Standardization of wind loading for buildings and bridges in China

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ABSTRACT: In order to introduce and harmonize the structural wind loading codes in APEC area, this paper presents the current legal specifications and the recent research results of wind loading for buildings and bridges in China, Load Code for the Design of Building Structures and Wind-Resistant Design Specification for High Bridges. The wind loading in China is defined as a force over unit area for buildings and along unit length for bridges with four factors including basic wind pressure, exposure factor, shape factor and dynamic response factor for buildings and dynamic and aerodynamic factor for bridges. The determination methods for these four factors are described with the reference of the current codes and the recent developments, and some prospective studies on dynamic and aerodynamic factor are suggested for further investigation.

KEYWORDS: wind loading, design specification, buildings, bridges, China.

1 INTRODUCTION

With the soaring of China's economy in the past two decades, civil engineering work in China has progressed achieving marvelous success, in particular in building and bridge construction. Thousands of high-rise buildings have risen in the cities, and hundreds of long-span bridges have been constructed across main rivers or bays. Based on the rapid increase of building height and bridge span length, the structures of buildings and bridges are becoming lighter and more flexible, whose structural characteristics result in a considerable importance of aerodynamic study and design related to wind action, including aerodynamic instability, stochastic buffeting and vortex-shedding vibration.

The current approach to wind resistant design for building and bridge structures is to follow a proper wind loading code, which should be specified from extensive studies, engineering experience and even mistakes. It is important to reach a common understanding and a reasonable specification on structural wind loading, and to develop methods and technologies for wind hazard mitigation.

1.1 *Wind loading codes for buildings*

According to some traditional reasons, building design and bridge design in China follow their individual specifications, for example, Design Specification for Building Structures, and Design Specification for Highway Bridges. The current wind loading used in building design is a part of China National Standard – Load Code for the Design of Building Structures (GB50009-2001)[1], which has been valid since March of 2002. This load code was originated firstly in 1954, and has five update versions, including Temporal Code of Loading (1-54) and (1-58), Loading Code for Industrial and Civil Building Structures (TJ9-74), Load Code for the Design of Building Structures (GBJ9-87) and (GB50009-2001) [1].

1.2 *Wind loading codes for highway bridges*

On the other hand, the wind loading for the structural design of highway bridges is one section of China's State Communication Ministry Standard –Wind-Resistant Design Specification for Highway Bridges (JTG/TXX-2004)[2], which is mainly based on Wind-Resistant Design Guidelines for Highway Bridges[3] in 1996 and will be issued by the end of 2004. The first version of design specification for highway bridges was issued in 1956, in which there is no provision for wind loading, and the second and third specifications including wind loading provisions were published in 1976 and 1989, respectively.

According to China's practice in high-rise buildings and long-span bridges, this paper presents a brief review of the structural wind loading codes based on Load Code for the Design of Building Structures (GB50009-2001)[1] and Wind-Resistant Design Specification for Highway Bridges (JTG/TXX-2004)[2], and some recent research and development results as well as further questions feedback from practice to design.

2 WIND LOADING DEFINITION

Since the wind loading definition for building design and bridge design is quite different in China, the general wind load expression is respectively introduced from building design code and highway bridge design code, respectively.

2.1 *Wind loading for buildings*

According to Load Code for the Design of Building Structures (GB50009-2001)[1], the wind load normally acted on surface of buildings is defined as wind force over unit area, and should be calculated as follows:

For main structures:

$$w_k = \beta_z \mu_S \mu_z w_0 \tag{1}$$

where: w_k = characteristic value of wind loads, kN/m^2;

β_z = dynamic response factor at the height of z;

μ_z = shape factor, the values for some common buildings and structures are tabulated in the code, and wind tunnel test is encouraged for unusual shapes;

μ_z = exposure factor;

w_o = basic wind pressure, kN/m^2.

For claddings and elements:

$$w_k = \beta_{zg} \mu_{Sl} \mu_z w_0 \tag{2}$$

where: β_{zg} = dynamic response factor at the height of z;

μ_{sl} = local shape factor.

2.2 *Wind loading for bridges*

Based on Wind-Resistant Design Specification for Highway Bridges (JTG/TXX-2004)[2], the wind load generally subjected on axis of bridges is defined as wind force along unit length, and should be calculated as follows:

$$F_k = \alpha_x \nu_S \nu_z D w_0 \tag{3}$$

where: F_k = characteristic value of wind loads, kN/m;
α_x = dynamic and aerodynamic factor at the span length of x;
ν_s = static force factor, the values are usually determinated through wind tunnel tests;
ν_z = exposure factor;
D = projected depth perpendicular to the axis, m;
w_o = basic wind pressure, kN/m^2.

3 BASIC WIND SPEED AND PRESSURE

Because of the differences in basic wind speed definition for building design and bridge design in China, the basic wind speed and pressure are respectively presented with the respects of building design code and highway bridge design code.

3.1 *Basic wind speed for buildings*

Based on Load Code for the Design of Building Structures (GB50009-2001)[1], the basic wind speed v_o is defined as the 10-minute average wind speed over a flat and open terrain at an elevation of 10m with a mean return period of 50 years.

3.2 *Basic wind speed for bridges*

Referred to Wind-Resistant Design Specification for Highway Bridges (JTG/TXX-2004)[2], the definition of basic wind speed v_o is the 10-minute average wind speed over a flat and open terrain at an elevation of 10m with a mean return period of 100 years, but not 50 years. Accordingly, the value of basic wind speed for bridge design is higher than that for building design in the same condition.

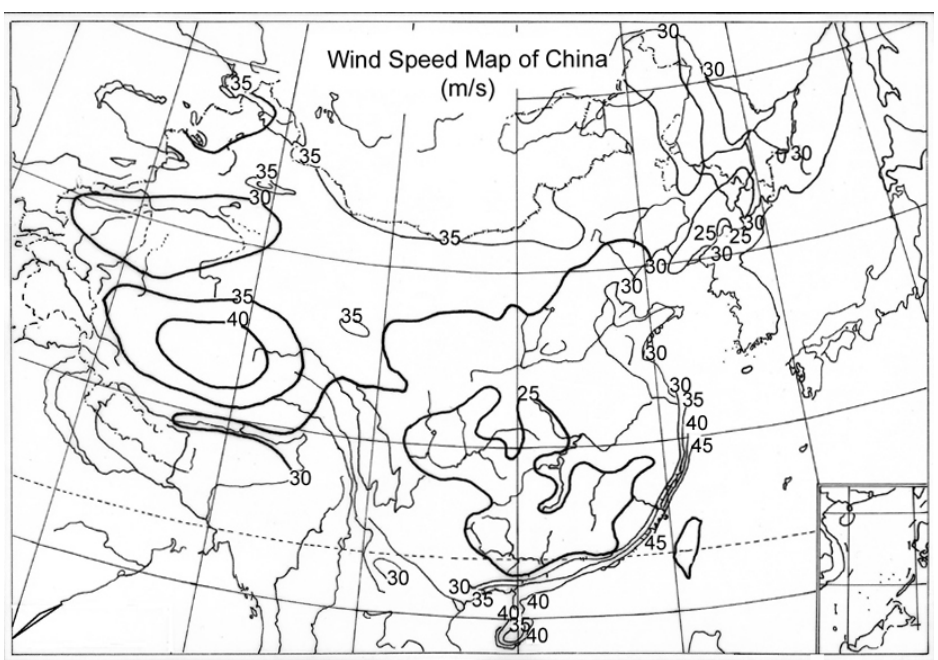

Figure 1. Wind speed map of China.

For bridge design practice, the fundamental parameter of structural wind loading is basic wind speed. The map of basic wind speed in China is shown in Figure 1, which has been formed based on the statistical records made in more than 350 stations with 35~40 year wind speed recording over the country. It can be concluded from this map that there are two strong wind areas. One is the southeast coast, in which the maximum wind speed mainly induced by Typhoon, and the other is the area of the northwest territory whose maximum wind speed is basically influenced by cold storm. Besides the map, the basic wind speed data for main cities are also given in the code corresponding to the return periods of 10, 50 and 100 years, respectively.

3.3 *Basic wind pressure*

For both building design and bridge design, basic wind pressure is numerically determined from the basic wind speed and the air density in same conditions, and should be calculated as follows.

$$w_0 = \frac{1}{2}\rho v_0^2 \tag{4}$$

where: v_o = basic wind speed, m/s;

ρ = air density, t/m^3, the normal value is 1.225×10^{-3} t/m^3, and this value can be modified with the elevation z (m) as:

$$\rho = 0.001225 e^{-0.0001z} \tag{5}$$

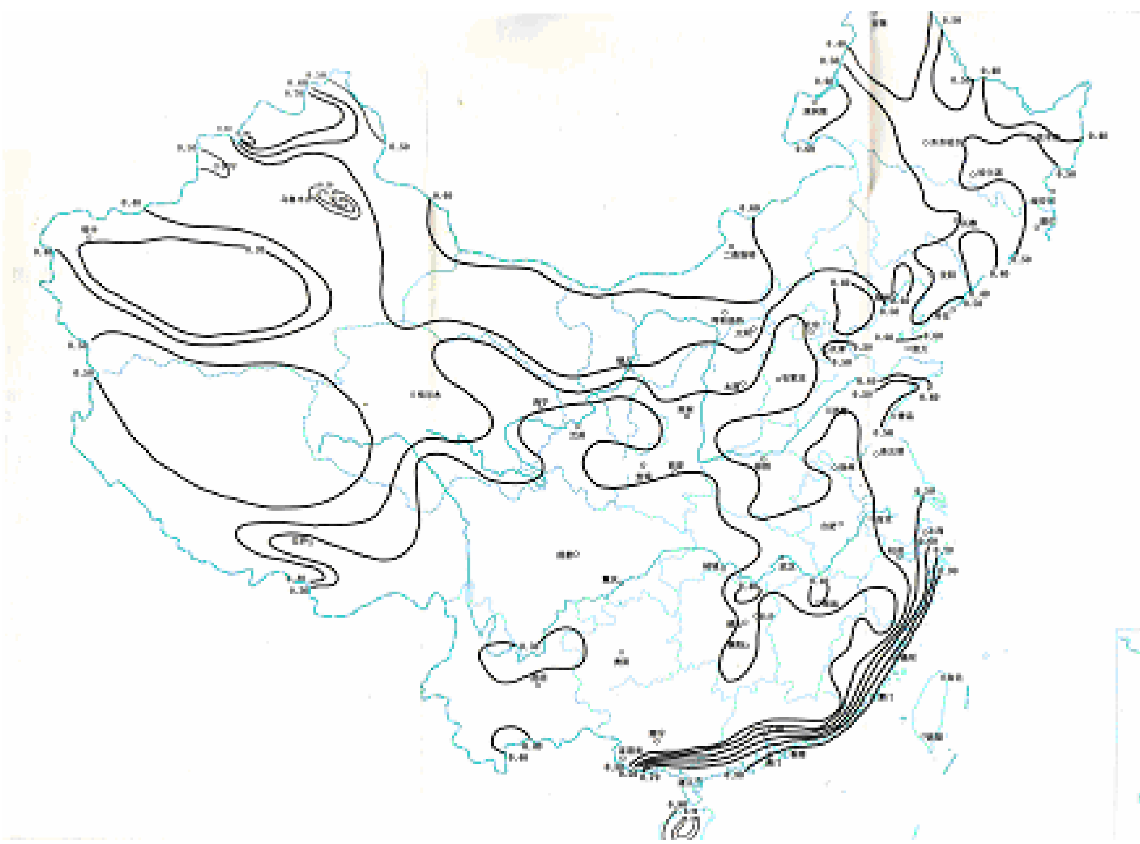

Figure 2. Wind pressure map of China.

For building design practice, the fundamental parameter of structural wind loading is basic wind pressure, but not basic wind speed. The map of basic wind pressure in China is shown in Figure 2, which has also been formed based on the statistical records made in those stations. Besides this map, the basic wind pressure data for main cities are also given in the code corresponding to the return periods of 10, 50 and 100 years, respectively.

4 BOUNDARY LAYER WIND PROFILE

Since both building design code and bridge design code have the same model of boundary layer wind profile in China, the wind profile model is introduced regardless of either building wind loads or bridge wind loads.

4.1 *Wind profile model*

In general, there are three kind models for describing boundary layer wind profile, that is, Power Law Profile Model, Logarithmic Profile Model and the combination of these two models. Although Logarithmic Profile Model has been once adopted as the legal wind profile model in China in 1960's and 1970's, Power Law Profile Model is currently the only model of boundary layer wind profile.

$$v_z = v_o \left(\frac{z}{z_o}\right)^{\alpha} \tag{6}$$

where: v_z = boundary layer wind speed at the level of z, m/s;
v_o = basic wind speed at the level of z_o, m/s;
α = exponential factor due to terrain roughness.

4.2 *Terrain roughness category*

There are four categories of terrain roughness in either building code or bridge code in China, which can be described as follows:

Class A: sea, sea shores, islands, lake and deserts;
Class B: open fields, villages, forests, hills, sparsely-built town and the suburb of cities.
Class C: urban area of densely-populated cities.
Class D: center of large city with closely spaced tall buildings.

Table 1 shows three specified parameters, including exponential value α, roughness height z_o and thickness of boundary layer δ, of these four categories of terrain roughness. Among these four categories, the standard class is Class B, which is corresponding to the roughness condition of daily wind speed recording made in meterological stations.

Table 1. Specified parameters of terrain roughness

Category	Exponential value	Roughness height (m)	B.L. thickness (m)
Class A	0.12	0.01	300
Class B	0.16	0.05	350
Class C	0.22	0.30	400
Class D	0.30	1.00	450

4.3 *Exposure factors*

According to Power Law Profile and exponential value, the exposure factor for wind loading calculation at the height of z can be determined by the following equation:

$$\mu_z = \nu_z = (\frac{z}{10})^{2\alpha} \tag{7}$$

For Class A, B, C and D, the values of exposure factor are given based on the standard terrain roughness, Class B, as follows:

$$\mu_z^A = \nu_z^A = 1.379(\frac{z}{10})^{0.24} \tag{8}$$

$$\mu_z^B = \nu_z^B = 1.000(\frac{z}{10})^{0.32} \tag{9}$$

$$\mu_z^C = \nu_z^C = 0.616(\frac{z}{10})^{0.44} \tag{10}$$

$$\mu_z^D = \nu_z^D = 0.318(\frac{z}{10})^{0.60} \tag{11}$$

5 DYNAMIC AND AERODYNAMIC FACTORS

To the best of authors' knowledge, the most significant and sophisticated parameter in wind loading definition is dynamic response factor β or dynamic and aerodynamic factor α among four factors in Equation (1), (2) or (3), because not only the value of the factor can vary from unit to several times but also this factor relates to various effects including wind fluctuation characteristics, mean wind profile, dynamic responses and the interaction between wind and structure.

5.1 *Along-wind factor*

Based on Load Code for the Design of Building Structures (GB50009-2001)[1], an along-wind dynamic response factor should be used for building structures and roofs with natural fundamental frequency less than 4 Hz, and for buildings with height over 30m and the ratio of height to breadth greater than 1.5, and its value can be derived from the following equation.

$$\beta_z = 1 + \frac{\xi \nu \varphi_z}{\mu_z} \tag{12}$$

where: ξ = gust amplitude factor, the value is tabulated in the code;

ν = wind turbulence and correlation factor, the value is also listed in the code;

φ_z = mode shape factor of a structure.

According to the recent research report on Bridge Buffeting Response Sepctrum and Equivelent Wind Loading[4], the along-wind dynamic and aerodynamic factor can be determined by Equation (13) for symmetrical vibration modes or Equation (14) for antisymmetrical vibration modes, respectively.

$$\alpha_x^s = 1 + \frac{gp_u}{\ln(z/z_o)}\sqrt{1+\varepsilon_u}\sqrt{\frac{z}{B}}\sqrt{\frac{\varphi_u \xi_s}{\xi_{tu}^2}}\frac{1}{(1+50f)^{\frac{5}{6}}}\sqrt{\frac{K}{1+\pi K}} \tag{13}$$

$$\alpha_x^a = 1 + \sqrt{2}\frac{gp_u}{\ln(z/z_o)}\sqrt{1+\varepsilon_u}\sqrt{\frac{z}{B}}\sqrt{\frac{\varphi_u \xi_s}{\xi_{tu}^2}}\frac{1}{(1+50f)^{\frac{5}{6}}}\sqrt{\frac{K}{1+\pi K}} \tag{14}$$

where: g = gust wind speed factor;
p_u = calculation coefficient related to drag force parameters;
ε_u = calculation coefficient related to along-wind turbulence specturum;
B = width of bridge deck;
φ_u = calculation coefficient related to along-wind turbluence correlation;
ξ_{tu} = total damping ratio including structure and along-wind aerodynamic damping;
ξ_s = structural damping ratio;
f = structural vibration frequency;
K = reduced structural vibration frequency.

5.2 *Cross-wind factor*

Based on Load Code for the Design of Building Structures (GB50009-2001)[1], a cross-wind loading is only considered in the case of vortex-shedding oscillation with the Reynolds number of Re $\geq 3.5\times10^6$, and the value of cross wind loading should be determined as follows:

$$w_c = \frac{\lambda v_{cr}\varphi_z}{12800\xi} \tag{15}$$

where: ξ = structural damping ratio;
λ = calculation coefficient;
v_{cr} = critical wind speed of vortex-shedding vibration;
φ_z = vibration mode shape coefficient;

According to the specific research on Bridge Buffeting Response Sepctrum and Equivelent Wind Loading[4], the cross-wind dynamic and aerodynamic factor can be determined by Equation (16) for symmetrical vibration modes or Equation (17) for antisymmetrical vibration modes, respectively.

$$\alpha_x^s = 1 + \frac{gp_w}{\ln(z/z_o)}\sqrt{1+\varepsilon_w}\sqrt{\frac{z}{B}}\sqrt{\frac{\varphi_w \xi_s}{\xi_{tw}^2}}\frac{1}{(1+4f)^2}\sqrt{\frac{K}{1+\pi K}} \tag{16}$$

$$\alpha_x^a = 1 + \sqrt{2}\frac{gp_w}{\ln(z/z_o)}\sqrt{1+\varepsilon_w}\sqrt{\frac{z}{B}}\sqrt{\frac{\varphi_w \xi_s}{\xi_{tw}^2}}\frac{1}{(1+4f)^2}\sqrt{\frac{K}{1+\pi K}} \tag{17}$$

where: p_w = calculation coefficient related to lift force parameters;
ε_w = calculation coefficient related to cross-wind turbulence specturum;
φ_w = calculation coefficient related to cross-wind turbluence correlation;

ξ_{tw} = total damping ratio including structure and cross-wind aerodynamic damping.

5.3 *Torsional wind loading factor*

Load Code for the Design of Building Structures (GB50009-2001) has no specification about torsional wind loading for building structure design.

According to the specific research on Bridge Buffeting Response Sepctrum and Equivelent Wind Loading[4], the dynamic and aerodynamic factor for torsional wind loading can be determined by Equation (18) for symmetrical vibration modes or Equation (19) for antisymmetrical vibration modes, respectively.

$$\alpha_x^s = 1 + \frac{gp_m}{\gamma_m^2 \ln(z/z_o)} \sqrt{1+\varepsilon_w} \sqrt{\frac{z}{B}} \sqrt{\frac{\varphi_w \xi_s}{\xi_{tm}^2}} \frac{1}{(1+4f)^2} \sqrt{\frac{K}{1+\pi K}} \tag{18}$$

$$\alpha_x^a = 1 + \sqrt{2} \frac{gp_m}{\gamma_m^2 \ln(z/z_o)} \sqrt{1+\varepsilon_w} \sqrt{\frac{z}{B}} \sqrt{\frac{\varphi_w \xi_s}{\xi_{tm}^2}} \frac{1}{(1+4f)^2} \sqrt{\frac{K}{1+\pi K}} \tag{19}$$

where: p_m = calculation coefficient related to pitching moment parameters;
γ_m = calculation coefficient related to torsional aerodynamic stiffness;
ξ_{tm} = total damping ratio including structure and torsional aerodynamic damping.

6 PROSPECTIVE STUDY ON WIND LOADING

Based on the above-mentioned wind loading expressions and their factors, it is necessary to take some further studies on the definitions and factors, in particular, dynamic response factors for building design or dynamic and aerodynamic factors for bridge design. Because of the significance of their values and the sophistication in the determination process, at lease the following four aspects should be further studied in the near future.

6.1 *Static and dynamic components*

The first aspect of the prospective study deals with the expression of wind loading, which is currently represented by the multiplication of static component. There are at least two reasons in defining wind loading as the summation of static component and dynamic component, Equation (20)[5], instead of the current expressions, Equation (1), (2) or (3). The distribution pattern of static component is quite different from the pattern of dynamic component, and the gust wind influence to static component is not similar to dynamic component.

$$w_t = w_s + w_d \neq C w_s \tag{20}$$

where: w_t = total value of wind loading;
w_s = static component of wind loading;
w_d = dynamic component of wind loading;
C = multiplication factor;

6.2 *Buffeting and vortex-shedding vibration*

Referred to wind induced vibration influence in wind loading definition, or dynamic component, there are basically two kinds of vibration, which should be considered, including buffeting vibration and vortex-shedding oscillation. It is obvious that the wind loading due to buffeting response, Equation (21), is definitively different from the wind loading due to vortex-shedding response, Equation (22), in aerodynamic vibration mechanism and related factors, for example, wind speed, vibration pattern, gust wind effect and so on[6].

$$w_{db} = g_b \sigma_{wb} \tag{21}$$

$$w_{dv} = A_{wv} \tag{22}$$

where: w_{db} = dynamic component of wind loading due to buffeting vibration;
g_b = gust factor of buffeting response;
σ_{wb} = root mean square of dynamic wind loading due to buffeting vibration;
w_{dv} = dynamic component of wind loading due to vortex-shedding oscillation;
A_{wv} = maximum amplitude of dynamic wind loading due to vortex-shedding oscillation;

6.3 *Structural stiffness influence*

It will be reasonable and precise to divide wind loading or vibration amplitude factor with the reference of structural stiffness, at least into three main groups[7,8]. For the most rigid structures, the wind loading definition, Equation (23), can only include static component including the actions of mean wind and wind fluctuation, but not structural vibration influence. With the decrease of structural stiffness, not only wind fluctuation but also structural vibration should be considered in wind loading, which can be defined by background component only, Equation (24), and both background and resonance component, Equation (25).

$$w_t^r = w_s \tag{23}$$

$$w_t^m = w_s + w_d^b \tag{24}$$

$$w_t^f = w_s + w_d^b + w_d^r \tag{25}$$

where: w_t^r = wind loading for rigid structures;
w_t^m = wind loading for middle structures;
w_d^b = background component of dynamic wind loading;
w_t^f = wind loading for flexible structures;
w_d^r = resonance component of dynamic wind loading.

6.4 *Distribution pattern*

Corresponding to three kinds of wind loading definitions based on structural stiffness, wind loading can be basically divided into three components, static component, background component and resonance component. It is necessary to make further study on distribution patterns of these three components, which can be represented by the following distribution forms[9,10].

$$w_t^f(s) = \overline{w}_s \eta_s(s) + \overline{w}_d^b \eta_b(s) + \overline{w}_d^r \eta_r(s) \tag{26}$$

where: $w_t^f(s)$ = wind loading for flexible structures;
$\eta_s(s)$ = distribution pattern of static component;
$\eta_b(s)$ = distribution pattern of background component;
$\eta_r(s)$ = distribution pattern of resonance component;
$\overline{w}_s$ = maximum value of static component;
$\overline{w}_d^b$ = maximum value of background component;
$\overline{w}_d^r$ = maximum value of resonance component.

7 CONCLUDING REMARKS

Based on the common understanding and the regional harmonization of structural wind loading codes in APEC area, the wind loading specifications for building design and bridge design in China are introduced in this paper with the aspects of wind loading definition, basic wind speed and pressure, boundary layer wind profile, dynamic and aerodynamic factor, and prospective study on wind loading. The wind loading in China is defined with four factors as a force over unit area for buildings and along unit length for bridges. The fundamental factor is basic wind speed or pressure, which is specified with figures or tables in the codes, and shape factor is encouragingly identified through wind tunnel testing although the values for some usual buildings and bridges are tabulated in the codes. The Power Law Model is adopted as a legal wind profile with four categories of terrain roughness in both building code and bridge code in order to determine the third factor, exposure factor. The final factor, dynamic response factor for buildings or dynamic and aerodynamic factor for bridges, is the most significant and sophisticated parameter among these four factors in wind loading definition. Although the current specifications or the recent research results provide the simplified calculation formulae or tables, there are still some aspects, which should be further studied in the near future.

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