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Internal Pressure Fluctuations in Industrial Buildings

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Abstract

Openings in a building envelope can generate large internal pressure in strong winds, and in combination with large external pressures can result in large net pressures across the envelope. Such a scenario, is a common cause of structural failure during windstorms. Internal pressures have been studied using analytical methods, wind tunnel and limited full-scale tests for over 40 years. This paper presents a review of past studies and describes a proposed study to determine internal pressure fluctuations in a range of industrial type buildings using full scale and model scale measurements, and analytical methods.[3]

Introduction

Industrial buildings are usually enclosed with large open internal spaces and a structural system (i.e. portal frame) to accommodate activities inside. Large doors are installed to provide access to the interior space. These buildings can be vulnerable to damage in windstorms from a combination of high external and internal (i.e net) pressures.

Internal pressure, generated by wind action, is dependent on the external pressure field, the position and size of all openings connecting the exterior to the interior and effective volume of the building. The internal pressure fluctuations in a nominally sealed building (with a porous envelope) are generally small in magnitude compared to external pressures. However, the failure of a door or window on the building can create a dominant opening and generate large internal pressures in strong winds that contribute a significant proportion to the total (i.e. net) design wind loads. The internal pressure fluctuations must be satisfactorily estimated when designing these types of buildings for each of these cases.

Liu (1975), Holmes (1979), Vickery (1986), Liu and Rhee (1986), Harris (1990) and Vickery and Bloxham (1992) studied internal pressures in buildings with a range of openings in the envelope from the 1970s to 90s, and presented methods for analysis. Since then, Ginger et al. (2008), Guha et al. (2013) and others have carried out further detailed studies. Holmes (1979) described correct scaling requirements, by applying dimensional analysis techniques. These non-dimensional parameters were used by Ginger et al. (2008, 2010) to derive relationships between fluctuating internal pressures and the external pressure at a dominant wall opening in terms of the size of volume, size of dominant opening and approach wind speed. Most of these studies are based on model scale wind tunnel and analytical methods, with limited data based from full-scale tests.

Standards such as AS/NZS 1170.2 (2011) typically provide internal pressure design data for buildings with porous walls and/or with large openings in the envelope. However, these standards do not provide data in terms of the magnitude of porosity or the sizes of openings in the envelope and building volumes. Hence, there is a need for analysing the effects of the size of volume and the envelope porosity on the internal pressures generated. This paper presents a review of past studies, and proposes a study to determine internal pressures in industrial type buildings using full scale and model scale measurements, and analytical methods.

Review

The unsteady discharge equation relating the flow Q, through an opening of area A, and the pressure drop Δp, across the opening is be given by Equation (1).

$$\Delta p = \frac{1}{2} C_L \, \rho U_0^2 + C_I \rho \frac{\partial U_0}{\partial t} \sqrt{A} \quad (1)$$

Here $U_0 = (Q/A)$ is the area averaged velocity through the opening and ρ is the density of air. The first term on the right hand side of Equation (1) represents the pressure drop due to viscous effects while the second is that required to accelerate the flow through the opening. The loss coefficient $C_{L,}$ is equivalent to $1/k^2$, where k is the discharge coefficient defined by Holmes (1979). The inertial coefficient C_I, defines the effective length l_e, of an air slug accelerated through the opening, $l_e = C_I\sqrt{A}$. Vickery (1986, 1994) indicated that C_L and C_I can only be defined for limited situations such as a sharp edged circular opening connecting two large volumes, where potential flow theory gives $C_L = [(\pi+2)/\pi]^2 = 2.68$ (i.e. k = 0.61) and $C_I = \sqrt{\pi/4} = 0.89$. The applicability of these values in flows such as that of unsteady wind flow through openings in a building is however uncertain.

External and internal pressures p_E and p_I, varying with time t, are defined in coefficient form as $C_p(t) = p(t)/\left(\frac{1}{2}\rho \bar{U}_h^2\right)$, where $\bar{U}_h$ is the mean wind speed at roof height, h. Pressures acting towards the surface are defined positive. The mean, standard deviation, maximum and minimum of the pressures are also defined in coefficient form. The characteristics (i.e. frequency distribution) of pressure fluctuations are studied by analysing the pressure spectral density, given by $S_p(f)$.

Vickery (1986, 1994) and Harris (1990) studied the internal pressure fluctuations in nominally sealed but leaky buildings. The studies applied the unsteady discharge equation to flow into and out of a building through "windward" and "leeward" surfaces, they showed that the inertial or acceleration term was negligible compared to the dampening term and can be ignored, and all the "windward" and "leeward" openings can be summed into two groups, A_W and A_L respectively, with spatially averaged pressures p_W and p_L and internal pressure p_I. Combined with the continuity equation gives Equation (2). Here C_{L_W} and C_{L_L} are the loss coefficients of the windward and leeward surface, $a_s = \left(\sqrt{\gamma p_0/\rho}\right)$ is the speed of sound, γ is the ratio of specific heats, p_0 is atmospheric pressure, and V_I is the effective internal volume.

$$\frac{1}{\sqrt{C_{L_W}}} A_W \sqrt{2\rho(p_W - p_I)}$$

[3] A similar paper is being submitted to ACMSM24.

$$-\frac{1}{\sqrt{C_{L_L}}}A_L\sqrt{2\rho(p_I-p_L)}=\frac{V_I}{a_s^2}\frac{dp_I}{dt} \quad (2)$$

For the same type of openings, (i.e. $C_{L_W}=C_{L_L}$) on porous surfaces, and taking $dp_I/dt=0$, rearranging Equation (2) gives the relationship between mean internal pressure coefficient $(\bar{C}_{pI})$, and mean external windward and leeward pressure coefficients $(\bar{C}_{pW})$ and $(\bar{C}_{pL})$ in Equation (3). AS/NZS 1170.2 (2011) and many other codes and standards use Equation (3) as the basis of deriving quasi-steady internal pressure coefficients for given A_W/A_L ratios in buildings.

$$\bar{C}_{pI}=\frac{\bar{C}_{pW}}{1+\left(\frac{A_L}{A_W}\right)^2}+\frac{\bar{C}_{pL}}{1+\left(\frac{A_W}{A_L}\right)^2} \quad (3)$$

Internal pressure Fluctuations

The characteristics of the internal pressure fluctuations will depend on the size and type of openings in the envelope. Nominally sealed buildings (with background leakage) are those that do not have large openings such as windows or doors. Vickery (1994) defined the porosity ($\mathcal{E}$) of these buildings would range from about 1×10^{-4} for "tight" envelopes to about 5×10^{-3} for envelopes with venting.

Building containing a dominant opening

In general terms, when the size of an opening is greater than about twice the total background leakage area (porosity), the opening can be considered as dominant. If the total background leakage area is less than about 10% of the dominant opening, the external pressure at the opening has a significant influence on the internal pressure, and the appropriate approach is to study the motion of air in a sealed building with a single dominant opening.

Holmes (1979) derived Equation (4) to describe the time dependent internal pressure in a building with a dominant opening of area *A*, in terms of internal pressure coefficient, C_{pI} and external pressure coefficient at the opening, C_{pE}, where $\dot{C}_{pI}$ and $\ddot{C}_{pI}$, denote the first and second derivative of C_{pI} with respect to time. Here, C_I and C_L are the coefficients used in equation (1) and the inertial coefficient and can be taken as $\sqrt{\pi/4}$.

$$\frac{C_IV_I}{a_s\sqrt{A}}\ddot{C}_{p_I}+\frac{C_L}{4}\left(\frac{V_I\bar{U}_h}{a_s^2A}\right)^2\dot{C}_{p_I}\left|\dot{C}_{p_I}\right|+C_{p_I}=C_{p_E} \quad (4)$$

The first term on the left hand side of Equation (4), describes the inertia in the flow, the second represents the damping, and the third is the stiffness. Furthermore, theoretical analysis also indicates that internal pressure resonance occurs close to the undamped Helmholtz frequency, $f_H=1/(2\pi)\sqrt{a_s^2A/(l_eV_I)}$. Equation (4) shows that the damping increases, as the ratio of opening area to internal volume decreases. However, this will decrease the Helmholtz frequency, and hence its overall effect on internal pressure fluctuations is not easily determined. Furthermore, an increase in the approach flow velocity will increase the damping.

Model scale studies by Sharma and Richards (2003) described the possible occurrence of self-sustaining vortex driven resonance inside a building when the opening in the wall is generally parallel to the approach flow. They also noted that these resonant effects could significantly increase the fluctuating component of internal pressure. In this case, this secondary resonant frequency was considered to be a function of the approach wind speed and size of the opening. In addition, to the external pressure field on the building and the position and size of all openings, the response of internal pressure to external pressure fluctuations also depends on the volume of the building and the flexibility of the envelope. Vickery (1986) showed that the effect of building flexibility on internal pressure fluctuations is accounted for in the analysis, by using an effective internal volume $V_I=\left(V_0(1+K_A/K_B)\right)$, where the actual "free" volume, V_0, is increased by a factor, K_A/K_B, where, K_A is the bulk modulus of air and K_B is the bulk modulus of the building.

Dimensional analysis and codification

Holmes (1979) showed that the internal pressure fluctuations can be represented as a function of the five non-dimensional parameters: $\Phi_1=A^{3/2}/V_I$, $\Phi_2=a_s/\bar{U}_h$, $\Phi_3=\rho\bar{U}_h\sqrt{A}/\mu$, $\Phi_4=\sigma_u/\bar{U}$ and $\Phi_5=\lambda_u/\sqrt{A}$, where, μ is the viscosity of air, $\bar{U}$ and $\sigma_u$are the mean velocity and turbulence intensity respectively of the flow at a given elevation, and λ_u is the integral length scale of turbulence. Equation (4) can then be written in the non-dimensional form, Equation (5), by introducing these non-dimensional parameters, and by defining a non-dimensional time, $t^*=t\bar{U}_h/\lambda_u$.

$$C_I\frac{1}{\Phi_1\Phi_2^2\Phi_5^2}\frac{d^2C_{PI}}{dt^{*2}}+\left(\frac{C_L}{4}\right)\left(\frac{1}{\Phi_1\Phi_2^2\Phi_5}\right)^2\frac{dC_{PI}}{dt^*}\left|\frac{dC_{PI}}{dt^*}\right|+C_{pI}=C_{pE} \quad (5)$$

Ginger et al. (2008, 2010) replaced the product $\Phi_1\Phi_2^2$ in Equation (5), with a single non-dimensional variable $S^*=\left(A^{3/2}/V_I\right)\times(a_s/\bar{U}_h)^2$, defined as the non-dimensional opening to volume parameter, and showed that the variation of internal pressure for given external pressure fluctuations is dependent on S^*, Φ_5, C_I and C_L, and that there is a unique solution for C_{pI}, for a given S^*, Φ_5, C_I and C_L. Ginger et al. (2008, 2010) showed that given the values C_I and C_L, the ratio of internal pressure fluctuations to external pressure fluctuations at the opening, can be presented by a family of curves, with variables of S^* and Φ_5. The Reynolds number (Φ_3) and the turbulence intensity (Φ_4) may influence C_L and the resulting internal pressure fluctuations. Equation (5) also shows similarity is maintained by keeping S^* constant, leading to the same volume distortion requirements recommended by Holmes (1979), for model tests. As shown by Ginger et al. (2008, 2010) fluctuating internal pressure depends on the Helmholtz frequency f_H, calculated for these combinations of opening sizes *A* and volumes V_I or the corresponding S^* and Φ_5. The design internal pressure can be presented in terms of S^* and Φ_5 and discharge coefficient C_L, in a form suitable for deriving expressions for use in design codes and standards as described by Holmes and Ginger (2009).

The loss coefficient C_L, is an important parameter in the damping term of Equation (4) and (5). However, the theoretical value for steady potential flow between infinite volumes does not apply to highly fluctuating turbulent flow in and out of a finite volume, which is characteristic of the flow through a wall opening, generating internal pressure in a building. The use of an unreliable value of C_L can result in the variations in the peak internal pressures in excess of 50%. Most C_L values used in previous studies have been obtained, by inference, from matching the spectra of internal pressures and rely on the theoretical models based on Equations (4) or (5), and assumed values for other parameters. The only direct measurements have been obtained in steady flow. Studies by Ginger et al. (2010) and Xu et al. (2016)

have shown that the loss coefficient increases with an increasing value of S^*, varying significantly.

Volume scaling requirements

Holmes (1979) applied dimensional analysis and suggested that the internal volume of the model building must be distorted in order to correctly simulate internal pressure fluctuations, at model scale. These same rules are derived using alternative non-dimensional parameters based on matching Helmholtz frequency (in buildings with a dominant opening) or the characteristic frequency (in nominally sealed buildings) with the frequencies in the approach turbulent flow.

The Helmholtz frequency is: $f_H \propto \sqrt{\frac{\sqrt{A}p_0}{\rho V_I}}$; $f_H^2 \propto \frac{\sqrt{A}p_0}{\rho V_I}$

For wind tunnel testing at normal atmospheric pressures the ratio of model to full-scale frequency is given by:

$$[f_H^2]_r = \frac{[L]_r[p_0]_r}{[\rho]_r[V_I]_r} = \frac{[L]_r}{[V_I]_r}$$

For tests carried out at normal pressure in air, $[p_0]_r$ = 1.0 and $[\rho]_r$ = 1.0, where the subscript r denote model to full scale ratio.

The approach flow frequency scaling requires that: $[f]_r = \frac{[U]_r}{[L]_r}$

Hence, for correct frequency scaling, $\frac{[L]_r}{[V_I]_r} = \frac{[U^2]_r}{[L^2]_r}$, giving

$$[V_I]_r = \frac{[L^3]_r}{[U^2]_r}$$

This same relationship can be derived from scaling the frequencies of the pressure fluctuations in a nominally sealed building. Thus, if the velocity ratio, $[U]_r$, is equal to 0.5, then the internal volume of the model should be scaled according to the length scale ratio $[V_I]_r = [L^3]_r \times 4.0$.

Nominally Sealed Building

Equation (2) was derived by Vickery (1986, 1994) and Harris (1990) for nominally sealed but leaky buildings, by applying principle of conservation of mass, and the discharge equation. Incorporating a ratio of leeward to windward openings $\Phi_6 = A_L/A_W$, introduced by Kim and Ginger (2013), and converting the pressures to coefficient form, Equation (6) is given.

$$\frac{A_W}{\sqrt{C_{L_W}}}\sqrt{(C_{PW} - C_{PI})} - \frac{\Phi_6 A_W}{\sqrt{C_{L_L}}}\sqrt{(C_{PI} - C_{PL})} = \frac{\bar{U}_h V_I}{2a_s^2}\dot{C}_{PI} \qquad (6)$$

Harris (1990) and Vickery (1986, 1994) linearised the discharge equation such that the internal pressure response to changes in external pressures can be described by a characteristic frequency f_c, given in Equation (7), where $\Delta\bar{C}_P = \bar{C}_{pW} - \bar{C}_{pL}$ is the net mean pressure difference between these *"windward"* and *"leeward"* surfaces. The interpretation of Equation (7), by Vickery (1994) was that external pressure fluctuations above the frequency f_c, are attenuated and not passed effectively into the building, conversely, frequencies below f_c are transmitted through the envelope.

$$f_c = \frac{1}{2\pi}\left(\frac{a_s^2(A_W^2 + A_L^2)^{3/2}}{V_I\bar{U}_h A_W A_L\left(C_L\Delta\bar{C}_p\right)^{1/2}}\right) \qquad (7)$$

Internal Pressure Measurements

It is proposed that external and internal pressures will be measured for a wind tunnel model and a full-scale industrial shed. A wind tunnel model will have a range of surface porosities, volumes and dominant opening locations and sizes that will be analysed for a series of configurations. The proposed full-scale study of an industrial shed, has a range of dominant opening sizes and locations and will also be analysed for a series of configurations. The characteristic pressure fluctuations will be determined by analysing pressure-time histories, statistical properties and spectral distributions, and used to evaluate analytical methods.

Wind tunnel model

The wind tunnel model is similar to that used by Ginger et al. (2010), with the addition of a range of porosities on all walls. Internal and external pressures will be measured for a nominally sealed building with leakage, with and without a dominant opening. The model will be tested in an atmospheric boundary layer wind tunnel at James Cook University (JCU) with an approach turbulence intensity equivalent of a terrain category of 2 from AS/NZS 1170.2 (2011). The model will be made of Perspex with the dimensions, 400mm wide × 200mm long × 100mm high with additional volume under the turn-table to distort the internal volume. A range of porosities and opening sizes will also be tested.

Full-scale testing

The full-scale industrial shed testing will consist of external and internal pressures, approach wind speeds and envelope flexion being recorded. The proposed shed in Figure 1 is 16m long × 8m wide × 4.3m high, and is located at the Cyclone Testing Station (CTS), at JCU, Townsville. External pressures will be measured on or next to potential openings, and internal pressures will be measured at a number of locations within the building. The measurements will be recorded for a nominally sealed case, and a range of typical dominant opening scenarios, (i.e roller doors, doors, windows). The porosity and building deformation will also be measured, quantifying the background leakage and building flexibility will enable the effective building volume to be calculated. Approach reference wind speeds will be measured using 3 anemometers located around the building on towers at a height of 3m.

Figure 1. Full-scale Cyclone Testing Station test building

Thirty two Honeywell TruStability® piezoresistive silicon differential pressure transducers will be used to record the external and internal pressures, with 6 distributed through the interior of the shed, the remaining measuring pressures on the external surface of the envelope. The pressure transducer range is ± 2.5kPa with an accuracy of 0.25% and total error band of 2%. The data acquisition system used will be a National Instruments™ CompactDAQ with LabVIEW system design software. Reference wind speeds will be recorded using marine rated R.M. Young propeller anemometers from the CTS SWIRLnet project, Henderson et al. (2013). Envelope flexion will be measured using linear variable displacement transducers (LVDT).

To define the buildings effective volume V_I, and porosity ε, a fan, and number of LVDT's and pressure transducers will be used to measure a flow rate in, pressure change and buildings volumetric change. The structural response will be used to calculate the bulk modulus of the building, K_B = (pressure change per volumetric strain), and the known flow rate through the fan and differential pressure will be used to calculate the porosity. The LVDT's will also be used during testing to record the buildings structural response to pressure fluctuations.

Static atmospheric pressure will be used as the reference pressure for the transducers. To ensure the reference pressure is not effected by the building pressure field, it will be obtained some distance away from the building in a box underground, the lid of the box will be smooth, flush with the ground and have a small hole on top. A tube will travel underground in a PVC pipe from the reference pressure box to the building. The reference pressure tube will be divided and travel to the reference side of all pressure transducers.

To account for drift, a zero calibration will be automated when necessary. The active side of each transducer will be connected via tubing to the nominally open port of a 3-way solenoid valve (SMC VT307 series). When un-energized (normal state), the active side of the transducer will measure pressures from the pressure tap, when energized, the solenoid will switch, and the active side of the transducer will measure the reference pressure. The reference pressure on the active side of the transducer, will be transferred though a separate tubing network back to the reference pressure box, to check for discrepancies in the reference pressures and to run calibrations in situ if needed.

Pressure taps on the external surface of the building will transfer pressures to the active side of the transducer inside the building, via a solenoid. An inherent problem will be water entering the pressure tap, blocking the pressure signal. To mitigate this problem, between the pressure tap and the solenoid, a tee piece connecting a 100mm tube capped at the end will extend down and act as a reservoir and collect trapped water.

Conclusion

In conclusion, the proposed study will provide much needed information into full-scale internal pressure fluctuations, induced by atmospheric wind flow, for a wide range of scenarios. The information gathered will be used to evaluate internal pressure fluctuations in typical industrial type buildings, and validation of analytical methods.

Acknowledgments

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References

Ginger J D, Holmes J D, Kim P Y (2010) Variation of internal pressure with varying sizes of dominant openings and volumes, *Journal of Structural Engineering, 136*(10), 1319–1326.

Ginger J D, Holmes J D, Kopp G A (2008) Effect of building volume and opening size on fluctuating internal pressures, *Wind and Structures, 11*(5), 361–376.

Guha T K, Sharma R N, Richards P J (2013) Internal Pressure in Real Flexible Porous Buildings with a Dominant Opening: Design Perspective, *Journal of Structural Engineering, 139*(2), 264–274 .

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

Henderson D, Mason M S, Ginger J (2013) *Wind speed measurements of land-falling tropical cyclones using SWIRLnet, a portable anemometer network*, Paper presented at the 16th Australasian Wind Engineering Society Workshop.

Holmes J D (1979) *Mean and fluctuating internal pressures induced by wind,* Paper presented at the Fifth international conference on wind engineering, Fort Collins, Collorado, U.S.A.

Holmes J D, & Ginger J D (2009) *Codification of internal pressures for building design,* Paper presented at the Seventh Asia-Pacific Symposium on Wind Engineering, Taipei, Taiwan.

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

Liu H (1975) *Wind pressure inside buildings,* Paper presented at the Proceedings of the 2nd US National Conference on Wind Engineering Research, Colorado State University, June.

Liu H, Rhee K H (1986) Helmholtz oscillation in building models, *Journal of Wind Engineering and Industrial Aerodynamics, 24*(2), 95–115.

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

Standards Australia, Standards New Zealand, (2011) AS/NZS 1170.2:2011 *Australian and New Zealand Standard Structural Design Part 2: Wind Actions*

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

Vickery B J (1994) Internal pressures and interactions with the building envelope, *Journal of Wind Engineering and Industrial Aerodynamics, 53*(1–2), 125–144.

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

Xu H, Yu S, Lou W (2016) Estimation Method of Loss Coefficient for Wind-Induced Internal Pressure Fluctuations, *Journal of Engineering Mechanics*, 04016041.