A Comparative Study on the Internal Pressure of Building Wind Codes (APEC-WW Report)

Chii-Ming Cheng   Yuan-Lung Lo

Wind Engineering Research Center, Tamkang University, Taiwan

ABSTRACT
The variation of the internal pressure coefficient is one of the many reasons that causes the difference on the building design wind loads among the building codes in the APEC region. This report made comparative study on the building internal pressure from several wind codes. A low-rise building example was used to demonstrate the variation of the design wind pressure based on different building codes.

KEYWORDS: internal pressure, building, porosity, wind load, wind code.

1 INTRODUCTION

The design wind load of a wall or roof is the pressure difference between external and internal pressures. It has the general form of $p = (qC_{dyn}C_{pe})_{exteranl} - (qC_{dyn}C_{pi})_{\text{int}ernal}$. In which, q is the wind velocity pressure; C_{dyn} is the dynamic coefficient; C_{pe} and C_{pi} are the exernal and internal pressure coefficient, respectively. If we exam the variation of design wind laod based on different wind codes, it will show that the provision on the internal pressure makes one of the largest difference. The internal pressure of buildings with different type of sealing conditions did attract some wind engineering researchers' attention but obviously not the building designers or the building code regulators. As far as author's knowledge, there has been large span coal storage dome and building façade failure in Taiwan that can be at least partially attributed to the inappropriate use of internal pressure.

Holmes (1979) first proposed a Helmholtz resonant model to describe the transient response of a suddenly appeared opening. It indicated that the transient internal pressure response of a suddenly appeared opening exhibits an initial overshoot followed by a steady state dynamic response. The initial overshoot of a lightly damped system can be significant. Later on, several other researchers (Liu & Saathoff, 1982; Vickery & Bloxham, 1992; Sharma & Richards,1997; Yu, Lou & Sun, 2006) proposed modified version of the Helmholtz resonant model. Liu and Saathoff suggested that when air passing through very small cracks, the flow becomes laminar, therefore, only the mean component of the internal pressure need to be considered. The studies of Stathopoulos & Luchian (1989) and Vickery & Bloxham (1992) indicated that the overshooting phenomenon would occur only in a smooth flow environment. Therefore, only the steady state dynamic response of the internal pressure is important. Sharma & Richards (2003) further indicated that when wind direction is oblique to the building wall, an "eddy dynamics over the opening" caused by the tangential flow rather than the "free stream turbulence" could significantly increase the peak internal pressure.

This paper will first briefly review the theory of building internal pressure. Then, the provisions and articles on building internal pressure from several wind codes were collected to make comparative study. A low-rise building example similar to the one given in APEC-WW 2005 was used to demonstrate the variation of the design wind pressure based on different building codes.

2 SUMMARY OF THEORIES

2.1 *Mean internal pressure*

The mean internal pressure coefficient of a building with multiple openings distributed over different walls can be derived from the continuity equation, and have the following form: (Holmes 2001, Liu 1991)

$$C_{pi} = \frac{C_{pL} + a^2 C_{pW}}{1 + a^2} \quad , \quad a = \frac{A_W}{A_L} \tag{1}$$

in which,

C_{pi} : mean internal pressure coefficient,

C_{pw}, C_{pL} : mean external pressure coefficient on windward and leeward sides,

A_w = average wall porosity × total windward wall area.

A_L = average wall porosity × total areas of leeward and side walls.

Equation (1) can be applied not only for the openings such as doors and windows, but also for the leakages on a nominally sealed building. However, if the cracks on the wall are so small that the air flow passing through it becomes laminar, then the mean internal pressure coefficient becomes (Liu, 1991)

$$C_{pi} = \frac{C_{pL} + bC_{pW}}{1 + b} \quad , \quad b = \frac{b_W}{b_L} \quad , \quad b_j = \frac{L_j W_j^3}{d_j} \ , \ j = W,\ L \tag{2}$$

C_{pi} is the mean internal pressure coefficient. C_{pw} and C_{pL} are the mean external pressure coefficient on windward and leeward sides. L_j, W_j, d_j are the length, width and depth of the jth group cracks. Subscript W is for the windward side and subscript L is for the leeward sides.

2.2 *Fluctuating internal pressure*

For this report, the linearized version of Sharma & Richards' model (1997) is used to evaluate the dynamic response of internal pressure. The "eddy dynamics over the opening" effect is not included.

$$\frac{\rho_a L_e V_0}{\gamma c A_0 p_a} \ddot{C}_{pi} + \frac{C_L \rho_a q V_0^2}{2(\gamma A_0 p_a)^2} \left|\dot{C}_{pi}\right| \dot{C}_{pi} + C_{pi} = C_{pw} \tag{3}$$

where c : the discharge coefficient of the opening ;

γ : the specific heat ratio for air ;

ρ_a : the density of the ambient air ;

p_a : the pressure of the ambient air ;

A_0 : the opening area ;

C_L : inertia coefficient ;

L_e : $L_e = L_0 + C_I\sqrt{A_0}$ the effective length of the air slug at the opening ;

L_0 : physical length of the opening ;

V_0 : the building volume ;

q : $0.5\rho_a \bar{U}_h^{\,2}$ the reference dynamic pressure ;

$\bar{U}_h$: the ridge-height velocity ;

Let $\left|\dot{C}_{pi}\right|\dot{C}_{pi} = \beta\sigma_{\dot{C}_{pi}}\dot{C}_{pi}$, where $\sigma_{\dot{C}_{pi}}$ is the RMS of $\dot{C}_{pi}$, and β is an equivalent coefficient to linearize the damping term. Then the governing equation can be written in the following linear form:

$$\ddot{C}_{pi} + 2\xi_{eq}\omega_H\dot{C}_{pi} + \omega_H^2 C_{pi} = \omega_H^2 C_{pw} \tag{4}$$

The Helmholtz frequency is given by:

$$f_H = \frac{1}{2\pi}\sqrt{\frac{\gamma c p_a A_0}{\rho_a L_e V_0}} = \frac{1}{2\pi}\frac{a_s A_0^{1/4}}{\sqrt{(C_I/c)V_0}} \tag{5}$$

and the equivalent damping ratio is:

$$\xi_{eq} = \frac{C_L c q V_0 \beta \sigma_{\dot{C}_{pi}}}{4\omega_H \gamma L_e A_0 p_a} \tag{6}$$

Since there is a $\sigma_{\dot{C}_{pi}}$ term in the numerator, ξ_{eq} has to be determined through iteration method. It was further suggested that the equivalent damping ratio can be put into a simpler form: (Yu et al. 2006)

$$\xi_{\mathrm{eq}} = \tau\left(\frac{\bar{C}_{pw}\bar{U}_h^2}{a_s^{\,2}}\right)^{2/3}\frac{V_0^{2/3}}{A_0}$$

$$\tau = \left[\frac{(C_L\beta|\chi_{aa}|)^2\pi}{64(C_I/c)^2}\frac{f_H S_u(f_H)}{\bar{U}_h^2}\right]^{\frac{1}{3}} \tag{7}$$

If the equivalent damping ratio is small (Vickery & Bloxham, 1992), the dynamic response of internal pressure fluctuations can be expressed as the sum of the background part and resonant part:

$$\sigma_{C_{pi}}^2 = \int_0^\infty S_{C_{pw}}(f)df + \frac{f_H\pi}{4\xi_{eq}}S_{C_{pw}}(f_H) \tag{8}$$

Applying the quasi-steady theorem and let the aerodynamic admittance to 1.0 for simplicity, then,

$$S_{C_{pw}}(f) = \left(\frac{2\bar{C}_{pw}}{\bar{U}_h}\right)^2 S_u(f) \tag{9}$$

In which, $S_u(f)$ is the von Karman spectrum. The peak internal pressure coefficient can be estimated by:

$$C_{pi,peak} \cong \bar{C}_{pi} + g\sigma_{C_{pi}} \quad , \quad g = 3.0 \sim 3.5$$

$$\sigma^2_{C_{pi}} = \int_0^\infty S_{C_{pw}}(f)df + \frac{f_H \pi}{4\xi_{eq}} S_{C_{pw}}(f_H)$$

$$= \left(\frac{2\bar{C}_{pw}}{\bar{U}_h}\right)^2 \left[\int_0^\infty S_u(f)df + \frac{f_H \pi}{4\xi_{eq}} S_u(f_H)\right] \qquad (10)$$

$$C_{pi,peak} \cong \bar{C}_{pi} \left[1 + 2g\frac{\bar{C}_{pw}}{\bar{C}_{pi}} \frac{\left(\sigma_u^2 + \frac{f_H \pi}{4\xi_{eq}} S_u(f_H)\right)^{\frac{1}{2}}}{\bar{U}_h}\right]$$

A cubic shaped building was used for the numerical demonstration, so that the wall area and internal volume is assumed to be $A_g = 5V_0^{2/3}$. The porosity ratio, $r = A_0 / A_g$, was selected as the controlling parameter. For the other coefficients, the values for the Texas Tech University test building mentioned in (Yu et al. 2006) were adopted. In which, V_0=497m^3, C_I=0.886, C_L=2.5, c=0.88, a_s=350m/s, U_h=30m/s, I_u=0.18, L_u=160m, $\bar{C}_{pw} = 0.75$, $\beta = (8/\pi)^{0.5}$ .Shown in Figure 1 is the percentage of the background part and resonant part of the internal pressure fluctuations calculated by the aforementioned procedure. When the porosity ratio, r>0.01, the Helmholtz resonant part counts for nearly 90% of the fluctuating internal pressure. In other words, for building with dominant opening with $r = A_0 / A_g \geq 0.01$, the peak internal pressure coefficient can be estimated by a simplified formula:

$$C_{pi,peak} \cong \bar{C}_{pi} \left[1 + 2g\frac{\bar{C}_{pw}}{\bar{C}_{pi}} \frac{\left(\frac{f_H \pi}{4\xi_{eq}} S_u(f_H)\right)^{\frac{1}{2}}}{\bar{U}_h}\right] \qquad (11)$$

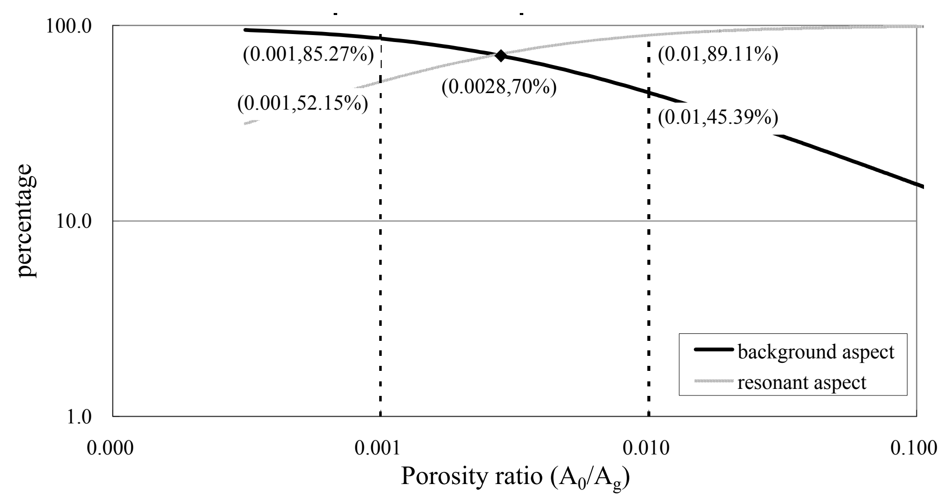


Figure 1 the percentage of background and resonant part of RMS internal pressure coefficient.

3 CLASSIFICATION OF INTERNAL PRESSURE

Based on the previous research works and to reflect the current wind code practice, the characteristics of internal pressure are categorized into three parts according to the building sealing conditions:

(1) Building is properly sealed; windows and doors are design to withstand design wind speed; only uniformly distributed small cracks are to be considered; the wall porosity is smaller than 0.1%. Under such circumstance, only the mean internal pressure need to be considered, and Liu's mean internal pressure formula for cracks can be used.

$$C_{pi} = \frac{C_{pL} + bC_{pW}}{1+b} \quad , \quad b = \frac{b_W}{b_L}$$

Assuming cracks are uniformly distributed over walls and roof of a building, and the width and depth are constant for all cracks, then,

$$b = \frac{b_W}{b_L} = \frac{1}{4} \quad , \quad \text{assuming } C_{pW} = 0.8 \ , \ C_{pL} = -0.5$$

$$C_{pi} = \frac{C_{pL} + bC_{pW}}{1+b} = -0.24$$

(2) Building has uniformly distributed small opening on all walls; the wall porosity is greater than 0.1%, but less than 1%. In this case, both mean and fluctuation of internal pressure need to be considered.

Mean internal pressure

$$C_{pi} = \frac{C_{pL} + a^2 C_{pW}}{1+a^2} \quad , \quad a = \frac{A_W}{A_L}$$

For a building with uniform openings over its four walls and roof, a=0.25, and assuming $C_{pW} = 0.8$ *and* $C_{pL} = -0.5$, the mean internal pressure coefficient is calculated to be:

$$C_{pi} = \frac{C_{pL} + a^2 C_{pW}}{1+a^2} = -0.44$$

Fluctuating internal pressure

The peak internal pressure coefficient can be estimated by:

$$C_{pi,peak} \cong \bar{C}_{pi}\left[1 + 2g\frac{\sigma_{C_{pi}}}{\bar{U}}\right] \quad , \quad g = 3.0 \sim 3.5$$

$$\sigma^2_{C_{pi}} = \int_0^\infty S_{C_{pw}}(f)df + \frac{f_H \pi}{4\xi_{eq}} S_{C_{pw}}(f_H)$$

(3) Building with dominant openings, damage of windows and doors to be considered; the wall porosity is greater than 1%, both mean and fluctuation of internal pressure need to be considered.

Mean internal pressure

In the case of dominant opening, mean internal pressure coefficient is same as the external mean pressure at the opening,

$$\bar{C}_{pi} = \bar{C}_{p,ext} = 0.8 \quad or \quad -0.5$$

Fluctuating internal pressure

For building with dominant openings, peak internal pressure coefficient can be estimated by:

$$C_{pi,peak} \cong \bar{C}_{pi}\left[1+2g\frac{\left(\frac{f_H\pi}{4\xi_{eq}}S_u(f_H)\right)^{\frac{1}{2}}}{\bar{U}_h}\right] \tag{12}$$

4 PRACTICE OF INTERNAL PRESSURE IN WIND CODES

Provisions and articles on building internal pressure from several wind code were collected to make comparative study. These building wind codes are: ISO4354-1997, NBC-1990, AIJ-1996, AIK-2000, AS/NZS1170.2-2002, BS6399-2:1997, ASCE 7-02. Since the definitions of basic design wind speed varied from3-second gust to hourly mean, the original internal pressure coefficients appear to be quite different. In this section, the internal pressure coefficients are tabulated by the classification of small crack, small openings and dominant openings. Then, all pressure coefficients are converted to the 10-minute average wind speed. Then the peak internal pressure coefficients can be compared on the same basis. The internal pressures from different wind codes although are not the same, but the scattering is significantly reduced.

Table 1 Basic information on the internal pressure coefficient of various wind codes

		ISO	NBC	AIJ	AIK	AS/NZS	BS	ASCE
Basic wind speed		10 min	1 hr	10 min	10 min	3 sec	1 hr	3sec
Cpi,original		$C_{fig,int}$	C_{pi}	C_{pi}	C_{pi}	(GC_{pi})	C_{pi}	(GC_{pi})
Multiplier	magnification	$C_{dyn,int}$	C_g	G	G	---	---	---
	Reduction	---	---	---	---	K_c=0.8 ~ 1.0	C_a=0.5 ~ 1.0	R=0.5 ~ 1.0
small cracks (<0.1%)		Yes	Yes	---	---	Yes	Yes	Yes
small openings (0.1%~1%)		Yes	Yes	Yes	Yes	Yes	---	---
dominant opening (>1%)		Yes	Yes	---	---	Yes	Yes	Yes

Listed in Table 1 is the basic information on the internal pressure coefficient of various wind codes. Besides the differences on the basic wind speed and the corresponding internal pressure coefficients, AS/NZS has the action combination (reduction) factor for the combination of wind loads, BS and ASCE adopt the reduction factors for the consideration of the ‘opening /volume” ratio. Some of the wind codes use rather obscure categories to classify the porosity, nevertheless, the mentioned three categories: small crack, small openings and dominant openings, are used based on the value of the internal pressure coefficients. The internal pressure provisions in ISO, NBC and AS/NZS covered all three categories; AIJ and AIK considered the small openings only; BS and ASCE covered both the small cracks and dominant openings.

Table 2 Internal pressure coefficients for sealed building with small cracks (porosity ratio<0.1%)

For small cracks (<0.1%)		ISO	NBC	BS	AS/NZS	ASCE
Basic wind speed		10 min	1 hr	1hr	3s	3s
Cpi,original		$C_{fig,int}$=0.0,-0.3	C_{pi}=-0.3, 0.0	C_{pi}=-0.3 ~ -0.2	(GC_{pi})=0.0,-0.2	(GC_{pi})=±0.18
Cpi,10-minute		$C_{fig,int}$=0.0,-0.3	C_{pi}=-0.267, 0.0	C_{pi}=-0.267 ~ -0.178	(GC_{pi})= 0.0,-0.416	(GC_{pi})=±0.375
Multiplier	Magnification	$C_{dyn,int}$=1.0	C_g=1.0	---	---	---
	Reduction	---	---	C_a=0.5 ~ 1.0	K_c=0.8~1.0	---
Cpi, peak, 10-minute		$C_{fig,int}C_{dyn,int}$= 0.0,-0.3	C_gC_{pi}= -0.267, 0.0	C_a C_{pi}= -0.267 ~ -0.178	K_c (GC_{pi})= 0.0,-0.416	(GC_{pi})= ±0.375

U_{3s} : U_{10min} : U_{1hr} = 2.08 : 1.00 : 0.89
◎ all reduction factor equals to 1.0
◎ C_{pe}=＋0.8 or -0.5

Listed in Table 2 are the internal pressure coefficients for buildings with small cracks only (porosity ratio less then 0.1%). Among the 5 wind codes, only ASCE7has a positive internal pressure at 0.375; ISO, NBC BS and AS/NZS have either zero or negative internal pressure, AS/NZS has the lowest negative value at -0.416. Table 3 listed the internal pressure coefficients for 'small openings' category, i.e., buildings with porosity ratio in between 0.1% to 1%. When the internal pressure is negative, the adjusted peak internal pressure coefficients for the 10-minute wind speed are in between -0.4 to -0.62, i.e., rather consistent among all wind code. However, ISO, AIJ and AIK do not have positive internal pressure. In other word, uniformly distributed small openings on all walls are presumed in these wind codes. NBC use the same positive internal pressure as the negative. AS/NZS has the highest positive value of 1.25 when considering porosity on the windward wall only. Table 4 is the internal pressure coefficients for buildings with dominant openings. The wall porosity ratio in this category is greater than 1%. BS has a relatively lower value of -0.34 to 0.64. The negative internal pressure coefficients of the rest of the wind codes, ISO, NBC, AS/NZS and ASCE vary from -1.04 (AS/NZS) to -1.4 (ISO). ISO doest not consider the positive internal pressure and the highest positive internal pressure coefficients of NBC, AS/NZS and ASCE are 1.25. 1.66 and 1.15, respectively.

Table 3. Internal pressure coefficients for nominally sealed building with cracks and small openings (0.1%<porosity ratio<1%)

		ISO	NBC	AIJ	AIK	AS/NZS
Basic wind speed		10 min	1 hr	10min	10min	3s
Cpi,original		$C_{fig,int}$=-0.7	C_{pi}=±0.7	C_{pi}=0.0,-0.4	C_{pi}=0.0,-0.4	(GC_{pi})=-0.3 ~ 0.6
Cpi,10-minute		$C_{fig,int}$=-0.7	C_{pi}=±0.623	C_{pi}=0.0,-0.4	C_{pi}=0.0,-0.4	(GC_{pi})=-0.624 ~ 1.248
Multiplier	magnification	$C_{dyn,int}$=1.0	C_g=1.0	G=1.0 (main frame) G=1.3 (cladding)	G=1.3 (main frame) G=1.3 (cladding)	---
	Reduction	---	---	---	---	K_c=0.8 ~ 1.0
Cpi, peak, 10-minute		$C_{fig,int}C_{dyn,int}$= -0.7	C_gC_{pi}=±0.623	G C_{pi}= 0.0,-0.4 (main frame) G C_{pi}= 0.0,-0.52 (cladding)	G C_{pi}= 0.0,-0.52	K_c (GC_{pi})= -0.624 ~ 1.248

U_{3s} : U_{10min} : U_{1hr} = 2.08 : 1.00 : 0.89
◎ all reduction factor equals to 1.0
◎ C_{pe}=＋0.8 or -0.5

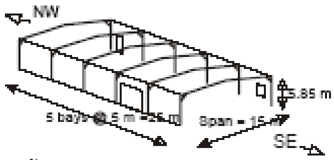
Table 4 Internal pressure coefficients for building with dominant openings (porosity ratio>1%)

		ISO	NBC	BS	AS/NZS	ASCE
Basic wind speed		10 min	1 hr	1hr	3s	3s
Cpi,original		$C_{fig,int}$= -0.7	C_{pi}= ±0.7	C_{pi}= 0.75C_{pe} ~ 0.9C_{pe}	(GC_{pi})= -0.3~C_{pe}	(GC_{pi})= ±0.55
Cpi,10-minute		$C_{fig,int}$= -0.7	C_{pi}= ±0.623	C_{pi}= 0.67C_{pe} ~ 0.8C_{pe}	(GC_{pi})= -0.624~2.08C_{pe}	(GC_{pi})= ±1.146
Multiplier	magnification	$C_{dyn,int}$= 2.0	C_g= 2.0	---	---	---
	Reduction	---	---	C_a= 0.5 ~ 1.0	K_c= 0.8 ~ 1.0	R_i= 0.5 ~ 1.0
Cpi, peak, 10-minute		$C_{fig,int}C_{dyn,int}$= -1.4	C_gC_{pi}= ±1.246	(C_{pe}=＋0.8) C_a C_{pi}= 0.536 ~ 0.64 (C_{pe}=－0.5) C_a C_{pi}= -0.335 ~ -0.4	(C_{pe}=＋0.8) K_c (GC_{pi})= -0.624 ~ 1.664 (C_{pe}=－0.5) K_c (GC_{pi})= -1.04 ~ -0.624	R_i (GC_{pi})= ±1.146
U_{3s} : U_{10min} : U_{1hr} = 2.08 : 1.00 : 0.89 ◎ all reduction factor equals to 1.0 ◎ C_{pe}=＋0.8 or -0.5						

5 EXAMPLE FOR COMPARATIVE STUDY

A slightly modified low-rise building example given in the APEC-WW 2005 workshop was used to demonstrate the effect of the internal pressure coefficient variation on the differences of the design wind load. The example is briefly stated below:

- A steel-framed warehouse in an flat, open country area
- 10-minute basic design wind speed (10m height, open terrain) : 26 m/s
- Dimensions of building:
  eaves height : 5.85 m, dimensions : 25 m × 15 m.
  gable roof with 5 degrees pitch.
  average roof height = 5.85 + 0.5(7.5 tan 5_o) = 6.2 m



- Steel portal frame construction. Frames are spaced at 5 m.
- The external pressure coefficient: 0.8 (windward), -0.5 (leeward).
- All size reduction factor ignored.

Determine the structural design wind pressure of the portal frames of the building (walls and roof), considering

(1) building is properly sealed, doors and windows are safe during storms, building porosity is less than 0.1%;
(2) building have uniformly distributed small opening, the wall porosity is in between 0.1-1.0 %;
(3) the doors and windows may be damaged during storms, i.e., dominant opening to be considered.

The calculated design pressure, in kN/m^2, are listed in table 5, 6 and 7 and the upper and lower bounds from each wind code are plotted in Figure 2.

Table 5 Design wind pressure for building with small cracks (porosity<0.1%). (kN/m^2)

	Walls			Roof		Walls			Roof	
	Windward	Leeward	Side	Windward	Leeward	Windward	Leeward	Side	Windward	Leeward
ISO	$C_{pi,peak(10\ min)} = 0.0$					$C_{pi,peak(10\ min)} = -0.3$				
	0.397	-0.248	-0.348	-0.397	-0.348	0.480	-0.166	-0.265	-0.315	-0.265
NBC	$C_{pi,peak(10\ min)} = 0.0$					$C_{pi,peak(10\ min)} = -0.267$				
	0.397	-0.248	-0.348	-0.397	-0.348	0.470	-0.175	-0.274	-0.324	-0.274
BS	$C_{pi,peak(10\ min)} = -0.178$					$C_{pi,peak(10\ min)} = -0.267$				
	0.446	-0.199	-0.299	-0.348	-0.299	0.470	-0.175	-0.274	-0.324	-0.274
AS/NZS	$C_{pi,peak(10\ min)} = 0.0$					$C_{pi,peak(10\ min)} = -0.416$				
	0.397	-0.248	-0.348	-0.397	-0.348	0.511	-0.134	-0.233	-0.283	-0.233
ASCE	$C_{pi,peak(10\ min)} = 0.375$					$C_{pi,peak(10\ min)} = -0.375$				
	0.294	-0.351	-0.450	-0.500	-0.450	0.500	-0.145	-0.245	-0.294	-0.245

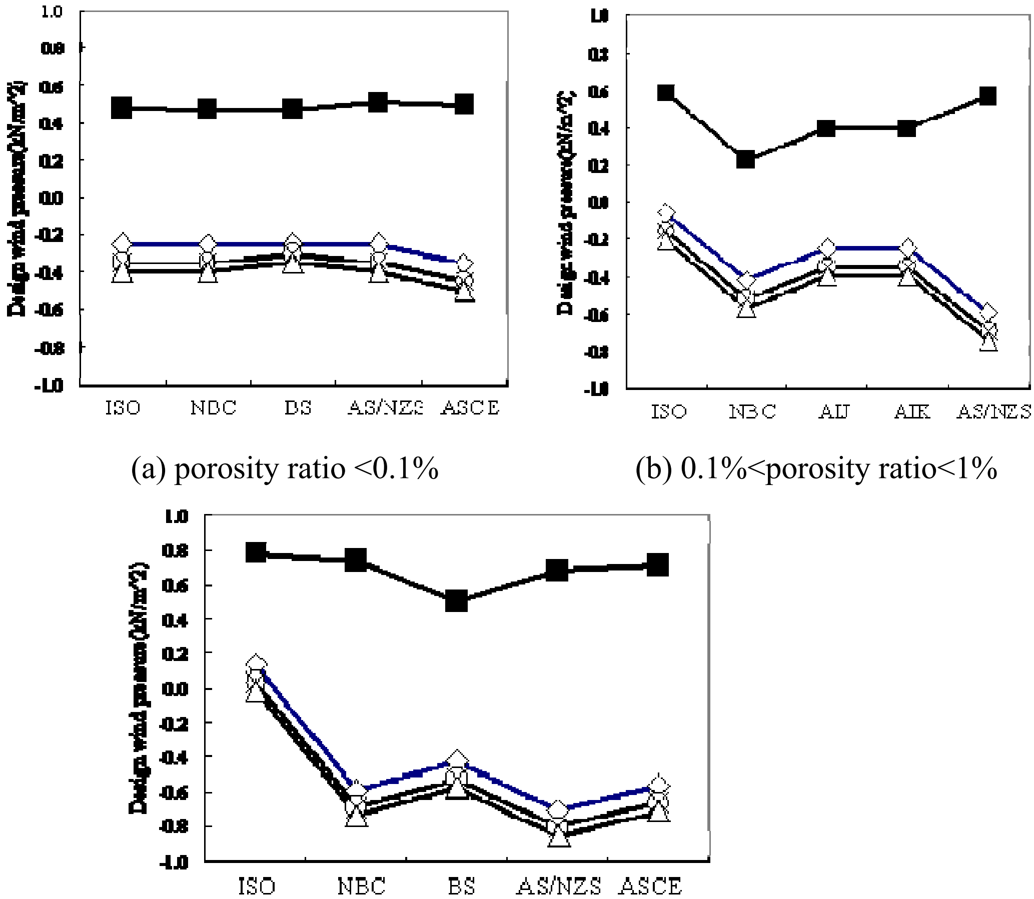
Table 6 Design wind pressure building with cracks and small openings (0.1%<porosity<1%).

	Wall			Roof		Wall			Roof	
	Windward	Leeward	Side	Windward	Leeward	Windward	Leeward	Side	Windward	Leeward
ISO	---					$C_{pi,peak(10\ min)} = -0.7$				
	---	---	---	---	---	0.589	-0.056	-0.155	-0.205	-0.155
NBC	$C_{pi,peak(10\ min)} = 0.623$					$C_{pi,peak(10\ min)} = -0.623$				
	0.226	-0.419	-0.519	-0.568	-0.519	0.568	-0.077	-0.177	-0.226	-0.177
AIJ	$C_{pi,peak(10\ min)} = 0.0$					$C_{pi,peak(10\ min)} = -0.4$				
	0.397	-0.248	-0.348	-0.397	-0.348	0.507	-0.139	-0.238	-0.287	-0.238
AIK	$C_{pi,peak(10\ min)} = 0.0$					$C_{pi,peak(10\ min)} = -0.52$				
	0.397	-0.248	-0.348	-0.397	-0.348	0.540	-0.106	-0.205	-0.255	-0.205
AS/NZS	$C_{pi,peak(10\ min)} = 1.248$					$C_{pi,peak(10\ min)} = -0.624$				
	0.055	-0.591	-0.690	-0.740	-0.690	0.568	-0.077	-0.176	-0.226	-0.176

(kN/m^2)

Table 7 Design wind pressure for building with dominant openings (porosity>1%). (kN/m^2)

	Wall			Roof		Wall			Roof	
	Windward	Leeward	Side	Windward	Leeward	Windward	Leeward	Side	Windward	Leeward
ISO	---					$C_{pi,peak(10\ min)} = -1.4$				
	---	---	---	---	---	0.781	0.136	0.037	-0.013	0.037
NBC	$C_{pi,peak(10\ min)} = 1.246$					$C_{pi,peak(10\ min)} = -1.246$				
	0.055	-0.590	-0.689	-0.739	-0.689	0.739	0.094	-0.006	-0.055	-0.006
BS	$C_{pi,peak(10\ min)} = -0.335$ (with $C_{pe} = -0.5$)					$C_{pi,peak(10\ min)} = -0.4$ (with $C_{pe} = -0.5$)				
	0.489	-0.156	-0.256	-0.305	-0.256	0.507	-0.139	-0.238	-0.287	-0.238
BS	$C_{pi,peak(10\ min)} = 0.536$ (with $C_{pe}=0.8$)					$C_{pi,peak(10\ min)} = 0.64$ (with $C_{pe}=0.8$)				
	0.250	-0.395	-0.495	-0.544	-0.495	0.222	-0.424	-0.523	-0.573	-0.523
AS/NZS	$C_{pi,peak(10\ min)} = -0.624$ (with $C_{pe} = -0.5$)					$C_{pi,peak(10\ min)} = -1.04$ (with $C_{pe} = -0.5$)				
	0.568	-0.077	-0.176	-0.226	-0.176	0.683	0.037	-0.062	-0.112	-0.062
AS/NZS	$C_{pi,peak(10\ min)} = 1.664$ (with $C_{pe}=0.8$)					$C_{pi,peak(10\ min)} = -0.624$ (with $C_{pe}=0.8$)				
	-0.059	-0.705	-0.804	-0.854	-0.804	0.568	-0.077	-0.176	-0.226	-0.176
ASCE	$C_{pi,peak(10\ min)} = 1.146$					$C_{pi,peak(10\ min)} = -1.146$				
	0.083	-0.563	-0.662	-0.712	-0.662	0.712	0.066	-0.033	-0.083	-0.033



(a) porosity ratio <0.1%

(b) 0.1%<porosity ratio<1%

(c) porosity ratio>1%

Figure 2 Design wind pressure for building with (a)small cracks, (b)small openings, (c)dominant opening. (■: windward wall, ◇: leeward wall, ○: side wall, △: windward roof, ×: leeward roof)

Figure 2 shows that, for building with small porosity (r<0.1`%), all wind codes under study have surprisingly uniform design wind pressure for all building components. When the porosity ratio is between 0.1 to 1.0 %, ISO has the highest positive design pressure for the windward wall and the smallest negative design pressure for the rest building components. That is caused by the lacking of positive internal pressure coefficient in ISO. AS/NZS has the highest design pressure of the negative pressure walls due to the largest positive internal pressure coefficient among all wind codes. For building have porosity ratio greater than 1.0%, ISO again has the highest positive design pressure and the smallest negative design pressure for the same reason.

6 CONCLUDING REMARKS

In this report, the building internal pressure theory was briefly reviewed. Based on the previous research works, the characteristics of internal pressure is categorized into three parts according to the building sealing conditions: (i) building with uniformly distributed small cracks, the wall porosity is smaller than 0.1%.; (ii) buildings with uniformly distributed small openings, the wall porosity is greater than 0.1%, but less than 1%.; (iii) building with dominant openings, damage of windows and doors to be considered; the wall porosity is greater than 1%. The internal pressure coefficient from several wind codes were collected to make a comparative study. These building wind codes are: ISO4354-1997, NBC-1990, AIJ-1996, AIK-2000, AS/NZS1170.2-2002, BS6399-2:1997, ASCE 7-02. A slightly modified low-rise building example given in the APEC-WW 2005 workshop was use to demonstrate the effect of the internal pressure coefficient variation on the differences of the design wind load.

REFERENCES

1. ASCE 7-02 Minimum Design Loads for Buildings and Other Structures, 2002.
2. AIJ Recommendation for Loads on Buildings, Architectural Institute of Japan, 1996.
3. Architectural Institute of Korea, Standard Design Loads for Buildings, 2000.
4. SAA Loadings Code, part 2-wind forces AS1170.2-2002, Australian Standard, 2002.
5. Supplement to the National Building Code of Canada 1990, National Research Council of Canada, 1990.
6. British Standard, Loading for Buildings-Part2: Code of Practice for Wind Loads, BS 6399-2:1997, 1997.
7. ISO4354-1997, Wind actions on structures, 1997.
8. Holmes, J.D., 1979, "Mean and fluctuating pressure induced by wind," Proceedings of 5th International Conference on Wind Engineering, Colorado State University, pp.435-450.
9. Holmes, J.D., 2001, Wind Loading of Structures. Spon Press.
10. Liu, H., Rhee, K.H., "Helmholtz oscillation in building models." J. Wind Eng. and Ind. Aero. 24(1986) 95-115.
11. Liu, H., 1991, Wind Engineering: A Handbook for Structural Engineers, Prentice Hall.
12. Vickery, B.J., 1986, "Gust factors for internal pressures in low rise buildings," J. Wind Eng. and Ind. Aero. 23(1986) 259-271.
13. Vickery, B.J., Bloxham, C., 1992, "Internal pressure dynamics with a dominant opening," J. Wind Eng. and Ind. Aero. 41-44(1992) 193-204.
14. Vickery, B.J. 1994, "Internal pressures and interactions with the building envelope," J. Wind Eng. and Ind. Aero. 53(1994) 125-144.
15. A.R. Woods, P.A. Blackmore, The effect of dominant openings and porosity on internal pressures., 1995. J. Wind Eng. and Ind. Aero. 51(1995) 167-177.
16. Ginger, J.D., Mehta, K.C., Yeatts, B.B., 1997, "Internal pressures in a low-rise full-scale building," J. Wind Eng. and Ind. Aero. 72, 163-174.
17. Chaplin. G. C., Randall, J.R, Backer, C.J., 2000, "The turbulent ventilation of a single opening enclosure," J. Wind Eng. and Ind. Aero. 85(2000) 145-161.
18. Stathopoulos, T., 2005, "Wind loads on low buildings: current and future design trends," The Sixth Asia-Pacific Conference on Wind Engineering (APCWE-VI) Seoul, Korea, 177-192
19. Sharma, R.N., Richards, P.J., 2003, "The influence of Helmholtz resonance on internal pressures in a low-rise building," J. Wind Eng. and Ind. Aero. 91(2003) 807-828.
20. Yu S.-C., Lou W.-J., Sun B.-N., 2006, "Wind-induced internal pressure fluctuation of structure with single windward opening," J. Zhejiang Univ. Science A., 7(3):415-423.