9th Asia-Pacific Conference on Wind Engineering
Auckland, New Zealand
3-7 December 2017

External and Internal Pressure Fluctuations on Industrial-Type Buildings

G.G. Bodhinayake[1], J.D. Ginger[1] and D.J. Henderson[2]

[1]College of Science and Engineering
James Cook University, Townsville, Queensland, 4811, Australia

[2]Cyclone Testing Station
James Cook University, Townsville, Queensland, 4811, Australia

Abstract

The external and internal pressures on a range of building configurations were studied by carrying out a series of wind tunnel model studies. The studies showed that low internal pressure in nominally sealed buildings compared to external pressure fluctuation at the windward wall opening and magnitude of the internal pressure varied with building porosity. Internal pressure fluctuations in buildings with a dominant opening closely followed the external pressure at the opening. In addition, the magnitude of the internal pressure increased in buildings with a dominant opening compared to that of nominally sealed buildings. The porosity of the building with a dominant opening significantly influenced the internal pressure, with the peak internal pressure being reduced at higher porosity. The measured internal pressure spectra showed an increase of energy close to the Helmholtz resonance frequency and this energy decreased with respect to increasing porosity. Background leakages reduced the internal pressure fluctuations in buildings with a dominant opening, while the Helmholtz resonance occurred at the same frequency.

Introduction

Industrial type buildings are identified as open plan buildings with a large internal volume. These buildings are enclosed by steel cladding, which is fixed to portal frames. Roller doors installed to access the internal space may be vulnerable to damage in windstorms. Doors/windows that are left open or damaged in high winds increase the internal pressure, thereby causing structural failures.

Internal pressure in the building is dependent on the size and location of openings, including the porosity of the building envelope and the effective internal volume, which is influenced by the flexibility of the envelope. Openings in the envelope link the inside to the outside, generating internal pressure. The pressure inside a porous building without a dominant opening (nominally sealed) is considerably smaller compared to external pressure. A large opening in the building envelope increases the internal pressures and thus increases the risk of damage in windstorms.

External and internal pressure studies have been conducted since the 1960s, with less attention given to internal pressure. Liu [7] and Holmes [5] conducted detailed studies on internal pressures in buildings using wind tunnel models. Holmes [5] showed that internal pressure fluctuations in buildings with a dominant opening can be found by the Helmholtz resonator model. He also emphasized the requirement for internal volume distortion based on scaling requirements. Liu and Saathoff [8], Vickery [11] and Harris [4] studied the internal pressure in nominally sealed low-rise buildings. In the past two decades, Ginger, et al. [1,2], Oh, et al. [9] and Guha, et al. [3] have carried out further detailed studies on internal pressures on a full scale and model scale buildings and compared the results with theoretical analysis. Internal pressure data specified in wind loading standards (i.e AS/NZS 1170.2, 2011) are based on studies conducted with a limited range of volume, porosities, and dominant opening sizes. Hence, designs carried out using these data may not produce optimum solutions.

This paper presents preliminary results on the variation of external and internal pressures obtained from a wind tunnel model study with a range of porosities and dominant openings in the envelope in industrial type buildings.

Theory

Mean Internal Pressure

External and internal pressures across an opening are related to flow Q, and opening area A. The unsteady discharge equation is applied for unsteady flow through the opening and derived a pressure difference Δp, of the external and internal pressures.

Mass conservation theory is applied to steady flow through multiple openings to give: the sum of mean inflow (Q_{in}), equals the sum of mean outflow (Q_{out}) through a building ($\sum Q_{in} = \sum Q_{out}$). Liu [7] used this principle to get, $A_W\sqrt{C_{\bar{p}_W} - C_{\bar{p}_i}} = A_L\sqrt{C_{\bar{p}_i} - C_{\bar{p}_L}}$, where, A_W is the total windward opening area, A_L is the total leeward opening area , $C_{\bar{p}_i}$ is the mean internal pressure coefficient, $C_{\bar{p}_W}$ is the mean external windward pressure coefficient, and $C_{\bar{p}_L}$ is the mean external leeward pressure coefficient. The pressure coefficient C_p, is the ratio of the pressure (p) to the dynamic pressure (q). Accordingly, $C_p = p/q = p/0.5\,\rho_a \bar{U}_h^2$; Where, ρ_a is the density of air, $\bar{U}_h$ is the mean wind speed at the reference height (h).

This relationship gives Equation 1, which used in many codes and standards to find corresponding $C_{\bar{p}_i}$ for given A_W/A_L ratio, in buildings.

$$C_{\bar{p}_i} = \frac{C_{\bar{p}_W}}{1 + (A_L/A_W)^2} + \frac{C_{\bar{p}_L}}{1 + (A_W/A_L)^2} \qquad (1)$$

Internal Pressure Fluctuations in Nominally Sealed Buildings

The envelopes of enclosed industrial buildings have small gaps that are distributed throughout the building envelope. These are called nominally sealed buildings with background leakage (i.e. porous walls). The porosity is assumed to be uniformly distributed on each wall surface.

Vickery [11,12] and Harris [4] studied internal pressure fluctuations in these buildings using the relationship of the wind flow through windward and leeward surfaces by combining the unsteady discharge equation and mass conservation. Kim and Ginger [6] introduced windward and leeward pressure coefficients and developed Equation 2, where C_{L_W} is the loss coefficient of windward surfaces and C_{L_L} is the loss coefficient of leeward surfaces.

$$\frac{A_w}{\sqrt{C_{L_W}}}\sqrt{2\rho_a(p_w - p_i)} - \frac{A_L}{\sqrt{C_{L_L}}}\sqrt{2\rho_a(p_i - p_L)} = \frac{\bar{U}_h V_0}{2a_s^2}\dot{C}_{pi} \qquad (2)$$

where, $a_s = \sqrt{(\gamma p_o/\rho_a}$ is the speed of sound, p_0 is atmospheric pressure, γ is the ratio of specific heats of air, V_0 - volume of the building and $\dot{C}_{pi}$ is first derivative of the C_{Pi} with respect to time.

Vickery [11] and Harris [4] derived the characteristic frequency, f_c in Equation 3 as a frequency above which external pressure fluctuations are not passed into the building (damped).

$$f_c = \frac{1}{2\pi}\left(\frac{a_s(A_w^2 + A_L^2)^{3/2}}{V_0 \bar{U}_h A_w A_L C_L \sqrt{C_{\bar{p}w} - C_{\bar{p}L}}}\right) \qquad (3)$$

Internal Pressure Fluctuations in a building with a Dominant Opening

Holmes [5] used the well-established “Helmholtz resonator model” given in Equation 4 to study the internal pressure fluctuations in a building with a dominant opening.

$$\frac{C_I V_0}{a_s^2\sqrt{A}}\ddot{C}_{pi} + C_L\left(\frac{V_0\bar{U}}{2a_s^2 A}\right)^2 \dot{C}_{pi}|\dot{C}_{pi}| + C_{pi} = C_{pe} \qquad (4)$$

Where, A-area of dominant opening, C_I −Inertial coefficient, C_L-Loss coefficient and $\ddot{C}_{pi}$ is second derivatives of the C_{pi} with respect to time.

Vickery [11] derived an identical equation to Holmes [5], by applying unsteady flow theory and assumptions. Liu and Saathoff [8], Sharma [10] used the unsteady Bernoulli Equation and obtained another version of the governing equation. The first term of the governing equation represents the inertia of the flow; the second term is damping of the system and the third is stiffness. Theoretically, the internal pressure resonance occurs close to undammed Helmholtz frequency, $f_H = 1/2\pi\sqrt{((a_s^2\sqrt{A})/(C_I V_0))}$.

The porosity in the envelope can influence the internal pressure in a building that has a dominant opening. Vickery and Bloxham [12] showed that the dynamic response of internal pressure reduced when the background leakage area exceeds 10% of the dominant opening area. Oh [9], Yu et al [13] and Kim and Ginger [6] also studied the effects of porosity using the lumped leakage approach, validating it with wind tunnel measurements of internal pressure in a building with a dominant opening and background leakage.

Experimental setup

External and internal pressures were measured on a 1:200 scale building model with the dimensions of 400mm × 200mm × 100mm shown in Figure 1, internal volume was distorted by an additional depth of 600mm under the turntable of the wind tunnel. The model was made of 6mm Perspex, consisted of three potential large openings, two of them (LO1 and LO2) equal to 80mm (height) x 120mm (wide) are on Wall W1, while the other opening (LO3) of 80mm (height) x 40mm (wide) is on Wall W4. In addition, 60, 3mm diameter holes (H1) and 180, 1.5mm diameter holes (H2) are evenly distributed along the four walls W1 to W4. A total of 44 external pressure taps were installed in the model, 20 taps on Walls W1 and W3, 10 taps on Walls W2 and W3 and 14 taps on the roof were evenly installed while four pressure taps were installed to measure internal pressure. The tests were carried out in the wind tunnel at James Cook University (JCU), in an approach terrain category 2. Atmospheric Boundary Layer flow as per AS/ANZ 1170.2 (2011) at a length scale of 1/200. Tests were carried out for a range of wind directions, θ =0° to 360° in 10 deg. intervals.

Wall W1 was the windward wall of the building at the θ = 0 ° wind direction. Then Wall W4 became a leeward wall while Wall W2 and Wall W3 represented the side walls of the building. Pressure taps PT05, PT25 and PT34 were installed on the opening LO1, Wall W4 and on the opening LO3 respectively.

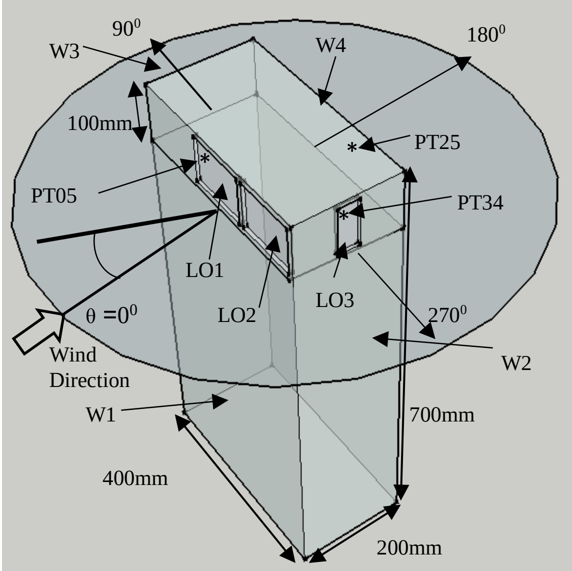

Figure 1. 1:200 Scale wind tunnel model.

The range of configurations tested and the ratio of total porous area into total wall area for different 6 cases are listed in Table 1. Cases 1 to 3 are nominally sealed buildings with different uniform wall porosities. Case 4 is a building with a dominant opening only while Cases 5 and 6 are buildings with a dominant opening and background leakage. Porosity is defined as the ratio of the sum of all opening areas of the wall (A_0) to total wall area (A_T). Cases 2 and 5 are the lowest porosity configurations for a nominally sealed building and a porous building with a dominant opening.

Case	Description	Wall porosity (A_0/A_T)(%)			
		W1	W2	W3	W4
1	H1 & H2 holes open	0.62	0.62	0.62	0.62
2	H2 holes open	0.27	0.27	0.27	0.27
3	H1 holes open	0.35	0.35	0.35	0.35
4	LO3 open	0	0	0	0
5	LO3 open	0.17	0	0.17	0.17
6	LO3 open	0.34	0	0.34	0.34

Table 1: Wind tunnel model test configurations.

Results and Discussion

Figure 2 presents the mean external $C_p s$ on PT5 and PT34 and the mean internal C_ps measured (for Nominally Sealed Cases 1 to 3) for θ = 0° to 90°. Mean $C_{pi}'s$ are small and negative in a nominally sealed building compared to mean C_{pe} that are large positive on the windward wall, large negative on the sidewalls and smaller negative on leeward wall. Porosity made a significant difference to the internal pressure fluctuations. The lowest negative internal pressures occurred for the smallest porosity in case 2. The variations in magnitude for the C_{pi} were less than the variations for C_{pe} over the building rotation.

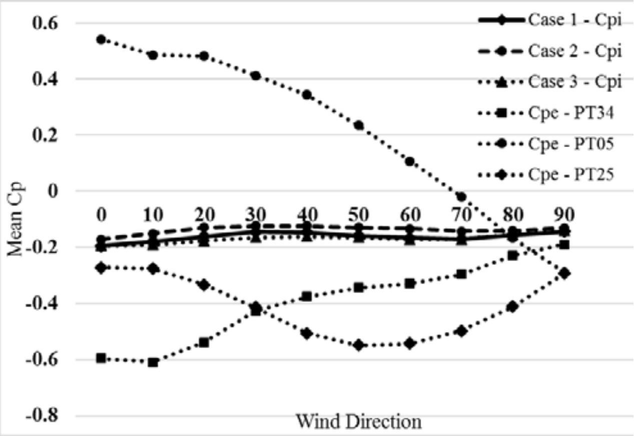

Figure 2. Internal and External Mean C_p of the nominally sealed building.

Figure 3 shows the mean external pressure of the pressure tap, PT34 and the mean internal pressure measured for cases 4, 5 and 6. As can be observed, the equivalent mean internal pressure closely followed the external pressures (PT34). This scenario is explained through Equation 1, when the building contains only a windward opening, $(A_L = 0)$, thus $C_{\bar{p}i} = C_{\bar{p}_W}$, on the contrary $C_{\bar{p}i} = C_{\bar{p}_L}$ when there are only leeward openings, $(A_w = 0)$. Higher positive internal pressure occurred at the θ = 270°, also the mean pressures significantly reduce with building rotation. Higher negative internal pressure was presented on Wall W2, which is a sidewall at the θ = 0°, since more suction pressure was applied to LO3. The large negative $C_{\bar{p}i}$ reduced with further building rotation while Wall W2 became the leeward wall at the wind direction θ = 90°. The mean internal pressure of the building reduced with increasing building porosity, for buildings with a dominant opening. The effect of the dominant opening and background leakage on the mean internal pressure changes with the wind direction.

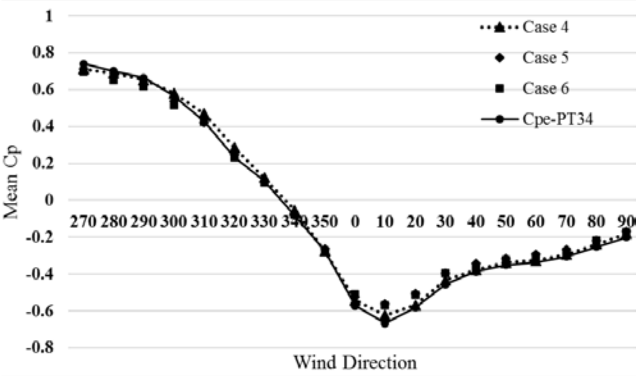

Figure 3. Building with dominant opening and background leakage.

Figure 4 compared the maximum and minimum internal and external pressures of the nominally sealed buildings at the θ = 0°, and buildings with dominant opening and background leakage at the θ = 270°. Higher difference of maximum C_{pi} and C_{pe} values can be observed, while close values between minimum C_{pi} and C_{pe} for nominally sealed buildings. The maximum C_{pi} was higher than C_{pe} in case 4 and 5 and close values can be noted for maximum internal and external pressures in case 6, which has higher porosity. The ratio of the total dominant opening area to total porous area is 0%, 5% and 10% for cases 4, 5 and 6 respectively showed the effect of porosity to peak internal pressure, and illustrated the decreasing trend in the peak C_{pi} in configurations 4, 5 and 6.

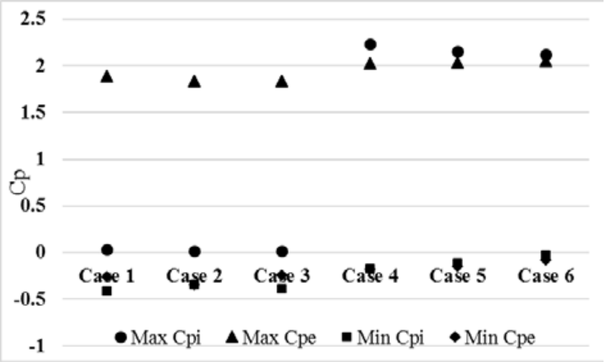

Figure 4. Maximum and Minimum C_p values for θ = 0^0 for Case 1,2 and 3, θ = 270^0 for case 4,5 and 6.

Figure 5 presents the external pressure spectrum on PT05, PT34 and the internal pressure spectra for cases 1, 2 and 3. The porosity effect on internal pressure can be identified by evaluating the internal pressure spectra of three configurations. Low energy in the internal pressure spectra was identified in case 2, which has low porosity. Windward (PT05) and sidewall (PT034) pressure spectra show that the sidewall pressure spectra contain less energy, influenced by flow separation, compared with windward wall pressure spectra.

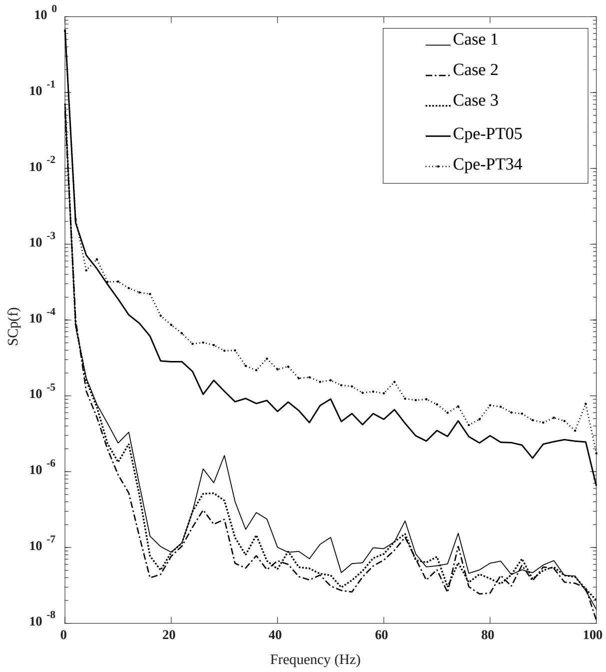

Figure 5. External and internal pressure spectra for a nominally sealed building for different porosity levels.

Figure 6 presents the external pressure spectrum on Wall W2 and the internal pressure spectra for cases 4, 5 and 6. The internal pressure spectra show that that Helmholtz resonance occurs at 34 Hz in all three cases. The energy at the Helmholtz frequency is reduced as porosity is increased. Figure 6 shows that internal pressure energy increased at the Helmholtz frequency. The higher energy in internal pressure creates higher net wind pressure on the building components compares to windward wall (W2) pressure fluctuations. In addition, this energy increases net loads on wall cladding and fixtures and accelerates cladding failures. The increased internal pressure reduced the net wind load on the windward wall and increased the net negative load on the roof, sides and leeward walls of the building.

The Helmholtz frequency can be calculated for a building with a dominant opening. For example, when LO3 opens with 0% porosity, $a_s = 340$m/s , $C_I = 0.8$, A = 0.0032m^2 , and V = 0.056m^3 then f_H = 61Hz. The calculated Helmholtz frequency was much higher than the measured frequency. The inertial coefficient, 0.8, was defined for small circular openings and may not be valid for square openings, since it depends on the effective length of the moving air. In these cases, C_I was calculated as equivalent to 2.56 for the actual Helmholtz frequency 34Hz. This calculation shows a contradiction in inertial coefficients, when a building contains a large opening. Vickery [12] stated that different flow conditions affect the internal pressure and therefore a constant value for inertial coefficient is not applicable for all openings.

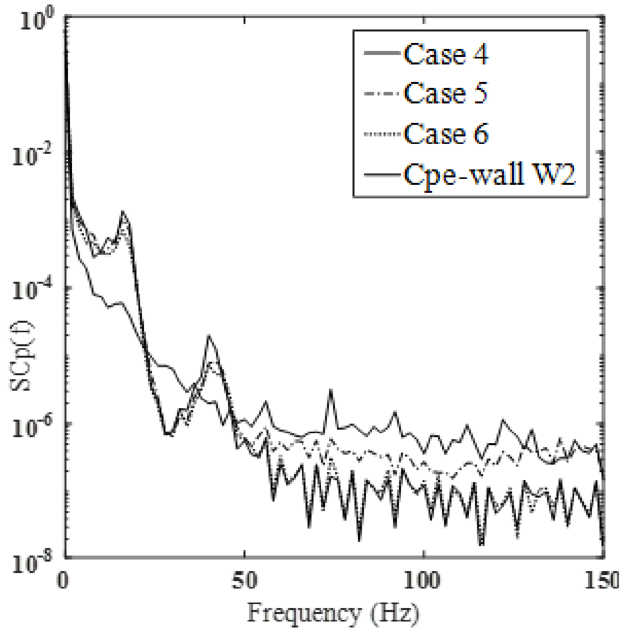

Figure 6. External and internal pressure Spectrum for building with dominant opening with and without porosity.

Conclusions

The results show the porosity effect on internal pressure fluctuations in a nominally sealed building with and without a dominant opening. The magnitude of the mean and fluctuating internal pressure coefficients was smaller in the nominally sealed building than the external pressures. The internal pressure variation over the rotation of a nominally sealed building is significantly low and the magnitude increases with increasing porosity. The internal pressures of the building with a dominant windward opening closely followed the external windward surface pressure. In addition, the magnitude of the internal pressure decreased with the decreasing porosity in a porous building with a dominant opening.

The measured internal pressure spectra shows an increase of energy close to the Helmholtz resonance frequency compared to the external pressure at the opening for building with a dominant opening. In addition, the energy close to the Helmholtz frequency decreases with increasing porosity. The effective range of the inertial coefficient needs to be investigated for large openings in industrial buildings. Further research is needed into areas such as Helmholtz resonance, the ratio of windward/leeward open areas, net pressures and area average pressures to determine the effect of porosity and external pressure on the internal pressure of the building envelope.

Acknowledgements

The authors gratefully acknowledge the support of the Australian Research Council Linkage Grant and Australian Steel Institute Ltd, JDH Consulting and Scott Woolcock Consulting Pty. Ltd as the industrial partners of this research. M.T. Humphreys, Ph.D. candidate; E.Farrell and J. P. Doolan, BE Thesis students in 2016 are also acknowledged

References

[1] Ginger, J. D.,Internal Pressures and Cladding Net Wind Loads on Full-Scale Low-Rise Building, Journal of Structural Engineering126(4),2000, 538-543.

[2] Ginger, J. D., et al., Variation of internal pressure with varying sizes of dominant openings and volumes, Journal of Structural Engineering 136(10), 2010, 1319-1326.

[3] Guha, T. K., et al, Internal pressure dynamics of a leaky building with a dominant opening, Journal of Wind Engineering and Industrial Aerodynamics 99(11), 2011, 1151-1161

[4] Harris, R. I.,The propagation of internal pressures in buildings, Journal of Wind Engineering and Industrial Aerodynamics 34(2),1990,169-184

[5] Holmes, J. D., Mean and fluctuating internal pressures induced by wind, Fifth international conference on wind engineering, Fort Collins, Colorado, U.S.A,1979.

[6] Kim, P. Y. and Ginger, J. D., Internal pressures in buildings with a dominant opening and background porosity, Wind and Structures 16(1),2013, 47-60

[7] Liu, H. (1975). Wind pressure inside buildings. Proceedings of the 2nd US National Conference on Wind Engineering Research, Colorado State University, June.

[8] Liu, H. and Saathoff, P. J., Building Internal Pressure: Sudden Change, Journal of the Engineering Mechanics Division 107(2),1981, 309-321.

[9] Oh, J.H., Wind-induced internal pressures in low-rise buildings, in Department of Civil and Environmental Engineering, The University of Western Ontario, Ontario, 2004.

[10] Sharma, R. N. and Richards, P. J., The influence of Helmholtz resonance on internal pressures in a low-rise building, Journal of Wind Engineering and Industrial Aerodynamics 91(6),2003, 807-828.

[11] Vickery, B. J. , Gust-Factors for Internal-Pressures in Low Rise Buildings, Journal of Wind Engineering and Industrial Aerodynamics 23(1-3),1986, 259-271.

[12] Vickery, B. J. and Bloxham,C.,Internal pressure dynamics with a dominant opening, Journal of Wind Engineering and Industrial Aerodynamics 41(1–3),1992, 193-204.

[13] Yu, S., W.-j. Lou, and B.-n. Sun, Wind-induced internal pressure response for structure with single windward opening and background leakage. Journal of Zhejiang University SCIENCE A, 2008. 9(3): p. 313-321.