_{pe} is external pressure coefficient, C_{pi} is internal pressure coefficient, $C_{\sigma pe}$ and $C_{\sigma pi}$ are standard deviation of external and internal pressure coefficients.

$$r_{p_e p_i}(0) = \frac{\int [\left(C_{pe}(\mathrm{t}) - \bar{C}_{\mathrm{pe}}\right) \times \left(C_{pi}(\mathrm{t}) - \bar{C}_{pi}\right)]}{C_{\sigma p_e}\, C_{\sigma p_i}} \quad (1)$$

The net pressure coefficient, $C_{p,net}$(t) is calculated from Eq.2.

$$C_{p,net}(t) = C_{pe}(t) - C_{pi}(t) \tag{2}$$

Reduction factors Rc_1 and Rc_2 that produce a measure of the reduction in peak net pressures compared to the difference of peak external and internal pressures on cladding elements are given by Eq.(3)

$$Rc_1(\theta) = \frac{\hat{C}_{p,net}(\theta)}{\hat{C}_{pe}(\theta) - \check{C}_{pi}(\theta)} \quad \& \quad Rc_2(\theta) = \frac{\check{C}_{p,net}(\theta)}{\check{C}_{pe}(\theta) - \hat{C}_{pi}(\theta)} \tag{3}$$

Net, external and internal coefficients are used for Rc_1 and Rc_2 calculations and should be within the same θ range ($\pm$ 45° of orthogonal wind directions) as in standard AS/NZS 1170.2,2011.

3. Results and Discussion

The time histories of C_{pi} at the four internal pressure taps for all wind directions have similar variations and are fully correlated. Accordingly, the internal pressure of one tap is used in the analysis.

3.1. Maximum, Minimum and Mean Pressures - Case #1

The internal pressure coefficient was observed in the nominally sealed building. It was small negative and has minimal fluctuation with wind directions. As an example, $\bar{C}_{pi}$, $\hat{C}_{pi}$ and $\check{C}_{pi}$ were observed as -0.18 , -0.008 and -0.27 at the θ = 0° wind direction.

Figure 3 presents mean, maximum and minimum external and net C_ps on W1-1, W1-3, W4-2 and R2 with wind directions. Mean external pressures are observed as; large positive on the windward wall, large negative on the sidewalls and smaller negative on leeward wall, also large negative on upwind roof and small negative on downwind roof. The results showed that net pressure were closely followed the External pressure of the walls and roof of the nominally sealed building, due to small negative internal pressure fluctuations. The maximum and minimum net C_ps were presented on windward wall and leeward wall. As an example, $\hat{C}_{p,net}$s of taps W1-1 and W4-2 are 1.8 and occurred at θ = 30° and θ = 100°, while $\check{C}_{p,net}$s of same taps are -1.9 at θ = 80° and θ = 10°.

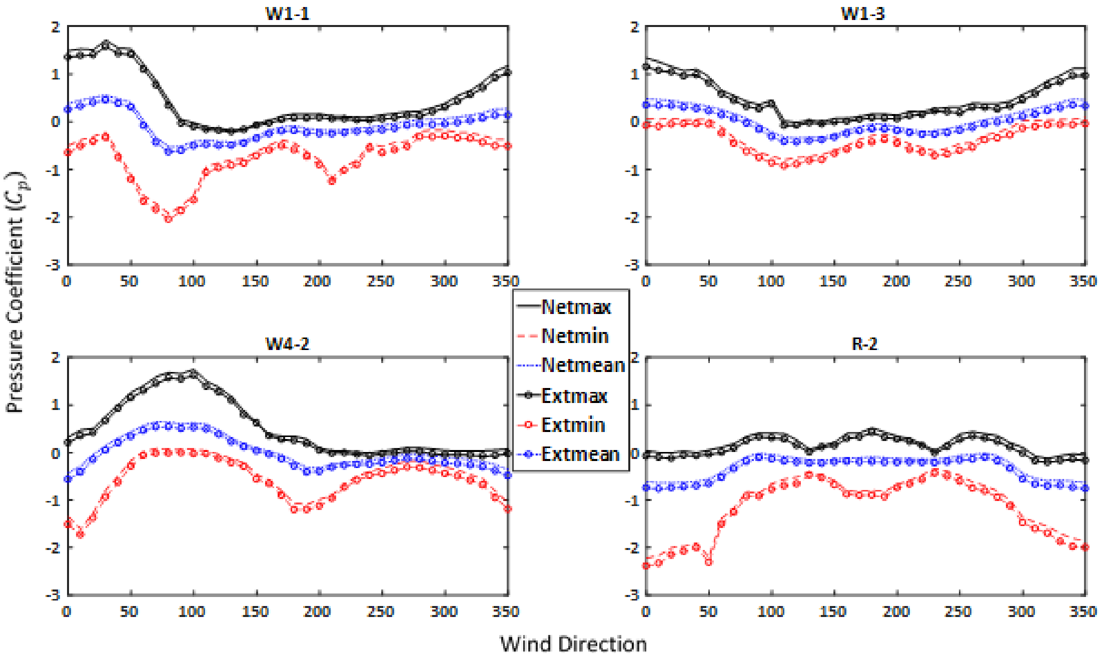

Fig. 3. Maximum, minimum and mean Net pressure and external pressure coefficients- case #1

3.2. Peak Pressure Coefficients

Table 2 shows net and external peak pressure coefficients with their corresponding wind directions and selected maximum or minimum internal pressure coefficients in the same θ range to all tested cases 1 to 4. Peak net and external C_ps occurred within the similar θ range, as an example, both peak net and external C_ps for W1-1 in the case 2 occurred at wind azimuth 70° in the θ= 90° $\pm$ 45°. The large suction peak pressures on the upwind roof edge is about 80% of the difference between large suction peak external and positive internal pressure within the same wind azimuth range. Based on the peak net C_ps, critical wind ranges are identified as, θ = 0° $\pm$ 45° for W1-3, W1-4, W4-1, W4-2, and R2 , θ = 90° $\pm$ 45° for W1-1 and W1-2. In summary, all peaks are observed for these four cases within the θ range 320° to 140°. Increasing porosity in cases 3 and 4 in the building envelope did not produce important influence on peak pressures and particular wind directions.

Table 2. Peak net and external pressure coefficients (C_{pk}), corresponding wind direction and selected maximum or minimum C_{pi} in the same θ range.

Tap No.	Case 1			Case 2			Case 3			Case 4		
	Net C_{pk} (θ°)	Ext C_{pk} (θ°)	$\hat{C}_{pi}$ (θ°)	Net C_{pk} (θ°)	Ext C_{pk} (θ°)	$\hat{C}_{pi}$ (θ°)	Net C_{pk} (θ°)	Ext C_{pk} (θ°)	$\hat{C}_{pi}$ (θ°)	Net C_{pk} (θ°)	Ext C_{pk} (θ°)	$\hat{C}_{pi}$ (θ°)
W1-1	-1.93 (80)	-2.05 (80)	0.03 (120)	-1.97 (70)	-1.96 (70)	0.85 (50)	-1.94 (80)	-1.93 (80)	0.91 (50)	-2.31 (80)	-2.28 (80)	0.91 (50)
W1-2	-2.16 (90)	-2.24 (90)	0.03 (120)	-1.78 (80)	-1.80 (90)	0.85 (50)	-1.70 (70)	-1.74 (70)	0.91 (50)	-1.83 (90)	-1.92 (90)	0.91 (50)
W1-3	1.34 (0)	1.15 (0)	-0.27 (0)	-1.28 (340)	-0.31 (0)	1.22 (20)	-1.18 (350)	-0.4 (0)	1.23 (10)	-1.17 (340)	-0.3 (0)	1.26 (10)
W1-4	1.60 (0)	1.45 (10)	-0.27 (0)	-1.54 (10)	-0.84 (30)	1.22 (20)	-1.56 (30)	-0.91 (30)	1.23 (10)	-1.59 (10)	-0.87 (20)	1.26 (10)
W4-1	-1.58 (10)	-1.73 (10)	0.03 (30)	-2.49 (10)	-1.79 (0)	1.22 (20)	-2.60 (10)	-1.83 (10)	1.23 (10)	-2.51 (10)	-1.83 (10)	1.26 (10)
W4-2	1.75 (100)	1.62 (100)	-0.22 (80)	-2.53 (10)	-1.76 (10)	1.22 (20)	-2.74 (10)	-1.96 (10)	1.23 (10)	-2.71 (10)	-1.87 (10)	1.26 (10)
R1	-4.31 (60)	-4.44 (60)	0.03 (120)	-4.92 (70)	-4.86 (70)	0.85 (50)	-4.77 (60)	-4.68 (60)	0.91 (50)	-4.98 (60)	-4.83 (70)	0.91 (50)
R2	-2.22 (0)	-2.39 (0)	0.03 (30)	-2.98 (350)	-2.22 (0)	1.22 (20)	-2.78 (0)	-2.24 (10)	1.23 (10)	-2.88 (350)	-2.38 (20)	1.26 (10)

3.3. External and Internal Pressure correlations on cladding elements

Figure 4 shows the correlation coefficients of external to internal pressures on individual cladding elements for all cases 1 to 4 with wind directions. External pressures on upwind roof edge (R2) has higher correlation with internal pressure as stated by Ginger and Letchford (1999), and poorly correlated on the roof corners (R1) as stated by Beste and Cermark in 1997. Correlation coefficients of external to internal pressures approximately equal to +0.5 for θ = 180° $\pm$ 45° on the W1-1, W1-2, W1-3 and W1-4 in the case 1, which illustrated the better correlation of suction external and internal pressures on the leeward wall. Similarly, $r_{p_i p_e}$ is +0.5 for θ = 270° $\pm$ 45° on W4-1 and W4-2, which is the leeward wall of that wind azimuths. External and internal pressures close to the large opening (LO) has better correlation, and is higher than +0.5 at wind direction from θ = 30° to θ = 240° on W1-3 and from θ = 120° to θ = 330° on W1-4.

Upwind edge of the sidewall with the large opening showed small negative correlation of external and internal pressures of the W1-1 and W1-2 at the θ = 90°, in contrast it showed a small positive value on the downwind edge of the sidewall at the θ = 270°. The correlations of external and internal pressures on the wall 4 in the cases 2, 3 and 4 are varied between -0.3 to +0.3, comparatively lower than case 1. This occurred due to higher internal pressure fluctuations in a building with large opening. The $r_{p_i p_e}$ is less than -0.5 for θ = 0° $\pm$ 45° on the W4-1, W4-2, R1 and R2 in the cases 2 to 4, which represents the upwind roof edge and the sidewall. Porosity did not create significant effect on the correlation of external and internal pressures of the building with a large opening, when the porosity level is less than 0.6%. Correlation of external and internal pressure are different between roof and wall (Haiwei Xu, 2017). Accordingly, different correlation coefficients of external to internal pressure were identified in cladding elements, which is varied based on the cladding location, large opening and wind direction.

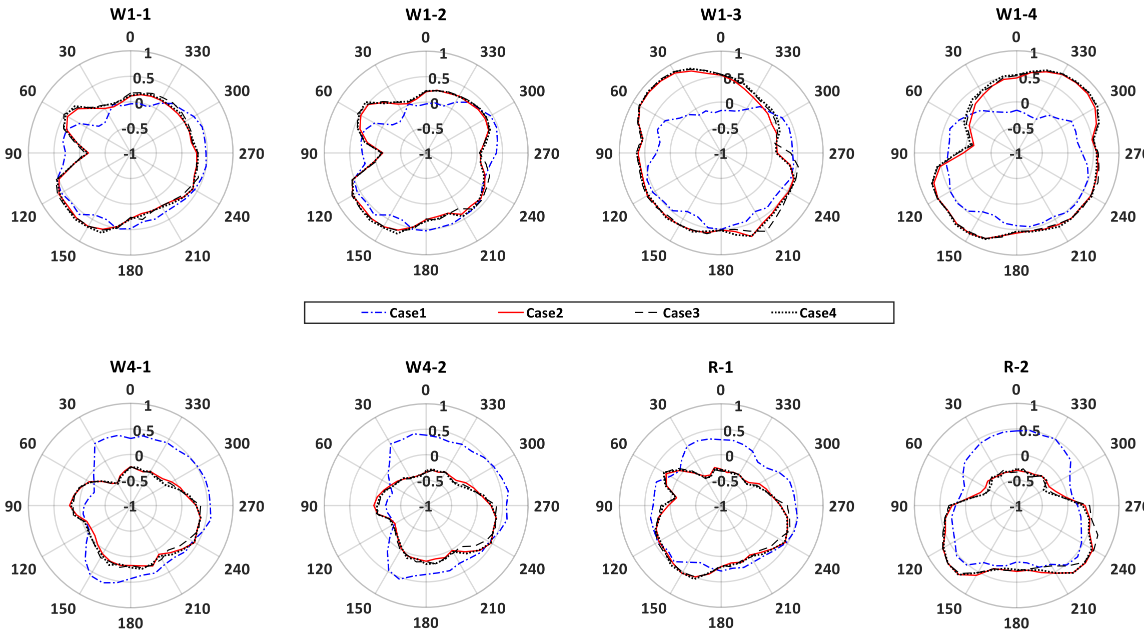

Fig. 4. External and Internal Pressure Correlation Coefficients for Cases 1 to 4

3.4. Reduction Factor (R_c)

Table 3 shows the Reduction factors, Rc_1 and Rc_2 on different claddings of the building for all cases 1 to 4. Calculated reduction factor can be compared with the Combination Factor (K_c) defined in AS/NZS 1170.2,2011. According to wind standard AS/NZS 1170.2,2011, when $|C_{pi}|$ < 0.2, K_c is defined as 1 for all for cladding designs by neglecting the effect of internal pressure. In addition, when there are pressures on two effective surfaces, K_c is 0.9 for all claddings of the building.

Different reduction factors were observed at the building wall and roof claddings, based on the location of the cladding and the building configurations. Since the internal pressure coefficient is less than 0.2 in case 1, K_c in the AS/NZS 1170.2:2011 equals 1. However, in the case 1, Rc_1 and Rc_2 values are approximately 0.9 which is 10% less than the defined K_c in the AS/NZS 1170.2,2011. Large positive internal pressure is influenced on reduction factor of case 2 and approximately 30% decreased than the R_c in the case 1. Comparison of R_c values in case 2, 3 and 4 was illustrated that effect of increasing porosity of the building is less than 2% of reduction factors on cladding elements. In addition, R_c values in case 2 to 4 are about 75% to 90% of the K_c value in the wind standard, which indicates that 10% reduction can be proposed to the value of K_c in the Standard.

Table 3. Reduction Factor for different claddings of the building for Cases 1 to 4

Tap No.	Case 1		Case 2		Case 3		Case 4	
	Rc_1	Rc_2	Rc_1	Rc_2	Rc_1	Rc_2	Rc_1	Rc_2
W1-1	0.93	0.93	0.72	0.70	0.72	0.68	0.74	0.72
W1-2	0.88	0.95	0.69	0.67	0.72	0.63	0.70	0.65
W1-3	0.94	0.83	0.53	0.84	0.65	0.73	0.53	0.75
W1-4	0.93	0.87	0.49	0.75	0.50	0.73	0.57	0.75
W4-1	0.94	0.90	0.66	0.83	0.71	0.85	0.67	0.81
W4-2	0.95	0.92	0.75	0.85	0.76	0.86	0.85	0.86
R1	0.71	0.96	0.53	0.86	0.57	0.84	0.53	0.87
R2	0.81	0.92	0.58	0.87	0.66	0.80	0.59	0.79

5. Conclusions

External and internal pressures obtained from the wind tunnel model test were used to study the correlation of external and internal pressures and reduction factors on building cladding elements. The experimental results were compared with design data specified in AS/NZS 1170.2,2011.

- Small negative peak internal pressures were experienced in the nominally sealed building, and positive external and negative internal pressures are poorly correlated on the windward wall.
- Large suction external pressures and large positive internal pressures produced large negative net peaks pressure on the upwind roof edge within the θ = 0° $\pm$ 45°, and external and internal pressures were well correlated in the same θ range.
- External and internal pressures are well correlated close to the large opening, and low correlations are experienced further away from the large opening.
- Different correlations of external to internal pressures and different reduction factors were identified on the building walls and roof cladding elements based on the location of the cladding element, building configurations and wind directions.
- The analysis showed that, Rc_1 and Rc_2 values were distinguished to K_c values defined in the wind standard AS/NZS 1170.2,2011. Accordingly, 10% reduction to the K_c values defined in the wind standard can be applicable on the cladding elements of the nominally sealed building and porous building with a large opening, when the porosity level is less than 0.6%.

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