

Internal pressure in real flexible porous buildings: A design perspective

Guha T. K.^a, Sharma R. N.^a, Richards P. J.^a

^a*Department of Mechanical Engineering, The University of Auckland, New Zealand*

ABSTRACT: Analytical and associated numerical investigations of the fluctuating internal pressures induced through a dominant opening in real buildings with leaky and flexible envelopes are undertaken. The damping effect of these factors both separately and in combination are quantified using Root Mean Square (RMS) internal pressure coefficients and equivalent damping ratios for a range of envelope flexibilities and background porosities for the case of the Texas Tech University (TTU) test building. In particular, the equivalent damping ratio and the RMS internal pressure coefficient for the TTU building with a flexibility parameter of 2 and porosity ratio of 20% is found to be around 4 times higher and 27% lower than for a rigid non-porous TTU building. Simulated ratios of the RMS internal pressures and the peak spectral response of internal pressure for leaky and flexible buildings to that of rigid, nonporous envelopes are presented in non-dimensional format for a range of building volumes, opening areas and porosity ratios. Additionally non-dimensional charts of the RMS internal to external pressure ratios for real flexible and leaky envelopes are presented in a form suitable for design purposes.

KEYWORDS: Internal Pressures, Envelope Flexibility, Background Leakage.

1 INTRODUCTION

Buildings in real life, excepting special circumstances, have flexible and leaky envelopes. Flexibility and background leakage are known to act as dampers to internal pressure fluctuations induced through a dominant opening in the building. This has been demonstrated previously by wind tunnel [1,2] and full-scale studies [3] that dealt with these two factors separately. Theoretical models [2,4], in accordance with the experimental predictions, that take into account the effect of either of these factors in isolation have also been proposed.

Research, both theoretical and experimental, into the combined effect of leakage and flexibility, as occurs in most real buildings, has received comparatively little attention [5]. In fact, many studies of internal pressure in the past have tended to neglect their effects altogether. While theoretical studies have been limited by the lack of knowledge of the structural characteristics of the envelope (such as stiffness) and the distribution of the leakages arising out of normal construction tolerances, experimental research has suffered mainly from the difficulties in the similarity based modeling such as the lack of suitable materials to simultaneously satisfy the mass and stiffness scaling of such a realistic scenario. Even fewer, if at all any, has been the quantitative studies of the combined effect of these two factors in moderating the fluctuating and peak internal pressure response compared to that for a rigid, non-porous building; an issue this paper attempts to address from a design perspective.

While full-scale measurements of internal pressure in real flexible and leaky buildings for a range of internal volumes and opening sizes under strong wind conditions offer a promising alternative, they are expensive, time consuming and resource intensive. Additionally controlling

the different factors such as the extent of flexibility and leakage in the building envelope presents difficulties in full-scale. This paper thus uses analytical modeling and associated numerical simulation technique to quantify the damping effects of envelope porosity and flexibility on the fluctuating internal pressure response. The damping influence of flexibility and background leakage are exhibited separately and in combination for different envelope flexibilities and porosities for the case of the Texas Tech University (TTU) test building [6] with an opening in terms of the simulated Root Mean Square (RMS) internal pressure coefficients and equivalent damping ratios. Results of the RMS and peak spectral response of internal pressure for leaky and flexible buildings in comparison to that of rigid, nonporous envelopes (of the same nominal internal volume and opening size) are presented in non-dimensional format for realistic values of non-dimensional parameters S^* , Φ_5 [7] and porosity ratio (r) [2]. Design charts of the RMS internal to external pressure ratios are also presented for ranges of S^* , Φ_5 and r in a form suitable for design purposes.

2 GOVERNING EQUATIONS

Internal pressure induced in a building is described using an air slug/jet oscillating through the opening, being forced by the turbulent external pressures against an air-spring inside the building volume and damped by the irrecoverable loss of energy due to viscous and radiation effects. Further damping is imparted by flexibility and background leakage in the envelope of real buildings. Such buildings usually behave quasi-statically to fluctuations in the onset wind, meaning structural displacements are linearly proportionally to the applied load at all times. Hence they are considered as static structures. The leakages in the building envelope are found to behave quasi-steadily to onset turbulence, low pass filtering the external pressure fluctuations beyond a critical frequency [2] that is dependent on the mean internal-external pressure difference and the total leakage area in the surface.

Figure 1 provides a schematic representation of a real flexible and leaky building with an opening for which a general equation of the internal pressure response is provided.

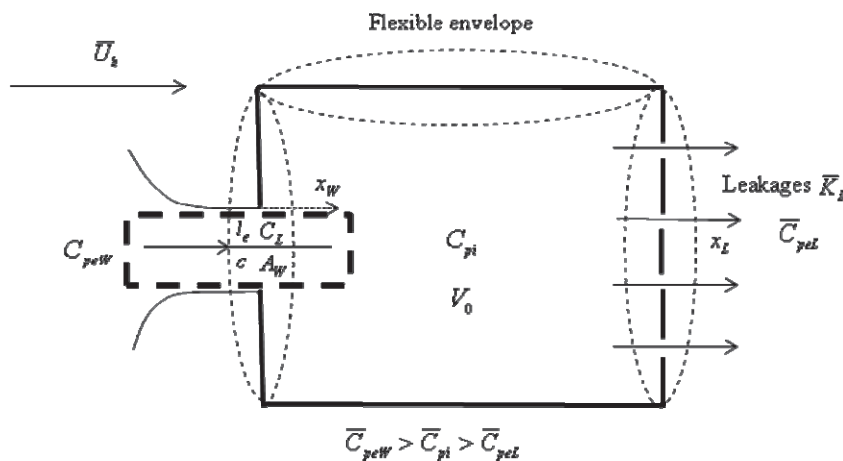


Figure 1. Schematic of a real flexible and leaky building with an opening

The unsteady equation of motion of the air-slug oscillating through the windward dominant opening under the fluctuating internal and external pressures (represented by the coefficients C_{pi} and C_{peW} respectively) and damped by energy losses through the opening, takes the form:

$$\rho_a l_e c A_W \ddot{x}_W + \frac{1}{2} \rho_a c A_W C_L |\dot{x}_W| \dot{x}_W = c A_W q (C_{peW} - C_{pi}) \quad (1)$$

where ρ_a , l_e , c and A_W are the density of air, effective length of the air slug, flow contraction coefficient and area of the opening respectively, C_L is the loss coefficient of flow through the opening, q is the ridge height dynamic pressure derived from the ridge height wind velocity $\bar{U}_h$ and $\dot{x}_W$, $\ddot{x}_W$ are the velocity and acceleration of the oscillating air-slug respectively.

The quasi-static response (i.e. displacement and its temporal derivatives) of the building envelope to fluctuating internal pressures in terms of the non-dimensional volume change (v) can be written as

$$v = \frac{q C_{pi}}{K_B} + 1; \dot{v} = \frac{q}{K_B} \dot{C}_{pi}; \ddot{v} = \frac{q}{K_B} \ddot{C}_{pi} \quad (2)$$

where K_B is the bulk modulus of the building envelope. The quantity v can be defined as V/V_0 where V is the instantaneous volume and V_0 is the nominal volume of the building.

The quasi-steady equation of motion through the leakages lumped together with predominant damping is given by

$$\frac{\rho_a}{2} A_L \bar{K}_L \dot{x}_L |\dot{x}_L| = q A_L (C_{pi} - \bar{C}_{peL}) \quad (3)$$

where $\bar{K}_L \approx 1/c^2$ and A_L and are the steady-state loss coefficient and area of the lumped leakage and $\dot{x}_L$ is the flow velocity through it for a mean leeward external pressure coefficient $\bar{C}_{peL}$.

Conservation of mass inside the building volume determined by the continuity equation with an isentropic pressure-volume relationship is given by

$$C_{pi} = \frac{\gamma P_a}{q V_0} [c A_W x_W - A_L x_L - V_0 (v - 1)] \quad (4)$$

where $\gamma = 1.4$ is the ratio of specific heat capacities for an isentropic process and P_a is the atmospheric pressure.

The governing equation of internal pressure in a quasi-static flexible and leaky building with an opening can be deduced from Equations 1-4 as

$$\begin{aligned} & \frac{\rho_a l_e V_e}{\gamma c A_W P_a} \ddot{C}_{pi} + C_L \frac{\rho_a q V_e^2}{2 (\gamma A_W P_a)^2} \left| \dot{C}_{pi} \right| + \frac{A_L \gamma P_a \bar{U}_h}{q V_e} \sqrt{\frac{C_{pi} - \bar{C}_{peL}}{\bar{K}_L}} \left(\dot{C}_{pi} + \frac{A_L \gamma P_a \bar{U}_h}{q V_e} \sqrt{\frac{C_{pi} - \bar{C}_{peL}}{\bar{K}_L}} \right) \\ & + \frac{\rho_a \bar{U}_h l_e}{2 q c \sqrt{\bar{K}_L} (C_{pi} - \bar{C}_{peL})} \left(\frac{A_L}{A_W} \right) \dot{C}_{pi} + C_{pi} = C_{pe} \end{aligned} \quad (5)$$

where V_e is the effective volume of the cavity and equal to V_0 (the nominal cavity volume) for a building with rigid envelope and equal to $V_0(1+b)$ for a flexible envelope, where $b = \gamma P_a / K_B$ is the ratio of the bulk modulus of air to that of the building envelope.

The Helmholtz frequency (f_{HH}) of internal pressure oscillations is given by

$$f_{HH} = \frac{\omega_{HH}}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{\gamma c A_w P_a}{\rho_a l_e V_e}} \quad (6)$$

where ω_{HH} is the corresponding angular frequency. It can be noted from Equation 6 that the effect of envelope flexibility is associated with a corresponding reduction in the Helmholtz frequency of the system (due to increase in the value of parameter b and hence effective volume V_e).

Putting $b = 0$ and $A_L = 0$ in Equation 5 leads to Sharma & Richards' [8] form of the well known dynamic equation of internal pressure for a rigid non-porous envelope originally proposed by Holmes [7].

A non-dimensional form of Equation 5 based on the parameters $S^* [= (A_w^{3/2}/V_e)(a_s/\bar{U}_h)^2]$, $\Phi_5 [= \lambda_U/\sqrt{A_w}]$, porosity ratio $r [= A_L/A_w]$ and a non-dimensional time $t^* [= t\bar{U}_h/\lambda_U]$ is given by

$$\begin{aligned} & \frac{C_I}{cS^*\phi_5^2} \frac{d^2 C_{pi}}{dt_*^2} + \frac{C_L}{4(S^*\phi_5)^2} \left| \frac{dC_{pi}}{dt_*} + 2\left(\frac{A_L}{A_w}\right) S^* \phi_5 \sqrt{\frac{C_{pi} - \bar{C}_{peL}}{\bar{K}_L}} \left(\frac{dC_{pi}}{dt_*} + 2\left(\frac{A_L}{A_w}\right) S^* \phi_5 \sqrt{\frac{C_{pi} - \bar{C}_{peL}}{\bar{K}_L}} \right) \right. \\ & \left. + \left(\frac{A_L}{A_w}\right) \frac{C_I}{\phi_5 c \sqrt{\bar{K}_L} (C_{pi} - \bar{C}_{peL})} \frac{dC_{pi}}{dt_*} + C_{pi} = C_{pe} \right. \end{aligned} \quad (7)$$

where $C_I = \sqrt{\pi/4}$ is the inertia coefficient of flow through the opening, a_s is the speed of sound and λ_U is the longitudinal integral length scale of turbulence at the building ridge height. It should be noted that S^* , as defined here, intrinsically incorporates the effect of envelope flexibility through usage of an effective volume (V_e) instead of the nominal building volume (V_0). For given values of C_I , c , C_L and $\bar{K}_L$, Equation 7 can be solved to yield the response of internal pressure as a function of S^* , Φ_5 and r .

3 QUANTIFICATION OF THE EQUIVALENT DAMPING RATIO (ζ_{eq})

It is a common practice to quantify all the damping effects of internal pressure fluctuations using the loss coefficient C_L . Attempts have been made in the past to match the predicted resonant response to the measured value by altering the value of C_L until a match is obtained. A review of such investigations and the values of C_L thus obtained are discussed by Holmes and Ginger [9]. A wide scatter of values ranging from 1.2 to 100 is observed in these studies. This brings forth the question as to whether C_L is being overloaded with the damping effects of other factors when it is solely meant to quantify the energy losses at the opening. While some of the values reported in literature, such as $C_L=1.2$, have been supported by CFD studies [8] of internal pressure involving rigid non-porous buildings with effects of other dampers eliminated, the particularly high values such as 44 and 100 used for spectral matching in some studies [3,10] seems unrealistic. The possibility of damping due to envelope compliance and leakage in the model and/or full-scale buildings seems to have been intrinsically included in C_L leading to such unrealistically high values.

It is therefore physically more realistic to quantify the effect of the different dampers operating separately or in combination using as equivalent damping ratio (ζ_{eq}). This can be done by re-

writing the governing equation of internal pressure (Equation 5) in the standard single degree-of-freedom dynamic system

$$\frac{1}{\omega_{HH}^2} \ddot{C}_{pi} + \frac{c_j}{k} \dot{C}_{pi} + C_{pi} = C_{pe} \quad (8)$$

where c_j is the damping coefficient and k is the stiffness of the air mass-spring system. The equivalent damping ratio (ζ_{eq}) can then be defined by comparing Equations 5 and 8, giving

$$\zeta_{eq} = \frac{c_j}{k} \frac{\omega_{HH}}{2} = \frac{1}{2} \sqrt{\frac{\gamma C_A W P_a}{\rho_a l_e V_e}} \left[C_L \frac{\rho_a q V_e^2}{2(\gamma A_W P_a)^2} \left| \dot{C}_{pi} \right| + \frac{A_L \gamma P_a \bar{U}_h}{q V_e} \sqrt{\frac{C_{pi} - \bar{C}_{peL}}{\bar{K}_L}} \left\{ 1 + \frac{A_L \gamma P_a \bar{U}_h}{q V_e \dot{C}_{pi}} \sqrt{\frac{C_{pi} - \bar{C}_{peL}}{\bar{K}_L}} \right\} + \frac{\rho_a \bar{U}_h l_e}{2 q c \sqrt{\bar{K}_L} (C_{pi} - \bar{C}_{peL})} \left(\frac{A_L}{A_W} \right) \right] \quad (9)$$

For non-leaky envelopes ($A_L=0$), the equivalent damping ratio (ζ_{eq}) simplifies to

$$\zeta_{eq} = \frac{c_j}{k} \frac{\omega_{HH}}{2} = C_L \frac{\rho_a q V_e^2}{2(\gamma A_W P_a)^2} \frac{1}{2} \sqrt{\frac{\gamma C_A W P_a}{\rho_a l_e V_e}} \left| \dot{C}_{pi} \right| \quad (10)$$

The damping effects of envelope flexibility and background leakage can then be quantified individually or in combination using ζ_{eq} by a spectral match of the solutions of Equation 5 and 8 by switching on and off the effect of the relevant dampers (i.e. flexibility and leakage). Such damping ratios (ζ_{eq}) with intrinsically loaded effects of flexibility and/or leakage provide for a better parameter than loss coefficient (C_L) to quantify the effect of the different dampers.

4 ANALYTICAL EXAMPLE USING THE TTU TEST BUILDING

An analytical example for the effect of envelope flexibility and background leakage on the fluctuating internal pressure response is provided for a building similar in dimensions to the TTU test building with a windward dominant opening (area ratio of 5%) under the following basic conditions:

$$V_o = 497 \text{ m/s}^3; A_W = 1.94 \text{ m}^2; l_e = \sqrt{\pi A_W / 4}; c = 0.6; C_L = 1.2; \bar{K}_L = 2.78; \bar{U}_h = 30 \text{ m/s}; \\ \bar{C}_{peW} = \bar{C}_{pi} = 0.7; \bar{C}_{peL} = -0.3; I_u = 0.20; \rho_a = 1.185 \text{ kg/m}^3; \gamma = 1.4; P_a = 101.3 \text{ KPa}$$

Numerical simulations of Equations 5 and 8 using a fourth-order Runge-Kutta method with adaptive time-stepping capability were used for quantitative analysis and comparison. The external pressure coefficient time history used to force the internal pressure response was obtained by applying an aerodynamic admittance and random phase to the Fourier coefficients derived from the Kaimal spectrum using an Inverse Fast Fourier Transform (IFFT) technique.

4.1 Effect of envelope flexibility

The effect of flexibility on internal pressure for the non-porous TTU test building with a windward dominant opening is studied by varying the parameter b from 0 to 2 in steps of 0.5, i.e. from a rigid to a relatively flexible envelope system. Figure 2a presents the simulated internal pressure coefficient spectra for $b = 0, 1$ and 2.

Table 1. Effect of flexibility on damping w.r.t. spectral response at resonance

b	0	0.5	1.0	1.5	2.0
c_j/k	0.005	0.008	0.013	0.018	0.022
ζ_{eq}	0.038	0.049	0.069	0.086	0.096

The overall damping of the system at resonance is found to increase with flexibility in the building envelope. The associated reduction in the Helmholtz frequency from 2.4Hz down to 1.3Hz is also evident in the figure for an increase in b from 0 to 2. The increased damping effect of envelope flexibility is further confirmed in Table 1 which shows an increase in the quantities c_j/k (damping term in Equation 8) and ζ_{eq} with b . A spectral match between the solutions of Equations 5 and 8 was used to estimate these quantities.

An increase in the equivalent damping ratio (ζ_{eq}) by a factor of 2.5 is observed for an increase in b from 0 to 2. The decrease in the Helmholtz frequency with flexibility is however neglected in this analysis in order to study the effect of flexibility induced damping in isolation.

The effect of the decrease in the Helmholtz frequency with flexibility and its effect on the internal pressure resonant response in terms of the overall damping using the concept of equivalent damping ratio is shown in Table 2. In this case, an iterative process was used to estimate the quantities c_j/k and ζ_{eq} until a match between the RMS internal pressures and gain of internal to external pressure at resonance as predicted by Equations 5 and 8 were obtained.

The increased damping effect of envelope flexibility notwithstanding the shift (decrease) in the Helmholtz frequency towards the more energy containing region of the external pressure forcing spectrum is evident from the values of c_j/k and ζ_{eq} in Table 2. The reduction in Helmholtz frequency with envelope flexibility is found to partially compensate for the increased internal pressure damping in a flexible envelope, e.g. 6% when reduction in Helmholtz frequency due to flexibility is accounted for in Table 2 against 9.6% when not considered in Table 1 for $b=2$.

Table 2. Effect of flexibility on damping w.r.t. equivalence of the RMS internal pressure

b	0	0.5	1.0	1.5	2.0
c_j/k	0.005	0.006	0.007	0.008	0.008
ζ_{eq}	0.038	0.047	0.051	0.057	0.060

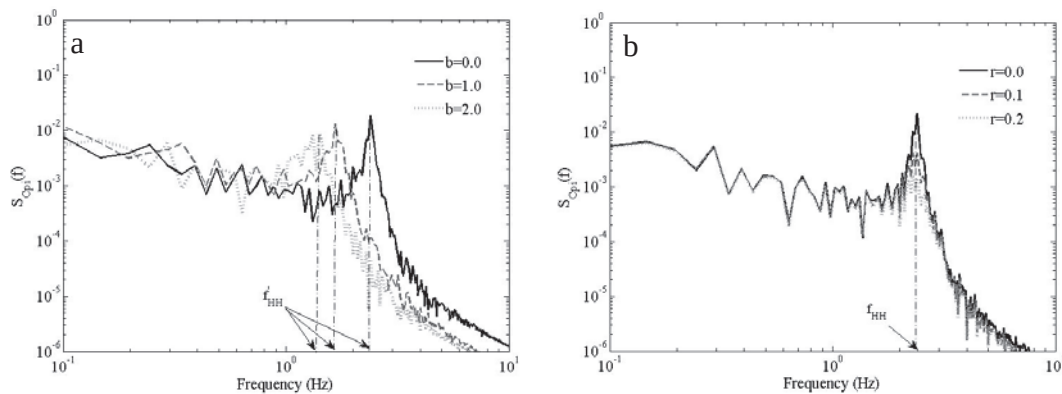


Figure 2. Simulated internal pressure coefficient spectra for the TTU building with (a) varying envelope flexibility and (b) varying envelope porosity

4.2 Effect of background porosity

The effect of background porosity on the internal pressure response for the rigid TTU test building with a windward dominant opening is studied by varying the porosity ratio r ($=A_L/A_W$) from 0 to 0.2 in steps of 0.05, i.e. from a non-porous to a relatively porous envelope system. Figure 2b presents the simulated internal pressure coefficient spectra for $r = 0, 0.1$ and 0.2 .

Increase in envelope porosity is expectedly found to further limit the amplitude of internal pressure fluctuations at resonance. Thus the peak spectral response is found to have decreased by a factor of 15 with increase in porosity from 0 to 20%. The corresponding equivalent damping ratio is found to increase from around 3.8% for a non-porous building to around 11% for a porosity ratio of 20%. This will decrease the RMS and peak internal pressures to a great extent compared to the non-porous model predictions.

4.3 Combined effect of envelope flexibility and background porosity

The combined influence of envelope flexibility and background porosity, as occurs in most real building envelopes, is further investigated for the TTU setup using the same range of flexibility parameter b and porosity ratio r as discussed in the preceding sections. Figures 3a, b and c presents a measure of the quantities c_j/k , ζ_{eq} and RMS internal pressure coefficient ($\tilde{C}_{pi}$) respectively as a function of the parameters b and r , visualized as 3-D surface plots.

The extent of the damping imparted by the two factors is evident in the plots. Particularly, the equivalent damping ratio for the TTU building with damping parameters $b=2$ and $r=20\%$ is found to be around 4 times higher compared to a rigid non-porous TTU building envelope. The corresponding RMS internal pressure coefficient (≈ 0.19) is found to decrease by around 27% for the flexible ($b=2$) and porous ($r=20\%$) envelope compared to the rigid non-porous case (≈ 0.26).

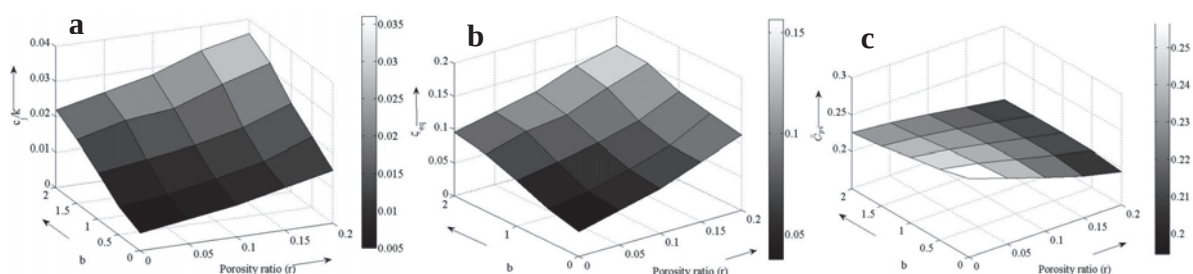


Figure 3. Simulated (a) c_j/k (b) Equivalent damping ratio (ζ_{eq}) and (c) RMS internal pressure coefficient for the TTU building as a function of envelope flexibility parameter, b , and background porosity ratio, r .

5 DESIGN APPROACH FOR INTERNAL PRESSURES IN REAL BUILDINGS

Recent internal pressure research [9,10] has been directed towards putting the dominant opening case in a non-dimensional format for useful design solutions. These studies have however looked into rigid non-porous envelope systems. This paper attempts to extend the work by incorporating the effects of envelope flexibility and background porosity into the ambit of the internal pressure design process. This is accomplished by numerically simulating the non-dimensional design Equation 7 for a range of realistic design parameters S^* , Φ_5 and r . Results are presented in the form

of non-dimensional design charts. It is worth noting that an experimental validation of the predictions of Equation 7 have been provided in Guha et al. [2] for selected cases of S^* , Φ_5 and r .

Typical values of the parameters S^* and Φ_5 for usual buildings encountered during normal design practices under wind speed conditions of 30-50m/s range from 0.1 to 15 and 10 to 100 respectively [11]. While values of S^* for small rigid structures of the size of garden-sheds at design wind speeds are usually around 10-15, a value of b ($= \gamma P_a / K_B$) around 2-5 for statically flexible large-span low-rise structures such as portal framed industrial buildings would render values of S^* to be less than 5. Hence S^* values of up to 5 are used in the current analysis. Values of Φ_5 are based on typical longitudinal integral length scales of 25-100m at the building ridge height of 5-7m in open and suburban terrains [11]. Porosities of buildings in the temperate climates of Australia/New Zealand are usually less than a conservative estimate of $r=20\%$ used in the current analysis. Figures 4a-d present the ratio of the simulated RMS internal pressure coefficients of leaky and flexible building to rigid non-porous envelopes as a function of the porosity ratio (r) for Φ_5 values 10, 20, 50 and 100 respectively.

The moderating effect of the background porosity on the internal pressure response is evident in all cases. The effect is more pronounced for higher porosity ratios (r) and larger Φ_5 (corresponding to smaller opening sizes). This is due to the reduced resonant response of internal pressure in smaller opening area-internal volume systems in which further damping effect of background porosity becomes significant. Reduction in the RMS internal pressure response for such cavity-opening systems with large S^* (i.e. small effective volume) is found to occur by as much as 50-70% compared to the non-porous building envelope at porosities beyond 10%.

For a given dominant opening size i.e. Φ_5 and porosity ratio (r), the RMS internal pressure ratios are found to decrease with decrease in effective building volume (i.e. large S^*). This is due to the moderating effect of background porosity and the associated reduction in the fluctuating internal pressure response becoming more pronounced for smaller building volumes.

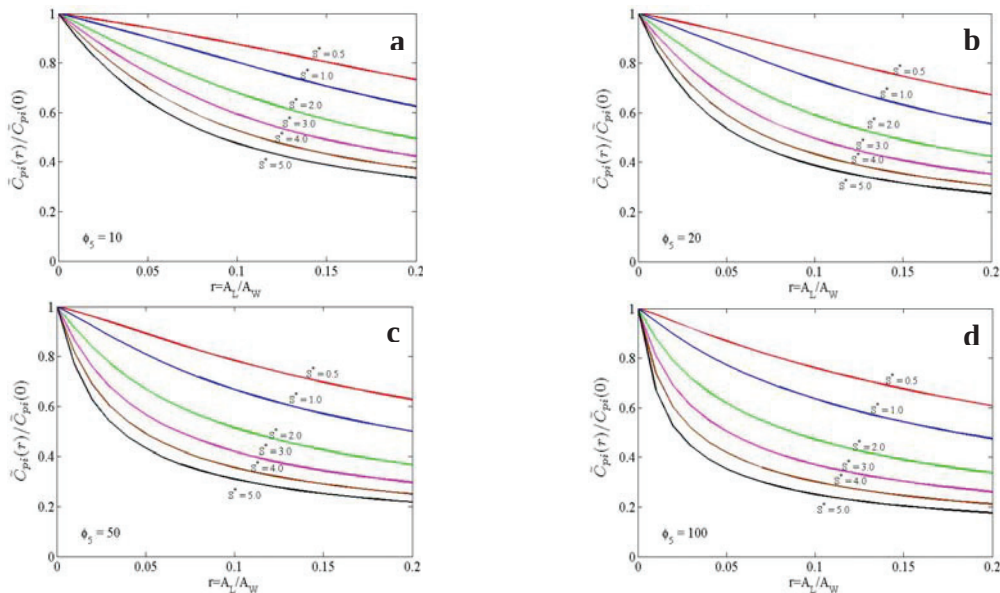


Figure 4. Simulated RMS internal pressure ratios for flexible and leaky envelopes to that for rigid non-porous buildings as a function of the porosity ratio for Φ_5 = (a) 10 (b) 20 (c) 50 (d) 100

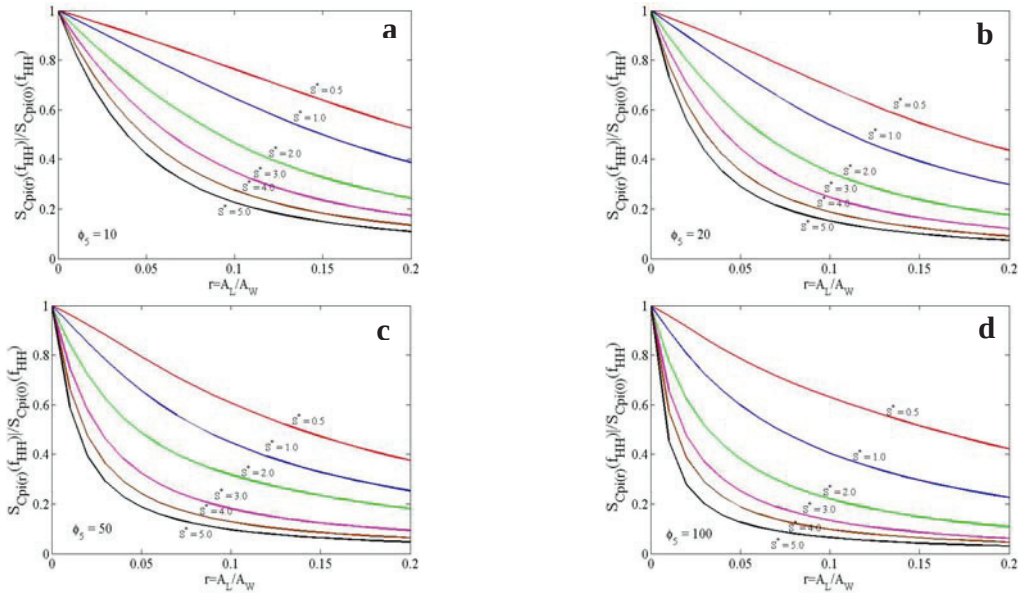


Figure 5. Simulated spectral ratios of internal pressure for flexible and leaky envelopes to that for rigid non-porous buildings for different building porosity ratios for Φ_5 = (a) 10 (b) 20 (c) 50 (d) 100

Figure 5a-d reinforces the fore-going discussion by showing the ratio of the peak spectral response (at resonance) of the fluctuating internal pressure for different S^* and r for Φ_5 values of 10, 20, 50 and 100 respectively. Similar observations as in Figure 4 can be made.

Efforts into developing a suitable design solution of internal pressure by incorporating the damping effects of envelope flexibility and background leakage are made in Figure 6a-d by presenting the RMS internal to external pressure coefficient ratios as a function of S^* and r for Φ_5 values of 10, 20, 50 and 100 respectively.

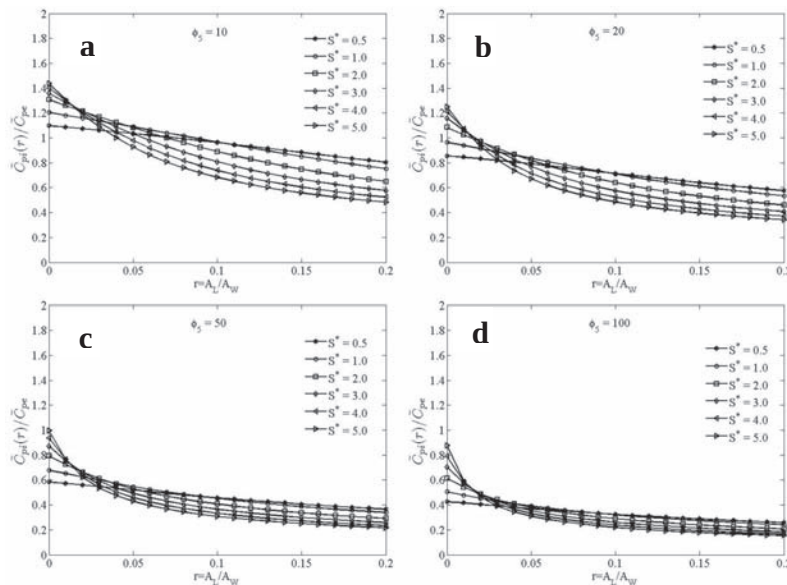


Figure 6. Simulated RMS internal to external pressure coefficient ratios for a range of building volumes and opening areas for different building porosity ratios for Φ_5 = (a) 10 (b) 20 (c) 50 (d) 100

The moderating effects of envelope flexibility (small S^*) and background porosity (larger r) is clearly evident in all the plots. For a given opening size (Φ_5), the RMS internal to external pressure coefficient ratio is found to be higher for smaller volumes (larger S^*) up to a porosity ratio of around 5%, beyond which the RMS ratios are higher for larger volumes. This, as explained before, is due to the damping effect of background porosity gaining more prominence than the resonant response of internal pressure in smaller building volumes compared to the larger ones.

6 CONCLUSIONS

An analytical and numerical study of the fluctuating internal pressures induced through a dominant opening in real buildings with leaky and flexible envelopes is carried out. The increase in magnitude of the equivalent damping ratio with increase in envelope flexibility and background leakage is exhibited for the case of TTU test building using different values of flexibility and leakage parameter. In particular, the equivalent damping ratio for the TTU building with a flexibility parameter of 2 and porosity ratio of 20% is found to be around 4 times higher than for a rigid non-porous TTU building. The corresponding RMS internal pressure coefficient for such a building configuration is found to be about 27% less than the rigid non-porous building case.

Simulated ratios of the Root Mean Square (RMS) internal pressures and the peak spectral response of internal pressure for leaky and flexible buildings to that of rigid, nonporous envelopes presented in non-dimensional format also exhibit the damping influence of envelope flexibility and leakage. Non-dimensional charts of the RMS internal to external pressure ratios are presented for a realistic range of building volumes, opening areas and background porosities by incorporating the damping effect of flexibility and leakage in a form suitable for design purposes.

7 REFERENCES

- 1 Pearce, W., Sykes, D. M., 1999. Wind tunnel measurements of cavity pressure dynamics in a low-rise flexible roofed building. *Journal of Wind Engineering and Industrial Aerodynamics* 82 (1999) 27-48.
- 2 Guha, T. K., Sharma, R. N., Richards, P. J., Internal pressure dynamics of a leaky building with a dominant opening. *Journal of Wind Engineering and Industrial Aerodynamics* 99 (2011) 1151-1161.
- 3 Ginger, J. D., Mehta, K. C., Yeatts, B. B., Internal pressures in a low-rise full scale building. *Journal of Wind Engineering and Industrial Aerodynamics* 72 (1997) 163- 174.
- 4 Vickery, B. J., Internal pressures and interactions with the building envelope. *Journal of Wind Engineering and Industrial Aerodynamics* 53 (1994) 125-144.
- 5 Guha, T. K., Sharma, R. N., Richards, P. J., On the internal pressure dynamics of a leaky and flexible low rise building with a dominant opening, in: *Proc. 13th Int. Conf. on Wind Eng.*, Amsterdam, Netherlands, July 2011.
- 6 Yeatts, B. B., Mehta, K. C., Field experiments for building aerodynamics. *Journal of Wind Engineering and Industrial Aerodynamics* 50 (1993) 213-224.
- 7 Holmes, J. D., 1979. Mean and fluctuating internal pressure induced by wind, in: *Proc. 5th Int. Conf. on Wind Eng.*, 435-450, Colorado State University, USA, 1979.
- 8 Sharma, R. N., Richards, P. J., Computational modelling of the transient response of building internal pressure to a sudden opening. *Journal of Wind Engineering and Industrial Aerodynamics* 72 (1997) 149-161.
- 9 Holmes, J. D., Ginger, J. D., Internal Pressures-The Dominant Opening Case-A Review, in: *Proceedings of the 9th UK Conference on Wind Engineering*, Bristol, UK, 2010.
- 10 Ginger, J. D., Holmes, J. D., Kim, P. Y., Variation of internal pressure with varying sizes of dominant openings and volumes. *Journal of Structural Engineering* 136 (2010) 1319-1326.
- 11 Ginger, J. D., Holmes, J. D., Kopp, G. A., Effect of building volume and opening size on fluctuating internal pressures. *Wind and Structures, An International Journal* 11 (2008) 361-376.