Comparison of APEC Wind Loading Codification and Revision of Chinese National Code

Yaojun Ge[a], Xinyang Jin[b], Shuyang Cao[c]

[a]*SLDRCE of Tongji University, 1239 Siping Road, Shanghai, China*
[b]*China Academy of Building Research, 30 Beisanhuan Donglu, Beijing, China*
[c]*SLDRCE of Tongji University, 1239 Siping Road, Shanghai, China*

ABSTRACT: This paper overviews wind loading codes and standards in the Asia-Pacific Region, in particular 15 countries and areas, and introduces new revision of national load code for the design building structures (GB50009-2002) in China. A general description of wind loading model is given as a famous wind load chain described by four variables including velocity pressure, exposure factor, pressure coefficient, and gust response factor. Through the extensive calculations for three building examples, these four important variables of wind loads are evaluated and compared with mean values and coefficients of variation. The main results of the comparison show some differences among 15 economies, and the reasons and further incorporation are discussed and suggested. A new version of wind load code for design of building structures has been presented.

KEYWORDS: Wind loading code, velocity pressure, exposure factor, pressure coefficient, gust response factor, new revision.

1 INTRODUCTION

After John Smeaton of England originated a formula for wind pressure loads in 1759, wind actions on structures and structural elements have to be considered in the design as one partial load among various design loads. In order to determine wind actions on structures, each country needs to have appropriate codification to specify wind loading and to determine wind induced responses in structural design, which results in numerous wind loading codes and standards in the world, for example, the ASCE Code[1], the Australian and New Zealand Standard[2], the National Building Code of Canada[3], the Japan Recommendations[4], the European Standard[5], the International Organization for Standardization[6], and so on. Under the globalization of construction industry and the development of unified international codes and standards, it is necessary to better understand and compare the underlying differences among international or regional wind loading standards in order to further incorporate for future alignments of wind loading and even wind resistance design codes and standards. The previous studies on the major international standards mentioned above have found that the dominant contributions to the scatter in wind loading were the varying definitions of wind field characteristics, including mean wind velocity profile and some turbulence wind parameters[7,8]. Some other published papers and reports for the Asia-Pacific Economic Cooperation (APEC) countries and areas have shown the significant importance on extreme wind speeds of tropical cyclones and the other extremes of benign monsoons and local thunderstorm downdrafts for design[9,10].

With the support of the Centre of Excellence (COE) and the Global COE in Wind Engineering at Tokyo Polytechnic University in Japan, a new practical outcome of comparative study on wind loading codes and standards among a regional area composed of a group of bordering countries or areas have been launched through five Workshops on Regional Harmonization of Wind Loading and Wind Environmental Specifications in the Asia-Pacific Economies (APEC-WW) since 2004. At the 2nd APEC-WW in Hong Kong in 2005, three particular examples were purposely assigned for each country or area representing three typical building models, including a low-rise building, a medium-rise building and a high-rise building. In the subsequent two Workshops, the design wind loads on three building examples have been evaluated and compared in accordance with the wind loading codes and standards of 15 Asia-Pacific Economies[11]. The basic results of three examples and the obvious reasons for differences were summarized by J. Holmes, Y. Tamura and P. Krishna[12]. A series of papers related to benchmark analysis of these three typical buildings were published and presented in the 7th Asia-Pacific Regional Conference on Wind Engineering[13,14,15,16,17,18,19], and the further discussion were made on regional wind velocity map, unified terrain categories and model code for low-rise buildings in the 5th APEC-WW Workshop at Chinese Taipei in 2009.

With the background of the APEC-WW Workshops, this paper is going to make further quantitative and statistical comparison and contrast of wind loading components based on various codes and standards in 15 Asia-Pacific Economies, including the Australian and New Zealand Standards (AN)[2], the National Building Code of Canada (CC)[3], the China National Standard (CS)[20], the Code of Practice on Wind Effects of Hong Kong (HK)[21], the Indian Standard Code (IC)[22], the Standard National Indonesia (IS)[23], the Recommendations for Loads on Buildings of Japan (JR)[4], the Korean Building Code (KC)[24], the Malaysian Standard (MS)[25], the National Structural Code of Philippines (PC)[26], the Singapore Standard (SS), the Taiwan Building Code (TC)[27], the Wind Load Code of Thailand (TC)[28], the United States' ASCE Code[1] and the Loads and Actions Norm for Design of Vietnam (VN)[29].

A general description of wind loading model can be given by a well known process, a wind loading chain, proposed by A.G. Davenport[30], and consisted of four components

$$W = qC_eC_pC_g \tag{1}$$

in which q is a reference wind pressure or velocity pressure mainly depending on wind velocity, C_e is an exposure factor to adjust for the terrain conditions and the height, C_p is a pressure coefficient related to structural shape and C_g is a gust response factor (GRF) due to turbulent wind actions (gust loading factor GLF) or structural dynamic response (dynamic response factor DRF). These four components are numerically calculated and statistically analyzed through three building examples and based on 15 wind loading codes and standards of Asia-Pacific Economies in this paper.

The revision of Chinese design code for building structures (GB50009-2002) began with load code and various material code in 2008 and is going to be finished in the middle of 2011. A new version of load code for building structures will be issued and put in practice gradually in 2012. Wind loading is one the most important tasks of the revision in the load code, and there will be some distinct modifications, for example, wind velocity profile, peak wind pressure on claddings, along wind dynamic response, cross wind and torsion dynamic response, and so on. Revision draft of wind load is introduced briefly in the last part of this paper.

2 VELOCITY PRESSURE AND BASIC WIND VELOCITY

Reference velocity pressure q can be simply described by the square of reference wind velocity U as follows:

$$q = \frac{1}{2}\rho U^2 \tag{2}$$

in which ρ is a air density and has the value of 1.16 kg/m^3 to 1.25 kg/m^3 with the average of 1.22 kg/m^3 and the coefficient of variation of 2% listed in Table 1[11], and the value of reference wind velocity U basically depends upon three conditions, including reference height, averaging time and return period, which are discussed as follows.

2.1 *Reference height*

Wind velocity varies with height above the ground in the atmospheric boundary layer, which can be described by wind velocity profiles with either Power Law or Logarithmic Law in most wind loading codes or standards. The values of design wind velocity are different at different levels, and are used to be calculated from the basic level or the reference height, at which the reference or basic wind velocity is defined. Table 1 shows that the unified reference height of 10 m is used in all 15 economies' codes.

Table 1. Characteristics of Reference Wind Velocity and Velocity Pressure

Economy	ρ (kg/m^3)	Reference Height (m)	Averaging time		Return period		Pressure Ratio η_q
			Time	Ratio	Years	Ratio	
Australian & New Zealand*	1.20	10	3-s	1.5	500	1.22	3.349
Canada	1.25	10	1-h	0.92	50	1.0	0.882
China	1.25	10	10-m	1.0	50	1.0	1.042
Hong Kong	1.20	10	1-h	0.92	50	1.0	0.846
India	1.20	10	1-h	0.92	50	1.0	2.250
Indonesia	1.20	10	3-s	1.5	50	1.0	2.250
Japan	1.22	10	10-m	1.0	100	1.07	1.164
Korea	1.25	10	10-m	1.0	100	1.07	1.145
Malaysia	1.20	10	3-s	1.5	50	1.0	2.250
Philippines	1.22	10	3-s	1.5	50	1.0	2.288
Singapore	1.20	10	3-s	1.5	50	1.0	2.250
Taiwan (Chinese Taipei)	1.16	10	10-m	1.0	50	1.0	0.967
Thailand	1.25	10	1-h	0.92	100	1.07	1.009
United States	1.25	10	1-h	0.92	50	1.0	0.882
Vietnam	1.20	10	10-m	1.0	50	1.0	1.000
Mean value	1.22	10		1.14		1.02	1.445
Coefficient of variation	0.02	0.00		0.23		0.03	0.42

* The values from Australian & New Zealand Standards did not include in statistical analysis.

2.2 *Averaging time*

The values of wind velocity are largely controlled by the averaging time since natural wind velocity fluctuates with time. The shorter averaging time is the higher value of wind velocity will be since the maximum wind velocity sample is always chosen in consideration. There are generally three kinds of averaging time adopted in wind loading codes and standards, that is, 3-seconds, 10-minutes and 1-hour. Theoretically, the averaging time should be determined by dominant extreme wind events, for example, 3 seconds for thunderstorm downdrafts or outflows, 10 minutes for tropical cyclones or typhoons and 1 hour for extratropical gales. In practice, each code or standard provides only one out of three kinds of averaging time shown in Table 1. If the ratio of wind velocity values is assumed to be 1.5:1.0:0.92 for the averaging time of 3-seconds:10-minutes:1-hour, the mean value and coefficient of variation of wind velocity values due to averaging time were computed and listed in Table 1 based on 14 economies' codes or standards excluding Australian & New Zealand Standards, which follows Deaves & Harris model.

2.3 *Return period*

Design wind velocity is also governed by the return period in the way that its value increases with the increase of a return period. The return period for the design wind velocity is 50 years, 100 years or 500 years among 15 economies' codes or standards in Table 1. Although there are good reasons for selecting one or another, the most popular return period is 50 years. With the assumption of Gumbel Distribution of wind velocity, the wind velocity ratio of R-year to L-year return periods can be expressed as follows:

$$\frac{U_R}{U_L} = a_L - b_L \ln\left[-\ln\left(1-\frac{1}{R}\right)\right] \quad (3)$$

in which U_R and U_L are the wind velocities for R-year and L-year return periods, respectively, a_L and b_L are constants for L-year return periods, and R is a return period. Taking the result from the statistical study for wind velocity in Shanghai[31], a_L and b_L are equal to 0.625 and 0.096 for 50-year return period, respectively, and accordingly the ratio of wind velocity values is 1:1.07:1.22 for the return periods of 50-years:100-years:500-years. The statistical analysis results of different wind velocity values due to return period are summarized in Table 1.

2.4 *Pressure ratio*

The velocity pressure ratio η_q is defined for representing relative velocity pressure as follows.

$$\frac{U_R}{U_L} = a_L - b_L \ln\left[-\ln\left(1-\frac{1}{R}\right)\right] \quad (4)$$

in which ρ_0 is a reference density of 1.20kg/m^3, which is the most popular value among 15 economies' codes and standards, and U_0 is a basic wind velocity defined in the conditions of the reference height of 10m, the averaging time of 10 minutes and the return period of 50 years. The velocity pressure ratios η_q for 15 economies' codes or standards are computed and listed in Table 1, and the mean value and the coefficient of variation of the pressure ratios excluding the value due to Australian & New Zealand Standards were calculated to be equal to 1.445 and 42.4%. Among the relative differences of air density, averaging time and return period, the most dominant difference comes from averaging time from Table 1.

3 TERRAIN CATEGORY AND EXPOSURE FACTOR

It has been well recognized that the variation of wind velocity above the ground can be described by wind profile, which is related to drag on the wind as it blows over upstream terrain. Since the drag mostly depends upon the surface roughness of the upstream terrain different roughness effects produce different types of terrain categories or different wind profiles. In order to represent these varying roughness conditions, different wind profiles are specified in different wind loading codes with the pattern of profile law and the number of terrain categories. Although there are three patterns of wind profile, including Power Law, Logarithmic Law and Deaves & Harris Model, currently used in 15 economies' codes and standards, the most popular one is Power Law, for example, 13 out of 15 economies' codes and standards shown in Table 2, described as

$$U_z = U_0\left(\frac{z}{z_0}\right)^{\alpha} \quad (5)$$

in which U_0 is the reference wind velocity at the reference height of z_0, U_z is the particular wind velocity at the height of z, and α is the exponent of Power Law due to surface roughness of upstream terrain.

The number of terrain categories specified in 13 economies' codes and standards is also very different. For example, Hong Kong has only one terrain category whereas Japan has five categories as shown in Table 2. The maximum and the minimum values of exponent α and the corresponding gradient heights δ are collected in Table 2 (through personnel communication with the participants of APEC-WW). In order to make the comparison and contrast of exposure factors, the basic values of α and δ are also provided for transferring wind pressure from the basic terrain roughness, in which basic wind velocity is defined, to the maximum or the minimum terrain roughness. This transformation can be done only through the condition that wind velocity always keeps in the same value at the gradient height. The exposure factor ratio η_e, therefore, can be defined as follows.

$$\eta_e = \left(\frac{\delta_b}{z_0}\right)^{2\alpha_b}\left(\frac{z_0}{\delta_s}\right)^{2\alpha_s} \tag{6}$$

in which α_b and δ_b are the exponent of Power Law and the gradient height (m) related to the basic terrain roughness, α_s and δ_s are the exponent of Power Law and the gradient height (m) related to the specific terrain roughness, and z_0 is the reference height assumed to be 10m in Table 2. The exposure factor ratios η_e in the maximum and the minimum values for 13 economies' codes or standards were computed and listed in Table 2, and the mean values and the coefficients of variation of the exposure factor ratios were calculated to be equal to 1.22 and 15% in the minimum terrain category and 0.360 and 67% in the maximum terrain category, respectively. The CoV of exposure factor ratio in the maximum terrain category is much larger than that in the minimum terrain category. The main reason can be attributed to the fact that the exponent α_{max} is much more scattered than the exponent α_{min} shown in Table 2.

Table 2. Characteristics of Terrain Categories and Exposure Factor

Economy	Law	N.	Minimum		Basic		Maximum		η_e	
			α_{min}	δ_{min}	α_b	δ_b	α_{max}	δ_{max}	Min	Max
Australian & New Zealand*	D&H	4								
Canada	Power	3	0.14	270	0.14	270	0.36	400	1.00	0.177
China	Power	4	0.12	300	0.16	350	0.30	450	1.38	0.318
Hong Kong	Power	1	0.11	500	0.11	500	0.11	500	1.00	1.000
India**	Power	4	0.10	250	0.14	270	0.34	500	1.32	0.176
Indonesia	Power	4	0.09	213	0.11	274	0.20	457	1.19	0.449
Japan	Power	5	0.10	250	0.15	350	0.35	650	1.53	0.156
Korea	Power	4	0.10	250	0.15	300	0.33	500	1.46	0.210
Malaysia	Power	4	0.12	250	0.15	300	0.30	500	1.28	0.265
Philippines	Power	4	0.09	213	0.11	274	0.20	457	1.19	0.449
Singapore*	Log	1								
Taiwan (Chinese Taipei)	Power	3	0.15	300	0.15	300	0.32	500	1.00	0.227
Thailand**	Power	3	0.14	270	0.14	270	0.36	600	1.00	0.132
United States	Power	3	0.11	210	0.15	270	0.25	360	1.38	0.448
Vietnam	Power	3	0.07	250	0.09	300	0.14	400	1.18	0.679
Mean value			0.111	271	0.135	310	0.274	483	1.22	0.360
Coefficient of variation			0.20	0.26	0.16	0.20	0.30	0.16	0.15	0.67

* The values of Australian & New Zealand and Singapore Standards did not include in statistical analysis.
** The values of gradient heights for India and Thailand Standards were assumed according to other standards.

4 PRESSURE COEFFICIENT AND CLADDING PRESSURE

The comparison of pressure coefficients related to structural shape were made among 15 economies' codes and standards through two typical models, including a low-rise building and a medium-rise building.

4.1 *Low-rise building example*

The low-rise building is a typical steel-framed warehouse located in a rural area with open terrain all around in Fig. 1. Design wind speeds at the top of the frame, 6m, are assumed to be equal to 39m/s, 26m/s and 23m/s for the averaging times of 3-seconds, 10-minutes and 1 hour, respectively.

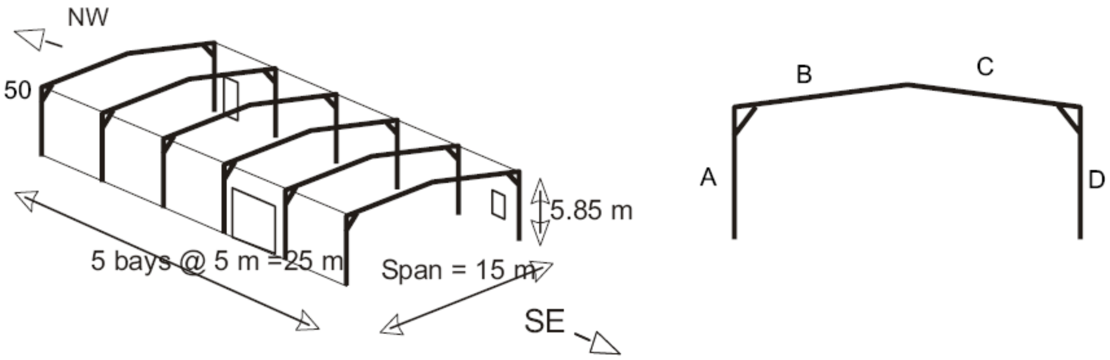


Figure 1. Low-rise building.

The main calculations include the net pressure coefficients at A, B, C and D of gable walls or roof of the frames at the end of the building and the maximum and minimum wind pressures on the 3m×4m roller door on SW wall and the 1m×1m window on NE wall, in which internal pressures from a large opening were considered for some wind directions[11,12]. Table 3 only lists the mean values and the coefficients of variation based on 15 economies' codes and standards whereas the detailed results from each economy's code or standard can be found in the reference[12]. For the frame structure, the coefficients of variation of net pressure coefficients range between 20% and 31% in SW wind and between 44% and 61% in NW wind, respectively. The maximum or minimum design pressures on the roller door and the small window have better statistical results, the CoV being within 13% and 26%.

Table 3. Mean and CoV values of pressure coefficient and cladding pressure of low-rise building

Wind Direction or Part	Statistical Value	Net Pressure Coefficient of Frame				Wind Pressure (kPa)	
		A	B	C	D	Max	Min
Wind SW or Door	Mean	0.05	-1.53	-1.14	-1.08	0.71	-0.65
	CoV	-	0.31	0.23	0.20	0.13	0.16
Wind NW or Window	Mean	-0.67	-0.92	-0.83	-0.66	0.80	-1.22
	CoV	0.44	0.61	0.57	0.44	0.14	0.26

4.2 *Medium-rise building example*

The medium-rise building is a 48m high, 60m long and 30m wide office building located in a tropical city with suburban terrain for all directions in Fig. 2. The building is of reinforced concrete frame construction with a facade consisting of mullions spaced at 1.5m. The building is assumed to be air-conditioned with non-opening windows, and can be considered effectively sealed with regard to internal pressures. Design wind speeds at the top of the building, 48m, are assumed to be equal to 56m/s, 36m/s and 33m/s for the averaging times of 3-seconds, 10-minutes and 1 hour, respectively, and a turbulence intensity of 0.20 at the top is assumed.

Table 4 compares the cladding pressures on window elements near the corners at the top level. Although the pressure coefficients are scattered with the CoV of 48% for the maximum values and 40% for the minimum values[11], respectively, the comparison is better in the cladding pressures, the CoV being about 21% to 22%[12].

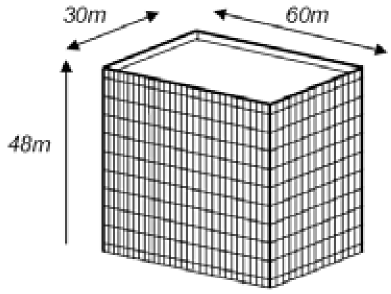


Figure 2. Medium-rise building.

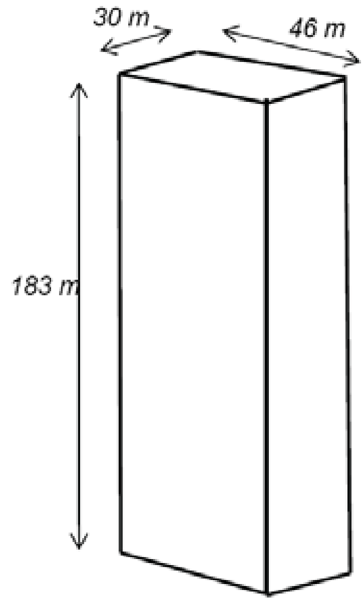


Figure 3. High-rise building.

Table 4. Characteristics of cladding pressure and base force of medium-rise building

Economy	Coefficient		Pressure (kPa)		GRF	Base Force	
	Max	Min	Max	Min	GLF	Shear (kN)	Moment (MNm)
Australian & New Zealand	1.20	-1.95	2.25	-3.67	1.00	5727	150
Canada	0.92	-1.08	1.80	-2.11	2.00	5332	142
China	1.00	-2.00	1.22	-2.44	1.00	3282	99
Hong Kong	1.00	-1.40	1.87	-2.62	1.00	4573	116
India	0.82	-1.20	1.55	-2.26	1.00	4957	131
Indonesia	1.20	-1.95	2.24	-3.64	1.00	7477	210
Japan	2.71	-3.00	2.14	-2.37	2.04	5061	132
Korea	1.92	-3.20	1.53	-2.54	2.20	5534	134
Malaysia	1.20	-1.95	2.26	-3.70	1.00	5698	152
Philippines	0.80	-1.60	1.32	-2.85	0.80	5026	128
Singapore	1.20	-1.95	2.26	-3.67	1.00	6556	163
Taiwan (Chinese Taipei)	1.80	-1.10	1.58	-2.95	1.73	3738	100
Thailand	1.00	-1.20	1.86	-2.23	2.09	3737	97
United States	1.77	-3.21	1.41	-2.56	0.85	4108	117
Vietnam	1.30	-0.98	2.44	-1.83	1.00	6423	165
Mean value	1.20	-1.85	1.85	-2.76	1.31	5149	136
Coefficient of variation	0.48	0.40	0.21	0.22	0.39	0.22	0.21

5 GUST LOADING FACTOR AND DYNAMIC RESPONSE FACTOR

Among the 15 economies' standards and codes, gust response factor (GRF) is specified to take into account of turbulent wind actions on stiff structures with gust loading factor (GLF), such as the above-mentioned low-rise building and medium-rise building, and structural dynamic response of very flexible structures with dynamic response factor (DRF), such as the high-rise building in Fig. 3. Table 4 also shows the comparison of gust loading factors and base forces of the medium-rise building due to 15 economies' codes[11]. The mean value and the CoV of GLF are equal to 1.31 and 39%, which shows quite large differences. The calculated values of base forces, however, reached to quite small CoV, 22% in base shears and 21% in base bending moments[12], which demonstrates no significant correlation between GLF and base force.

The high-rise building, shown in Fig. 3, was 183m high, with the rectangular cross section of 46m by 30m located in urban terrain. The building was assumed to have an average density of 160 kg/m3, and linear mode shapes in both sway directions with natural frequencies of 0.20Hz. The structural damping ratio was specified to be 0.012 for base force calculation. Design wind speeds at the top of the building, 183m, was assumed to be 59m/s for 3-seconds averaging time, 41m/s for 10-minutes and 37m/s for 1 hour, respectively, and a turbulence intensity of 0.17 at the top was also assumed. For wind direction normal to the 46m wall, only along-wind loading and base force are discussed in the following.

Table 5. Characteristics of wind loading and base force of high-rise building

Economy	q_H kN/m^2	C_e	C_p	C_g	W kN/m^2	Base Force Shear (kN)	Base Force Moment (MNm)
Australian & New Zealand	2.089	0.800	1.30	1.05	2.281	21500	2085
Canada	0.856	0.781	1.30	2.40	2.086	19844	1994
China	1.051	0.694	1.30	1.32	1.252	13867	1554
Hong Kong	0.821	0.820	1.10	2.53	1.874	15817	1583
India	0.821	0.725	1.43	2.23	1.898	17648	1819
Indonesia	2.089	0.781	1.20	0.94	1.958	21292	2264
Japan	1.025	0.649	1.21	2.44	1.964	21540	2162
Korea	1.051	0.602	1.30	2.20	1.810	19637	2017
Malaysia	2.089	0.704	1.30	1.05	2.007	21870	2110
Philippines	2.123	0.714	1.30	0.80	1.576	16100	1574
Singapore*	-	-	-	-	-	-	-
Taiwan (Chinese Taipei)	0.975	0.667	1.30	2.12	1.792	17076	1748
Thailand	0.856	0.714	1.30	2.10	1.669	15091	1539
United States	0.856	0.667	1.30	2.20	1.633	18305	1795
Vietnam*	-	-	-	-	-	-	-
Mean value	1.285	0.717	1.28	1.80	1.831	18430	1865
Coefficient of variation	0.43	0.09	0.06	0.35	0.14	0.14	0.13

* The values due to Singapore and Vietnam Standards were not available.

Table 5 shows the characteristics of wind loading and base force of the high-rise building. Since design wind speeds were provided in three kinds of averaging time among 13 economies' standards or codes excluding Singapore and Vietnam standards, the four standards representing Australian & New Zealand, Indonesia, Malaysia and Philippines adopted design wind speed of 3-seconds averaging time while the four standards of China, Japan, Korea and Taiwan (Chinese Taipei) used 10-minutes design wind speed, and the rest five standards of Canada, Hong Kong, India, Thailand and United States used 1-hour values. These design wind speed values resulted in quite large CoV, 43%, of the velocity pressure qH at the top of the building[11]. The exposure factor Ce was defined as

$$C_e = \frac{\int_0^H (\frac{z}{H})^{2\alpha} dz}{H} = \int_0^H (\frac{z}{H})^{2\alpha} d(\frac{z}{H}) = \frac{1}{1+2\alpha} \tag{7}$$

in which H is the height of the building and α is the exponent of Power Law. The calculated mean value and CoV of C_e are equal to 0.717 and 9% in Table 5. The pressure coefficient C_p was specified in each standard or code, and its mean value and CoV are 1.28 and 6%. Both C_e and C_p have very small value of CoV. The GLF or DRF C_g was provided in each standard or code, and the mean value and CoV are 1.80 and 35%, respectively. It is interesting to see that the CoV of the wind loading W is only about 14%, which is much smaller than that of q_H or C_g. In order to find out the reason of this difference, the coefficient of variation of the product of $q_H \cdot C_g$ is purposely calculated, and the CoV of the product is tremendously reduced to 14%, which shows significant correlation between velocity pressure and GLF or DRF. Furthermore, the calculated values of base forces supported to similar CoVs, 14% in base shears and 13% in base bending moments[12].

6 REVISION OF WIND LOADING CODE

The major revision of wind loading code covers wind velocity profile, peak wind pressure on claddings, along wind dynamic response factor, and cross wind dynamic response factor.

6.1 *Wind velocity profile*

With the ever-growing urbanization in China, the scale and area of cities are expanded quickly in recent decades. Some urban groups such as Yangtze River Delta, Pearl River Delta and Bohai Sea Ring Area have been formed. The thickness of boundary layer and the gradient of wind velocity shall be affected to some extent, and the corresponding modification should be made in the new wind loading code. Table 6 lists the new modification in the thickness of boundary layer, by which the thickness of boundary layer increases from 400m to 450m in Class C and from 450m to 550m in Class D, respectively.

Table 6. Modification in thickness of boundary layer

Category	Exponential value α	Old thickness (m)	New thickness (m)
Class A	0.12	300	300
Class B	0.16	350	350
Class C	0.22	400	450
Class D	0.30	450	550

6.2 *Peak wind pressure on claddings*

In the current version of the wind load code, only one case of impermeable was prescribed. The building with dominant opening will be considered and two more cases are provided in the new version as follows:

1) The area ratio of dominant opening to one side wall $\leq$ 0.3: 0.7(external pressure coefficient);
2) The area ratio of dominant opening to one side wall $>$0.3: 1.0(external pressure coefficient).

For elements their area is great than 25m^2, a reduction factor of 0.8 for Table 7, and 0.6 for Table 8 (absolute value great than 1.0 only) may be used. Logarithmic linear interpolation may be used for intermediate values of 1～25m^2 , and can be calculated as:

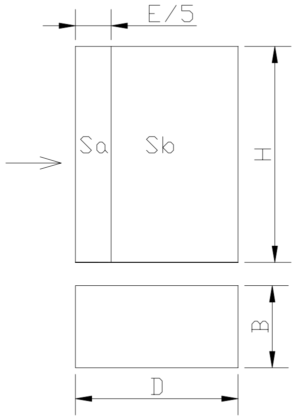
$$\mu_{sl} = \mu_{sl}(1) + [\mu_{sl}(25) - \mu_{sl}(1)]\log A \tag{8}$$

In calculating of wind load for claddings, a gust factor μ_{gz} should be used, and it is expressed as:

$$\beta_{zg} = 1 + 2gI_{10}\left(\frac{z}{10}\right)^{-\alpha} \tag{9}$$

where: g is the peak factor, g=2.5; I_{10} is the turbulent intensity at the height of 10m, takes 0.13, 0.16, 0.23 and 0.34 for exposure category of A, B, C and D, respectively.

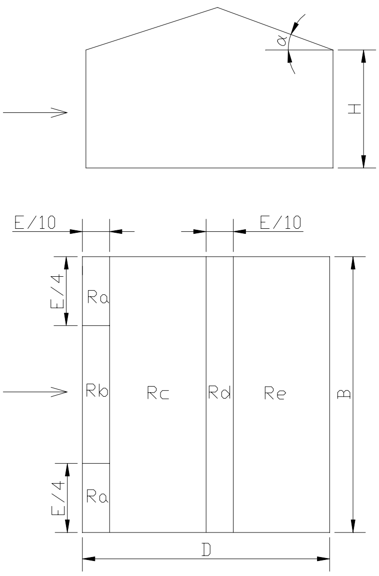
Table 7. Local pressure coefficients for walls



Front wall		1.0
Side wall	Sa	$-1.4\mu_H/\mu_z$
	Sb	$-1.0\mu_H/\mu_z$

Note: E takes the smaller of 2H and B.

Table 8. Local pressure coefficients for roofs



α		≤5	15	30	≥45
Ra	H/D ≤0.5	-1.8 +0	-1.4 +0.2	-1.5 +0.7	-0 +0.7
	H/D ≥1.0	-2.5 +0	-2.0 +0.2		
Rb		-2.0 +0	-1.5 +0.2	-1.2 +0.7	-0 +0.7
Rc		-1.2 +0	-0.3 +0.2	-0.2 +0.4	-0
Rd		-0.6 +0.2	-1.6 +0	-0.5 +0	-0.3 +0
Re		-0.6 +0	-0.4 +0	-0.4 +0	-0.2 +0

Note: Linear interpolation may be used for intermediate values

6.3 *Along wind dynamic response factor*

For tall buildings and towers, the modified along wind dynamic response factor β_z is defined as:

$$\beta_z = \frac{\bar{p}_z + \tilde{p}_z}{\bar{p}_z} \tag{10}$$

where $\bar{p}_z$ is static wind load, and $\tilde{p}_z$ is equivalent load of dynamic response.

β_z can be calculated by expression as:

$$\beta_z = 1 + 2gI_{10}B_{1z}\sqrt{1+R^2} \tag{11}$$

where R is the resonance response factor, and β_{1z} is the background response factor.

The resonance response factor R may be calculated by following expression:

$$R^2 = \frac{\pi n_n}{6\zeta_1} \frac{x_1^2}{n_1\left(1+x_1^2\right)^{4/3}} \tag{12}$$

$$x_1 = \frac{30n_1}{\sqrt{w_0}} \tag{13}$$

where n_1 is the natural frequency of structure, and ζ_1 is the damping ratio of structure.

The background response factor may be approximated as:

$$B_{1z} = kH^{a_H}\rho_x\rho_z\frac{\phi_1(z)}{\mu_z(z)} \tag{14}$$

where $\phi_1(z)$ is the first mode shape of structure, H is the height of structure, and ρ_z and ρ_x are the coefficients of spatial correlation in vertical and horizontal direction, respectively, and can be expressed as:

$$\rho_z = \frac{10\sqrt{H+60e^{-H/60}-60}}{H} \tag{15}$$

$$\rho_x = \frac{10\sqrt{B+50e^{-B/50}-50}}{B} \tag{16}$$

The experiential parameters k and a_H are given in Table 9.

Table 9. Experiential parameters k and a_H

Category		A	B	C	D
Buildings	k	1.012	0.651	0.314	0.119
	a_H	0.155	0.198	0.261	0.346
Towers	k	1.374	0.888	0.431	0.165
	a_H	0.185	0.228	0.291	0.376

6.4 *Cross wind dynamic response factor*

The new cross wind dynamic response factor β_{za} is defined as:

$$\beta_{za} = \sqrt{1+R_L^2} \tag{17}$$

$$R_L = K\sqrt{\frac{\pi S_F(f_1)/\gamma_{CM}^2}{4(\zeta_{s1}+\zeta_{a1})}} \tag{18}$$

$$K = \frac{1}{2\beta+1}\cdot\frac{1}{2\alpha+\beta+1}\cdot\left(\frac{z}{H}\right)^{\beta} / \left(\frac{z}{H}\right)^{2\alpha} \tag{19}$$

$$\zeta_{a1} = \frac{0.0025[1-(U/9.8)^2](U/9.8)+0.000125(U/9.8)^2}{[1-(U/9.8)^2]^2+0.0291(U/9.8)^2} \tag{20}$$

$$S_F(f_1) = \frac{S_p \beta_k (n_1 / f_p)^{\gamma} C_{sm}(n_1)}{\left\{1-(n_1 / f_p)^2\right\}^2 + \beta_k (n_1 / f_p)^2} \tag{21}$$

7 CONCLUSIONS

This paper examines the differences and similarities of wind loading codes or standards in 15 Asia-Pacific Economies. Following wind loading chain, four variables including velocity pressure, exposure factor, pressure coefficient and gust response factor were evaluated and compared with mean values and coefficients of variation. From the comparison and contrast of wind loading calculations of three typical buildings, the conclusions and further harmonization can be reached as follows.

1) Velocity pressure q mainly depends on four parameters including air density, reference height, averaging time and return period. Since both air density and return period have very small coefficients of variation of 2% and 3%, respectively, and the reference height of 10 m is uniformly adopted in all 15 economies' codes or standards, the only major variation comes from averaging time, which has the CoV of 23% and contributes over 40% CoV to velocity pressure. In order to harmonize the calculation of velocity pressures, further incorporation in the Asia-Pacific Region should be considered in developing agreed regional wind velocity maps for 3-second, 10-minute and 1-hour extremes with 50-year return period.

2) The number of terrain categories is from one in Hong Kong to five in Japan, and the exponent values of Power Law are between 0.07 and 0.15 in the minimum category and between 0.11 and 0.36 in the maximum category, respectively. These scattered values resulted in the exposure factor CoVs of 15% in the minimum category and 67% in the maximum category. Future harmonization should begin with simplification and unification of terrain categories for surface roughness exposures, in particular for basic or reference terrain category.

3) Pressure coefficient has rather large coefficients of variation, for example, 20% to 61% in the low-rise building and 40% to 48% in the medium-rise building, and cladding pressure has relatively smaller CoVs, between 13% and 26% in the first building and between 21% and 22% in the second building. Although the CoV differences between pressure coefficient and cladding pressure need to be identified, the main cause of quite large CoVs would seem to be on the fact that different standards have different wind tunnel testing sources on which the coefficients have been based. This could be resolved by benchmark site measurement and wind tunnel testing in the future.

4) Gust response factor is generally specified to take into account of structural dynamic response and turbulent wind actions. The former is totally governed by structural flexibility, and can be called as dynamic response factor (DRF), which has no correlation with velocity pressure. The latter includes the main account for varying averaging time, and can be defined as gust loading factor GLF, for example, GLF being 1.92 and 2.06 from 3-second wind velocity pressure to 10-minute and 1-hour velocity pressure. Accordingly, GLF has significant correlation with velocity pressure related to averaging time, and results in quite large CoV among 15 economies' codes and standards. The future incorporation should be conducted on not only gust response factor itself but also the combination of gust response factor and velocity pressure.

5) Future alignments of wind loading codes and standards in the Asia-Pacific Region are very much necessary and optimistic.

8 ACKNOWLEDGEMENTS

This study was partially supported by the grant 90715039 from the Natural Science Foundation of China and the grant 2008BAG07B02 from the Ministry of Science and Technology. The authors gratefully acknowledge the contributions of the participants of the APEC-WW

workshops, including J. Cheung and J.D. Holmes from Australia, T. Stathopoulos from Canada, E.C.C. Choi and K.C.S. Kwok from Hong Kong, A. Gairola and P. Krishna from India, Fariduzzaman from Indonesia, Y. Tamura from Japan, Y.C. Ha and Y.D. Kim from Korea, N.M. Ali from Malaysia, R.G.J. Flay and A. King from New Zealand, R.E.R. Aquino from Philippines, V. Boonyapinyo from Thailand, C.M. Cheng from Chinese Taipei, R. Bashor and A. Kareem from United States, and N.D. Bich from Vietnam.

9 REFERENCES

1 ASCE, Minimum Design Loads for Buildings and Other Structures, Reston, VA, ASCE/SEI 7-05, New York, 2006.

2 Standards Australia/Standards New Zealand, Structural Design Actions, Part 2 Wind Actions, AS/NZS1170.2:2002.

3 National Research Council of Canada, National Building Code of Canada, NRCC, Ottawa, 2005.

4 Architectural Institute of Japan, Recommendations for Loads on Buildings, AIJ-RLB-2004, Tokyo, 2004

5 Eurocode 1, Actions on Structures, Part 1-4: Wind Actions, London, British Standards Institute, 2004.

6 ISO 4354, Wind Actions on Structures, Switzerland, 2009.

7 ZHOU Y., KIJEWSKI T. and KAREEM A., "Along-Wind Load Effects on Tall Buildings: Comparative Study of Major International Codes and Standards", Journal of Structural Engineering, Vol. 128, No. 6, 2002, pp. 788-796.

8 TAMURA Y., KAREEM A., SOLARI G., KWOK K.C.S., HOLMES J.D. and MELBOURNE W.H., "Aspects of the Dynamic Wind-Induced Response of Structures and Codification", Wind and Structures, Vol. 8, No. 4, 2005, pp. 251-268.

9 HOLMES J.D. and MELBOURNE W.H., "Design Wind Speeds in the West Pacific", Proceedings of the 4th Asia-Pacific Conference on Wind Engineering, Golden Coast, Australia, July 14-16, 1997.

10 HOLMES J.D. and WELLER R., "Design Wind Speeds for the Asia-Pacific Region", Standards Australia, Handbook HB 212-2002, Sydney, NSW, Australia, 2002.

11 GAIROLA A. and MITTAL A., Part 2: Work Examples, Proceedings of the 3rd APEC-WW Workshop, New Delhi, India, November 2-3, 2006.

12 HOLMES J.D., TAMURA Y. and KRISHNA P., "Wind Loads on Low, Medium and High-Rise Buildings by Asia-Pacific Codes", Proceedings of the 4th International Conference on Advances in Wind and Structures, Jeju, Korea, May 29-31, 2008.

13 HOLMES J.D., "Developments in Codification of Wind Loads in the Asia Pacific", Proceedings of the 7th Asia-Pacific Conference on Wind Engineering, Chinese Taipei, November 8-12, 2009.

14 HOLMES J.D. and GINGER J.D., "Codification of Internal Pressures for Building Design", Proceedings of the 7th Asia-Pacific Conference on Wind Engineering, Chinese Taipei, November 8-12, 2009.

15 BASHOR R. and KAREEM A., "Comparative Study of Major International Standards", Proceedings of the 7th Asia-Pacific Conference on Wind Engineering, Chinese Taipei, November 8-12, 2009.

16 KASPERSKI M., "Incorporation of the LRC-Method into Codified Wind Load Distributions", Proceedings of the 7th Asia-Pacific Conference on Wind Engineering, Chinese Taipei, November 8-12, 2009.

17 CHOI E.C.C., "Proposal for Unified Terrain Categories Exposures and Velocity Profiles", Proceedings of the 7th Asia-Pacific Conference on Wind Engineering, Chinese Taipei, November 8-12, 2009.

18 KRISHNA P., "Comparisons of Building Wind Loads and Proposal for an A-P Model Code", Proceedings of the 7th Asia-Pacific Conference on Wind Engineering, Chinese Taipei, November 8-12, 2009.

19 TAMURA Y., HOLMES J.D., KRISHNA P., GUO L. and KATSUMURA A., "Comparison of Wind Loads on Medium-Rise Building according to Asia Pacific Codes/Standards", Proceedings of the 7th Asia-Pacific Conference on Wind Engineering, Chinese Taipei, November 8-12, 2009.

20 China Architecture and Building Press, Load Code for the Design of Building Structures, China National Standard, GB 50009-2001 (revised), 2006.

21 Buildings Department, Code of Practice for Wind Effects in Hong Kong, Buildings Department of Hong Kong, 2004.

22 Bureau of Indian Standards, Indian Standard Code of Practice for Design Loads (other than earthquake) for Buildings and Structures, Part 3: Wind Loads, IS: 875 (Part 3), 1987.

23 Agency for National Standardization (BSN), Standard National Indonesia, SNI 03-1727, BSN, Jakarta, 2003.

24 Korean Government Guidelines of Korean Building Code – Structures, KGG-KBCS-05, 2005.

25 Department of Standards, Code of Practice on Wind Loading for Building Structures, Malaysian Standard, MS 1553, 2002.

26 Association of Structural Engineers of the Philippines, National Structural Code of the Philippines, 5th edition, NSCP-2001, 2001.

27 Taiwan Architecture and Building Research Institute, Specifications for Building Wind-Resistant Design, (Wind Load Provisions of Taiwan Building Code), 2006.
28 Engineering Institute of Thailand, Wind Loading Code for Building Design, EIT Standard 1018-46, 2003.
29 Tieu Chuan Viet Nam, Loads and Actions Norm for Design, TCVN 2737-1995, 1995.
30 DAVENPORT A.G., "The Wind Loading Chain – 2004 Update", Proceedings of the International Workshop on Wind Engineering and Science, New Delhi, India, October 29-30, 2004.
31 GE Y.J. and XIANG H.F., "Statistical Study for Mean Wind Velocity in Shanghai Area", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 90, 2002, pp. 1585-1599.