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Wind induced internal pressure overshoot in buildings with opening

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Abstract. The wind-induced transient response of internal pressure following the creation of a sudden dominant opening during the occurrence of high external pressure, in low-rise residential and industrial buildings was numerically investigated. The values of the ill-defined parameters namely the flow contraction coefficient, loss coefficient and the effective slug length were calibrated by matching the analytical response with the computational fluid dynamics predictions. The effect of a sudden i.e., "instantaneously created" windward opening in the Texas Technical University (TTU) test building envelope was studied for two different envelope flexibility-leakage combinations namely: (1) a quasi-statically flexible and non-porous envelope and (2) a quasi-statically flexible and porous envelope. The responses forced by creating the openings at different time leads/lags with respect to the occurrence of the peak external pressure showed that for cases where the openings are created in close temporal proximity to the peak pressure, the transient overshoot values of internal pressure could be higher than the peak values of internal pressure in the pre-sequent or subsequent resonant response. In addition, the influence of time taken for opening creation on the level of overshoot was also investigated for the TTU building for the two different envelope characteristics. Non-dimensional overshoot factors are presented for a variety of cavity volume-opening area combinations for (1) buildings with rigid/quasi-statically flexible non-porous envelope, and (2) buildings with rigid/quasi-statically flexible and porous envelope (representing most low rise residential and industrial buildings). While the factors appear slightly on the high side due to conservative assumptions made in the analysis, a careful consideration regarding the implication of the timing and magnitude of such overshoots during strong gusts, in relation to the steady state internal pressure response in cyclonic regions, is warranted.

Keywords: internal pressure; transient response; low-rise building; envelope flexibility-leakage; nondimensional overshoot factor

1. Introduction

Internal pressures induced by the wind in buildings through leakages; through dominant openings; and through flexibility of the structure can contribute significantly to the wind loading of a low-rise building. Of particular interest, and often the most critical case for wind load design consideration, is the internal pressure inside a building due to a single dominant opening, either

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left open accidently, created by sudden impact of debris carried by the gusting wind against the building envelope or by direct wind loading during storms. The ensuing internal pressure response caused by the breakage of doors and/or windows during severe storms presents two issues of concern; the internal pressure overshoot, if any, and the resonant (Helmholtz) response. While the second of these two issues is often observed in wind tunnel studies (Sharma 1996) and is believed to produce maximum (hence design) internal pressure, the first issue of transient overshoot is usually thought to be insignificant.

The creation of dominant openings in the building envelope during passage of strong gusts (resulting in high external pressure around the opening) by accompanying debris or by direct wind loading is far too common to be ignored. Various researchers using wind tunnel and full scale studies have however relegated the significance of the transient overshooting of internal pressure that follows a cladding failure by concluding that it gets lost amidst turbulence induced fluctuations and is usually not larger than the steady-state resonant value.

Stathopoulos and Luchian (1989) carried out a study of the internal pressure overshoot response under simulated wind condition with a sudden opening created using a specially designed and fabricated mechanical device. The study concluded that the peak internal pressure after an opening is established are always higher than the transient overshoots. Yeatts and Mehta (1992) carried out full scale studies of the overshoot internal pressure response of the TTU building by breaking tempered glass lite window at a desired time in the data acquisition runs and drew similar conclusions. Vickery and Bloxham (1992) measured the overshoot response of internal pressure from sudden opening tests carried out in smooth uniform as well as turbulent boundary layer flow in the wind tunnel. The low overshoot factors obtained in the study was attributed to the limitation of the experimental setup to trigger a sudden opening when the external pressure exceeded a threshold level. Matsui *et al.* (2008) carried out a wind tunnel study of the sudden opening response of internal pressure using a shutter opening that could be opened instantaneously.

Understandably, none of these studies, as shown in Fig. 1 for example, were able to capture the overshoot response during very high windward-wall pressure associated with a strong sustained gust, since it is virtually impossible to synchronize the creation of a sudden opening with the occurrence of a strong gust in wind tunnel and full scale test studies. While advanced experimental techniques such as “damage models” might prove useful, it still requires the problem of finite time required for opening creation and the associated issue of initial overpressure (Stathopoulos and Luchian 1989) to be overcome. On the other hand, analytical modelling, shown to perform satisfactorily in both sudden (Liu and Saathoff 1981, Stathopoulos and Luchian 1989, Vickery and Bloxham 1992, Sharma and Richards 1997a) and steady state (Sharma and Richards 1997c) opening situations, offers a convenient way to study the overshoot effect with greater degree of flexibility such as control over the time and “suddenness” of opening creation. This thus offers an interesting area of investigation, and Sharma (2000) using analytical modelling for a rigid building reported the possibility of significant internal pressure overshoot in the turbulent wind. In response to a remark made by Stathopoulos on the relative importance of overshoot versus the steady state response of internal pressure, Vickery made the following comment (Cook 1992): “If the failure of the window is assumed to be independent of the external wind speed, then the expected value of the peak immediately following failure is definitely less than that induced during some extended period following the failure. If, however, it is assumed that the failure occurs during an extreme gust, then the peak immediately following failure may well exceed the peak achieved during the remainder of the storm”. The critical question now is whether, or not, the sudden overshooting of internal pressure may be higher than the subsequent steady state (resonant) value under realistic storm and building (with leakages and flexibility) conditions encountered in practice. If so, what special provisions (such as over-shoot factors) should be provided in the wind standards to accommodate this potential effect? This paper seeks to address these questions through numerical modelling of the internal pressure response of a range of building cavity volume-opening area combinations of low rise residential and industrial structures.

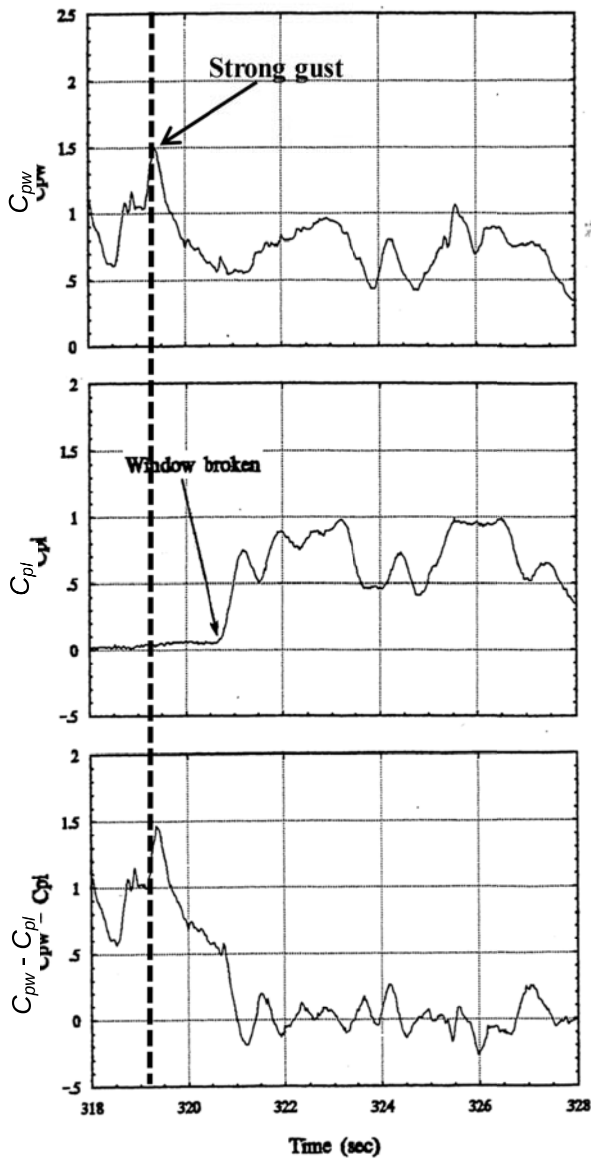


Fig. 1 Field tests of overshoot response of internal pressure with the opening created at an arbitrary time (Yeatts and Mehta, 1992) not coinciding with the occurrence of high external pressure near the opening

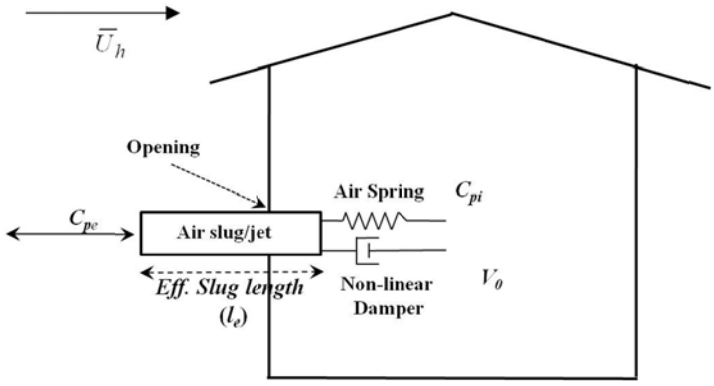


Fig. 2 The oscillating air slug model

As a ‘control’, numerical simulations of the internal pressure overshoot response to a sudden windward opening for a building representing the TTU full scale test facility (Yeatts and Mehta 1992) were carried out. The windward dominant opening (area ratio of 5%) was being created at four different time leads/lags with respect to the occurrence of the peak external pressure in the synthetically generated external pressure coefficient time series. Computational fluid dynamics (CFD) modelling of a sudden opening was used to determine appropriate values of flow contraction and loss coefficients (c and C_L respectively) for the internal pressure system (Sharma and Richards 1997a). The modelled values of c and C_L were used to study the overshoot internal pressure response of two different envelope flexibility-leakage combinations of the TTU building namely (1) with a quasi-statically flexible, non-porous envelope and (2) with a quasi-statically and porous envelope. The effect of the “suddenness” or rapidity of opening creation was further analyzed for the case of TTU building with different envelope flexibility/leakage combinations, involving linear variation of the opening area from 1-100% over five different “durations”, at different time leads/lags to the occurrence of the peak external pressure.

The study is then extended to encompass a range of building volume-opening area configurations encountered in normal design practices for (1) buildings with rigid/quasi-statically flexible, non-porous (or nearly so) envelope, and (2) buildings with rigid/quasi-statically flexible and porous envelope (representing most low-rise residential and industrial buildings) by carrying out simulations using the non-dimensionalized form of the appropriate governing equations. These two envelope flexibility-leakage combinations are to be subsequently referred to as C1 and C2 respectively for brevity.

2. Governing equations

2.1 Non-porous rigid and quasi-statically flexible building

Holmes (1979), Liu and Saathoff (1981), Vickery and Bloxham (1992), and Sharma and Richards (1997a) among others have separately proposed analytical models to predict the internal pressure response of a building with a dominant opening. The models use a second order non-linear differential equation similar to that for a single degree of freedom spring-mass-damper system to predict the internal pressure response assuming a slug/jet of air oscillating through the opening, acting against an air spring inside the building cavity as shown in Fig. 2.

Using the unsteady discharge equation of flow through a sharp edged dominant opening combined with the mass balance of air flow inside the building and isentropic density formulation (assuming small air density change between the immediate external and internal region within the convergent flow zone), the internal pressure response can be shown (Sharma and Richards 1997a) to be governed by

$$\frac{\rho_a l_e V_e}{\gamma c A_o P_a}\ddot{C}_{pi} + C_L \frac{\rho_a q V_e^2}{2(\gamma A_o P_a)^2}\left|\dot{C}_{pi}\right|\dot{C}_{pi} + C_{pi} = C_{pe} \tag{1}$$

where ρ_a is the density of fluid (air in this case) inside the building cavity, l_e is the effective length of the oscillatory air slug at the opening of area A_o with flow contraction coefficient and loss coefficient of c and C_L, V_e is the effective volume of the cavity and equal to V_o (the nominal cavity volume) for a building with rigid envelope, $\gamma = 1.4$ is the ratio of specific heat capacities, P_a is the ambient pressure of air, $q = 0.5\rho_a \overline{U}_h^2$ is the ridge height dynamic pressure, $C_{pi} = p_i/q$ and $C_{pe} = p_e/q$ are the internal and external pressure co-efficient respectively where p_i and p_e are the internal and external pressure around the opening. Ginger *et al.* (2008) following the work of Holmes (1979) non-dimensionalized Eq. (1) as a function of two non-dimensional parameters (S^* and ϕ_5) as

$$\frac{C_I}{cS^*\phi_5^2}\frac{d^2C_{pi}}{dt_*^2} + \frac{C_L}{4(S^*\phi_5)^2}\left|\frac{dC_{pi}}{dt_*}\right|\frac{dC_{pi}}{dt_*} + C_{pi} = C_{pe} \tag{2}$$

where C_I is the inertia coefficient of the oscillating air-slug through the opening, ϕ_5 [$= \lambda_U/\sqrt{A_o}$, λ_U is the integral length of turbulence at ridge height of the building and A_0 is the effective opening area] and S^* [$= (a_s/\overline{U}_h)^2(A_o^{1.5}/V_e)$, a_s and $\overline{U}_h$ are the speed of sound and mean velocity of wind at building ridge height respectively] are non-dimensional quantities and t_* [$= t\overline{U}_h/\lambda_U$] is the non-dimensional time. The Helmholtz frequency of resonance (f_{HH}) derived from Eq. (1) is given by

$$f_{HH} = \frac{1}{2\pi}\sqrt{\frac{\gamma c A_o P_a}{\rho_a l_e V_e}} \tag{3}$$

When the structural frequency of the building components (e.g., the roof) is considerably higher than the frequencies over the energy containing region of onset wind turbulence, the structure will respond in a quasi-static manner to the applied loading i.e., to envelope external and internal pressure). Assuming the structural deflections to be linearly related to the applied loading, the resulting analytic equation of internal pressure response as shown by Vickery (1994) and Sharma and Richards (1997b) can be represented by Eq. (1) with the nominal cavity volume (V_o) exaggerated by a factor $(1+\gamma P_a/K_B)$ such that $V_e = V_o(1+\gamma P_a/K_B)$, where K_B is the bulk modulus of the building envelope.

2.2 Building with envelope flexibility and background leakage

The most representative case of a real residential, industrial or a small internally partitioned building is the one with a quasi-statically flexible and leaky envelope; both of which act as dampers to the internal pressure response. Guha *et al.* (2009), following the work of Yu *et al.* (2008), have used an analytical model of internal pressure dynamics for a building with a windward dominant opening and background leakage based on lumping of leakages on the leeward side along with the usage of a time and area averaged leeward external pressure coefficient as forcing function. The resulting non-linear equation with lumped leakage is

$$\frac{\rho_a l_e V_e}{\gamma c A_o P_a}\ddot{C}_{pi} + C_L \frac{\rho_a q V_e^2}{2(\gamma A_o P_a)^2}\left|\dot{C}_{pi} + \frac{A_L \gamma P_a \overline{U}_h}{q V_e}\sqrt{\frac{C_{pi}-\overline{C}_{peL}}{C_L'}}\right|\left(\dot{C}_{pi} + \frac{A_L \gamma P_a \overline{U}_h}{q V_e}\sqrt{\frac{C_{pi}-\overline{C}_{peL}}{C_L'}}\right) + \frac{A_L \rho_a \overline{U}_h l_e}{2A_o q c\sqrt{C_L'(C_{pi}-\overline{C}_{peL})}}\dot{C}_{pi} + C_{pi} = C_{pe} \tag{14}$$

This can be non-dimensionalized to

$$\frac{C_I}{cS^*\phi_5^2}\frac{d^2C_{pi}}{dt_*^2} + \frac{C_L}{4(S^*\phi_5)^2}\left|\frac{dC_{pi}}{dt_*} + 2\left(\frac{A_L}{A_o}\right)S^*\phi_5\sqrt{\frac{C_{pi}-\overline{C}_{peL}}{C_L'}}\right|\left(\frac{dC_{pi}}{dt_*} + 2\left(\frac{A_L}{A_o}\right)S^*\phi_5\sqrt{\frac{C_{pi}-\overline{C}_{peL}}{C_L'}}\right) + \left(\frac{A_L}{A_o}\right)\frac{C_I}{\phi_5 c\sqrt{C_L'(C_{pi}-\overline{C}_{peL})}}\frac{dC_{pi}}{dt_*} + C_{pi} = C_{pe} \tag{5}$$

where A_L is the total or lumped area of the leakages on the leeward side, C_L' is the representative loss coefficient of the lumped leakage opening and $\overline{C}_{peL}$ is the area and time averaged leeward wall external pressure coefficient.

Wide-span low-rise light industrial buildings and warehouses (with a large un-partitioned internal volume) with leaky and flexible envelopes are usually designed as static structures such the internal pressure response may be sufficiently modelled using Eq. (5). For such buildings, the envelope usually has a greater flexibility, especially in the roof. The roof, though not very common, under certain conditions such as during tropical cyclone with an inherent shift in the spectrum towards higher frequencies near the natural frequency of the envelope (roof), may respond dynamically to the fluctuating wind.

Sharma (1996) and Sharma and Richards (1997b) following the work of Novak and Kassem (1990) and Vickery and Georgiou (1991) have proposed a coupled non-linear model of internal pressure response of such dynamically flexible roofed buildings but without background leakage in which the interaction between the roof-internal pressure system is inherent. It represents a coupled mechanical system consisting of two mass-spring dampers exhibiting double resonance with natural frequencies displaced somewhat from the uncoupled situation. The resulting dynamic equations of internal pressure and roof responses respectively are

$$\ddot{C}_{pi} + \frac{\gamma P_a}{q}\ddot{\upsilon} + \dot{\upsilon}\dot{C}_{pi} + C_L\frac{cV_e\gamma P_a}{2A_o l_e q}\left|\frac{q}{\gamma P_a}\dot{C}_{pi} + \dot{\upsilon}\right|\left(\frac{q}{\gamma P_a}\dot{C}_{pi} + \dot{\upsilon}\right) = \frac{cA_o\gamma P_a}{l_e V_e \rho_a}\left(C_{pe} - C_{pi}\right) \tag{6}$$

$$\ddot{\upsilon}+2\varsigma_r\omega_r\dot{\upsilon}+\omega_r^2(\upsilon-1)=\frac{qA_r^2}{m_rV_e}C_{pi} \tag{7}$$

were ω_r, ς_r, m_r and A_r are the natural (structural) frequency, damping ratio, mass and area of the flexible roof respectively while $\upsilon=V/V_e$, where V is the instantaneous volume of the building, is the time varying non-dimensional volumetric ratio. The structural frequency of the roof (or of the supporting beams) can be approximately estimated as shown by Vickery (1986) to be

$$\omega_r=0.36\pi\left(\frac{Ng}{\sqrt{A_r}}\right)^{1/2}\left(\frac{DL}{LL}\right)^{1/2}=\frac{F}{\sqrt[4]{A_r}} \tag{8}$$

where DL and LL are uniform dead and live loads per unit lengths, g is the acceleration due to gravity, N is 180-360 (unit less) for industrial and residential structures for which the constant F approximately varies from 60-90 $m^{1/2}/s$.

Eqs. (6) and (7) need to be solved simultaneously to yield the response of internal pressure and roof being forced by the turbulent external pressure fluctuations at the opening. A non-dimensional form of Eqs. (6) and (7) in terms of the inverse of Mach number $\phi_2\,(=a_s/\overline{U}_h)$, S^* and ϕ_5 can be written respectively as

$$\frac{d^2C_{pi}}{dt_*^2}+2\phi_2^2\frac{d^2\upsilon}{dt_*^2}+\frac{d\upsilon}{dt_*}\frac{dC_{pi}}{dt_*}+\frac{cC_L}{4C_IS^*}\left|\frac{dC_{pi}}{dt_*}+2\phi_2^2\frac{d\upsilon}{dt_*}\right|\left(\frac{dC_{pi}}{dt_*}+2\phi_2^2\frac{d\upsilon}{dt_*}\right)=\frac{cS^*\phi_5^2}{C_I}\left(C_{pe}-C_{pi}\right) \tag{9}$$

$$\frac{d^2\upsilon}{dt_*^2}+2\left(\frac{\varsigma_r}{C_I}\frac{\omega_r}{\omega_e}\phi_5\phi_2\right)\frac{d\upsilon}{dt_*}+\left(\frac{\omega_r\phi_5\phi_2}{C_I\omega_e}\right)^2(\upsilon-1)=\phi_6C_{pi} \tag{10}$$

where (Sharma and Richards 2009)

$$\omega_e=2\pi f_e=\frac{a_s}{l_e} \tag{11}$$

is the inverse of the time taken for the internal pressure fluctuations to be transmitted inside the building cavity through the opening and

$$\phi_6=\left(\frac{\rho_a}{\rho_r}\right)\left(\frac{\lambda_U}{\sqrt{A_r}}\right)^2\left(\frac{A_r}{2ht}\right) \tag{12}$$

is a non-dimensional quantity that depends on the roof height, nature of roofing material, overall dimensions of the roof in comparison to the gust size as well as the building and roof geometry. In Eq. (12), ρ_r is the density of the roof, h is the building ridge height and t is the thickness of the roof slab/sheet. The roofs of low rise industrial buildings, warehouses and factory sheds, with ridge heights of the order of 5-20 m, are usually made of fibre-cement or galvanized-steel corrugated sheeting 1-6 mm thick in addition to lap and fastenings. For roofs of such materials and for typical ridge height integral length scales of velocity (~100-150 m), values of ϕ_6 ranging from 25-100 can be considered as an upper-bound estimate in cyclonic areas with a high potential for dynamic overshooting of internal pressure following a sudden breach in the envelope. Eqs. (9) and (10) can be simultaneously solved for a range of realistic values of non-dimensional parameters S^*, ϕ_5 and ϕ_6 to turbulent external pressure forcing.

Eq. (6) representing the coupled model of the internal pressure response of buildings with dynamically flexible envelope have been further extended to incorporate the effect of background leakage using the lumped leakage model presented in Eq. (4) yielding

$$\ddot{C}_{pi} + \frac{\gamma P_a}{q}\ddot{\upsilon} + \dot{\upsilon}\dot{C}_{pi} + \frac{\gamma P_a c A_L}{V_e \rho_a \overline{U}_h \sqrt{C'_L\left(C_{pi} - \overline{C}_{peL}\right)}}\dot{C}_{pi} + C_L \frac{c V_e \gamma P_a}{2 A_o l_e q}\left|\frac{q}{\gamma P_a}\dot{C}_{pi} + \dot{\upsilon} + \frac{A_L \overline{U}_h}{V_e}\sqrt{\frac{C_{pi} - \overline{C}_{peL}}{C'_L}}\right| \left(\frac{q}{\gamma P_a}\dot{C}_{pi} + \dot{\upsilon} + \frac{A_L \overline{U}_h}{V_e}\sqrt{\frac{C_{pi} - \overline{C}_{peL}}{C'_L}}\right) = \frac{c A_o \gamma P_a}{l_e V_e \rho_a}\left(C_{pe} - C_{pi}\right) \tag{13}$$

Non-dimensionalizing Eq. (13) leads to

$$\frac{d^2 C_{pi}}{dt_*^2} + 2\phi_2^2 \frac{d^2\upsilon}{dt_*^2} + \frac{d\upsilon}{dt_*}\frac{dC_{pi}}{dt_*} + \left(\frac{A_L}{A_o}\right)\frac{cS^*\phi_5}{\sqrt{C'_L\left(C_{pi} - \overline{C}_{peL}\right)}}\frac{dC_{pi}}{dt_*} + \frac{cC_L}{4C_I S^*}\left|\frac{dC_{pi}}{dt_*} + 2\phi_2^2\frac{d\upsilon}{dt_*} + 2\left(\frac{A_L}{A_o}\right)S^*\phi_5\sqrt{\frac{\left(C_{pi} - \overline{C}_{peL}\right)}{C'_L}}\right| \left(\frac{dC_{pi}}{dt_*} + 2\phi_2^2\frac{d\upsilon}{dt_*} + 2\left(\frac{A_L}{A_o}\right)S^*\phi_5\sqrt{\frac{\left(C_{pi} - \overline{C}_{peL}\right)}{C'_L}}\right) = \frac{cS^*\phi_5^2}{C_I}\left(C_{pe} - C_{pi}\right) \tag{14}$$

Eq. (14) can be solved simultaneously with Eq. (10) to yield the response of internal pressure under forcing from external pressure.

In order to correctly simulate the internal pressure response using the governing equations (a) appropriate values of the uncertain or ill-defined parameters of the internal pressure system, namely c and C_L and (b) characteristics of external pressure at the opening, are required.

3. Determination of flow contraction and loss coefficient using CFD

The first objective here is satisfied through Reynolds-averaged Navier Stokes (RANS) CFD modelling of the internal pressure response of the rigid walled TTU building cavity following the creation of a sudden windward opening (area ratio 5%). 3D modelling of the problem has been conducted using the finite volume based commercial computational fluid dynamics package Ansys CFX (Version 11.0, 2007).

A rectangular structured mesh setup with 92x92x79 hexahedral cells is used to mesh the domain 23 H (H is the building height) long and wide and 12 H high. Figs. 3(a) and (b) show the meshed computational domain in stream-wise and stream-normal direction while Fig. 3(c) shows the meshed up TTU building with the windward opening placed inside the domain.

An appropriate boundary layer velocity profile along with the turbulent boundary conditions based on the recommendations of Richards and Hoxey (1993) was assigned to the inlet. An isentropic density formulation was incorporated for the entire flow field according to the physics of the problem. The ground of the computational domain was treated as a rough wall and the first node was carefully placed beyond the roughness height. The sides and top of the computational domain were treated as free slip boundaries. Computations were carried out using the shear-stress turbulence (SST) turbulence model of Menter (1994) for a ridge height wind speed of 30 m/s.

A steady-state solution was first obtained for the sealed building situation such that the pressure and velocity of flow inside the building remain nearly zero. The result of the steady run was used as the initial field for the transient computations with cell blocks corresponding to the opening in the windward face removed to simulate a sudden opening. Typically a time step of 1/100th of the period of Helmholtz oscillation (f_{HH} = 3 Hz for the TTU test building) was used for transient CFD simulations for 1 seconds.

The overshoot response obtained using CFD with a mean internal pressure coefficient ($\overline{C}_{pi}$), was compared with the analytical predictions obtained by numerically simulating Eq. (1) to a step change in the mean internal pressure. The analytical equation was solved as an initial value problem of zero pressure using the fourth order Runge-Kutta scheme with an adaptive time-step (Matlab 7.9.0.529, The MathWorks^{TM}) of less than or equal to 0.0001 seconds. A flow contraction coefficient (c) of 0.6, effective slug length (l_e) of $\sqrt{\pi A_o/4}$ and different loss coefficient (C_L)

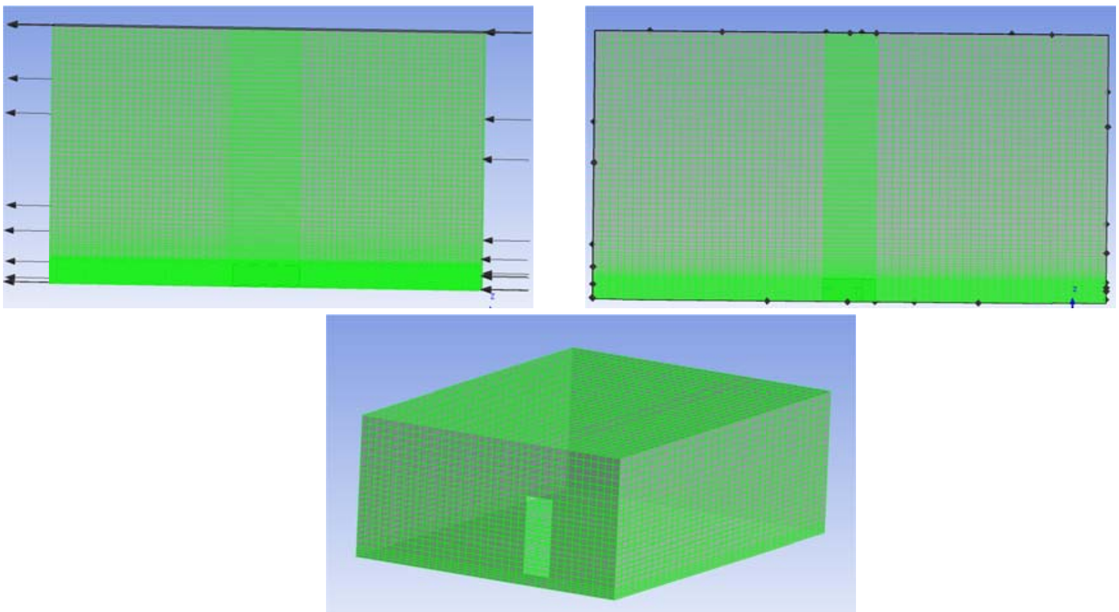


Fig. 3 Meshed computational domain in the (a) stream-wise; (b) stream-normal direction and (c) meshed up TTU building with the windward opening

values were used to fit the analytical estimates to the CFD predictions. Fig. 4 compares the CFD results with the analytical predictions of the overshoot response for loss coefficients of 2.78 and 1.2.p

While a good agreement between CFD and analytical predictions in terms of matching of the Helmholtz frequency was obtained by using a flow contraction coefficient of *c* = 0.6 in the analytic equation, the CFD results were found to consistently over predict the decay rate of response.

Sharma and Richards (1997a) attributed this enhanced damping to increased viscosity associated with turbulence models to simulate the onset free stream turbulence and to the aerodynamic damping caused due to the relative motion of the oscillating slug at the opening with respect to the external flow. As suggested by Sharma and Richards (1997a), the effect of first possible source of damping in the CFD solution was eliminated by subjecting the TTU building to a smooth laminar onset flow instead of a boundary layer flow referred by the authors as "smooth flow". The effect of second possible source of damping was nullified by creating an initial internal-external pressure difference equal to the onset flow dynamic pressure used in smooth flow situations referred to as the "static test" by Sharma and Richards (1997a).

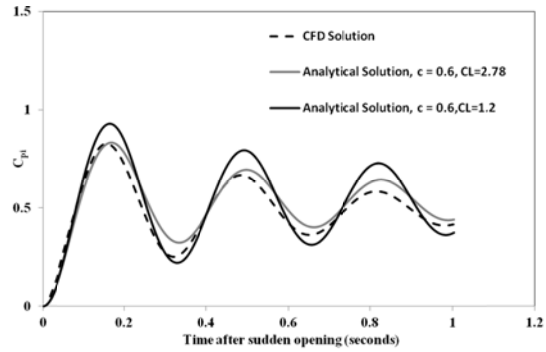


Fig. 4 Comparison of internal pressure overshoot response between boundary layer CFD model and analytic solution for a wind speed of $\overline{U}_h$ = 30 m/s

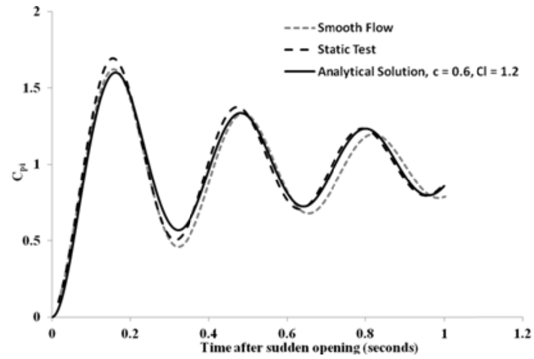


Fig. 5 Comparison of internal pressure overshoot response between Smooth flow, Static test and analytic solution for a wind speed of $\overline{U}_h$ = 30 m/s

Fig. 5 compares the "smooth flow" and "static test" CFD predictions to the analytic solution of Eq. (1) to a step change in external pressure. A loss coefficient of 1.2 along with a flow contraction coefficient of c = 0.6 and $l_e = \sqrt{\pi A_o / 4}$ is found to give a reasonably good match in terms of predicting the damping characteristics and the Helmholtz frequency of fluctuating internal pressure for the TTU building with the opening.

The calibrated values of c, C_L and l_e as 0.6, 1.2 and $0.89\sqrt{A_o}$ respectively were hence used to simulate the internal pressure response in buildings with a thin windward door opening (l_e/d <<1, d being the effective diameter of the opening) for all the configurations investigated. The chosen values of c and C_L have previously been validated experimentally by Sharma and Richards (1997a,c). Chaplin *et al.* (2000) also reported values of C_L similar or very close to those being used here from their wind tunnel measurements. Owing to computational complexities however, CFD was not used to model the building with a flexible envelope.

4. Generation of synthetic velocity and pressure time history

An Inverse Fast Fourier Transform (IFFT) method was used to generate a synthetic external pressure time history (Shinozuka and Jan 1972, Yang 1972) after applying appropriate aerodynamic admittance (Vickery 1965) and randomized phase to the Fourier coefficients derived from Kaimal spectrum (Kaimal *et al.* 1972) at 100 Hz. Fig. 6 summarizes the steps involved in the synthesis. The internal pressure response was forced by the external pressure time series by creating the opening at different time leads/lags corresponding to the peak external pressure in the generated time series.

5. Numerical simulations of the over-shoot response: Results and discussions

Due to the recognized practical difficulties of experimentally simulating such scenarios,

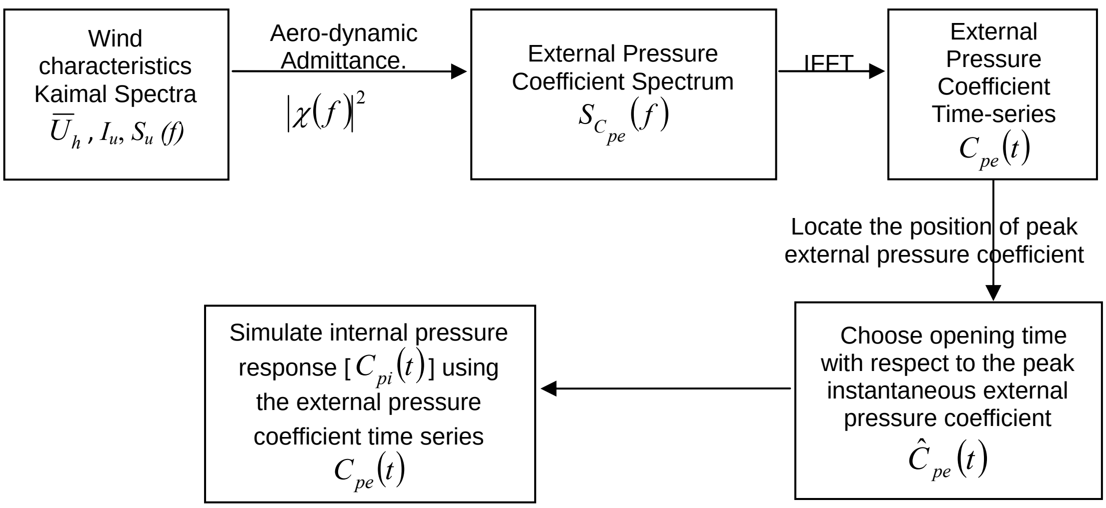


Fig. 6 Synthesis of external pressure time series and simulation of internal pressure response

numerical simulations of the overshoot internal pressure response of the TTU building for envelope flexibility-leakage combinations C1 and C2 were carried out. The first set of simulations involved instantaneous (i.e., very sudden) creation of openings at different temporal proximities to the peak external pressure for comparison of the transient internal pressure overshoots to the peak values in the subsequent resonant response. The second set of simulations involved comparison of the overshoot transient values of internal pressure, for openings created at the instance of peak external pressures, to the peak resonant response of internal pressure for already existing openings. It should be noted that these existing openings were created at least 50 cycles (based on the Helmholtz frequency of the system) prior to the occurrence of the peak external pressure to eliminate the initial transients in the internal pressure response. Also investigated numerically is the influence of the duration of opening creation or 'suddenness of opening' during high gust events on the overshoot response of internal pressure. All numerical simulations of the analytical model(s) were carried out using the fourth order Runge-Kutta method with an adaptive time-step (Matlab 7.9.0.529, The MathWorks^{TM}) of less than or equal to 0.0001 seconds.

5.1 Overshoot vs. subsequent resonant response of internal pressure

5.1.1 Rigid/Quasi-statically flexible TTU building (C1)

Eq. (1) was used to numerically simulate the internal pressure response of a quasi-statically flexible TTU building (V_o = 497 m^3) with $b = \gamma P_A / K_B$ = 1.5 (Ginger *et al.* 1997) for 10 seconds following the creation of a windward dominant opening (A_o = 1.94 m^2) for a design ridge height

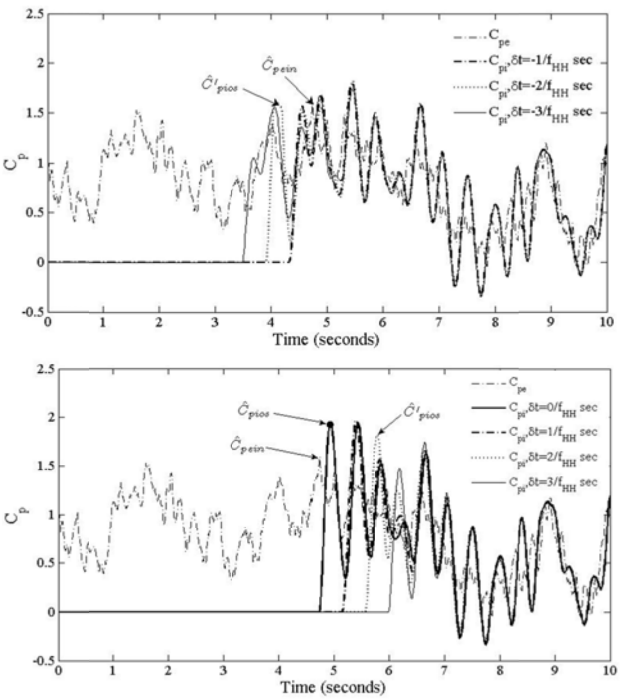


Fig. 7 Internal pressure response of a quasi-statically flexible building with opening created at different time (a) leads (- δt) and (b) lags (δt) to the occurrence of peak external pressure

wind velocity of 30 m/s. The opening was created at different time leads/lags [$\delta t = 0$, $\pm 1/f_{HH}$, $\pm 2/f_{HH}$, $\pm 3/f_{HH}$; $f_{HH} \approx 3$ Hz] with respect to the occurrence of the peak pressure in the external pressure time series.

Figs. 7(a) and (b) present one of several such realizations of the internal pressure response for a quasi-statically flexible TTU building. The peak overshoot response of internal pressure ($\hat{C}_{pios}$), when the instantaneous creation of opening is well synchronized (δt =0) with the occurrence of the peak external pressure [in Fig. 7(b)], is found to exceed the subsequent steady state peak value ($\hat{C}_{pi-ss}$). It should be noted that $\hat{C}_{pi-ss}$, the steady state peak internal pressure is the peak value that occurs sufficiently (at least 3 periods) after the opening has been created. $\hat{C}_{pios}$ is also found to be higher than the corresponding overshoot response of internal pressure ($\hat{C}'_{pios}$) for the opening created at different lead/lag time to the peak external pressure [in Figs. 7(a) and (b)]. The ratio of the peak internal pressure overshoot coefficient for the opening created at zero time-lag ($\hat{C}_{pios}$) to the peak instantaneous external pressure coefficient ($\hat{C}_{pein}$) i.e., $\hat{C}_{pios} / \hat{C}_{pein}$ =1.25 for the particular realization shown here qualitatively indicates that significant overshooting is possible for openings created during strong gusts. This is similar to the findings of Sharma (2000) for a rigid building.

5.1.2 Quasi-statically flexible and porous TTU building (C2)

The most realistic representation of a residential, industrial or an internally multi-partitioned building usually designed as a "static structure" is one with a quasi-statically flexible and leaky

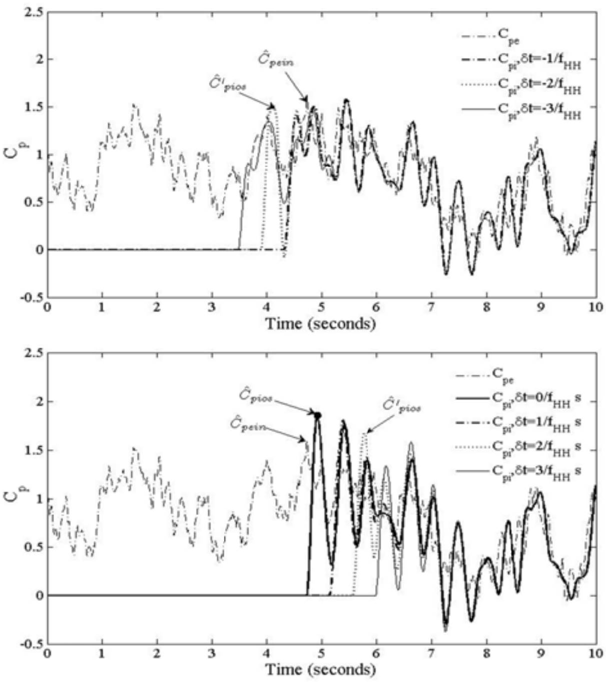


Fig. 8 Internal pressure response of a quasi-statically flexible and leaky building with opening created at different time (a) leads (- δt) and (b) lags (δt) to the occurrence of peak external pressure

envelope. The internal pressure response of such a building representing the full scale TTU setup was obtained by numerically simulating Eq. (4) for a porosity ratio (A_L/A_o) of 10%, $b=\gamma P_A/K_B$ = 1.5, C'_L =2.78 and $\overline{C}_{peL}$ = -0.2 and a ridge height wind speed of 30 m/s. One such realization of the internal pressure response for different leads and lags with respect to the peak instantaneous external pressure are presented in Figs. 8(a) and (b), respectively. A porosity ratio (ratio of the area of leakage to that of the dominant opening) of 10% can be considered as an upper-bound estimate for typical residential and industrial buildings in the temperate climates of Australia/New Zealand; porosities beyond this value lead to significant damping of internal pressure fluctuations (Vickery and Bloxham 1992).

The overall response of internal pressure for C2 is lower compared to C1, but the overshoot response ($\hat{C}_{pios}$) of internal pressure is approximately 1.15 times higher than the corresponding peak external pressure ($\hat{C}_{pein}$) at the instant of opening creation, notwithstanding the enhanced damping due to the envelope flexibility and background leakage.

The importance of the timing of opening creation in relation to the peak external pressure and its effect on overshoot internal pressure response is illustrated in Table 1 for the two cases (C1 and C2). Comparison is made with the subsequent steady state peak response. To account for the statistical variability in numerical simulation, results are presented as the ensemble average of ten representative 10 second simulations for each lead/lag time and envelope configuration. It is evident that strong overshoot response of internal pressure ($\hat{C}_{pios}$), higher than the subsequent steady state response ($\hat{C}_{pi-ss}$), is possible for openings created at the instant (in bold in Table 1) of high external pressure near the opening. For most other time lead/lags investigated, the overshoot response ($\hat{C}'_{pios}$) was found to be lower than the subsequent resonant response of internal pressure ($\hat{C}_{pi-ss}$).

5.2 Overshoot vs. existing resonant response of internal pressure

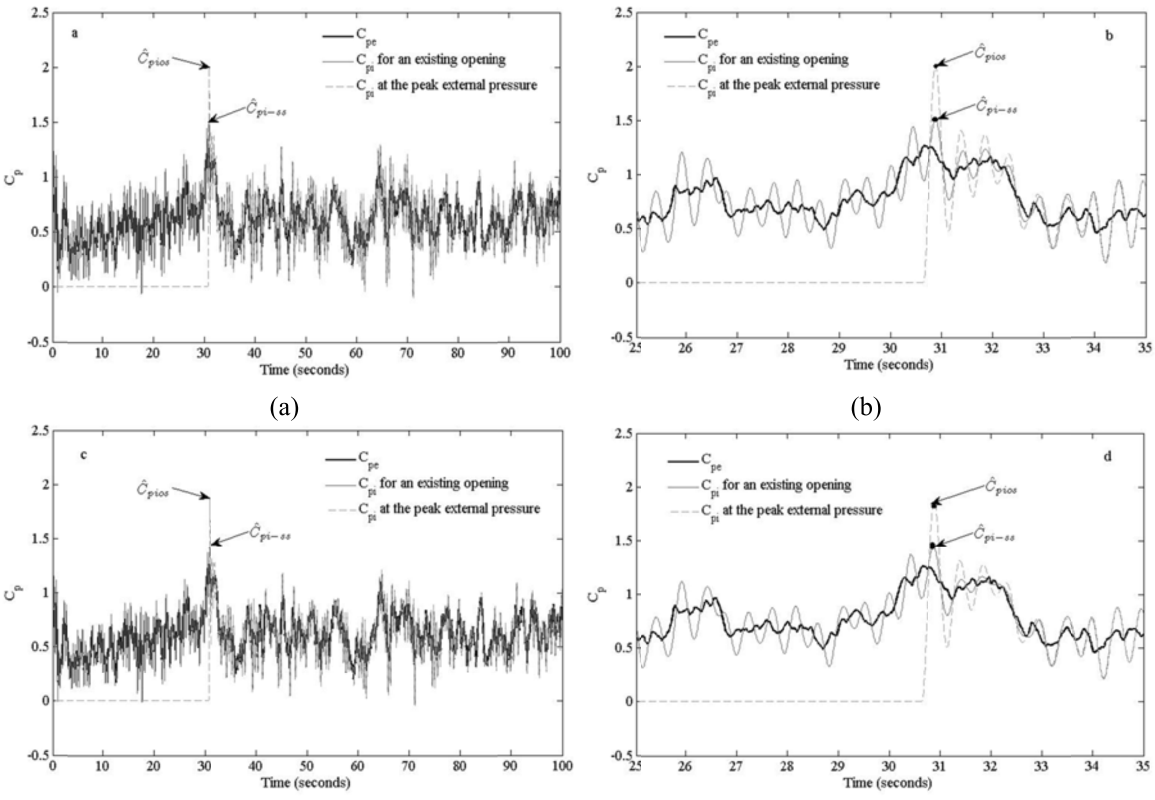
In order to investigate the effect of high external pressure near the opening on the resonant response of internal pressure and vis. a vis. its severity in relation to the overshoot response in the case of openings created almost instantaneously during a similar peak event, numerical simulations were carried out for cases C1 and C2. Ten different 100 second time histories of representative external pressures for a ridge height wind speed of 30 m/s were used to force the response of internal pressure. The peak instantaneous pressures in each of these external

Table 1 Comparison of overshoot and subsequent resonant response of internal pressure with openings created at different lead/lags to peak external pressures for the TTU building

Lead/Lag time to peak gust	C1 (flexible envelope)		C2 (flexible and porous envelope)	
	$\hat{C}_{pios}/\hat{C}'_{pios}$	$\hat{C}_{pi-ss}$	$\hat{C}_{pios}/\hat{C}'_{pios}$	$\hat{C}_{pi-ss}$
-3/f_{HH}	1.10		1.40	
-2/f_{HH}	1.35		0.90	
-1/f_{HH}	1.85		1.71	
0/f_{HH}	**2.02**	**1.80**	**1.95**	**1.72**
1/f_{HH}	1.75		1.55	
2/f_{HH}	1.45		1.20	
3/f_{HH}	1.50		0.75	

Table 2 Comparison of overshoot response during peak external pressures to the resonant response of internal pressure with already existing openings for the TTU building

Simulations (Run) No.	C1 (flexible envelope)			C2 (flexible and porous envelope)		
	$\hat{C}_{pios}$	$\hat{C}_{pi-ss}$	% diff.	$\hat{C}_{pios}$	$\hat{C}_{pi-ss}$	% diff.
1	1.44	1.30	**9.70**	1.36	1.10	**19.12**
2	1.53	1.31	**14.40**	1.43	1.12	**21.67**
3	1.45	1.33	**8.27**	1.37	1.08	**21.17**
4	1.40	1.22	**12.86**	1.35	1.07	**20.74**
5	1.42	1.22	**14.08**	1.32	1.04	**21.21**
6	1.53	1.23	**19.61**	1.42	1.10	**22.53**
7	1.43	1.16	**18.88**	1.33	1.02	**23.31**
8	1.43	1.24	**13.29**	1.34	1.09	**18.66**
9	1.41	1.32	**6.38**	1.31	1.11	**15.26**
10	2.07	1.53	**26.08**	1.88	1.45	**22.87**
Mean	**1.51**	**1.29**	**14.6**	**1.48**	**1.12**	**24.32**



(a) (b) (c) (d)

Fig. 9 (a) Overshoot and resonant internal pressure response, (b) Enlarged view of the overshoot vs. resonant response of a quasi-statically flexible TTU building, (c) Overshoot and resonant internal pressure response and (d) Enlarged view of the overshoot vs. resonant response of a quasi-statically flexible and porous (10%) TTU building pressure time histories occurred between the 30th and the 60th second. This ensured that the initial transients of internal pressure for the opening created right at the beginning of the simulation (i.e., at time zero) get attenuated before the occurrence of the peak external gust, and the steady-state response of internal pressure, if any, is induced primarily by resonance. The overshoot response of internal pressure was triggered at the instant of that peak gust.

Figs. 9(a) and (c) show one such realization of the internal pressure responses (resonant and transient) for configurations C1 and C2 respectively. Also plotted are the external pressure traces used to force the responses.

For the particular realization shown in Fig. 9(a) for configuration C1 (and in Table 2, Simulation no. 10) and a blow-up of the peak responses in Fig. 9(b), the overshoot internal pressure coefficient ($\hat{C}_{pios} \approx 2.07$) is found to exceed the global peak resonant response ($\hat{C}_{pi-ss} \approx 1.53$) of internal pressure by around 26%. It is interesting to note that the peak resonant response ($\hat{C}_{pi-ss}$) and the overshoot response ($\hat{C}_{pios}$) of internal pressure occurred at the same instance in time associated with the peak external pressure in the time series. This implies that while the resonant response of internal pressure may usually be the guiding design criteria for already existing openings left open accidentally during storms, the overshoot response associated with strong external pressures near the opening could well exceed this value under exceptional circumstances. Similar conclusions can be drawn for configuration C2 in Fig. 9(c) with a blow-up of the peak responses in Fig. 9(d), in which the overshoot response ($\hat{C}_{pios} \approx 1.88$) exceeds the global peak resonant response by approximately 23%. However, both the overshoot and resonant response of internal pressure for C2 are comparatively weaker to those for C1 due to additional damping by background porosity in the envelope.

This investigation, thus reveals that the internal pressure overshoots should not be seen in isolation to that of the resonant effects, but the implication of the severity of such overshoots, at the time of high external pressures near the opening, should be carefully analyzed in relation to the situation of an already existing opening with equalized (or nearly so) mean pressures for design considerations.

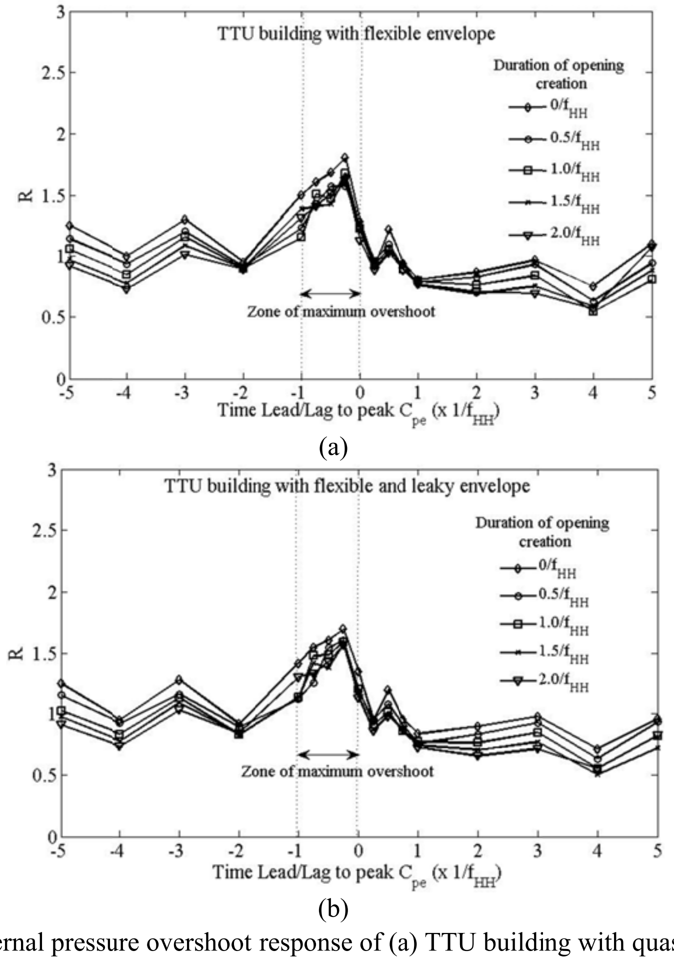
5.3 Duration of opening creation

The above analyses of internal pressure overshoot response are based on the assumption of an instant opening creation (or almost so when the opening is created much faster compared to the time constant of the building volume-opening combination). In certain situations involving ductile/malleable building envelope materials however, it may take some time for a façade or a cladding to fully breach so that the severity of the overshoot response may be reduced. Such scenarios have been numerically investigated for the TTU building with configurations C1 and C2 using four different "opening durations" namely $0.5/f_{HH}$, $1.0/f_{HH}$, $1.5/f_{HH}$ and $2.0/f_{HH}$.

The size of the opening was assumed to linearly vary from 1 to 100% of the final size (A_o = 1.94 m^2) over the different "opening durations". As before, openings were initiated at different leads/lags with respect to the peak instantaneous pressure in the external pressure time series. In order to minimize the effect of localized random peaks of external pressure on the overshoot internal pressure response, an ensemble average of the overshoot response of internal pressure for a given time lead/lag and "opening duration" was calculated using ten different representative external pressure time histories of 50 seconds duration each. Fig. 10(a) presents the averaged overshoot factors (R) for case C1 while Fig. 10(b) presents the same for C2. The over-shoot factor (R) is defined as

$$R = \frac{\hat{C}_{pios}}{\hat{C}_{pein}} \tag{15}$$

The time leads/lags for opening creation used for the purpose of analyses was varied from $-5/f_{HH}$ (lead) to $5/f_{HH}$ (lag); f_{HH} being the Helmholtz frequency based on the final opening size. As expected, the overshoot response of internal pressure for a given "duration of opening creation" and time lead/lag with respect to the peak external pressure decreases with increase in envelope flexibility and background leakage. The rapidity of the duration of opening creation is also found to induce a higher overshoot (see for example the curves for $0.5/f_{HH}$ compared to those for $2/f_{HH}$) for both C1 and C2. It is interesting to note that the zone of influence for maximum overshoot involving initiation of opening creation lies between -1 to about 0 periods leading to the



(b)

Fig. 10 Average internal pressure overshoot response of (a) TTU building with quasi-statically flexible envelope (KB = 1.5 Pa) and (b) TTU building with quasi-statically flexible (KB = 1.5 Pa) and leaky (r = 10%) envelope for different "opening duration" and time leads/lags to the occurrence of peak external pressure occurrence of the peak external pressure for cases C1 and C2 both. This is because a slightly early initiation of the opening creation (but close enough to be in the temporo-spatial zone of influence of the peak external pressure) that grows steadily in size with the peaking gust induces a strong air mass movement through the opening dominated by inertia resulting in significant overshooting of internal pressure.

Within the zone of maximum overshoot, the effect of the duration of opening creation on the overshoot response seems less obvious though. Over a broad zone of influence and opening duration, however, the overshooting of internal pressure is found to be significant (> 1) for the cases analyzed.

Thus, it appears from the above analyses for the TTU building that adequate provisions such as over-shoot factors may need to be provided for such buildings in the wind loading standards, especially for cyclone prone areas, where potential for opening creation during strong external pressures remains high. However, the TTU building setup with its relatively smaller internal volume and a comparatively larger door opening is representative of small workshops or partitioned halls in a larger residential building for which the results of the study can roughly be extended. As such it represents only one of the several combinations of design scenarios possible and hence would not be prudent to base an inference on the above analyses alone. The non-dimensional governing equations offer a distinct advantage in such cases where simulations carried out for a vast range of realistic non-dimensional parameters can be used to derive conclusive inferences as to whether or not such provisions are necessary at all or if necessary under what circumstances.

It is also worth noting at this stage that the level of internal pressure overshoot obtained through numerical analysis is highly sensitive to the value of loss coefficients used for simulation. While a value of C_L = 1.2 used here is based on matching the analytical and the CFD predictions as discussed in section 3, a summary provided by Oh *et al.* (2007) and Holmes and Ginger (2010) of the value of loss coefficient reported in literature shows a wide-spread scatter. Values as high as 44.44 and 100, obtained through spectral match of the measured and the predicted internal pressure spectra in some studies, when used for numerical simulations will generally lead to smaller overshoots than presented in Figs. 7-10.

6. Non-dimensional overshoot factors

For building configurations C1 and C2, non-dimensionalized over-shoot factors (R) already defined in Eq. (15) were derived by numerically simulating the respective non-dimensional equations to obtain a family of curves of R as a function of S^* ranging from 0.5 to 15 for realistic values of ϕ_5 varying between 20 and 100. Values of ϕ_5 are based on a typical longitudinal integral length scale (λ_U) of 100m (Ginger *et al.* 2008) for low-rise buildings. A loss coefficient (C'_L) of 2.78 and an area and time averaged external pressure coefficient ($\overline{C}_{peL}$) of -0.2 was used to simulate the leakage properties (Yu *et al.* 2008) for porous envelopes. Overshoot factors (calculated by triggering the internal pressure response at the instance of peak external pressure) are presented as an ensemble average of ten realizations to account for the statistical variability in the magnitude of the peak external pressures in the time series used.

Figs. 11(a) and (b) present a family of non-dimensional curves of over-shoot factors for configurations C1 and C2 obtained by numerically simulating Eqs. (2) and (5) respectively. A porosity ratio of 10% used for simulation and can be considered to represent one extreme for leaky buildings (both residential and industrial) in temperate climates, no leakage in the envelope being the other extreme end. Overshoot factors for buildings with intermediate leakages (or porosities) can be linearly interpolated from Figs. 11(a) and (b).

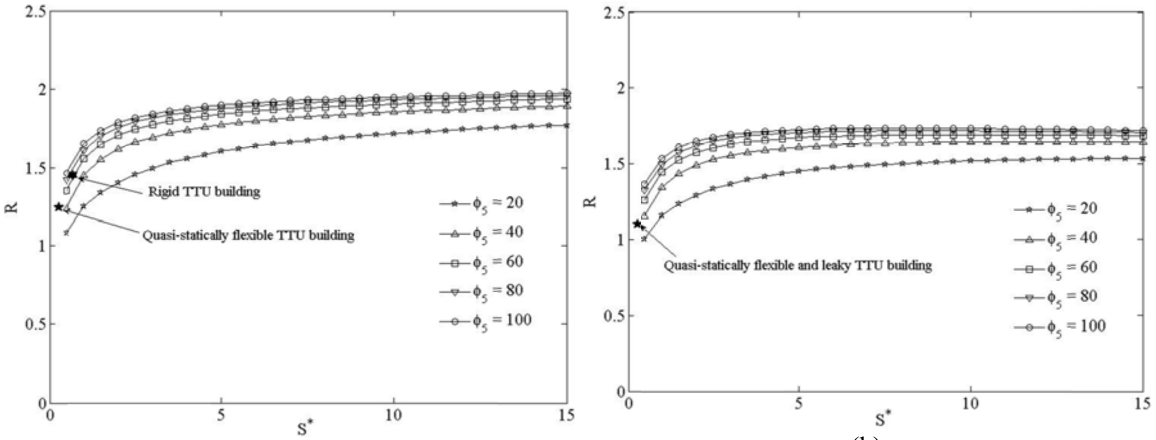
It can be seen that the overshoots are still significant for the range of building cavity-opening combinations investigated but gradually decreasing with increasing area of the opening for a given S^* due to the corresponding increase in internal volume induced damping. As discussed earlier, the significantly high overshoot ratios (R) in excess of unity obtained in Figs. 11(a) and (b) can also be partially attributed to the small loss coefficient value of $C_L = 1.2$ used in the analysis, in addition to the high external pressure used to force the internal pressure transient response. The overshoot factors also tend to gradually diminish with reduction in S^* (or increase in envelope flexibility) for a given ϕ_5 (i.e., opening size) and beyond S^* of around 2, the overshoot factors are found to be more or less constant.

The damping influence of background porosity is reflective in the relatively smaller overshoots in Fig.11(b) than in Fig. 11(a) for a given value of S^* and ϕ_5. The overshoot factors of the TTU building configurations investigated as a 'control' corresponding to S^*=0.698 for a rigid envelope and S^* = 0.279 as a quasi-statically flexible envelope are also marked (as black dots) in Fig. 11(a) while that of a quasi-statically flexible and porous TTU building is shown in Fig. 11(b).

It can thus be inferred from Figs. 11(a) and (b) that the effect of the sudden opening tends to get negated by the damping influence of the building flexibility and background leakage such that for porous structures with large flexible envelope, sudden overshooting of internal pressure may be quite small. In addition to the practical difficulty in synchronization of the creation of an opening to a strong gust event with high external pressures, this partially explains the reason why sudden opening overshooting have never been captured in limited wind tunnel and full scale studies under turbulent wind conditions (e.g., Stathopoulos and Luchian 1989, Yeatts and Mehta 1992).

Of paramount importance and ultimate interest to structural engineers is the response of the building envelope to sudden overshooting of internal pressure following envelope breakage during the occurrence of strong gust. The response, whether dynamic or quasi-static, depends on the relative magnitude of the structural frequency of the buildings components such as the roof with respect to the Helmholtz frequency of the building. An estimation of the non-dimensional volumetric ratio overshoot υ_R ($=\hat{\upsilon}$, where $\hat{\upsilon}$ is the peak non-dimensional volumetric ratio following the creation of an opening; υ just at the instant of opening creation being unity) following a sudden opening will help to ascertain whether the structural deflection of the envelope is within permissible limits or not and what precautions, if necessary, should be undertaken to keep the structural response within the allowable limit states (ultimate and serviceability). Fig. 12 provides a realization of the non-dimensional volumetric ratio overshoot (υ_R) vs. S^* for different values of ϕ_5 and $\phi_6 = 25$.

The volumetric overshoots are relatively higher at lower values of S^* (higher internal volume and roof area) for a given ϕ_5, because at lower structural frequencies, the dynamic or inertial response of the roof becomes significant. On the other hand, at higher values of S^* corresponding to higher roof structural frequencies (smaller roof areas), the stiffness of the envelope (roof) mitigates the dynamic volumetric overshoot response. Marked as black dashed line in the figure is the approximate divide between dynamically sensitive and quasi-statically responsive envelopes depending on the roof natural frequency being lower or higher than 1 Hz (ACSE 7-05, 2005), calculated as a function of the roof area using Eq. (8) for different values of S* and ϕ_5 (ϕ_6 being



(a) (b)

Fig. 11 R vs. S^* simulated with c = 0.6, C_L = 1.2 for a range of ϕ_5 for (a) rigid/quasi-statically flexible building and (b) building with quasi-statically flexible envelope and leakage (10%) using C'_L = 2.78

essentially independent of the roof area).

The internal pressure overshoot factors presented in this paper appear to be slightly on the higher side due to the conservative assumptions made in the analysis (high external pressures, instantaneous opening creation and low C_L value) and will possibly be over-ridden by the steady-state resonant factors for most part due to the small window of time and conditions necessary for overshoots to exceed the ensuing resonant response of internal pressure. Nevertheless, a careful consideration regarding the implication of the timing and magnitude of such overshoots during strong gusts in relation to the steady state internal pressure response for already existing openings, especially in cyclonic regions, is warranted.

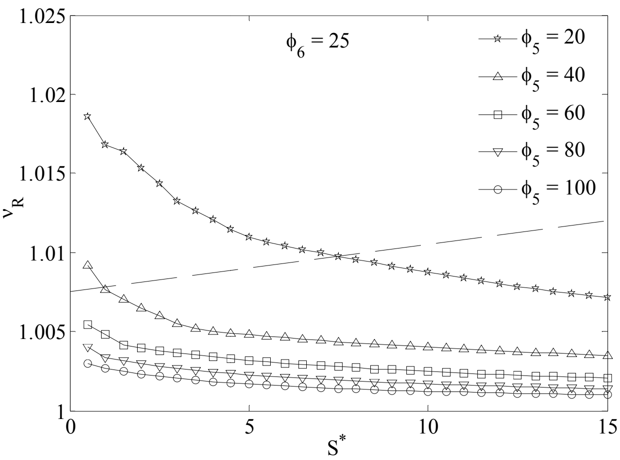


Fig. 12 Non-dimensional volumetric ratio overshoots (υ_R) vs. S^* for different ϕ_5 as a measure of the simulated structural response of quasi-statically and dynamically flexible structures

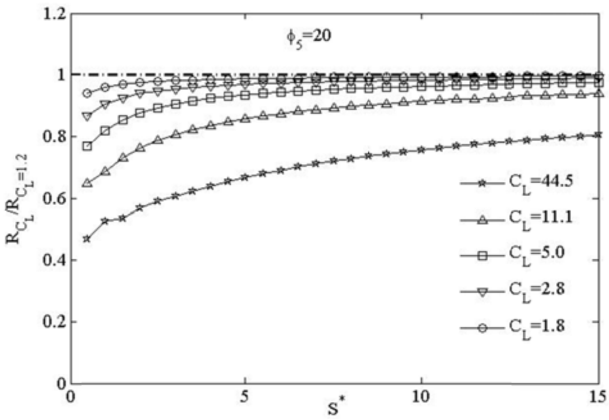


Fig. 13 Sensitivity of internal pressure overshoots (R) to the value of C_L for a non-porous rigid/quasi-statically flexible building envelope

7. Sensitivity of overshoot response to loss coefficient (C_L)

The value of loss coefficient (C_L) through the opening reported in the literature for the kind of unsteady flow considered in the current study shows widespread scatter, derived either from fan-pressurization tests or through fitting of the numerical predictions to the experimental data. The value of $C_L = 1.2$ used in this study, primarily derived from fitting the analytical predictions to CFD results, as mentioned earlier was also experimentally validated by Sharma and Richards (1997a,c).

However, it is useful to carry out a sensitivity analysis of the overshoot response of internal pressure to the opening loss coefficient. Fig. 13 provides a realization of the ratio of the overshoot factors for different values of C_L to the overshoot factors for C_L = 1.2 ($R_{CL}/R_{CL=1.2}$) vs. S^* for a non-leaky rigid/quasi-statically flexible building of opening size $\phi_5 = 20$. The influence of loss coefficient on overshoot factors is evident, such that for loss coefficients higher than 1.2 (as used in the study), the overshoot factors are predictably lower. For very high values of the loss coefficient such as 11.1 and 44.4 used for numerical simulation, the overshoot internal pressure response practically ceases to exist.

8. Conclusions

The importance of wind-induced transient response of internal pressure following the creation of a sudden dominant opening during the occurrence of strong external pressure in low rise residential and industrial buildings have been numerically investigated. The values of flow contraction and loss coefficient obtained by fitting the analytical response to that predicted by the CFD model for the windward opening in the TTU test building were used for numerical investigations. Simulations of internal pressure overshoot response following the creation of a sudden windward opening (area ratio of 5%) in the TTU building at different time leads/lags to the occurrence of a peak instantaneous external pressure for (1) a quasi-statically flexible non-porous envelope and (2) a quasi-statically flexible and porous envelope showed that significant overshooting of internal pressure, higher than the pre-sequent or subsequent steady state resonant values, are possible when the openings are created almost instantaneously during the occurrence of high external pressure near the opening. For all other situations, the steady state resonant response of internal pressure was found to supersede the overshoot response. Investigation into the effect of the "suddenness" of opening creation on the TTU building, with different envelope-leakage combination, using five different "opening durations" revealed the influence of the duration of opening creation on the internal pressure response. In particular it was found that the maximum overshooting of internal pressure is produced by the opening creation initiated 0-1 periods preceding the occurrence of high external pressure, the level of overshoot being inversely proportional to the duration of opening creation.

Non-dimensional overshoot factors are presented for a variety of cavity volume-dominant opening combinations for: (1) buildings with rigid/quasi-statically flexible but non-leaky envelope and, (2) buildings with rigid/quasi-statically flexible and leaky envelope (representing most low rise residential and industrial buildings) by simulating the non-dimensional form of the governing equations. These show that significant overshooting can occur when a sudden opening creation is well-synchronized with high external pressures near the opening. The transient response and the level of internal pressure overshoot are, as expected, found to diminish with increase in flexibility and background porosity in the building envelope.

However, it is also concluded that the values of overshoot factors obtained in this study are slightly high, due to a relatively lower value of loss coefficient used in the analysis than some previously reported studies. This adds to the higher overshoot values obtained under the conservative assumptions of high external pressures at the time of instantly created openings.

A sensitivity analysis was carried out to quantify the effect of loss coefficient on the level of overshoot obtained numerically. It is shown that for very high values of the loss coefficient used for numerical simulation, the overshoot internal pressure response practically ceases to exist.

It is suggested that a careful consideration regarding the implication of the timing and level of internal pressure overshoots, associated with high external pressure near the opening, be made in relation to the situation of an already existing opening, especially in cyclonic regions with high possibility of such occurrence.

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