INTERNAL PRESSURES IN THE TEXAS TECH WERFL FULL-SCALE TEST BUILDING

J. D. Ginger, B. B. Yeatts and K. C. Mehta
Wind Engineering Research Center, Texas Tech University, Lubbock TX 79409, USA.

INTRODUCTION

Studies have shown that, in many cases, low-rise building roof and wall failures in strong winds, have been the result of a combination of large internal pressure and external pressure acting in the same direction. Wind tunnel and theoretical studies have been carried out by Holmes (1979), Vickery (1986) and Harris (1990), on the mean and fluctuating internal pressures in nominally sealed buildings and buildings with large openings in the envelope. Results from these tests form the basis of many of the latest wind load standards (i.e. AS-1170.2 (1989)).

The internal pressure is mainly controlled by the external pressure field around the building, and position and size of all openings connecting the interior of the building to the outside. The typical porosity (ε) in most nominally sealed, engineered buildings ranges from 10^{-4} to 10^{-3} and controls the generation of internal pressure in such buildings. With typical porosities being so small, a large opening (i.e. failure of a door) in the building envelope may generate significant internal pressures in strong wind conditions, and is an important consideration for ultimate design conditions.

The external and internal pressures and their interaction on a nominally sealed building and a building with large openings were studied in detail at the Wind Engineering Research Field Laboratory (WERFL) low-rise, full scale test building at Texas Tech University and reported by Ginger et al (1995).

EXPERIMENTAL SETUP AND PRESSURE MEASUREMENTS

The WERFL has been described in detail by Levitan and Mehta (1992). The WERFL consists of a 9.1 (B) × 13.7 (L) × 4.0 (H) m (30 × 45 × 13 ft) rotatable prefabricated metal test building shown in Fig 1. The approach terrain is typically open, the topography flat and the turbulence intensity $\sigma_u/\overline{U}$, at roof height is ~ 0.20. The nominal internal volume of the test building, V_I, is estimated at 470 m^3.

The pressure signals are low-pass filtered at 8 Hz, and sampled at 40 Hz for 15 mins for a single run. The mean, standard deviation, maximum and minimum pressure coefficients are defined as,

$$C_{\overline{p}} = \frac{\overline{p} - p_0}{(1/2)\rho\overline{U}^2}, \quad C_{\sigma_p} = \frac{\sigma_p}{(1/2)\rho\overline{U}^2}, \quad C_{\hat{p}} = \frac{\hat{p} - p_0}{(1/2)\rho\overline{U}^2}, \quad C_{\check{p}} = \frac{\check{p} - p_0}{(1/2)\rho\overline{U}^2} \qquad \text{where,}$$

$\overline{p}, \sigma_p, \hat{p}, \check{p}$, are the mean, standard deviation, maximum and minimum pressure in a 15 min run, p_0, is the reference atmospheric pressure, ρ is the density of air, and $\overline{U}$ is the mean wind speed at roof height.

Results from averaging up to six runs, for wind orientations (α) of 0° ± 5°, and 180° ± 5° (i.e. wind flow normal to the 30 ft walls) are presented in this paper. External pressures (p_E) were measured at tap locations 11407, 31407, 22306 and 42306 on the windward, leeward and side walls, and 51423 on the roof (Levitan and Mehta (1992)), and the internal pressure (p_I) was measured at different points within the building shown in Fig 1. The porosity (ε) of the nominally sealed WERFL test building is ~ 2.5×10^{-4}. Windward wall openings (A_W) of 0.4, 0.8, 2.0 m^2 (i.e. 1%, 2% and 5% of windward wall) and leeward wall openings (A_L) of 0.8, 2.0 m^2 (i.e. 2% and 5% of leeward wall) were also tested for a range of (A_W/A_L) ratios.

MEAN AND FLUCTUATING INTERNAL PRESSURES

The laws of conservation of mass and turbulent flow through an orifice are used to obtain the relationship between mean internal pressure ($\overline{p}_I$), mean external windward pressure ($\overline{p}_W$) and mean external leeward pressure ($\overline{p}_L$) in a building with total windward opening area A_W and total leeward opening area A_L,

$$C_{\overline{p}_I} = \frac{C_{\overline{p}_W}}{1 + (A_L/A_W)^2} + \frac{C_{\overline{p}_L}}{1 + (A_W/A_L)^2} \qquad (1)$$

The internal pressure will respond in some manner to the external pressure fluctuations. The factors that influence the internal pressure fluctuations are the external pressure field around the building, position and size of all openings connecting the interior to the exterior, the internal volume of the building and stiffness of the walls and roof. The internal pressures were found to be spatially well correlated within the WERFL test building.

When a building is flexible, the internal volume V_I, will expand and contract with the changes in internal pressure, and the internal pressure response is slowed. The natural frequency of the WERFL test building envelope is outside the range of the pressure fluctuations, and the deflections are considered to follow the wind loads in a quasi-static manner. Vickery (1986) showed that the internal pressure dynamics can be determined by increasing the internal volume of the building, V_I, by the ratio of the bulk modulus of air K_A, to the bulk modulus of the building K_B, to an effective internal volume of, $V_{Ie} = V_I\left(1+\left(K_A/K_B\right)\right)$. The walls and roof of the WERFL test building are constructed from flexible cladding material and the ratio of bulk modulus of the contained air to the bulk modulus of the building, K_A/K_B, was estimated at 1.5. The effective interior volume of the WERFL test building for dynamic pressure analysis $V_{Ie} = 470 \times (1 + 1.5) = 1175\ \mathrm{m}^3$.

Holmes (1979), described the motion of air in a building with a single dominant opening, using the principle of the Helmholtz resonator (i.e. Eqn 2), by an adiabatic process (coefficient n), in terms of internal pressure coefficient C_{p_I} and external pressure coefficient C_{p_E} on the face containing the opening of area A. The opening discharge coefficient is k, and the effective length of the slug of air moving in and out of the opening, $l_e = \sqrt{\pi A/4}$. Holmes (1979) carried out wind tunnel model studies and showed that internal pressure resonance occurs close to the undamped Helmholtz frequency, $f_0 = \left(1/2\pi\right)\sqrt{\left(nAp_0/\rho l_e V_{Ie}\right)}$.

$$\frac{\rho l_e V_{Ie}}{n p_0}\ddot{C}_{p_I} + \frac{\rho^2 V_{Ie}^2 \overline{U}^2}{4k^2 n^2 A p_0^2}\dot{C}_{p_I}\left|\dot{C}_{p_I}\right| + AC_{p_I} = AC_{p_E} \tag{2}$$

Openings in nominally sealed conventional building envelopes tend to be small and uniformly distributed, and the inertia term is negligible compared with the damping term in Eqn 2. Vickery (1986) and Harris (1990) studied the highly damped case with both windward and leeward openings, and showed that the response of internal pressure to changes in external pressure can be described by a characteristic frequency f_C;

$$f_C = \frac{1}{2\pi}\left(\frac{nkp_0\left(A_W^2 + A_L^2\right)^{3/2}}{\rho V_{Ie}\overline{U}A_W A_L\left(\Delta C_{\overline{p}}\right)^{1/2}}\right) \tag{3}$$

Here area A_W includes all openings on the surfaces having higher pressures than the interior while area A_L includes all openings on the surfaces having lower pressures than the interior, and $\Delta C_{\overline{p}} = C_{\overline{p}_W} - C_{\overline{p}_L}$ is the net mean pressure difference between these "windward" and "leeward" surfaces. The interpretation of Eqn 3, by Vickery (1986) is that external pressure fluctuations above the frequency f_C, are attenuated and not passed effectively into the building.

RESULTS

The characteristics of internal and external pressures on the nominally sealed WERFL test building and the building with large openings and the interaction between the pressures are reported in this paper.

For the nominally sealed building, for an approach wind flow normal to the 30 ft wall, the windward wall experiences mean positive pressure and the other walls and roof experience mean suction pressures. The mean pressure coefficients on the windward wall, side wall, roof, leeward wall and building interior were 0.70, -0.29, -0.34 and -0.14 respectively. The non-dimensional pressure spectra $fS_p(f)\big/\left(\tfrac{1}{2}\rho\overline{U}^2\right)^2$ for the windward wall, leeward wall, side wall, roof and interior of the nominally sealed building are presented in Fig 2. These spectra show that the internal pressure fluctuations contain much less energy compared with the external pressure fluctuations, and are significantly attenuated above 0.4 Hz with a sharp drop off. Assuming uniform porosity, $\varepsilon = 2.5 \times 10^{-4}$ over the whole nominally sealed WERFL test building envelope, for an approach wind flow normal to the 30 ft wall, Ginger et al (1995) showed that Eqn 3 yields $f_C = 0.53$ Hz.

The variation of the mean, standard deviation, maximum and minimum internal pressure coefficients over a range of windward and leeward openings (i.e. A_W/A_L ratios, neglecting background leakage) and the mean internal pressure curve from Eqn 1 for $C_{\overline{p}_W} = 0.65$ and $C_{\overline{p}_L} = -0.30$, are shown in Fig 3. The experimental mean internal pressure data agree with the theoretical analysis of flow through an orifice.

The internal pressures in the WERFL test building containing a single large opening were simulated using a finite difference numerical technique, and applying the external pressures measured on the wall at the opening (p_E) to the right hand side of Eqn 2. Part of a measured and simulated ($n = 1.4$, and $k = 0.65$ and 0.15)

internal pressure-time histories obtained for the WERFL test building with 5% single windward wall opening (i.e. A_W = 2.0 m^2) are given in Fig 4. The time histories in Fig 4 show that the numerical scheme using k = 0.15, simulates the measured internal pressures better than that using k = 0.65.

The windward wall pressure spectrum and the measured and simulated (k = 0.65 and 0.35) internal pressure spectra, $fS_p(f)/\left(\frac{1}{2}\rho\bar{U}^2\right)^2$ for the building with a 2% single windward wall opening (i.e. A_W = 0.8 m^2) are shown in Fig 5. In Fig 5, the simulated spectrum for k = 0.35 agrees with the measured internal pressure spectrum with a peak close to the Helmholtz frequency, f_0 of 1.58 Hz. The use of k = 0.15 to simulate the internal pressure provides better agreement with the measured internal pressure spectrum than k = 0.65.

The leeward wall pressure spectrum and the measured and simulated (k = 0.65 and 0.10) internal pressure spectra, $fS_p(f)/\left(\frac{1}{2}\rho\bar{U}^2\right)^2$ for the building with a 5% single leeward wall opening (i.e. A_L, = 2.0 m^2) are shown in Fig 6. In Fig 6, the simulated spectrum for k = 0.10 agrees with the measured internal pressure spectrum with a peak close to the Helmholtz frequency, f_0 of 2.00 Hz. The use of k = 0.10 to simulate the internal pressure shows better agreement with the measured internal pressure spectrum than k = 0.65.

Under steady flow conditions the orifice discharge coefficient k is ~ 0.65. However, this study shows that under highly fluctuating and reversed flow conditions, as in the case of a single dominant opening, the value of k is in the range of 0.10 to 0.35. Holmes (1979) also obtained a k value of 0.15 for a single windward opening and found similar resonance effects in his model study.

CONCLUSIONS

The following conclusions are drawn from a combination of theoretical analysis, numerical simulation and full scale measurements of internal pressures in the WERFL test building.

The mean and fluctuating internal pressure coefficients in a nominally sealed building are smaller in magnitude than the pressure on the external surfaces. Mean and fluctuating internal pressure coefficients increase with increasing windward/leeward open area ratio. These mean internal pressure coefficients agree with the values obtained from the theoretical analysis of turbulent flow through an orifice.

The effect of building flexibility on the internal pressure response is accounted for by increasing the nominal internal volume (V_I) by a factor of the ratio of bulk modulus of air (K_A) to the bulk modulus of the building (K_B). The experimental results are in good agreement with the theoretical analysis carried out using an effective interior volume of $V_{Ie} = V_I \times \left(1+\left(K_A/K_B\right)\right)$.

In the nominally sealed building, the internal pressures above the characteristic frequency f_C are significantly attenuated.

For the building with a single dominant opening on either the windward or leeward side, measured internal pressure data show an increase of pressure energy close to the Helmholtz frequency, f_0, compared with the pressure fluctuations at the opening. The time history and spectra of simulated internal pressure with a discharge coefficient, k, between 0.10 and 0.35 is in good agreement with the measured internal pressures.

REFERENCES

AS-1170.2 (1989), "Australian Standard SAA Loading Code Part 2", Wind Loads, Standards Australia.

Ginger, J. D., Yeatts, B. B. and Mehta K. C., (1995), "Internal Pressures in a Low-rise Full Scale Buildings", (Submitted to 9 Int. Conf. on Wind Engg, New Delhi, India, Jan 1995).

Harris, R. I. (1990), "The Propagation of Internal Pressures in Buildings", Jour. of Wind Engineering and Industrial Aerodynamics, Vol. 34, 169-184.

Holmes, J. D. (1979), "Mean and Fluctuating Internal Pressures Induced by Wind", Proc. 5th Int. Conf. on Wind Engg., Colorado USA, Vol. 1, 435-450.

Levitan, M. L. and Mehta, K. C. (1992), "Texas Tech Field Experiments for Wind Loads Part I and II", Jour. of Wind Engineering and Industrial Aerodynamics, Vol. 43, 1565-1588.

Vickery, B. J. (1986), "Gust Factors for Internal Pressures in Low rise Buildings", Jour. of Wind Engineering and Industrial Aerodynamics, Vol. 23, 259-271.

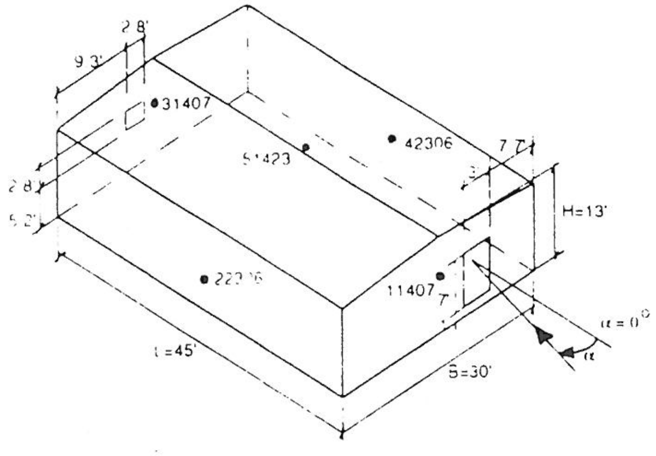

Fig 1. Wall openings and pressure tap locations •, on the full scale low-rise WERFL test building.

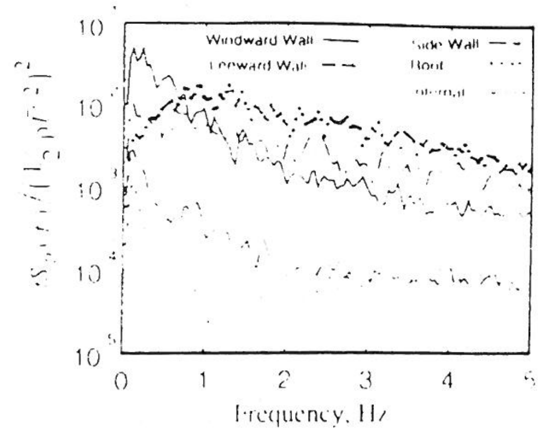

Fig 2. Windward wall, leeward wall, side wall, roof and internal pressure spectra on the nominally sealed WERFL building.

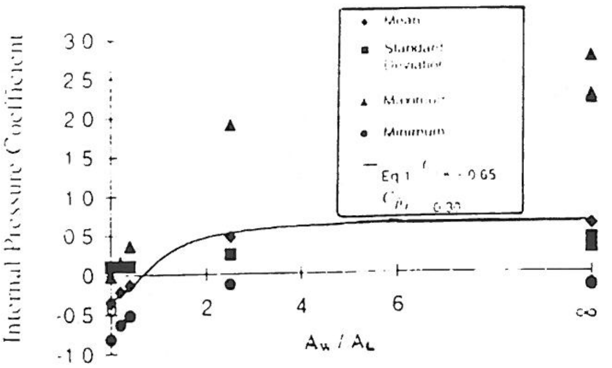

Fig 3. Internal pressure coefficients vs. Aw/AL (background leakage is neglected).

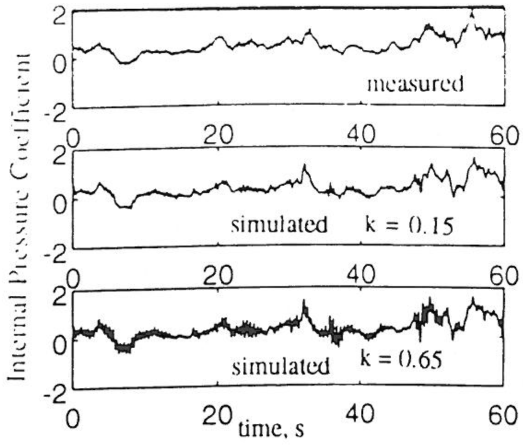

Fig 4. Portion of measured and simulated (k = 0.15 k = 0.65) internal pressure vs. time, single 5% windward wall opening.

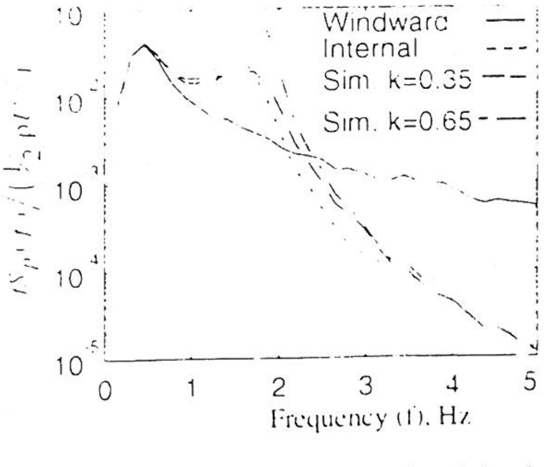

Fig 5. Windward wall, and measured and simulated (k = 0.35 and k = 0.65) internal pressure spectra on the building with a single 2% windward wall opening.

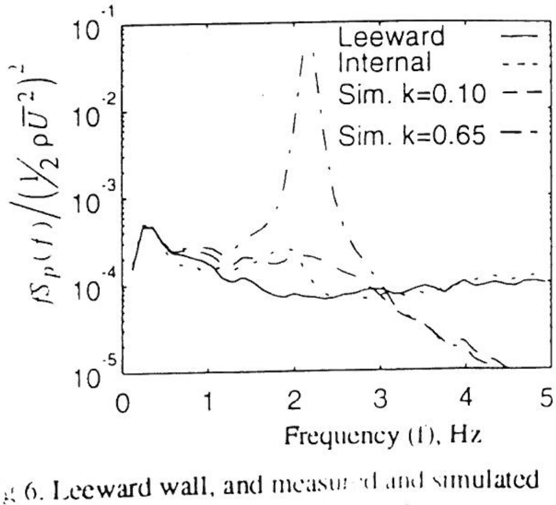

Fig 6. Leeward wall, and measured and simulated (k = 0.10 and k = 0.65) internal pressure spectra on the building with a single 5% leeward wall opening.