9th International Congress of Croatian Society of Mechanics
18-22 September 2018
Split, Croatia

Fluctuating and peak internal wind pressures in buildings – some recent results

John HOLMES*, John GINGER+

**JDH Consulting, Mentone, Victoria, Australia*
***e-mail:** john.holmes@jdhconsult.com*

+James Cook University, Townsville, Queensland, Australia.
***e-mail:** john.ginger@jcu.edu.au*

Abstract. *Recent research on fluctuating and peak internal pressures produced by large openings in buildings during windstorms is reviewed. The governing equation of the fluctuating internal pressures forced by the external pressures near an opening is presented. Experimental data have been fitted with a simple bilinear function enabling the ratio of fluctuating internal pressures to the corresponding external values to be calculated. The treatment of internal pressures in three major wind standards is also discussed*

1 Introduction

Numerous surveys of damage after strong wind events have shown internal pressures to be a major contributor of net wind loads on building surfaces, particularly on the roofs of low-rise buildings when a large opening occurs in a windward wall, produced by the failure of a door or window.

The complex dynamics of internal pressure fluctuations, including the effect of opening area and internal volume, and possible resonance effects, have been studied for nearly forty years. However, coefficients of internal pressure specified in design standards, are still generally based on studies from a limited range of opening sizes and volumes, and a simple quasi-steady theoretical analysis.

This paper reviews previous work on this topic, including the governing equations and values of the discharge (loss) coefficient for fluctuating and reversing flow through an opening. It is noted that proposed relationships for the ratio of internal to external pressure fluctuations differ considerably depending on whether inertial effects are included, and on the assumed value of loss coefficient for fluctuating flow through the opening.

The specifications of internal pressures in some major international codes and standards are discussed.

2 Review of previous work for large openings

Euteneuer [1] was apparently the first to study internal pressures within buildings with a large opening in a wall. He derived an expression for the response time of the pressure in a building subjected to a sudden change in external pressure such as that caused by a sudden failure of a window. He however neglected inertial effects on the flow through the opening. Holmes [2] considered the response to a step change, but incorporated inertial effects through application of the 'Helmholtz resonator' model (see following section). He considered the response of internal volume with a large opening to atmospheric turbulence, using both numerical and experimental model (wind-tunnel) simulations. Holmes [2] also described the scaling requirements for model studies of internal pressures, by applying dimensional analysis techniques.

Vickery and Bloxham [3] studied internal pressures in buildings with large openings at model scale. Ginger *et al.* [4] carried out full scale-studies on internal pressure, and showed that the results compared favorably with theoretical analysis. The non-dimensional parameters derived by Holmes [2] were used by Ginger *et al* [5, 6] to derive relationships between fluctuating internal pressures and the external pressure at a dominant wall opening, in terms of the sizes of volume and dominant opening. Further experimental studies at model scale were carried out by Ginger *et al.* [6], and indicated a range of values of the discharge coefficient, *k*, for fluctuating flow through an opening – a critical parameter for the theoretical prediction of internal pressures.

3 Helmholtz resonator model

The occurrence of Helmholtz-type resonance in buildings with a single windward opening in wind-tunnel tests, was identified by the first author nearly forty years ago [2]. The following gives a slightly different derivation of the governing equation based on this model.

3.1 Flow through an opening

The unsteady discharge equation relating the flow (Q) through an opening of area A and the pressure drop (Δp) across the opening is given by Eq. (1) [3].

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

$U_O = (Q/A)$ is the area-averaged velocity through the opening. The first term on the right hand side of Eq. (1) represents the pressure drop due to flow separation, 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 used by Holmes [2]. The effective length of the 'slug' of air accelerated through the opening is:

$$l_e = C_I \sqrt{A} \qquad (2)$$

Vickery and Bloxham [3] noted that C_L and C_I can be defined for limited situations, such as steady flow through a sharp edged circular opening connecting two large volumes, where potential flow theory gives:

$$C_L = [(\pi + 2)/\pi]^2 = 2.68 \text{ (i.e. } k = 0.61), \qquad (3)$$

$$C_I = \sqrt{\pi/4} = 0.89 \qquad (4)$$

3.2 Governing equation for internal pressures with a single opening

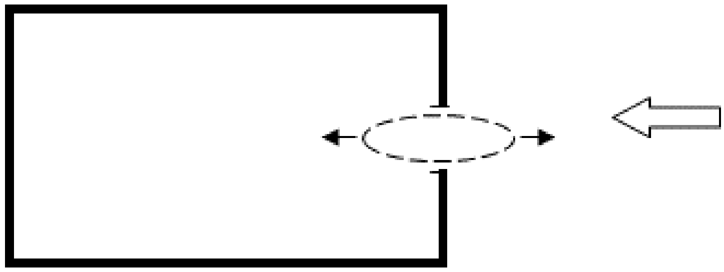

Figure 1: The Helmholtz resonator model of internal pressures – an air 'slug' near an opening responding to external pressure changes

Based on the simplified model shown in Figure 1, Holmes [2] derived Eq. (5) 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 the non-dimensional pressure coefficient is defined as $C_p = (p - p_0)/\left(\frac{1}{2}\rho\bar{U}_h^2\right)$, ρ is the density of air, p_o is the atmospheric (static) pressure, and $\bar{U}_h$ is the mean wind speed at roof height, *h* of the building.

$$\frac{\rho l_e V}{n p_0 A}\ddot{C}_{pi} + \left[\frac{\rho V \bar{U}_h}{2nkAp_0}\right]^2 \dot{C}_{pi}\left|\dot{C}_{pi}\right| + C_{pi} = C_{pe} \qquad (5)$$

l_e is the effective length of the "slug" of air moving in and out of the opening. *n* is the ratio of specific heats of air. The first term in Eq. (5), represents inertial effects, and the second term represents the damping provided by losses in the flow through the opening.

The undamped resonant frequency, known in acoustics as the Helmholtz frequency, is given by:

$$f_H = \frac{1}{2\pi}\sqrt{\frac{nAp_0}{\rho l_e V}} \qquad (6)$$

Eq. (5) shows that the damping, is reduced as the ratio of opening area to internal volume, *V*, is increased. However, the Helmholtz frequency is also increased, and hence the overall effect on internal pressure fluctuations is not easily determined.

Application of Equation (6) shows that buildings with large internal volume can have Helmholtz resonant frequencies that are under 1 Hertz, and in the range of potential excitation frequencies by atmospheric turbulence. Whether flow losses through the opening, background porosity and/or building flexibility are sufficient to generate enough damping so that amplification of internal pressure fluctuations in *real* full-scale buildings is never large, has not yet been completely answered.

3.3 Non-dimensional formulation and relevant non-dimensional parameters

In [2], Eq. (5) was also written in the non-dimensional form of Eq. (7) by introducing the non-dimensional parameters given following, and by defining a non-dimensional time, $t^* = \frac{t\overline{U}_h}{\lambda_U}$, where λ_U is a characteristic length in the approaching turbulent flow, here represented by the integral length scale of turbulence.

$$\left(\frac{\sqrt{\pi}}{2}\right)\frac{1}{\Phi_1\Phi_2^2\Phi_5^2}\frac{d^2C_{p_i}}{dt^{*2}} + \left(\frac{1}{4k^2}\right)\left[\frac{1}{\Phi_1\Phi_2^2\Phi_5}\right]^2 \frac{dC_{p_i}}{dt^*}\left|\frac{dC_{p_i}}{dt^*}\right| + C_{p_i} = C_{p_e} \qquad (7)$$

where, $\Phi_1 = \frac{A^{\frac{3}{2}}}{V}$, $\Phi_2 = \frac{a_s}{\overline{U}_h}$, $\Phi_5 = \frac{\lambda_U}{\sqrt{A}}$, where a_s is the speed of sound.

Other relevant non-dimensional parameters identified by Holmes [2] are:

$\Phi_3 = \frac{\rho\overline{U}_h\sqrt{A}}{\mu}$ (Reynolds Number), and $\Phi_4 = \frac{\sigma_U}{\overline{U}}$ (turbulence intensity).

The product $\Phi_1\Phi_2^2$ can be replaced by a single non-dimensional variable and defined as the non-dimensional opening size to volume parameter,

$$S^* = (a_s/\overline{U}_h)^2\,(A^{\frac{3}{2}}/V) \qquad (8)$$

It may be noted that S^* is related to the parameter S adopted by Yu *et al.* [7] by $S^*=S^{3/2}$. Eq. (7) shows that the variation of internal pressure for given external pressure fluctuations (i.e. the forcing function $C_{pe}(t)$) is dependent on S^*, Φ_5 and k, and that there is a unique solution for C_{pi} with S^*, for a given Φ_5 and k. Therefore, given the value of k, the ratio of internal pressure fluctuations to external pressure fluctuations at the opening, can be represented by a family of curves, with variables of S^* and Φ_5. However, as shown by Holmes and Ginger [8], the dependence on Φ_5 is weak, with S^* being the more important variable.

3.4 Wind-tunnel model scaling rules

In wind-tunnel model measurements of internal pressures that are intended to be representative of full-scale conditions, equality of S^* should be maintained. Since wind speeds in wind-tunnel testing are normally much lower than in full scale, Equation (8) shows that S^* will be higher in model scale by a factor equal to the square of the wind speed ratio, if exact geometric similarity is retained. However, ‘distortion’ of the internal volume, by providing additional volume below the model, can be used to restore S^* to the correct value (see Figure 2). It is clear from Eq. (8) that the volume should be increased by a factor equal to the square of the ratio of wind-tunnel to full-scale wind speed, (see also [2] and [9]).

Figure 2: Additional volume provided for correct scaling of wind-tunnel measurements of internal pressures (image by the Aurecon Group).

3.4 Discharge coefficient

The discharge coefficient, k, as defined in Section 3.1 (also equal to $1/\sqrt{C_L}$), is an important non-dimensional parameter in the damping terms in Eqs. (5) and (7). However, the theoretical value for steady potential flow between infinite volumes, given in Eq. (3), cannot be expected to apply to highly fluctuating and reversing turbulent flow into a finite volume, which is characteristic of the flow through a wall opening generating internal pressure in a building. The discharge coefficient, k, was found by Ginger *et al.* [6] not to have a constant value, but to reduce with increasing S^*, with, an average value of about 0.3. To illustrate this Figure 3 shows discharge coefficients estimated from the peak of the spectral densities of internal pressure fluctuations measured in wind-tunnel studies, plotted as a function of S^*.

3.5 Very long buildings

The Helmholtz resonator model is essentially based on the instantaneous transmission of pressure fluctuations into an internal volume. It has been suggested that this assumption may not apply to the case of a very long building, in which the time for transmission of pressure fluctuations, at the speed of sound, is finite. Although the speed of sound (about 340 m/s at normal temperatures and pressures) greatly exceeds the wind velocity, the separation of S^* into its two non-dimensional constituents, Φ_1 and Φ_2, may be appropriate in such a case.

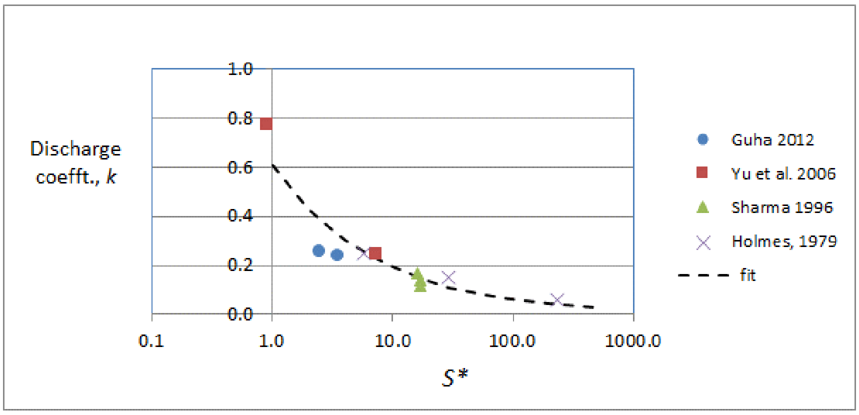

Figure 3: Variation of discharge coefficient, k, with the non-dimensional parameter, S^*

4 Design solutions for the large opening case

The critical design case for a building with a single opening occurs when the opening is on a windward wall, and the internal pressures are driven by external pressure fluctuations associated with upwind turbulence. The design equations described following focus on this case.

It should be noted that a simple quasi-steady analysis, in which both the inertial and damping terms in Eq. (5) or (9) are neglected, gives $C_{pi}(t) = C_{pe}(t)$, and the ratio of the standard deviations of internal and external pressure fluctuations, $(\sigma_{pi}/\sigma_{pe})$, equal to 1.0. This is the usual assumption in wind codes and standards.

Vickery and Bloxham [3] and Irwin and Dunn [10] have developed design equations which take account of the internal volume and opening area. However, Holmes and Ginger [8] showed that the former was conservative, and that the Irwin and Dunn formula was always un-conservative as inertial effects were neglected in its development.

Holmes and Ginger [8] found that experimental data for the ratio of the standard deviation of internal pressure to that of external pressures near the opening is enveloped well by:

$$\frac{\sigma_{pi}}{\sigma_{pe}} = 1.1 + \left(\frac{4}{\Phi_5}\right)\log_{10}(S^*) \qquad \text{for } 0.1 < S^* < 1.0 \qquad (9)$$

$$\frac{\sigma_{pi}}{\sigma_{pe}} = 1.1 \qquad \text{for } S^* \geq 1.0 \qquad (10)$$

The quasi-steady assumption, which implies that σ_{pi} is equal to σ_{pe}, and the bilinear function represented by Equations (9) and (10), with Φ_5 fixed at an average value of 20, are shown in Figure 3, together with experimental data from wind tunnels. The sources for the latter are listed in Reference [8].

Figure 4 shows that internal pressure fluctuations generally exceed the external pressure fluctuations when the non-dimensional parameter, S^*, exceeds about 1; this is the result of resonance at the Helmholtz frequency. However, for S^* is less than about 0.7, the result of large internal volumes combined with a relatively small opening area, internal pressure fluctuations will be damped**.**

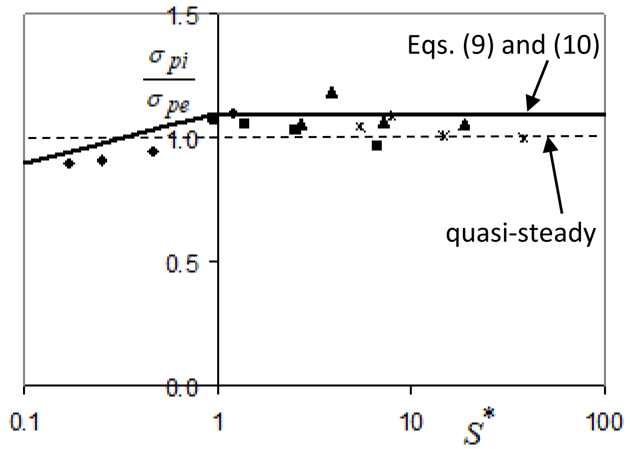

Figure 4: Ratio of standard deviation of internal and external pressures – comparison of the quasi-steady assumption, and Eqs. (9) and (10), with wind-tunnel measurements

The ratio of the expected *peak* internal pressure to *peak* external pressure can be determined from Equation (11).

$$\frac{\hat{p}_i}{\hat{p}_e} = \frac{1+2gI_u\left(\sigma_{pi}/\sigma_{pe}\right)}{1+2gI_u} \tag{11}$$

where g is a peak factor (3.5 to 4), and I_u is the turbulence intensity in the approach flow (Φ_4 in [2]).

A simplified version of Eqs. (9) and (10) has been proposed [11], and takes the form:

$$\frac{\sigma_{pi}}{\sigma_{pe}} = 1.1 + 0.053\sqrt{A}\,log_{10}\left(\frac{KA^{3/2}}{V}\right), \quad \text{for } \frac{A^{3/2}}{V} < \frac{1}{K} \tag{12}$$

$$\frac{\sigma_{pi}}{\sigma_{pe}} = 1.1, \text{ for } \frac{A^{3/2}}{V} \geq \frac{1}{K} \tag{13}$$

K is a parameter that depends on design wind speed and, hence the wind region and terrain at the building site,

5 Internal pressure specifications in three major codes and standards

5.1 American Standard ASCE-7 [12]

The loading standard of the United States ASCE/SEI 7-16 [12] has a simplified specification of internal pressure coefficients, depending on whether a building is 'enclosed', 'partially enclosed' or 'open'.

The 'partially enclosed' category is intended to cover the case with one or more large openings in a windward wall.

To satisfy that definition, the conditions that must be satisfied, are:

1. $A_0 > 1.1\, A_{0i}$, and
2. $A_0 > 0.37$ m^2 or $> 0.01\, A_g$, whichever is the smaller, and $A_{0i} / A_{gi} \leq 0.20$

A_0 is the total area of openings in a wall with positive pressure,
A_g is the gross area of the wall with positive pressure.
A_{0i} is the sum of all open areas in the building envelope, not including A_0.
A_{gi} is the sum of the gross areas in the building envelope, not including A_g.

With the above conditions, the internal pressure coefficients (GCp) are given as ±0.55.

ASCE-7 also provides a reduction factor for buildings with large internal volumes. This is based on the analysis by Irwin and Dunn [9].

5.2 Australian/New Zealand Standard AS/NZS 1170.2 [13]

AS/NZS 1170.2:2011 contains detailed treatment of internal pressure, with different rules depending on whether or not a building is in a high-wind region (i.e. subject to tropical cyclones). Two tables are provided for buildings with small or large openings (less or greater than 0.5% of a wall surface). Buildings in the high-wind areas of Australia are required to use the table for large openings due to the history of severe building damage resulting from high internal pressures.

The pressure coefficients are based on the quasi-steady model, and when there is more than one opening in a building, on a simple mass-flow balance. The pressure coefficients resulting from a single large opening are generally higher than those in ASCE 7.

5.3 Eurocode EN 1991-1-4 [14]

The Eurocode provides for internal pressures produced by openings in a 'dominant face', defined as one with area of openings at least twice the area of openings and leakage in the other faces of the building. When the area of openings in the dominant face is twice the area of openings in the other faces, the internal pressure coefficient is specified to be 75% of the external pressure coefficient near the opening. When the area of openings in the dominant face is a more than three times the area of openings in the other faces, 90% of the external pressure is assumed. These values are similar to those in AS/NZS 1170.2, and are generally more conservative than ASCE 7.

It is noted that none of the codes and standards considered allow for any amplification of the internal pressure, which Helmholtz resonance could produce, as shown in Figure 4.

6 Conclusions

Studies of fluctuating and peak internal pressures in buildings produced by a single dominant opening have been reviewed. The governing equation of the fluctuating internal pressures forced by the external pressures near the opening is presented. The discharge, or loss, coefficient for fluctuating and reversing flow through the opening is discussed.

Recent experimental data have been fitted with a simple bilinear function enabling the ratio of fluctuating internal pressures to the corresponding external values to be calculated. A second equation allows the ratios of the peak pressures to be estimated.

A review of the specification of internal pressures in major codes and standards reveal significant differences in the both the complexities of the treatment and in the magnitudes of the internal pressure coefficients in buildings with large openings. There are also differences in the requirements for a designer to consider large openings occurring accidentally, as a result of failures of doors or windows under wind forces, or by impacts from windborne debris.

References

[1] Euteneuer G.A. Einfluss des Windeinfalls auf Innendruck und Zugluft erscheinung in teilweise offenen Bauwerken, *Der Bauingenieur,* 46: 355-360, 1971.

[2] Holmes, J.D. Mean and fluctuating internal pressures induced by wind. *Proceedings, Fifth International Conference on Wind Engineering*, Fort Collins, USA, July 8-14, 1979, pp 435-450, Pergamon Press

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

[4] Ginger, J.D., Mehta, K.C., and Yeatts, B.B. Internal pressures in a low-rise full scale building, *Journal of Wind Engineering and Industrial Aerodynamics*, 72: 163-174, 1997.

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

[6] Ginger J.D., Holmes J.D. and Kim P. Variation of internal pressure with varying sizes of dominant openings and volumes, *Journal of Structural Engineering, ASCE,* 136: 1319-1326, 2010.

[7] Yu S., Lou W. and Sun B. Wind-induced internal pressure fluctuations in a structure with a single windward opening, *Journal of Zheijang University, Science B,* 7: 415-423, 2006.

[8] Holmes, J.D. and Ginger, J.D. Internal pressures – the dominant windward opening case, *Journal of Wind Engineering and Industrial Aerodynamics*, 100: 70-76, 2012.

[9] Holmes, J.D. Discussion of: 'Net pressures on the roof of a low-rise buildings with wall openings'. *Journal of Wind Engineering and Industrial Aerodynamics*, 97: 320-321, 2009.

[10] Irwin, P.A. and Dunn, G. *Review of internal pressures on low-rise buildings,* RWDI Report 93-270, Guelph, Ontario, Canada, 1993.

[11] Holmes, J.D., Kwok, K.C.S and Ginger, J.D. *Wind loading handbook for Australia and New Zealand*, Australasian Wind Engineering Society, AWES-HB-001-2012.

[12] American Society of Civil Engineers. *Minimum design loads for buildings and other structures*, ASCE Standard, ASCE/SEI 7-16, ASCE Reston, Virginia, USA, 2016.

[13] Standards Australia, *Structural design actions. Part 2: Wind actions*, Australian/New Zealand Standard, AS/NZS 1170.2:2011, with Amendments 1-4, 2012-2016, Standards Australia, Sydney, NSW, Australia, 2016.

[14] British Standards Institution, *Eurocode 1: Actions on structures. Part 1-4: General actions – wind actions*, BS EN 1991-1-4:2005, BSI, London, U.K., 2005.

Acknowledgement

The authors thank Dr. Neil Mackenzie of Aurecon Group for providing Figure 2.