



CODIFICATION OF INTERNAL PRESSURES FOR BUILDING DESIGN

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ABSTRACT

Internal pressures in buildings are dependent on the type, position and sizes of openings in the envelope, volume of the building and the approach wind speed. In the case of a building with a dominant opening, Helmholtz resonance could also have a significant influence on the internal pressure fluctuations. This paper reviews the governing equation for fluctuating internal pressure based on the Helmholtz resonator model and previous proposals for codification of peak internal pressures, and presents a new simpler form based on recent experimental data.

KEYWORDS: *BUILDING, CODES, INTERNAL PRESSURE, STANDARDS, WIND LOADS*

Introduction

Internal pressures, produced by wind action, are dependent on the external pressure field and the position and size of all openings connecting the exterior to the interior, and the effective volume of the building. The internal pressure in a nominally sealed building is generally small in magnitude compared to external pressures. However, the failure of a door or window in such a building will create a dominant opening and can generate large internal pressures in strong winds, and in combination with large external pressures acting in the same direction will result in large net pressures across the envelope causing failures.

Holmes (1979) and Vickery and Bloxham (1992) studied internal pressures in buildings with large openings. Ginger *et al.* (1997) carried out full scale studies on internal pressure, and showed that the results compared favorably with theoretical analysis. Holmes (1979) described correct scaling requirements for model studies, by applying dimensional analysis techniques. The non-dimensional parameters were used by Ginger *et al.* (2008) 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.* (2009), and indicated a range of values of discharge coefficient, k , for fluctuating flow through an opening – a critical parameter for the theoretical prediction of internal pressures.

Internal pressure data specified in design standards such as AS/NZS 1170.2 (Standards Australia, 2002) are based on studies from a limited range of opening sizes and volumes, and a simple quasi-steady theoretical analysis. In most cases, reduced internal pressures are specified for designing large buildings without due consideration given to the sizes of potential dominant openings. Hence there is a need for quantifying the effects on the internal pressures generated of the sizes of volume and openings in buildings. In this paper,

fluctuating and peak internal pressures are considered with variations in the types and sizes of wall openings, building volume and wind speed in buildings with wall openings. Previous semi-theoretical solutions are discussed, and a new simplified form appropriate for design codes and standards is presented.

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).

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

Here $U_O = (Q/A)$ 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 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 used by Holmes (1979). The effective length of the ‘slug’ of air accelerated through the opening, $l_e = C_I \sqrt{A}$. Vickery and Bloxham (1992) indicated 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 $C_L = [(\pi + 2)/\pi]^2 = 2.68$ (i.e. $k = 0.61$) and $C_I = \sqrt{\pi/4} = 0.89$.

Governing equation for internal pressures with a single opening

For a building with a single opening, the mean internal pressure is equal to the mean external pressure at the opening. In general terms, when the size of an opening is greater than about twice the total background leakage area, 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 Eq. (2) 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 $C_p = (p - p_0) / (\frac{1}{2} \rho \bar{U}_h^2)$, ρ is the density of air, p_0 is a reference static pressure, and \bar{U}_h is the mean wind speed at roof height, h of the building.

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

l_e is the effective length of the ‘slug’ of air moving in and out of the opening taken equal to $\sqrt{(\pi A/4)}$. n is the ratio of specific heats of air. The first term in Eq. (2), describes the inertia in the flow, and the second term represents the damping available. The undamped resonant frequency, known as the Helmholtz frequency, is given by.

$$f_H = \frac{1}{2\pi} \sqrt{\frac{n A p_0}{\rho l_e V}} \quad (3)$$

Eq. (2) 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. Furthermore, an increase in the approach flow velocity will increase the damping.

Eq. (2) can be written in the non-dimensional form of Eq. (4), by introducing the non-dimensional parameters given following, and by defining a non-dimensional time, $t^* = \frac{t\bar{U}_h}{\lambda_U}$.

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

where, $\Phi_1 = \frac{A^2}{V}$, $\Phi_2 = \frac{a_s}{\bar{U}_h}$, $\Phi_5 = \frac{\lambda_U}{\sqrt{A}}$. a_s is the speed of sound and λ_u is the integral length scale of turbulence. Other relevant non-dimensional parameters identified by Holmes (1979) are $\Phi_3 = \frac{\rho\bar{U}_h\sqrt{A}}{\mu}$ (Reynolds Number), and $\Phi_4 = \frac{\sigma_U}{\bar{U}}$ (turbulence intensity).

The product $\Phi_1\Phi_2^2$ in Eq. (4), can be replaced by a single non-dimensional variable and defined as the non-dimensional opening size to volume parameter, $S^* = (a_s/\bar{U}_h)^2 (A^{\frac{3}{2}}/V)$. Eq. (4) 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 .

The discharge coefficient, k , was found by Ginger *et al.* (2009) not to have a constant value, but to reduce with increasing S^* . However, an average value of about 0.3 was found to be more appropriate than the theoretical (potential flow) value for steady flow of 0.61.

Design equations

The critical design case for a building with a single opening usually occurs when in 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.

Vickery and Bloxham formula

Vickery and Bloxham (1992) derived a formula for the ratio of the standard deviations of internal and external pressure fluctuations based on a solution of Eq. (2) in the frequency domain, and made certain assumptions, including linearization of the damping term, and the theoretical value for steady flow of 0.6 for the discharge coefficient, k . They also assumed a dominant contribution from the resonant (Helmholtz) component, separated it from the 'background' low frequency contributions, and approximated it with a 'white noise' approximation, as used in the calculation of dynamic response of structures to turbulent wind.

For a standard deviation fluctuating external pressure coefficient of 0.35, and assuming the von Karman spectral density (as used in AS/NZS1170.2:2002 and several other standards) for the external pressure fluctuations, it can be shown that the Vickery and Bloxham expression reduces to:

$$\frac{\sigma_{pi}}{\sigma_{pe}} = \left\{ \left[1 - \frac{0.564}{(S^* \Phi_5^2)^{1/3}} \right] + 1.25 \left[\frac{S^*}{\Phi_5} \right]^{4/9} \right\}^{1/2} \quad (5)$$

An alternative form in which the discharge coefficient, k is kept as a variable is:

$$\frac{\sigma_{pi}}{\sigma_{pe}} = \left\{ \left[1 - \frac{0.564}{(S^* \Phi_5^2)^{1/3}} \right] + 2.41 \left[\frac{k^3 S^*}{\Phi_5} \right]^{4/9} \right\}^{1/2} \quad (6)$$

The Vickery-Bloxham formula gives reasonable predictions of measured fluctuating and peak internal pressures when a lower value of discharge coefficient than 0.6 is used (Ginger *et al.*, 2009). However, at high values of S^* , the internal pressures are overestimated due to an overestimation of the resonant component. Furthermore, Eq. (5) or (6) may be considered too complex for a code or standard.

ASCE- RWDI formula

An alternative expression was derived by RWDI (1993) and later adopted by the American Loading Standard ASCE 7-05 (American Society of Civil Engineers, 2006). To derive it, the inertial term (i.e. the first term in Eq. (2)) was neglected. The ratio of the standard deviation of internal pressure fluctuations to that of the external pressure fluctuations was then approximated by:

$$\frac{\sigma_{pi}}{\sigma_{pe}} = \frac{1}{\sqrt{(\tau/10)+1}} \quad (7)$$

where τ is equal to the response time of the internal pressure to a step change in external pressure.

Specifying fixed values for the speed of sound (340 m/s), discharge coefficient (0.15), mean wind speed (25 m/s), and integral length scale of turbulence (100 m) results in:

$$\frac{\tau}{10} = \frac{1}{2.5kS^* \Phi_5} \cong \frac{1}{7000} \frac{V}{A} \quad (8)$$

where V and A are the internal volume and area of opening in m^3 and m^2 , respectively.

For ASCE 7-05, Eq. (8) was adjusted to account for V and A being in ft^3 and ft^2 , and to a ratio of peak internal peak to peak external pressure, assuming that the latter is composed of 50% mean component which translates to a mean internal pressure unchanged, and 50% fluctuating component which is 'filtered' by application of Eqs. (7) and (8).

The main disadvantage of the RWDI-ASCE formula arises from the neglect of the inertial term in Eq. (2), and results in under-prediction of the fluctuating and peak internal

pressures, for all except very small values of S^* , i.e. very large volumes and/or small opening areas. In the latter cases the inertial term can legitimately be neglected in comparison to the damping term – i.e. the second term in Eq. (2).

Comparison with experimental data

In Figure 1, the Vickery and Bloxham and RWDI formulae are compared with the recent experimental data reported by Ginger *et al.* (2009). In both cases, the value of the discharge coefficient, k , has been taken as 0.3. The discontinuities in the curves correspond to changes in the parameter Φ_5 .

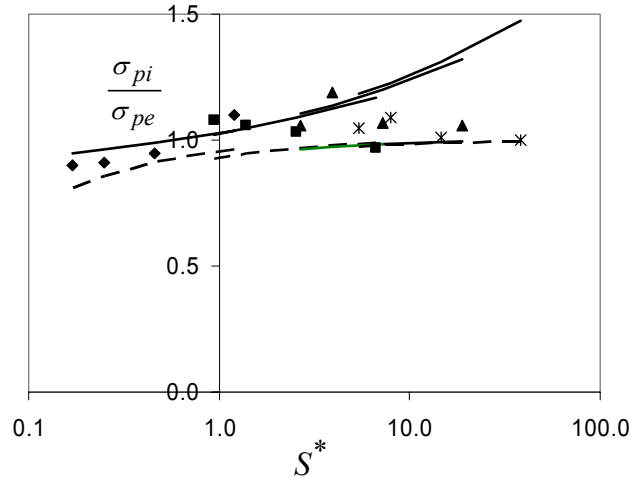


Figure 1: Comparison of Vickery and Bloxham formula (Eq. (6) – solid lines) and RWDI formula (Eqs. (7) & (8) - dashed lines) with experimental data from Ginger *et al.* (2009) (◆ $\Phi_5 = 15$; ■ $\Phi_5 = 8.5$; ▲ $\Phi_5 = 6$; × $\Phi_5 = 4.7$)

It is clear from Figure 1 that the Vickery and Bloxham formula, even with a reduced value of discharge coefficient, generally over-estimates the experimental values, particularly for values of S^* greater than 10. Use of the value of discharge coefficient of about 0.6 proposed by Vickery and Bloxham would result in even higher values and greater conservatism.

The RWDI formula, which always gives ratios less than 1.0, under-predicts the experimental data for all values of S^* . The ASCE version, which uses a lower value of k of 0.15, would give even lower values than those shown in Figure 1.

Thus the Vickery – Bloxham and RWDI expressions appear to approximate upper and lower limits to the ratio of fluctuating internal and external pressures, but neither is completely satisfactory for design purposes. Alternative formulae are explored in the following section.

Alternative formulae

Measured values of the standard deviation of the internal pressure to the standard deviation of external pressure at the opening, for a fixed value of discharge coefficient, can be represented, to a reasonable approximation, by the following empirical expression:

$$\frac{\sigma_{pi}}{\sigma_{pe}} = A + \left(\frac{B}{\Phi_5} \right) \log_{10}(S^* / C) \quad (8)$$

where A, B and C are adjustable ‘constants’ adjusted to match the experimental data. For example, C would be set to the value of S* for which the ratio of standard deviations is equal to the value A.

Recent experimental data obtained by Ginger *et al.* (2009) is fitted well by:

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

(i.e. A is taken as 1.1, B as 4 and C as 1.0 in Eq. (8))

$$\frac{\sigma_{pi}}{\sigma_{pe}} = 1.1 \quad \text{for } S^* \geq 1.0 \quad (9b)$$

Figure 2 compares the bilinear function of Eq. (9) with measured data reported by Ginger *et al.* (2009). The fit is satisfactory - slightly conservative over the range of S* in the data.

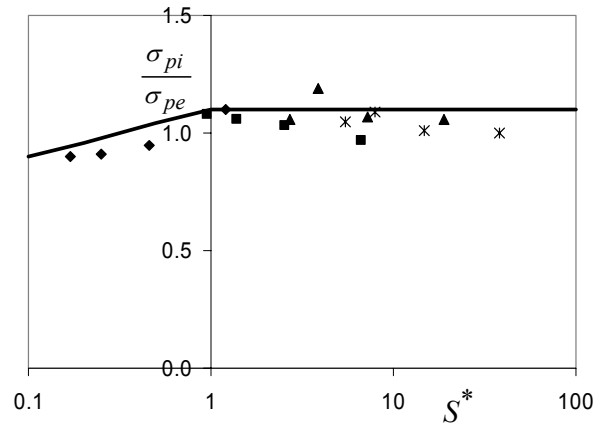


Figure 2: Ratio of standard deviation of internal and external pressures – comparison of Eq.(9) (solid line) with measured data by Ginger *et al.* (2009) (for values of Φ_5 for the experimental data see caption to Figure 1)

Then, for internal pressure fluctuations generated by atmospheric turbulence (such as at a dominant opening on a windward wall), the ratio of the peak internal pressure to peak external pressure can be determined from:

$$\frac{\hat{p}_i}{\hat{p}_e} = \frac{1 + 2gI_u(\sigma_{pi}/\sigma_{pe})}{1 + 2gI_u} \quad (10)$$

where g is a peak factor (3.5 to 4), and I_u is the turbulence intensity (Φ_4 in Holmes (1979)).

Recommended equations for design

For more simplicity for the code user, Eq. (9) could be written more explicitly in terms of internal volume and opening area, by selecting appropriate average values of the speed of sound, a_s , the mean wind speed \bar{U} , and the integral length scale of turbulence, λ_u . For example, taking these values as 340 m/s, 25 m/s and 100 m, respectively (as used by RWDI, 1993), Eq (9) becomes:

$$\frac{\sigma_{pi}}{\sigma_{pe}} = 1.1 + 0.04\sqrt{A} \log_{10} \left(\frac{185A^{3/2}}{V} \right) \quad \text{for } \frac{A^{3/2}}{V} < \frac{1}{185} \quad (11a)$$

$$\frac{\sigma_{pi}}{\sigma_{pe}} = 1.1 \quad \text{for } \frac{A^{3/2}}{V} \geq \frac{1}{185} \quad (11b)$$

Although some further research on the appropriate value(s) of k and more measurements of internal pressures, especially in full scale, would be useful, it is recommended, based on current information, that Eqs. (9) and (10) be the basis of a design rule for the amplification/attenuation of internal pressures for the single opening case. The use of these equations is illustrated by the following examples.

Design examples

As a numerical example, the following values (for a large industrial building with a dominant opening caused by a failure of a roller door) are assumed:

$$V = 50,000 \text{ m}^3; \quad A = 12 \text{ m}^2; \quad \bar{U}_h = 30 \text{ m/s}; \quad \lambda_u = 75 \text{ m}; \quad I_u = 0.193; \quad a_s = 340 \text{ m/s}; \quad g = 3.7.$$

Then $S^* = 0.107$ and $\Phi_5 = 21.7$. Eq. (9a) then gives $(\sigma_{pi}/\sigma_{pe}) = 0.92$, and Eq. (10) gives the ratio of peak pressures as 0.95. Thus, in this case, there is a reduction in the fluctuating and peak internal pressure with respect to the external pressure at the opening. Note that the quasi-steady assumption gives value of 1.0 for the right-hand side of Eq. (10) – i.e. the peak internal pressure is assumed to be the same as the peak external pressure. For the numerical example used above, this assumption would have overestimated the internal pressure.

A reduction of the internal volume to 2250 m³, with the other parameters remaining the same, results in a value of S^* of 2.37. Eq. (9b) then gives $(\sigma_{pi}/\sigma_{pe}) = 1.10$, and Eq. (10) gives the ratio of peak pressures as 1.06 – an increase compared with the quasi-steady assumption.

Conclusions

The fluctuating and peak internal pressures in buildings produced by a single dominant opening have been considered. 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. These equations could conveniently be adopted in wind loading codes and standards.

Numerical examples are given (industrial buildings with a large opening created by an open, or failed, roller door), indicating that the usual quasi-steady assumption adopted in current standards (e.g. AS/NZS1170.2:2002) can either over- or under-estimate the fluctuating and peak internal pressures, depending on the parameters involved – particularly the magnitude of the internal volume.

Design equations suggested previously are found to be either too conservative with respect to recent experimental data (Ginger *et al.*, 2009), due to over-prediction of the resonant response (Vickery and Bloxham, 1992), or unconservative due to the neglect of the inertial term in the governing equation (RWDI, 1993).

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