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# Across-wind loads and effects of super-tall buildings and structures

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Across-wind loads and effects have become increasingly important factors in the structural design of super-tall buildings and structures with increasing height. Across-wind loads and effects of tall buildings and structures are believed to be excited by inflow turbulence, wake, and inflow-structure interaction, which are very complicated. Although researchers have been focusing on the problem for over 30 years, the database of across-wind loads and effects and the computation methods of equivalent static wind loads have not yet been developed, most countries having no related rules in the load codes. Research results on the across-wind effects of tall buildings and structures mainly involve the determination of across-wind aerodynamic forces and across-wind aerodynamic damping, development of their databases, theoretical methods of equivalent static wind loads, and so on. In this paper we first review the current research on across-wind loads and effects of super-tall buildings and structures both at home and abroad. Then we present the results of our study. Finally, we illustrate a case study in which our research results are applied to a typical super-tall structure.

**super-tall building and structure, across-wind aerodynamic force, across-wind aerodynamic damping, across-wind effects, across-wind quivalent static wind loads, case study**

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## 1 Introduction

With the development of science and technology, structures are becoming larger, longer, taller, and more sensitive to strong wind [1–4]. Thus, wind engineering researchers are facing with more new challenges, even problems they are currently unaware of. For example, the construction of super-tall buildings is now prevalent around the world. The Chicago Sears Tower with a height of 443 m has kept the record of the world's tallest building for 26 years now. Dozens of super-tall buildings with heights of over 400 m are set to be constructed. Burj Dubai Tower with a height of 828 m has just been completed. In developed countries, there are even proposals to build "cities in the air" with thousands of meters of magnitude. With the increase in height and use of light and high-strength materials, wind-induced dynamic responses, especially across-wind dynamic responses of super-tall buildings and structures with low damping, will become more notable. Hence, strong wind load will become an important control factor in designing safe super-tall buildings and structures.

Davenport [5–7] initially introduced stochastic concepts and methods into wind-resistant study on along-wind loads and effects of buildings and other structures. Afterward, researchers developed related theories and methods [8–17], and the main research results have already been reflected in the load codes of some countries for the design of buildings and structures [18–23].

For modern super-tall buildings and structures, across-

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wind loads and effects may surpass along-wind ones. Although researchers have been focusing on the complex problem for over 30 years now, the widely accepted database of across-wind loads and computation methods of equivalent static wind loads have not been formed yet. Only a few countries have accordingly adopted the related contents and provisions in their codes [18, 20].

Therefore, studying across-wind vibration and the equivalent static wind loads of super-tall buildings and structures is of great theoretical significance and practical value in the field of structural design of super-tall buildings and structures. The current paper thus reviews the research situation of across-wind loads and effects of super-tall buildings and structures both at home and abroad. Then, the research results given by us are presented. Finally, a case study of across-wind loads and effects of a typical super-tall structure is illustrated.

## 2 Research situation

### 2.1 Mechanism of across-wind loads and effects

Previous researches focused mainly on the mechanism of across-wind load. Kwok [24–26] pointed out that across-wind excitation comes from wake, inflow turbulence, and wind-structure interaction effect, which could be recognized as aerodynamic damping. Solari [27] attributed the across-wind load to across-wind turbulence and wake excitations, considering wake as the main excitation. Islam et al. [28] and Kareem [13] claimed that across-wind responses are induced by lateral uniform pressure fluctuation due to separation shear layer and wake fluctuation. Currently, the mechanism of across-wind load on tall buildings and structures has been recognized as inflow turbulence excitation, wake excitation, and aeroelastic effect. Inflow turbulence and wake excitation are essentially the external aerodynamic force, which is collectively referred to in the present paper as aerodynamic force. Meanwhile, aeroelastic effect can be treated as aerodynamic damping. Across-wind aerodynamic force no longer conforms to quasi-steady assumption as the along-wind one; thus, the across-wind force spectra cannot be directly expressed as a function of inflow fluctuating wind velocity spectra. Wind tunnel test technique for unsteady wind pressures or forces is presently a main tool for studying across-wind aerodynamic forces. The wind tunnel experiment technique mainly involves the aeroelastic building model experiment technique, high frequency force balance technique, and rigid model experiment technique for multi-point pressure measurement. Using data of across-wind external aerodynamic force and across-wind aerodynamic damping, across-wind responses and the equivalent static wind load of buildings and structures can be computed for the structural design of super-tall buildings and structures.

### 2.2 Across-wind aerodynamic force

As stated above, the across-wind aerodynamic force can be obtained basically through the following channels: (i) identifying across-wind aerodynamic force from across-wind responses of an aeroelastic building model in a wind tunnel; (ii) obtaining across-wind aerodynamic force through spatial integration of wind pressure on rigid models; (iii) obtaining generalized aerodynamic force directly from measuring base bending moment using high frequency force balance technique.

#### *2.2.1 Identification of across-wind aerodynamic force from dynamic responses of aeroelastic building model*

This method employs across-wind dynamic responses of the aeroelastic building model, combining the dynamic characteristics of the model to identify across-wind aerodynamic force. Saunders [29], Kwok [24], Kwok and Melbourne [30], Kwok [25], and Melbourne and Cheung [31] performed aeroelastic model wind tunnel tests on a series of circular, square, hexagon, polygon with eight angles, square with reentrant angles and fillets, and tall or cylindrical structures with sections contracting along height. However, further studies showed that across-wind aerodynamic damping force and aerodynamic force mixed together make it difficult to extract aerodynamic damping force accurately. As such, the method has been seldom used.

#### *2.2.2 Wind pressure integration method*

Researchers have recommended wind pressure integration to obtain more accurately the across-wind aerodynamic forces on tall buildings. Islam et al. [28], Cheng et al. [32], Nishimura and Taniike [33], Liang et al. [34, 35], Ye [36], Tang [37], Zhang [38], and Gu et al. [39] adopted this method to obtain across-wind aerodynamic forces on tall buildings and structures. Cheng et al. [32] experimentally studied across-wind aerodynamic forces of typical buildings under different wind field conditions and derived empirical formulas for the power spectrum density (PSD) of the across-wind aerodynamic force reflecting the effects of turbulent intensity and turbulent scale. Turbulent intensity was found to widen the bandwidth of PSD of the across-wind aerodynamic force and reduce the peak value. However, turbulent intensity was determined to have almost no effects on total energy. Thus, researchers have recognized the quantitative rules of variation of across-wind aerodynamic force with wind condition to some extent. Liang et al. [34, 35] examined across-wind aerodynamic forces on typical rectangular buildings in a boundary layer wind tunnel using this method, thus proposing empirical formulas for PSD of across-wind aerodynamic forces of tall rectangular buildings and an analytical model for across-wind dynamic responses. Ye [36] and Zhang [38] decomposed across-wind turbulence excitation and vortex shedding excitation in across-wind aerodynamic forces on typical super-tall buildings. The results showed that the across-wind turbulence contributed much less to across-wind aerodynamic force than the wake excitation. Based on a large number of results, we derived PSD formulas for the across-wind turbulence excitation and the wake excitation, and further derived a new formula for the across-wind aerodynamic force.

The first- and higher-mode generalized across-wind aerodynamic forces can be calculated through the integration of pressure distribution on rigid building models, which is an important advantage of this method. However, given the need for a large number of pressure taps for very large-scale structures in this kind of method, synchronous pressure measurements are difficult to make. Moreover, for buildings and structures with complex configurations, accurate wind pressure distribution and aerodynamic force are difficult to obtain using this kind of method.

### 2.2.3 *High frequency force balance technique*

Compared with the pressure measuring technique, high frequency force balance technique has its unique advantage for obtaining total aerodynamic forces. The test and data analysis procedures are both very simple; hence, this technique is commonly used for selection studies on architectural appearance in the initial design stage of super-tall buildings and structures. Currently, this technique is widely used for total wind loads acting on super-tall buildings and structures, and for dynamic response computation as well.

The high frequency force balance technique has been gradually developed since the 1970s. Cermak et al. [40] were the first to use this technique for building model measurement. They initially pointed out that the balance-model system should have a higher inherent frequency than the concerned frequency of wind forces. The five-component balance developed by Tschanz and Davenport [41] marked the maturity of balance facility.

Kareem [13] conducted an experimental study on across-wind aerodynamic forces on tall buildings with various section shapes in urban and suburban wind conditions. The research showed that for the buildings with aspect ratios of 4–6, uncertainties of wind and structural parameters have small effects on PSD of the across-wind aerodynamic force, and the correlation between the along-wind aerodynamic force and the across-wind aerodynamic force or the torsion moment is negligible, but there is a strong correlation between the across-wind aerodynamic force and the torsion moment. This conclusion is important for the development of three-dimensional refined wind load model. Particularly, Gu and Quan [42] and Quan et al. [43] made detailed studies on the effects of the side ratio of a rectangular building, cross-section shape of a building, aspect ratio of a building, and wind field condition on the PSD of the across-wind aerodynamic force of tall buildings using a five-component balance. In fact, based on a large number of wind tunnel test results, formulas for across-wind aerodynamic force coefficients of the typically tall buildings have been derived by us and other researchers, some of which are listed in Table 1. In addition, in Table 1, the formula derived by Gu and Quan [42] has already been adopted in related design codes in China. In Table 1, $C'_{ML}$ is the RMS value of across-wind aerodynamic base moment coefficient reduced by the local approaching wind pressure at the top height of the building, $\bar{C}_L$ is the mean value of RMS across-wind aerodynamic force coefficients at different levels reduced by the local approaching wind pressure, and $\tilde{C}_L(z)$ is the RMS value of across-wind aerodynamic force coefficient at $z$ level reduced by the local approaching wind pressure.

## 2.3 Across-wind aerodynamic damping

In 1978, Kareem [44] performed an investigation on across-wind dynamic responses of tall buildings based on both of the aeroelastic model technique and the wind pressure integration method. He found out that the across-wind dynamic responses calculated with the across-wind aerodynamic forces obtained from the wind pressure tests at a

**Table 1** Formulas for across-wind aerodynamic force coefficients of typical tall buildings

| Authors | Across-wind aerodynamic force coefficients |
|---|---|
| Marukawa et. al. (1992, 1996) | $C'_{ML}=0.0141\left(\frac{D}{B}\right)^3-0.129\left(\frac{D}{B}\right)^2+0.325\left(\frac{D}{B}\right)-0.0757+\left(-0.0737\left(\frac{D}{B}\right)^3+0.688\left(\frac{D}{B}\right)^2-1.20\left(\frac{D}{B}\right)+0.566\right)I_H$ |
| Liang et. al. (2002) | $\bar{C}_L=0.045\left(\frac{D}{B}\right)^3-0.335\left(\frac{D}{B}\right)^2+0.868\left(\frac{D}{B}\right)-0.174$ |
| AIJ (2004) | $C'_{ML}=0.0082\left(\frac{D}{B}\right)^3-0.071\left(\frac{D}{B}\right)^2+0.22\left(\frac{D}{B}\right)$ |
| Gu and Quan (2004) | $C'_{ML}=(0.002\alpha_w^2-0.017\alpha_w-1.4)\times(0.056(D/B)^2-0.16(D/B)+0.03)\times((H/T)^2-0.622(H/T)+4.357)$ ,<br>where $\alpha_w$ is 1, 2, 3 or 4 represent wind terrain category A, B, C or D in GB50009-2001 [23], respectively; $T$=min($B$, $D$). |
| Tang (2006) | $\tilde{C}_L(z)=a_1^{(L)}+a_2^{(L)}\left(\frac{z}{H}\right)+a_3^L\left(\frac{z}{H}\right)^2$, where $a_1^{(L)}$, $a_2^{(L)}$, and $a_3^{(L)}$ are fitted with $D/B$ (side ratio). |

certain test wind velocity range were always smaller than those of the aeroelastic model of the same building model. This important result made researchers realize the existence of across-wind negative aerodynamic damping.

Subsequently, researchers carried out numerous studies on the problem and developed effective methods for identifying aerodynamic damping. The first kind of method obtains aerodynamic damping by comparing the dynamic responses computed based on the aerodynamic forces from rigid building model tests and those from aeroelastic model tests. The second one separates aerodynamic damping force from the total aerodynamic force measured from aeroelastic building models or forced vibration building models. The third kind employs identification methods for extracting aerodynamic damping from random responses of aeroelastic models. Moreover, researchers realized the effect law of factors, including structural shape, structural dynamic parameters, wind conditions, and so on, on aerodynamic damping, Isyumov et al. [45] were the first researchers to propose a method for aerodynamic damping through comparing responses from a rigid building model test using HFFB technique with those of an aeroelastic model of the same building. Cheng et al. [46] adopted the method to study across-wind responses and aerodynamic damping of tall square buildings and proposed an aerodynamic damping formula.

Steckley [47, 48] initially developed a set of forced vibration devices for measuring total aerodynamic forces, including aerodynamic damping force and aerodynamic force. He measured the base bending moment of a tall building model, which was vibrated by a specially designed device. The aerodynamic force related to structure motion was separated from the total aerodynamic force, and then it was decomposed into aerodynamic stiff force and aerodynamic damping force to obtain aerodynamic damping. Vickery and Steckley [49] proposed a negative aerodynamic damping model. Cooper et al. [50] attempted to measure wind pressure on a harmonically vibrating building model to obtain total aerodynamic force. Aerodynamic damping was then computed using a method similar to Steckley's. The advantage of this kind of method is that the characteristics of real buildings do not have to be taken into consideration in wind tunnel tests, which makes this kind of method more convenient to use, especially in popularizing the test results. The main shortcoming of this kind of method is that it requires complicated devices, especially because a multi-component coupling device was not available until now.

Identifying aerodynamic damping based on the stochastic vibration responses of aeroelastic building models can be performed using appropriate system identification techniques, which include frequency domain methods, time domain methods, and frequency-time domain methods. Among these methods, the random decrement method, one of the time domain methods, is broadly adopted to identify the aerodynamic damping of tall buildings and structures. Jeary [51, 52] introduced the random decrement technique to identify structural damping. Marukawa et al. [53] employed the random decrement method to identify along-wind and across-wind aerodynamic dampings of tall buildings with rectangular sections. They analyzed the effects of building aspect ratio, side ratio, and structural damping on aerodynamic damping. Tamura et al. [54] conducted a detailed study on the application of random decrement technique to identify the aerodynamic damping of super-tall buildings. Quan [43] and Quan et al. [55] adopted RDT to identify across-wind aerodynamic damping of the square-section tall buildings with different structural dampings in different wind fields and derived an empirical formula. These research results have been adopted into the related China Codes [23, 56]. Gu and Qin [57] and Qin and Gu [58] were the first researchers to introduce stochastic sub-space identification method into identification of aerodynamic parameters including aerodynamic stiffness and damping of long-span bridges, obtaining satisfying results. Compared with random decrement method, the stochastic sub-space identification method has more merits than RDT and MRDT and can overcome their main shortcomings i.e., weak noise-resistantce ability and need for large experimental data. Qin [59] adopted this method to identify the aerodynamic damping of tall buildings.

### 2.4 Application to the codes

As stated above, although researchers have been focusing on across-wind loads on tall buildings for over 30 years now, the widely accepted database of across-wind loads and computation methods of equivalent static wind loads have not been developed yet. Moreover, only a few countries have adopted related contents and provisions in their codes.

Compared with the codes of other countries, the Architectural Association of Japan [18] provides the best method for across-wind loads for structural design of tall buildings. Nevertheless, the formula for PSD of the across-wind force in the code can only be applied to tall buildings with aspect ratios of less than six, which seems difficult to meet the actual needs. In addition, the method takes across-wind inertia load of fundamental mode as across-wind equivalent static wind load including background and resonant components, making it seem questionable. Moreover, aerodynamic damping has not been considered in the method.

In the present load code for the design of building structures (GB50009-2001) of China [23], only a simple method for calculating vortex-induced resonance of chimney-like tall structures with a circular section is provided, which is not applicable to the wind-resistant design for tall buildings and structures in general. In the design specification titled "Specification for Steel Structure Design of Tall Buildings" [56], our related research results [42, 43, 55] have been adopted.

## 3 Our research

### 3.1 Across-wind forces on typical buildings

We have made a series of wind tunnel tests on typical tall building and structure models for across-wind forces using wind pressure scanning technique and high-frequency force balance technique. There were a total of 121 general building models and dozens of real tall structure models. Twenty-five building models for wind pressure tests and 96 building models for direct measurements of wind forces were sampled using the HFFB technique. The models had different cross-section shapes, including square, rectangular, triangle, Y-type, polygon, L-type, corner-modified square cross-section shape, ladder shape, twin-tower shape, and with continuous contraction cross section. Some of these models are shown in Figure 1. The tests were carried out under simulated wind conditions in accordance with the Chinese Code [23] definitions.

The cross-wind forces acting on the buildings were computed by integrating the wind pressures on the buildings or obtained directly from force balance test results. The wind force characteristics including wind force coefficient, PSD, coherence function, and so on were then analyzed in detail. Some results are shown in this paper. Figures 2 and 3 show the variations of wind force coefficients on heights of 57.15, 50.95, 43.8, and 35.7 mm on the building models with triangular and Y-type sections for different wind directions in exposure category B. Figure 4 presents the effects of parameters on the across-wind forces acting on rectangular buildings. It should be especially noted that when the short sides for some rectangular buildings (for example: $D/B>2$, where $D$ and $B$ are the depth and width of the building cross section, respectively) are windward, the separated flow at the front edges of the building cross

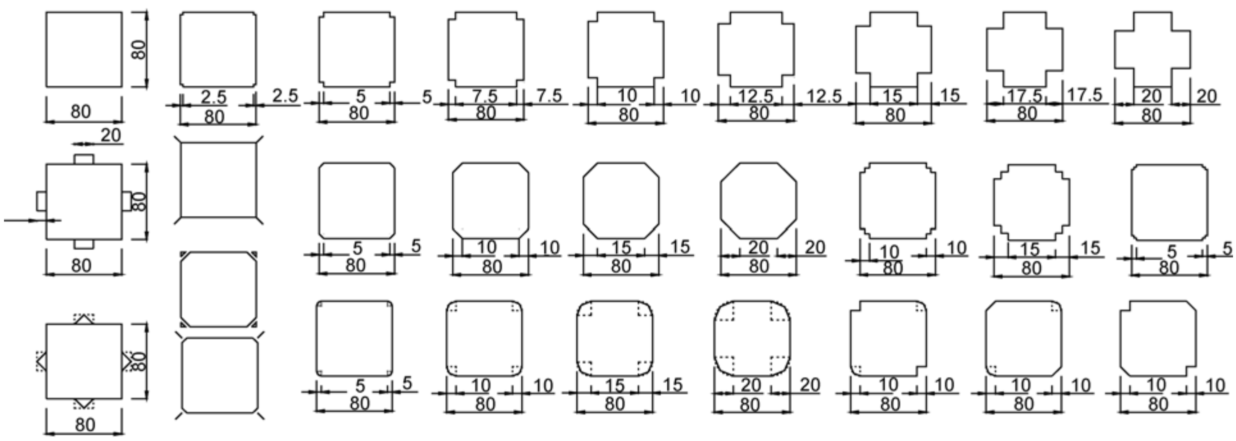

**Figure 1** Cross sections of some wind tunnel test models.

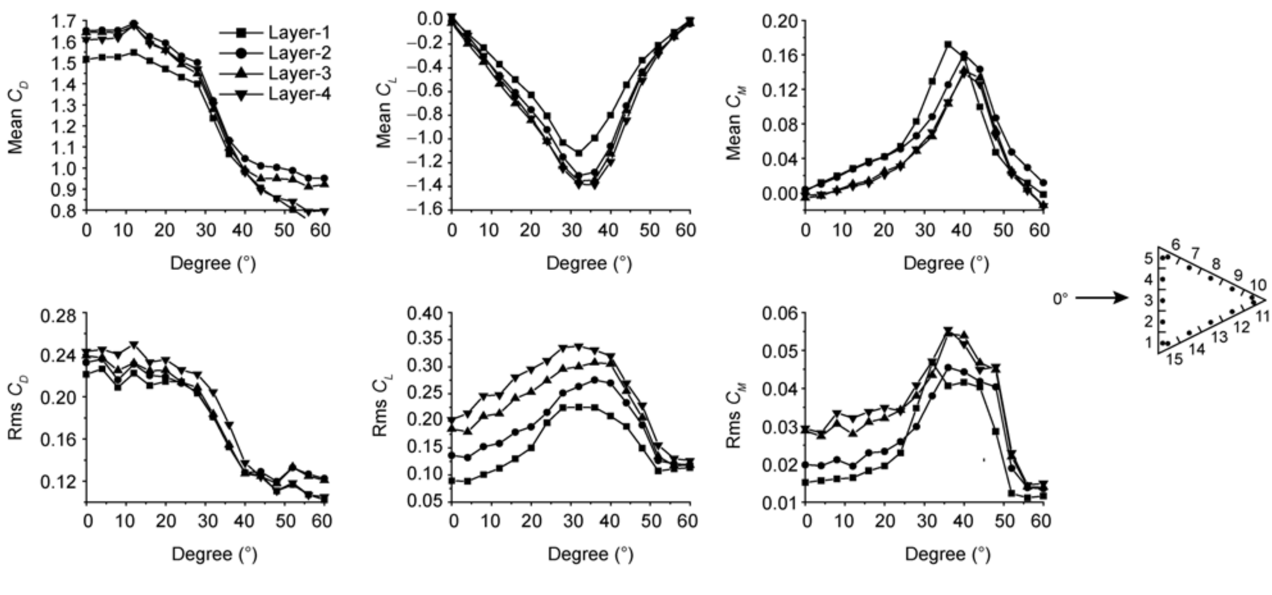


**Figure 2** Wind force coefficients of triangular model vs. wind direction (Terrain B).

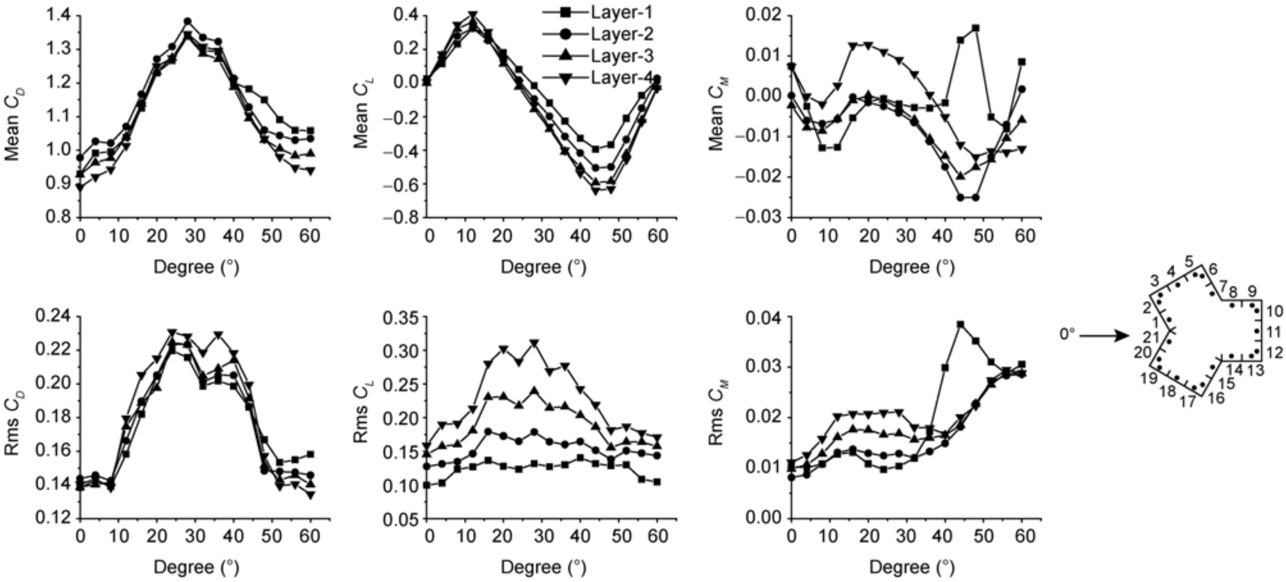


**Figure 3** Wind force coefficients of Y-type model vs. wind direction (Terrain B).

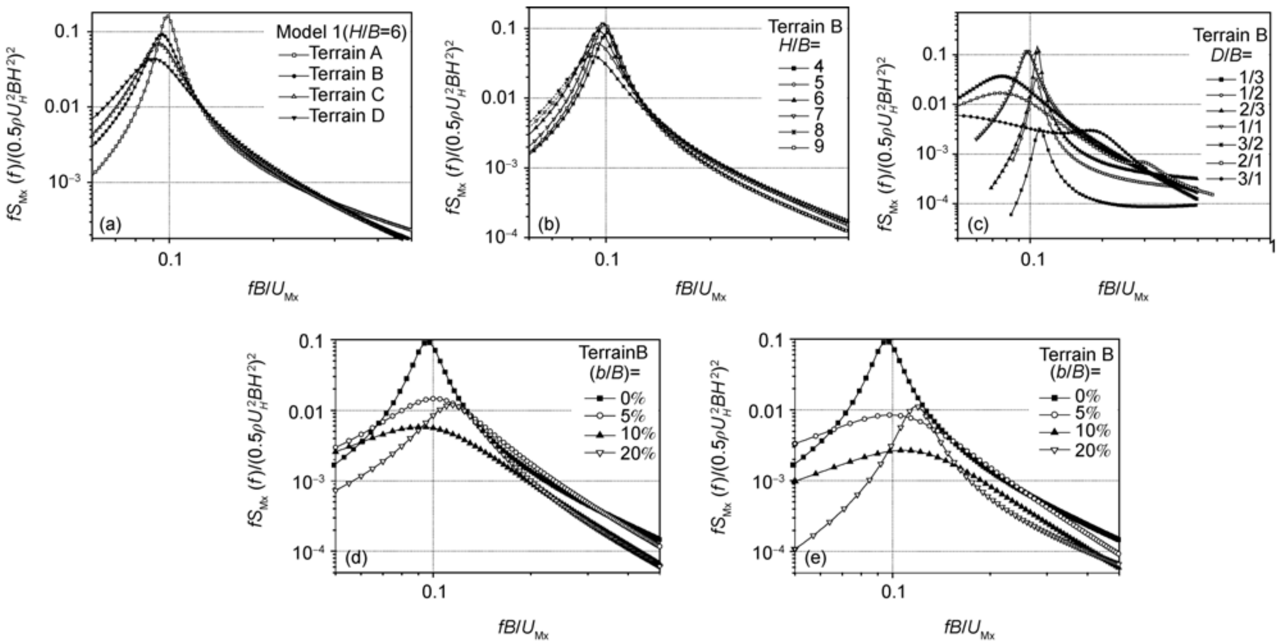


**Figure 4** Effects of parameters on the across-wind forces acting on rectangular buildings. (a) Effect of terrain condition; (b) effect of aspect ratio; (c) effect of side ratio; (d) effect of corner-cut size (bevel corner model); (e) effect of corner-cut size (concave corner model).

section will re-attach at the side wall. More results can be found in refs. [1, 36, 37].

As shown in the above experimental results from the wind tunnel tests, formulas for across aerodynamic forces were derived for practical use. As an example, a unified formula for non-dimensional PSD of across-wind force of the rectangular buildings and square buildings with corner modifications is given as follows:

$$\frac{fS_{Mx}(f)}{\left\{0.5\rho U_H^2 BH^2\right\}^2}=\frac{S_p\beta(n/f_p)^{\alpha}}{\left\{1-(n/f_p)^2\right\}^2+\beta(n/f_p)^2}, \quad (1)$$

where $S_{Mx}(f)$ is the first generalized across-wind force spectrum; $f$ is the frequency; $n=fB/U_H$; $U_H$ is the mean wind speed at the top of the buildings; parameters $f_p$, $S_p$, $\beta$, and $\alpha$, being functions of aspect ratio, side ratio of the cross section of the buildings, and wind field condition, are as follows:

$$f_p=10^{-5}(191-9.48\alpha_w+1.28\alpha_{hr}+\alpha_{hr}\alpha_w)(68-21\alpha_{db}+3\alpha_{db}^2), \quad (2)$$

$$S_p=(0.1\alpha_w^{-0.4}-0.0004e^{\alpha_w})(0.84\alpha_{hr}-2.12-0.05\alpha_{hr}^2)\times(0.422+\alpha_{db}^{-1}-0.08\alpha_{db}^{-2}), \quad (3)$$

$$\beta = (1+0.00473e^{1.7\alpha_w})(0.065+e^{1.26-0.63\alpha_{hr}})e^{1.7-3.44/\alpha_{db}}, \quad (4)$$

$$\alpha = (-0.8+0.06\alpha_w+0.0007e^{\alpha_w})(-\alpha_{hr}^{0.34}+0.00006e^{\alpha_{hr}}) \times(0.414\alpha_{db}+1.67\alpha_{db}^{-1.23}), \quad (5)$$

$$\alpha_{hr} = H/\sqrt{BD}, \quad (6)$$

$$\alpha_{db} = D/B, \quad (7)$$

$$\alpha_w = 1(A);\ \ 2(B);\ \ 3(C);\ \ 4(D), \quad (8)$$

where $H$ is the height of the building; $B$ and $D$ are the width and depth of the building cross section, respectively; $\alpha_{db}$, $\alpha_{hr}$, and $\alpha_w$ are the side ratio, aspect ratio, and wind terrain series number, respectively. The above equations are suitable for estimating the across-wind forces of square buildings with aspect ratios between 4 and 9, and rectangular buildings with side ratios between 0.5 and 2.0 under the four categories of terrain.

### 3.2 Across-wind aerodynamic damping of typical buildings

As mentioned above, across-wind aerodynamic damping may play an important role in the computation of across-wind dynamic responses of super-tall buildings, and likewise for their structural design. Related studies have also been performed by us.

The aeroelasitic model technique was used to investigate the aerodynamic damping characteristics of buildings. A single-degree-of-freedom tall building aeroelastic model was specially designed for the test. The frequency, mass distribution, and damping could be easily adjusted for parametric studies. Three series of buildings including rectangular buildings, corner-modified square buildings, and buildings with continuous contraction cross section were modeled and tested under four categories of terrain conditions in the TJ-1 Boundary Layer Wind Tunnel in Tongji University. The effects of cross-section shape and dynamic parameter of buildings as well as terrain condition on the aerodynamic damping were investigated in great detail. The time-averaging method of random decrease technique and the stochastic sub-space identification method were adopted in the current study to identify the aerodynamic damping ratio. Figure 5 shows the variations of aerodynamic damping ratio of a square building with terrain condition and structural damping. Negative aerodynamic damping at the reduced wind speed of about 10–13 can be seen in the figure. Based on the testing results and the analyses, a simplified formula for aerodynamic damping ratio of the square building can be derived for practical purpose as follows:

$$\zeta_a = \frac{0.0025\left(1-(U^*/9.8)^2\right)(U^*/9.8)+0.000125(U^*/9.8)^2}{\left(1-(U^*/9.8)^2\right)^2+0.0291(U^*/9.8)^2}, \quad (9)$$

where $U^*$ is the reduced wind velocity, which is defined as $U_H/(f_1B)$; $U_H$ is the approaching wind velocity at the height of the building; $f_1$ is the first natural frequency of the building; $B$ is the breadth of the building.

### 3.3 Applications to the Chinese Codes

The present Chinese Code [23] does not have relevant clauses of across-wind load on buildings; thus, it cannot meet the needs of the design of super-tall buildings. Nevertheless, the code is being revised. Eqs. (2)–(8) will be adopted in the revised Chinese Code. As for the square buildings with corner modifications, the non-dimensional PSD of across-wind force $S_{Mm}(f)$ has the following style and will also be adopted in the revised code.

$$S_{Mm}(f) = C_m(f)S_{M0}(f), \quad (10)$$

where $S_{M0}(f)$ is the non-dimensional power spectrum of across-wind force of the square building, i.e., $S_{Mx}(f)$ in eq. (1), and $C_m(f)$ is a non-dimensional ratio between $S_{Mm}(f)$ and $S_{M0}(f)$, which is listed in Table 2.

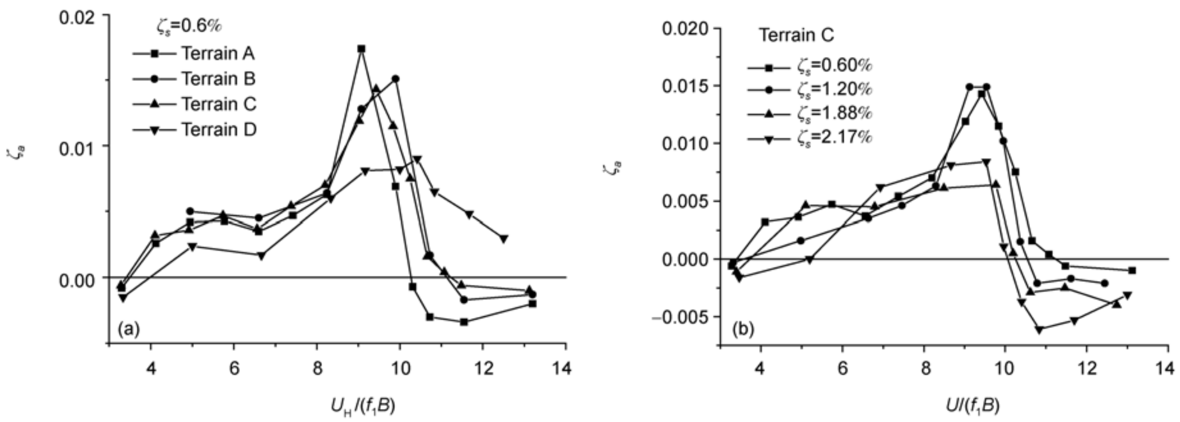


**Figure 5** Variations of aerodynamic damping ratio with different parameters. (a) Effect of terrain condition; (b) effect of structural damping.

**Table 2** Values of $C_m(f)$

| Cross section | Wind condition | $b/B$ | Reduced frequency ($fB/U_H$) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 0.100 | 0.125 | 0.150 | 0.175 | 0.200 | 0.225 | 0.250 |
| Bevel corner | Category B | 5% | 0.183 | 0.905 | 1.20 | 1.20 | 1.20 | 1.20 | 1.10 |
| | | 10% | 0.070 | 0.349 | 0.568 | 0.653 | 0.684 | 0.670 | 0.653 |
| | | 20% | 0.106 | 0.902 | 0.953 | 0.819 | 0.743 | 0.667 | 0.626 |
| | Category D | 5% | 0.368 | 0.749 | 0.922 | 0.955 | 0.943 | 0.917 | 0.897 |
| | | 10% | 0.256 | 0.504 | 0.659 | 0.706 | 0.713 | 0.697 | 0.686 |
| | | 20% | 0.339 | 0.974 | 0.977 | 0.894 | 0.841 | 0.805 | 0.790 |
| Concave corner | Category B | 5% | 0.106 | 0.595 | 0.980 | 1.0 | 1.0 | 1.0 | 1.0 |
| | | 10% | 0.033 | 0.228 | 0.450 | 0.565 | 0.610 | 0.604 | 0.594 |
| | | 20% | 0.042 | 0.842 | 0.563 | 0.451 | 0.421 | 0.400 | 0.400 |
| | Category D | 5% | 0.267 | 0.586 | 0.839 | 0.955 | 0.987 | 0.991 | 0.984 |
| | | 10% | 0.091 | 0.261 | 0.452 | 0.567 | 0.613 | 0.633 | 0.628 |
| | | 20% | 0.169 | 0.954 | 0.659 | 0.527 | 0.475 | 0.447 | 0.453 |

The RMS coefficients of the aerodynamic base moment and the aerodynamic base shear force are respectively

$$\begin{aligned} C_M &= (0.002\alpha_w^2 - 0.017\alpha_w - 1.4) \\ &\times(0.056\alpha_{db}^2 - 0.16\alpha_{db} + 0.03) \\ &\times(0.03\alpha_{ht}^2 - 0.622\alpha_{ht} + 4.357), \end{aligned} \tag{11}$$

and

$$\begin{aligned} C_S &= (0.018\alpha_w^2 + 0.0006\alpha_w - 2.4) \\ &\times(0.0375\alpha_{db}^2 - 0.11\alpha_{db} + 0.0117) \\ &\times(0.04\alpha_{ht}^2 - 0.928\alpha_{ht} + 6.7), \end{aligned} \tag{12}$$

where

$$\alpha_{ht} = H/T, (T = \min(B, D)). \tag{13}$$

The above formulas have also been adopted in ref. [56]. In addition, eq. (9) has been adopted in ref. [56], and it will also be adopted in the revised Chinese Code.

These formulas have also been used by us to compute the across-wind loads and dynamic responses of real high-rise structure in the initial design stage. The computation results were then compared with the detailed wind tunnel test and computation results. Generally, the results reasonably matched.

Furthermore, a method of across-wind equivalent static wind loads was proposed [43] and adopted in ref. [56] and the revised Chinese Code. The across-wind equivalent static wind load was firstly divided into mean, resonant and background components for separate computation, and finally these components were combined into the total equivalent static wind load. The resonant component is equal to the inertial force due to vibration of the structure and the background component is essentially the base moment-aimed equivalent static wind loads.

## 4 A case study

The target structure in its original design stage was a quasi-square tower, with a height of 172.6 m and side length of 16.8 m as shown in Figure 6. The lower part from 3/4 of the tower was a standard square cylinder, and the upper part from 1/4 of the building had a somewhat complicated section, as shown in Figure 2. The fundamental frequency of the tower building is 0.3 Hz, and the structural damping is 0.02. The terrain category of the building site is B, and the design wind velocity at 10 m height for 100-year return period is 31 m/s.

The rigid tower model was tested for wind pressure measurement in a wind tunnel. The mean and root mean square values of along-wind and across-wind aerodynamic base bending moments and shearing forces at 24 wind azimuth were obtained from the wind pressure distributions, some of which are shown in Table 3. In addition, as shown

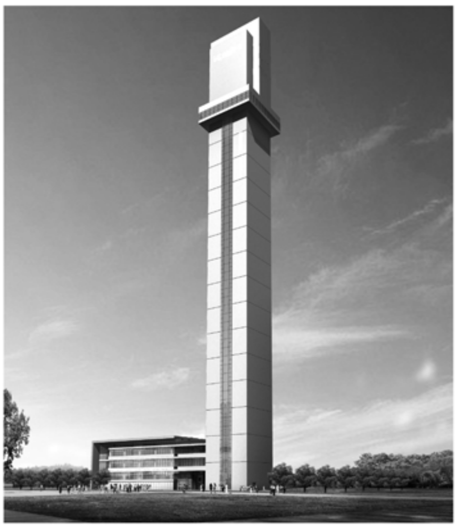

**Figure 6** Target structure.

**Table 3** Base bending moment and shearing force under design wind velocity for 0° wind azimuth

| Base bending moment (×10$^5$ kN m) | | | | Base shearing force (×10$^3$ kN) | | | |
|---|---|---|---|---|---|---|---|
| Along-wind | | Across-wind | | Along-wind | | Across-wind | |
| Mean | RMS | Mean | RMS | Mean | RMS | Mean | RMS |
| 3.94 | 0.23 | 0 | 0.68 | 4.38 | 0.28 | 0 | 0.85 |

in Table 3, the along-wind mean aerodynamic base bending moment and the shearing force are much larger than the across-wind mean values, which are both zero. However, the root mean square values of the across-wind aerodynamic base bending moment and the shearing force are about three times the along-wind values.

The PSDs of the along-wind and across-wind generalized aerodynamic of the tower are presented in Figure 7, in which the PSD of the across-wind aerodynamic force of standard square tall buildings in ≪Specification for Steel Structural Design of Tall Buildings≫ (DG/TJ 08-32-2008) [56] is also shown. As shown in Figure 7, the energy in the PSD of along-wind aerodynamic force decreases monotonously with the increase of frequency. However, an obvious peak value appears at 0.285 Hz in the PSD of the across-wind aerodynamic force, and the Strouhal frequency for square cylinder is 0.1. The frequency corresponding to the peak value of the PSD of across-wind aerodynamic force is very close to the fundamental frequency of 0.3 Hz of the tower, thus results in strong resonant responses of the tower. Figure 8 shows the along-wind and across-wind equivalent static wind loads at wind azimuth of 0°. It can be seen that the across-wind equivalent static wind load is much larger than the along-wind one, especially on the top of the model.

Since there is no corresponding guidance in the present Chinese Code, the across-wind loads and responses were not considered by the structure engineers in the initial design stage of the tower. The above research results remind structural designers of attaching importance to the problem of across-wind loads, and of modifying the initial design plan of the tower accordingly. In the new plan, the side length increases by 7% from 16.8 to 18 m, and this in turn makes the fundamental frequency of the structure increase from 0.3 to 0.33 Hz. The mass of the structure increases slightly as well. Table 4 shows the equivalent static wind

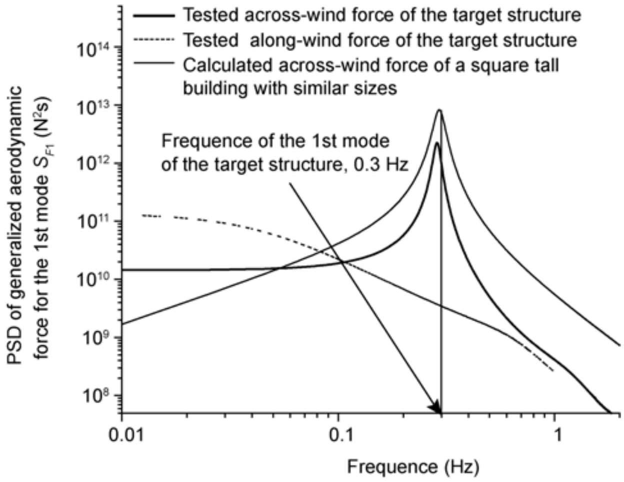


**Figure 7** The along-wind and across-wind generalized aerodynamic spectra of the tower.

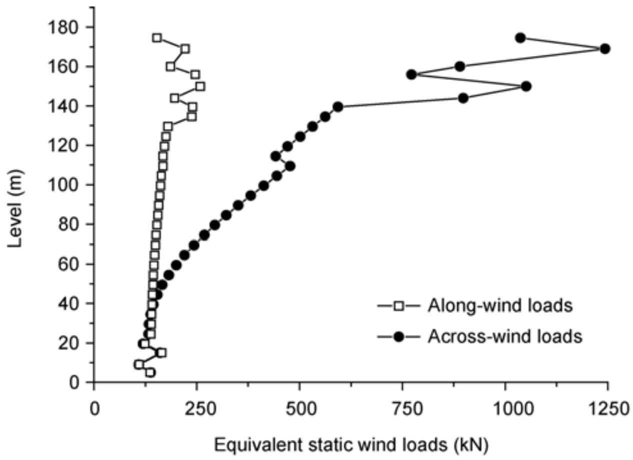


**Figure 8** Equivalent static wind load distribution of the original plan.

**Table 4** Equivalent static wind load distributions of the original and modified towers

| Response types | | Original design plan | | | New design plan | | |
|---|---|---|---|---|---|---|---|
| | | 0° | 90° | 180° | 0° | 90° | 180° |
| Total base bending moment responses (×10$^5$ kN m) | *X* | –5.13 | 5.77 | 5.20 | –6.64 | 5.51 | 6.77 |
| | *Y* | 16.37 | 5.71 | 12.72 | 7.42 | 7.30 | 7.04 |
| Total base shearing force responses (×10$^3$ kN) | *X* | –5.67 | 5.06 | 5.81 | –6.56 | 4.77 | 6.74 |
| | *Y* | 14.19 | 6.02 | 11.00 | 6.96 | 6.89 | 6.33 |

load distributions of the modified tower with those of the original tower for comparison. The across-wind equivalent static wind load was firstly divided into mean, resonant and background components for separate computation, and finally these components were combined into the total equivalent static wind load. The resonant component is equal to the inertial force due to vibration of the structure and the background component is essentially the base moment-aimed equivalent static wind load. It can be seen from Table 4 that the along-wind responses of the new tower increase by about 15%, whereas the maximum across-wind equivalent static wind loads greatly reduce by more than 50%. The modified tower plan is now the final one.

## 5 Concluding remarks

With the continuing increase in the height of buildings, across-wind loads and effects have become increasingly important factors for the structural design of super-tall buildings and structures. The current paper reviews researches on across-wind loads and effects of super-tall buildings and structures, including the mechanism of across-wind loads and effects, across-wind aerodynamic forces, across-wind aerodynamic damping, and applications in the code. Consequently, some of our research achievements involving across-wind forces on typical buildings, across-wind aerodynamic damping of typical buildings, and applications to the Chinese Codes are presented. Finally, a case study of a real typical tower, where strong across-wind loads and effects may be observed, is introduced. The recent trend in constructing higher buildings and structures implies that wind engineering researchers will be faced with more new challenges, even problems they are currently unaware of. Therefore, more efforts are necessary to resolve engineering design problems, as well as to further the development of wind engineering.

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