Bridge and Structure Wind Resistance Analysis and Test

Wind load is the most general and ambiguous long-duration load for bridges, high-rise buildings, cooling towers, large span shells and roofs, and other civil engineering structures. Wind induced effect will induce stability and fatigue problems for those structures. Wind resistance analysis and design is critical for ensuring life-cycle performance of bridges and structures. Recent research works in BE at Tongji University that address bridge and structure wind resistance analysis and test include: Across-wind equivalent static wind loads and responses of super-high-rise buildings; Aero-elastic model test study on a bridge pylon considering the interference effects of surrounding structures; Torsional stiffness degradation and aerostatic divergence of suspension bridge decks; Experimental study of wind loads on cylindrical reticulated shells; Multiple loading effects on wind-induced static performance of super-larege cooling towers; Parametric vibration of stay cables under axial narrow-band stochastic excitation; Wind-induced responses of a large-scale membrane structure; Superposability of unsteady aerodynamic loads on bridge deck sections.

Across-Wind Equivalent Static Wind Loads and Responses of Super-High-Rise Buildings

Wind tunnel test results have indicated that the across-wind dynamic responses of super-high-rise buildings are often larger than along-wind ones. Based on a series of wind tunnel tests on 15 rectangular super-high-rise building models with side ratios smaller than 2 in four categories of simulated wind fields with high-frequency force balance technique, the present study develops an analytical method for across-wind equivalent static wind loads on super-high-rise buildings and their corresponding responses.

Objective & Approach: Using several formulas of across-wind aerodynamic forces and aerodynamic damping of rectangular super-high-rise buildings with side ratios smaller than 2 proposed previously by the authors, across-wind equivalent static loads and responses of super-high-rise buildings are evaluated through a proper combination of resonant and background components. The resonant component is computed according to the power spectral density of the base moment and the aerodynamic damping. The background component, whose vertical distribution is derived from background moment responses at different heights and then expressed as a cubic equation of the relative height, is computed using the base moment coefficients. Furthermore, comparisons are made for the equivalent static wind loads and responses of a hypothetical typical building between the present method and the AIJ (1996) method, which indicate the applicability of the present method. Finally, the effects of background component and aerodynamic damping on the equivalent wind loads and responses are also discussed.

Principal Investigator:
Yong Quan and Ming Gu

Funding: National Natural Science Foundation of China (Grant Nos. 50878159 and 0715040) and the Shanghai Pujiang Program (Grant No. 08PJ1409500)

Key Publications:

Quan Y, Ming Gu, 2012, Across-Wind Equivalent Static Wind Loads and Responses of Super-High-Rise Buildings. *Advances in Structural Engineering*, 15(12), 2145-2155.

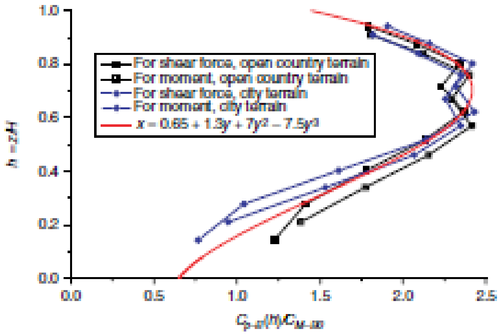


Figure 1. Vertical distibution of across-wind background wind loads of high-rise buildings

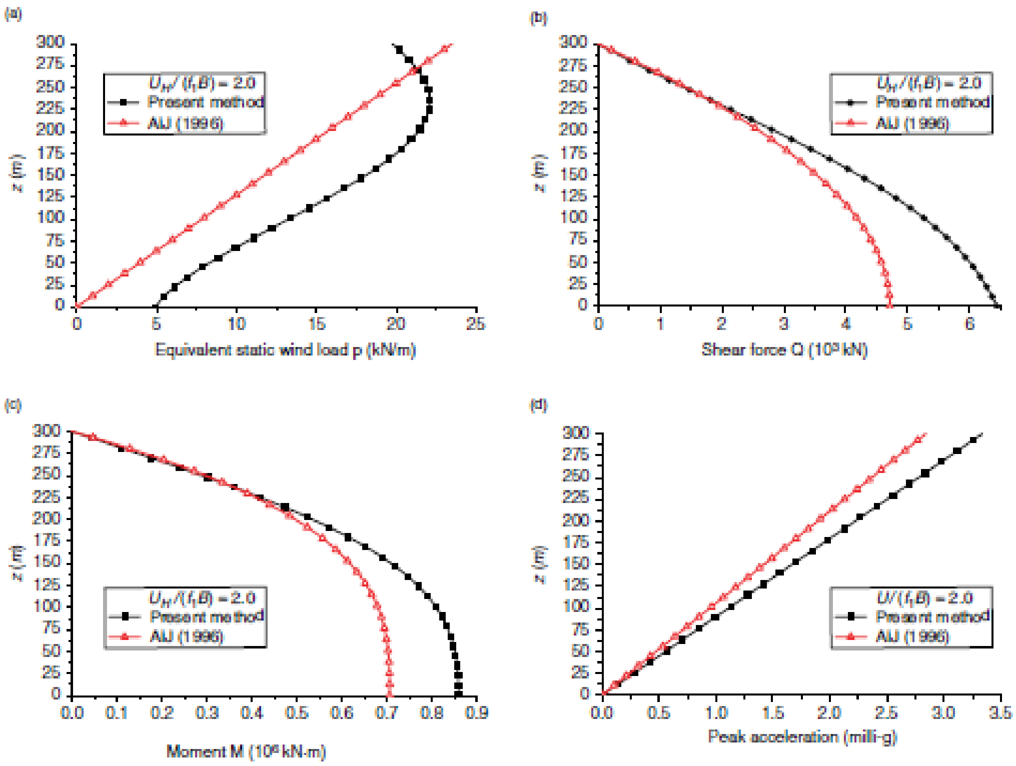


Figure 4. Across-wind equivalent static wind loads and responses (reduced wind velocity = 2)

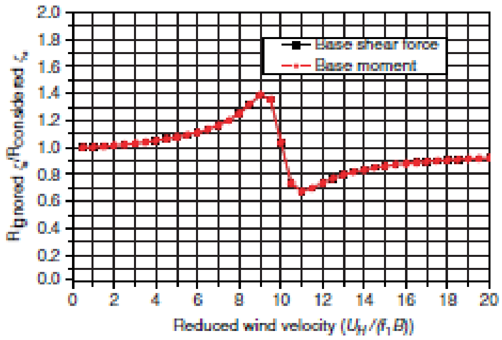


Figure 6. Ratios of responses that ignored aerodynamic damping and those considered aerodynamic damping

Aero-elastic Model Test Study on a Bridge Pylon Considering the Interference Effects of Surrounding Structures

Through the wind tunnel test, investigators noted that the torturing response of the Empire State building would have been doubled if two brand-new buildings were to be constructed in its two neighboring blocks. In this paper, the interference effect of surrounding structures on the wind induced vibrations of a bridge pylon of the already-finished Mingpu Bridge was investigated through wind tunnel tests. The static and buffeting responses at the top of the bridge pylon in along-wind, across-wind directions are acquired and analyzed, respectively. Meanwhile, some conclusions referring to the effect of cooling towers on the bridge pylon are drawn. At the end, boundary layer wind tunnel tests are conducted to verify the interference effect of the two cooling towers.

Objective: The interference effect between buildings has been a popular issue in structural wind engineering for a long time. Most researches about this issue have been focused mainly on high-rise buildings. For long-span bridges, the interference effects between structures arc rarely discussed.

Approach: In this paper, an aerodynamic elastic model test of a free-standing bridge pylon located adjacent to two large-scale cooling towers is presented. Through the mode analysis, the structure mode shapes arc obtained. Then by the simulation of the two cooling towers in the boundary layer during the aeroclastic model test, the vibration responses of the bridge pylon in smooth and turbulence flows arc obtained respectively.

Significant Result: The study shows that the interference effect of the two hugo-volume cooling towers on the wind induced vibration responses of the bridge pylon should not be neglected. In smooth flow, due to the regular shedding vortex from the upwind cooling towers, the interference effect is evident in that strong resonant responses arc induced on the lower-order modes of the downwind bridge pylon. However, in turbulence flow, this kind of interference effect is greatly reduced. Moreover, more attention should be paid to the case when the cooling towers arc located at the perfectly right upwind direction of the bridge pylon. Their interference effect will certainly cause great resonant vibrations in the longitudinal direction, which cannot be ignored for granted. Furthermore, the turbulence flow at the bridge pylon considering the interference effect is measured through a 1:500 flow experiment to discover the interference effect of the cooling towers. In the end, a dynamic magnification factor is proposed to take the interference effect into consideration, with a value of 2.25 suggested for the design of pylons.

Principal Investigator: RU-JIN MA and XIAO-HONG HU

Funding: National Natural Science Foundation of China (Grant Nos. 5150708073)

Key Publications:

1. Ma R J, Hu X H. AEROELASTIC MODEL TEST STUDY ON A BRIDGE PYLON CONSIDERING THE INTERFERENCE EFFECTS OF SURROUNDING STRUCTURES[J]. International Journal of Structural Stability and Dynamics, 2013, 13(05).

Fig. 3. (Color online) The aeroelastic model of the pylon of the Minpu Bridge.

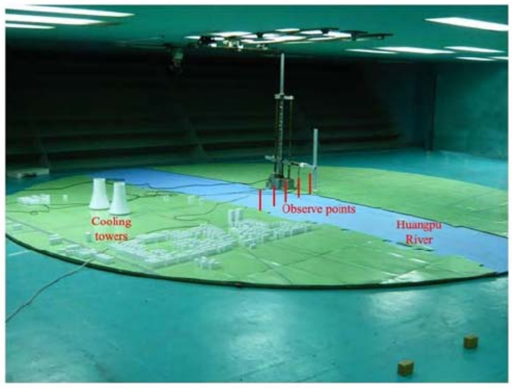
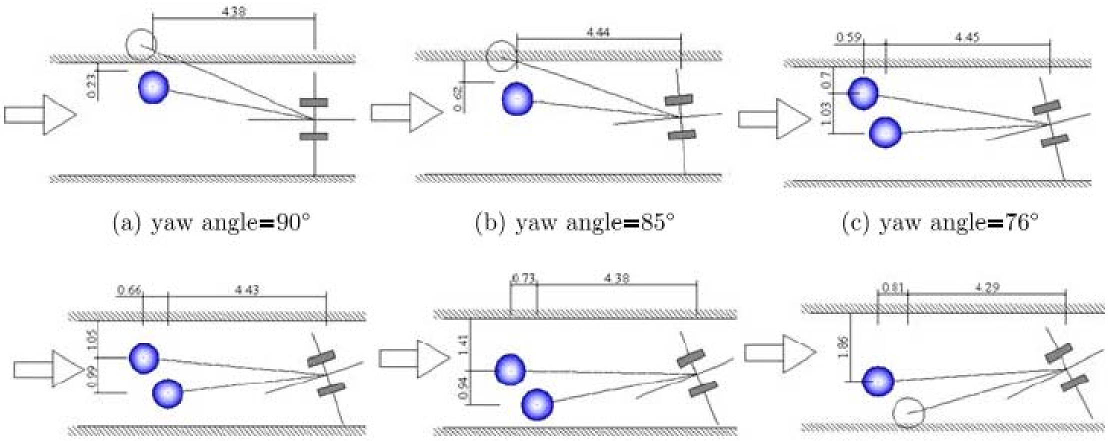


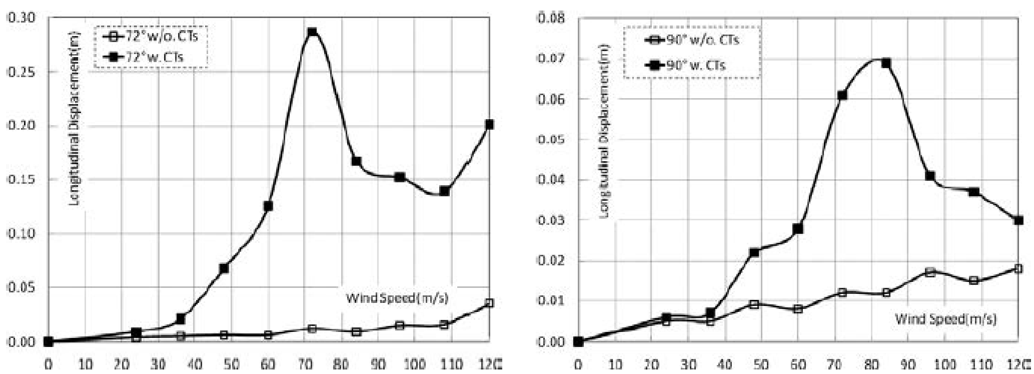
Fig. 11. (Color online) 1:500 Boundary layer model of bridge site.



(a) yaw angle=90° (b) yaw angle=85° (c) yaw angle=76°

(d) yaw angle=72° (e) yaw angle=68° (f) yaw angle=63°

Fig. 4. (Color online) Layout of the pylon and cooling towers in different yaw angles in TJ-2 wind tunnel (yaw angle of m0° is perpendicular to the bridge, while yaw angle of 90° is along the bridge).



(a) (b)

Fig. 6. Comparison of longitudinal buffeting response of the pylon in smooth flow. Yaw angle (a) 72° and (b) 90°.

Torsional stiffness degradation and aerostatic divergence of suspension bridge decks

A classical concept of the ATD, involves a critical flow speed beyond which an unlimited growth in structural rotation occurs. However, an unlimited growth in deformation is unrealistic, and hence it is more reasonable to define the critical divergence wind speed as one at which the twist of an airfoil increases rapidly to the point of failure. The objective of this study is, specific to long-span suspension bridges, investigating the motion-induced effects on the system stiffness and the mechanism of the ATD of suspension bridges immersed in turbulent flows.

Objective: The mechanism of aerostatic torsional divergence (ATD) of long-span suspension bridges is investigated. A theoretical analysis on the basis of a generalized model is presented, showing that the vertical motion of a bridge deck is crucial to the torsional stiffness of the whole suspended system, and that the vertical motion of either cable with a magnitude beyond a certain threshold could result in a sudden degradation of the torsional stiffness of the system. This vertical motion-induced degradation of stiffness is recognized as the main reason for the ATD.

Approach: Long-span suspension bridges are susceptible to such a type of divergence, especially when they are immersed in turbulent wind fields. The divergences that occur in turbulent wind fields differ significantly from those in smooth wind fields, and the difference is well explained by the generalized model that the loosening of any one cable could result in the vanishing of the part of stiffness provided by the whole cable system.

Significant Result: The mechanism revealed in this paper leads to a definition of the critical wind speed of the ATD in a turbulent flow; that is, the one resulting in a vertical motion so large as to loosen either cable to a stressless state. Numerical results from the nonlinear finite-element (FE) analysis of the Xihoumen suspension bridge, in conjunction with observations from wind tunnel tests on an aero-elastic full bridge model, are in support of the viewpoint presented in this study.

Principal Investigator:

Z.T. Zhang, Y.J. Ge and Y.X. Yang

Funding: The National Science Foundation (Grant nos. 51178182 and 90915002), and the open project of the state key laboratory of disaster reduction in civil engineering (Project no.SLDRCE10-MB-03).

Key Publications:

Zhang Z T, Ge Y J, Yang Y X. Torsional stiffness degradation and aerostatic divergence of suspension bridge decks [J]. Journal of Fluids and Structures, 2013, 40: 269-283.

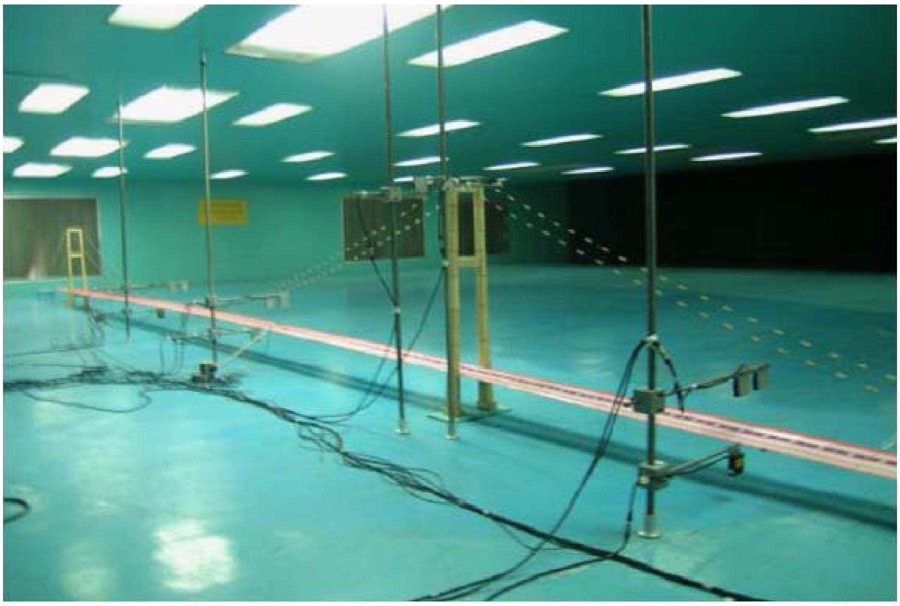


Fig. 6. Full aeroelastic model of Xihoumen bridge.

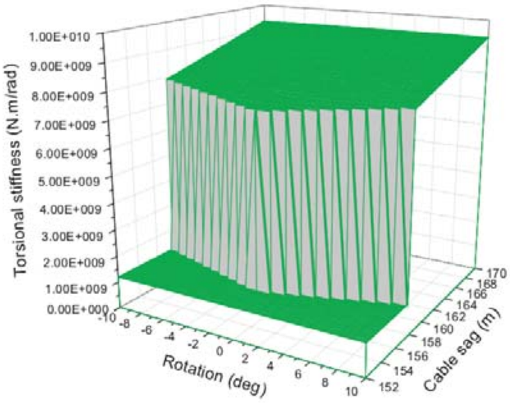


Fig. 9. $\tilde{K}_T$ versus cable sag and deck rotation.

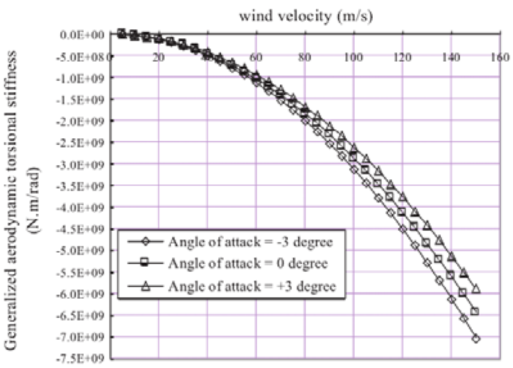


Fig. 10. Generalized aerodynamic stiffness.

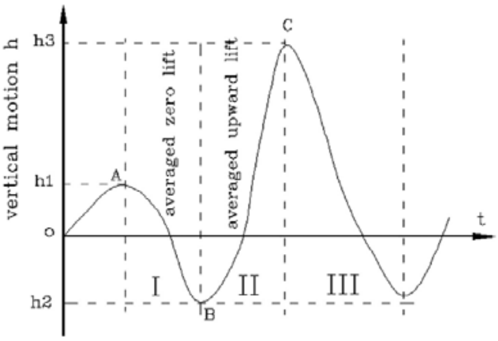


Fig. 17. Sketch map of a typical intermittent torsional divergence.

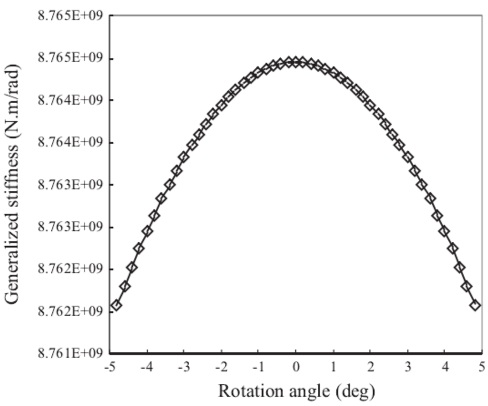


Fig. 8. $\tilde{K}_T$ versus rotation angle α (f= 165 m).

Experimental study of wind loads on cylindrical reticulated shells

With the increases in the height and span of dry-coal sheds, wind loads become one of the key factors in structural designs. Unfortunately, wind loads of dry-coal sheds do not exist in codes or standards, which will provide guidance to the design of dry-coal sheds. The current study presents in detail the characteristics of the wind pressures on the upper and lower surfaces and the net pressures. The block mean and fluctuating (rms) pressure coefficients, which are suitable for engineering applications, are given as references for wind load codes.

Objective: The cylindrical reticulated shell structures without side walls, which are normally arranged in pairs, are usually used as dry-coal sheds in a thermal power plant. The wind loads of these shells do not exist in standards or codes.
Approach: Therefore, this study investigates the mean and fluctuating wind loads on a cylindrical reticulated shell with a rise-to-span ratio of 0.39 through a series of wind tunnel tests. The characteristics of the wind pressures on the upper and lower surfaces and the net pressures are presented.
Significant Result: The results show that the wind direction and another shell structure significantly affect the wind loads on the principal shell. The most unfavorable wind direction is around 30°, whereas the effects of the wind field and the height of the coal stack are small. The surfaces of the shells are divided into nine blocks, and the block mean and fluctuating (rms) pressure coefficients suitable for engineering applications are given as references for wind load codes.

Principal Investigator:
Peng HUANG, Xuan-yi ZHOU, Ming GU
Funding:
Key Publications:
Huang P, Zhou X, Gu M. Experimental study of wind loads on cylindrical reticulated shells [J]. Applied Mathematics and Mechanics, 2013, 34: 281-296.

Fig. 3 Rigid models in wind tunnel test

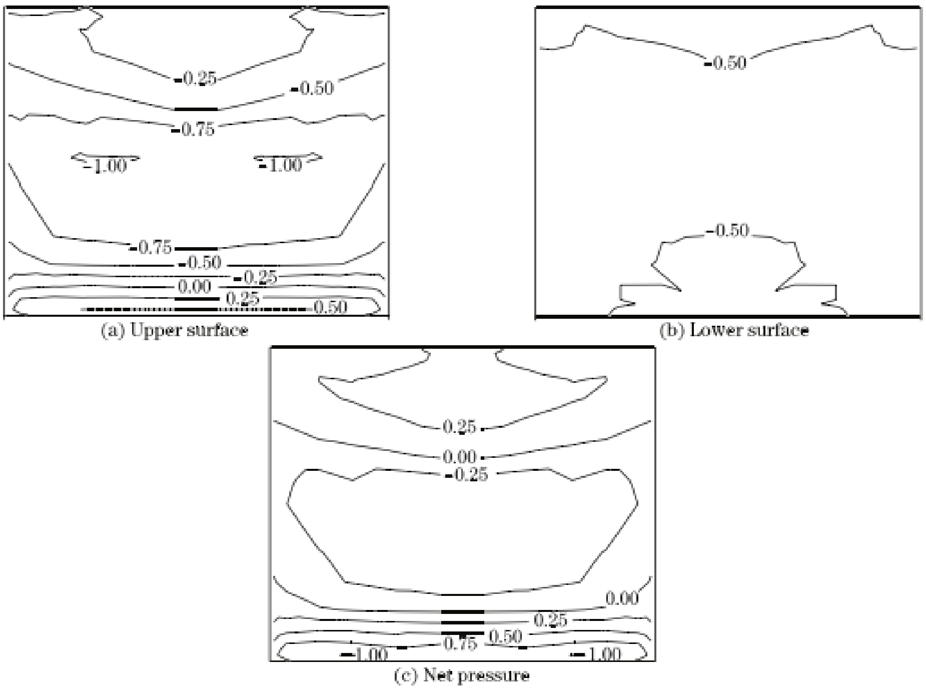


Fig. 4 Contours of mean pressure coefficient in 0° direction (open terrain, low coal stack, and isolated situation)

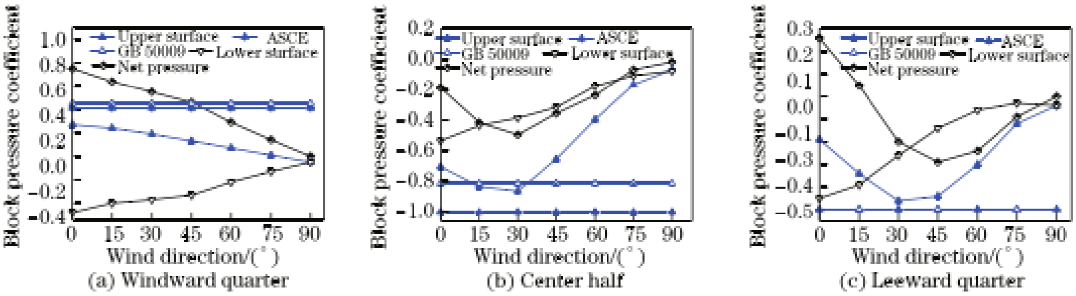


Fig. 15 Comparison of pressure coefficients on middle part of shell with results of codes

Multiple Loading Effects on Wind-Induced Static Performance of Super-Larege Cooling Towers

The present Codes NDGJ5-88, GB/T 50102-2003 and DL/T 5339-2006 (hereafter referred as the Chinese Codes) can hardly provide the necessary technical support for the structural design of super-large cooling towers for the following reasons. To avoid potential unfavorable designs brought by adopting the unreal external pressure distribution, comparative studies of structural responses obtained by loading the actual extreme external wind pressure and those produced by traditional design methodology are indispensable. To study potential problems with the present design methodology for super-large cooling towers, pressure measurements on an actual 176 m super-large cooling tower's rigid model in different tower group scenarios are conducted in an ABL wind tunnel to produce the accurate cladding wind loads.

Objective: Currently, four grouped 177 m super-large cooling towers, i.e. column-supported hyperboloidal shells, are to be constructed in a typical electric power plant in Southeast China. To this end, simultaneous pressure measurements on 1:200 rigid tower models are carried out in an atmospheric boundary layer (ABL) wind tunnel, aimed at accurately obtaining the external/ internal cladding wind loads on these shells.

Approach: The wind-induced static behavior of the cooling towers is analyzed by applying the wind loads acquired via the pressure model tests, using both linear elastic and nonlinear elastic finite element (FE) analyses. The corresponding responses (structural deformation, internal force and local buckling state) are compared with those obtained by the traditional design approach, focused on the effects of internal suction and external pressure distribution. Besides, the tower group interference effects are studied by comparing the results computed of a freestanding tower, with those of the tower groups during two deferent construction stages.

Significant Result: The main findings about the loading effects on the static performance of the super-large cooling towers are helpful for improving the current Chinese Codes that govern the design of super-large cooling towers.

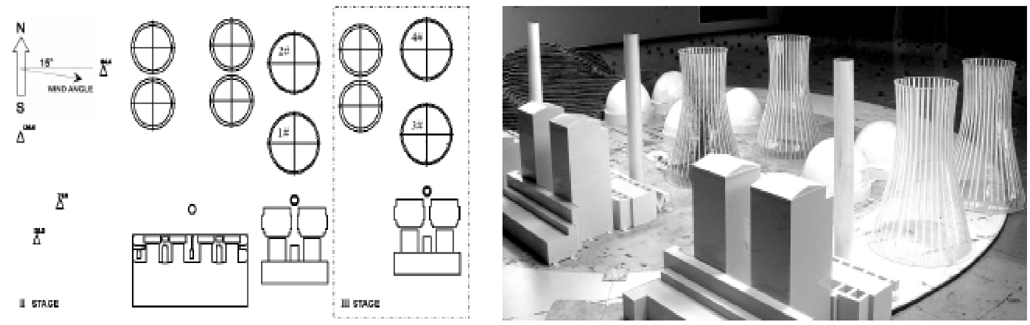
Principal Investigator:

X. X. CHENG, L. ZHAO and Y. J. GE

Funding: the National Natural Science Foundation of China (91215302, 51178353, and 51208254), the National Key Basic Research Program of China (i.e. 973 Program) (2013CB036300)

Key Publications:

Cheng X X, Zhao L, Ge Y J. MULTIPLE LOADING EFFECTS ON WIND-INDUCED STATIC PERFORMANCE OF SUPER-LARGE COOLING TOWERS [J]. International Journal of Structural Stability and Dynamics, 2013, 13(08).



(a) Site plan

(b) 1:200 site models

Fig. 1. Grouped cooling towers and adjacent buildings for second and third construction stages.

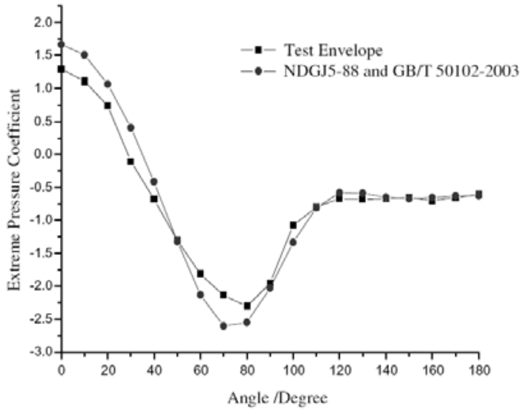


Fig. 5. Distribution of test extreme value and Codes for a freestanding tower.

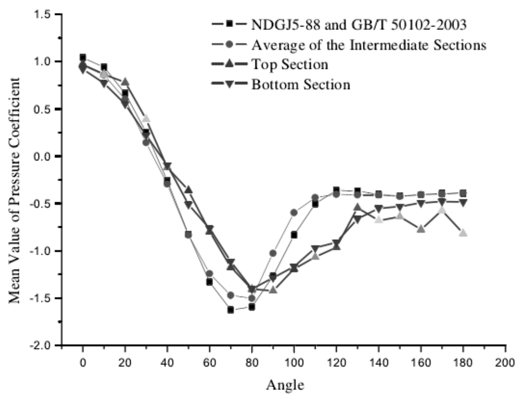


Fig. 6. Test pressure distributions and Codes.

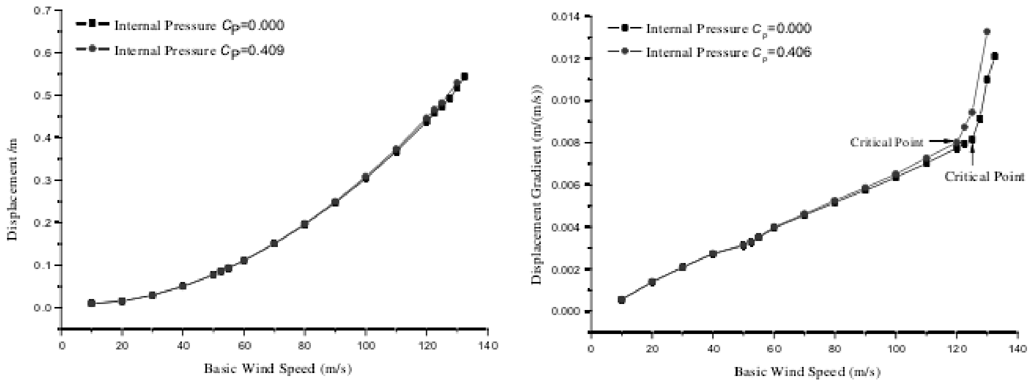


Fig. 8. Maximum displacement/displacement gradient — basic wind speed curves for different internal suction coefficients.

Parametric Vibration of Stay Cables under Axial Narrow-Band Stochastic Excitation

Studying the response characteristics of the parametric vibration of stay cables under axial stochastic excitations is of great significance to bridge structural designers. Relatively few studies have focused on the response problem of cables under axial stochastic excitations. A long cable, i.e. Cable A20 of No. 2 Nanjing Bridge over the Yangtze River, is taken as an example to illustrate the application of the theoretical model presented.

Objective: The differential equation for inclined cables under axial narrow-band stochastic excitations is established with consideration of the cable sag and variations of cable tension along the cable.

Approach: Gaussian and first-order non-Gaussian closed-form solutions are derived by employing the statistical moment truncation method to solve the moment equation. A long cable (Cable A20 of No. 2 Nanjing Bridge over the Yangtze River) is taken as an example to demonstrate the application of the theoretical model presented. The Monte Carlo method is also adopted to simulate the responses of the cable numerically under investigation.

Significant Result: The general response characteristics of the cable are analyzed, particularly, the variation characteristics of the response of the cable depending on the excitation bandwidth when the ratio of the central frequency of excitation to the first frequency of cable is equal to one or two. Parametric vibrations of the real Cable A20 excited by the buffeting vibration of the bridge deck of No. 2 Nanjing Bridge over the Yangtze River are also calculated.

Principal Investigator:

MING GU and SHU-YAN REN

Funding: the National Natural Science Foundation of China (Grant No. 50621062)

Key Publications:

Gu M, Ren S Y. PARAMETRIC VIBRATION OF STAY CABLES UNDER AXIAL NARROW-BAND STOCHASTIC EXCITATION [J]. International Journal of Structural Stability and Dynamics, 2013, 13(08).

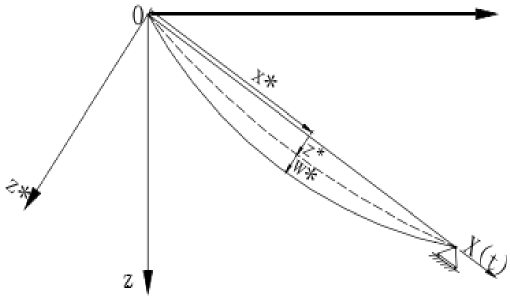


Fig. 1. Stay cable vibration model.

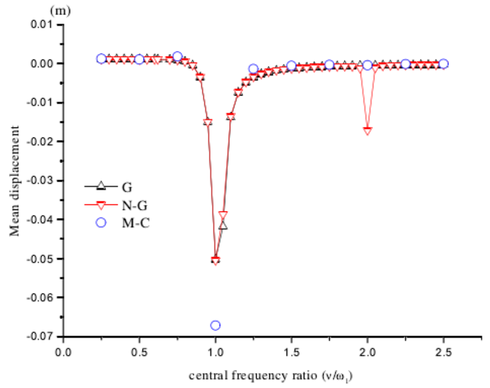
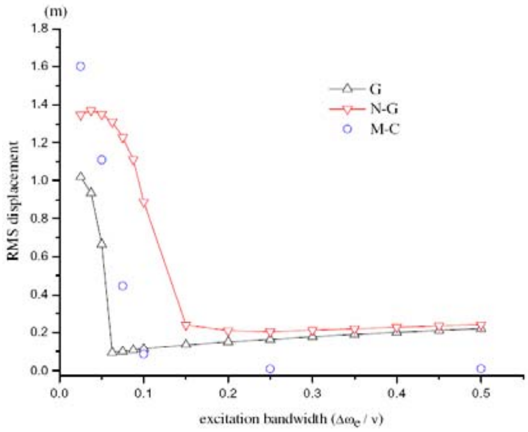
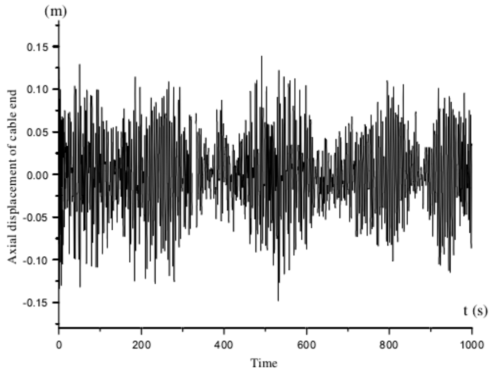


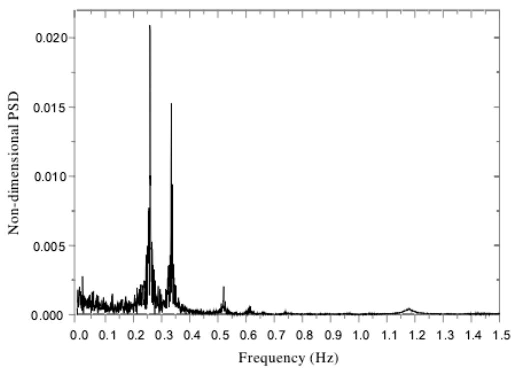
Fig. 2. Variation of mean displacement of cable with excitation frequency ratio.





(a) Displacement time history of bridge deck at cable end

Fig. 8. Time history and PSD of axial displacement at cable end.



(b) PSD of axial displacement of bridge deck at cable end

Fig. 8. (*Continued*)

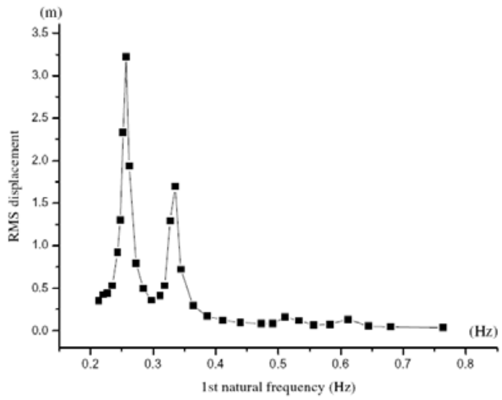


Fig. 9. Variation of RMS displacement of cable with first-mode cable frequency.

Research on wind-induced responses of a large-scale membrane structure

Due to the special features of the membrane structure, such as intensive mode of vibration, obvious nonlinear characteristics, and non-ignorable three-dimensional effect, the method for analyzing wind-induced response adopted for high-rise buildings and large-span roof structures cannot be directly applied to a membrane structure. Expo Boulevard, the most important building of Expo 2010 Shanghai China, is the research subject in this paper. The study intends to provide a practical method for analyzing wind-induced responses of membrane structures.

Objective: The wind-induced responses of a large-scale membrane structure, Expo Boulevard, are evaluated in this study.
Approach: To obtain the wind pressure distribution on the roof surface, a wind tunnel test is performed. A brief analysis of wind pressure on the membrane roof is conducted first and then an analysis of the wind-induced responses of the structure is carried out using a numerical integral method in the time domain. In the process of calculation, the geometrical nonlinearity is taken into account.
Significant Result: Results indicate that mean, RSM and peak values of the structure responses increase nonlinearly while the approaching flow velocity increases. Strong nonlinear characteristics are observed in the displacement responses, whereas the responses of nodal stress and cable axial force show minimal nonlinear properties when the membrane structure is subjected to wind loads. Different values of the damping ratio only have a minimal impact on the RSM response of the structure because the background component is a dominant part of the total dynamic response and the resonant component is too small. As the damping ratio increases from 0.02 to 0.05, the RMS responses of vertical displacement, nodal stress and cable axial force decrease by 8.1%, 6.7% and 17.9%, respectively. Since the mean component plays a significant role in the wind-induced response, the values of the gust response factor are not high for Expo Boulevard.

Principal Investigator:
Zhou Xuanyi, Han Zhihui, Gu Ming, Zhang An-an, Zhang Weiyu and Fang Wei
Funding: the National Natural Science Foundation of China (Grant No. 51278368)
Key Publications:
Zhou X, Han Z, Gu M, et al. Research on wind-induced responses of a large-scale membrane structure[J]. Earthquake Engineering and Engineering Vibration, 2013, 12(2): 297-305.

Fig. 3 Model for wind tunnel test

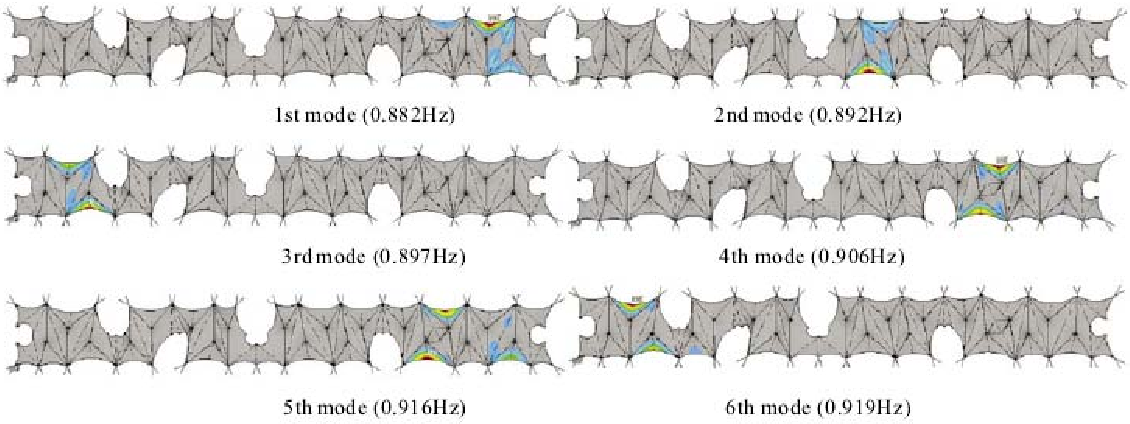


Fig. 6 Mode shapes of the structure

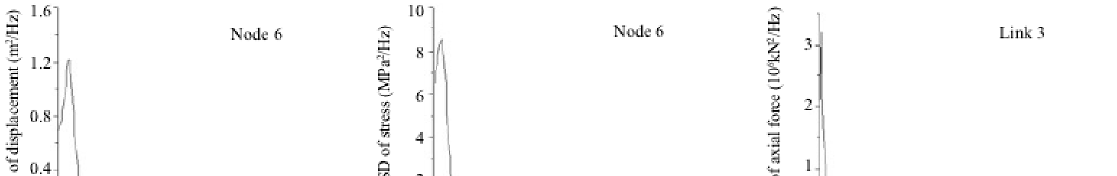


Fig. 9 Power spectral density of responses

Superposability of unsteady aerodynamic loads on bridge deck sections

Aerodynamic forces acting on bridge decks have generally been classified into steady and unsteady ones, according to whether or not the loads are time-varying. However, these assumptions don't work for a bluff bridge section and, therefore, the question arises as to whether these loads can be linearly superposed or, in another words, as to whether there exist a group of AA functions independent neither on the turbulent gust structure nor on the structural motions. This is the main concern of this work.

Objective: The 2-dimensional unsteady aerodynamic forces, in the context of both a thin airfoil where theory of potential flow is always applicable and a bluff bridge-deck section where separated flow is typically induced, are investigated from a point of view of whether or not they conform to the principle of linear superposition in situations of various structural motions and wind gusts. It is shown that some basic preconditions that lead to the linear superposability of the unsteady aerodynamic forces in cases of thin airfoil sections are no longer valid for a bluff section. Theoretical models of bridge aerodynamics such as the one related to flutter-buffeting analysis and those concerning aerodynamic admittance (AA) functions, however, necessitate implicitly this superposability.
Approach: The contradiction revealed in this work may throw light on the perplexing problem of AA functions pertaining to the description of buffeting loads of bridge decks. Some existing theoretical AA models derived from flutter derivatives according to interrelations valid only for thin airfoil theories, which have been employed rather extensively in bridge aerodynamics, are demonstrated to be illogical.
Significant Result: Finally, with full understanding of the preconditions of the applicability of linear superposability of the unsteady aerodynamic forces, suggestions in regard to experiment-based AA functions are presented.

Principal Investigator:
ZHANG Zhi-tian , GE Yao-jun and ZHANG Wei-feng

Funding: The National Natural Science Foundation of China; The Open Project of the State Key Laboratory of Disaster Reduction in Civil Engineering, China.

Key Publications:

Zhang Z, Ge Y, Zhang W. Superposability of unsteady aerodynamic loads on bridge deck sections[J]. Journal of Central South University, 2013, 20: 3202-3215.

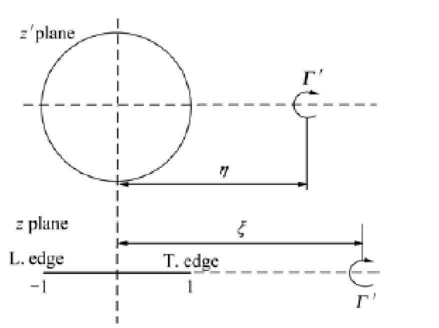


Fig. 1 Conformal representation of thin airfoil and wake vortex

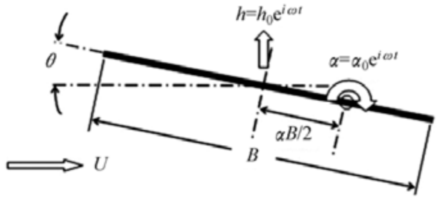
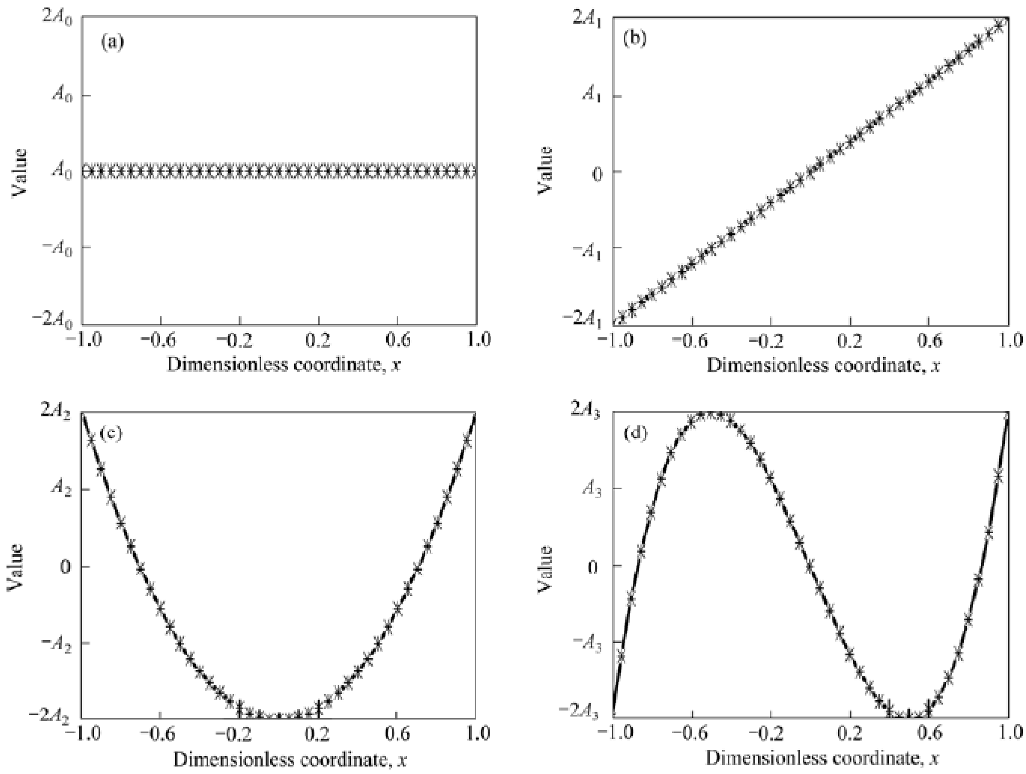


Fig. 3 Rigid motion of airfoil



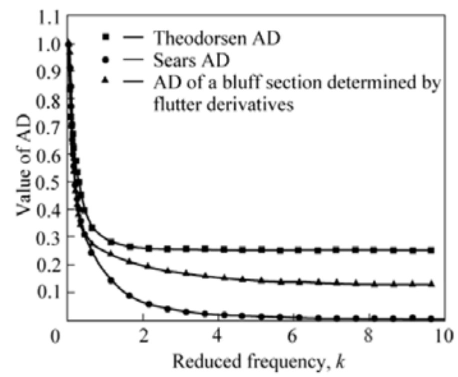


Fig. 6 Thoedorsen and Sears aerodynamic admittance

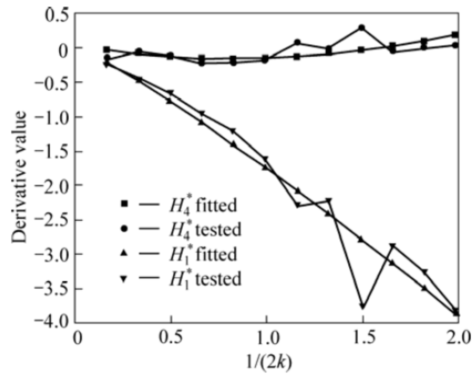


Fig. 7 Comparison of fitted flutter derivatives with those originally tested