Chinese Industry and Technology of Eco-environment
2025, VOL. 6, NO. 1, 5-9
DOI: 10.47297/wspciateWSP2633-772X01.20250601

Dynamic response and optimization design of civil engineering structures under wind load

Hao Chen, Lin Chen, Ruidong Gao

Cangzhou Vocational and Technical College, Cangzhou, Hebei, 061001

ABSTRACT
Wind load is a key factor affecting the stability and safety of civil engineering structures, and its variability and unpredictability pose great challenges to building design. This study analyzed the basic characteristics of wind loads and conducted a detailed exploration of the dynamic response of various civil engineering structures under wind loads, including high-rise buildings, large-span bridges, and high-rise structures. The mechanical manifestations and response mechanisms of these structures under wind loads were elucidated. Optimization design strategies such as wind tunnel testing, computational fluid dynamics (CFD) technology, and structural topology optimization have been proposed to enhance the wind resistance of civil engineering structures. Research has found that adopting diversified optimization design methods can improve the performance of structures while ensuring higher safety standards and economic benefits.

KEYWORDS
Wind load; Civil engineering structures; Dynamic response; Optimize design; Wind tunnel test

Wind load, as a key environmental force in nature, has a profound impact on the performance and safety stability of building structures. With the development of civil engineering towards super high-rise, large space, and lightweight, the dynamic response of structures under wind loads has become more prominent, which poses more severe challenges to engineering design and construction. Therefore, exploring the dynamic response and design optimization of structures under wind loads has important theoretical value and practical application significance. Typical representatives of civil engineering such as high-rise buildings, large-span bridges, and towering structures have different response characteristics under wind loads, and it is necessary to conduct in-depth research based on their respective characteristics.

1 Basic characteristics of wind load

The pressure and traction forces generated by wind on buildings are collectively referred to as wind loads, which play a crucial role in the design and stability of civil engineering structures[1]. The basic characteristics of wind load include randomness, time-varying, and non-uniform distribution in space, which can be clearly observed from Figure 1. Wind load has strong randomness, and is influenced by various factors such as topographical features, meteorological conditions, and the surrounding environment of buildings, resulting in continuous changes in wind speed and direction in an instant. The time-varying nature of wind load is also very prominent, which is mainly reflected by the temporal variation of wind speed and the fluctuation of wind pressure. It has a direct impact on the vibration and fatigue performance of buildings. The distribution of wind force borne by the exterior of buildings appears inconsistent due to the spatial characteristics of wind loads, and there are significant differences in the magnitude of wind force borne by each part[2]. The unevenness of this distribution is deeply influenced by the exterior design of the building, the obstruction of the surrounding environment, and the separation of air flow. At the same time, wind loads exhibit directional changes and periodic fluctuations, especially in coastal areas and areas with frequent typhoons. The variability of wind direction brings additional challenges to building structure design. Given the variable nature of wind loads, it is necessary to comprehensively consider their dynamic characteristics and design optimization strategies in the design process of civil engineering to ensure the stability and economic rationality of the structure.

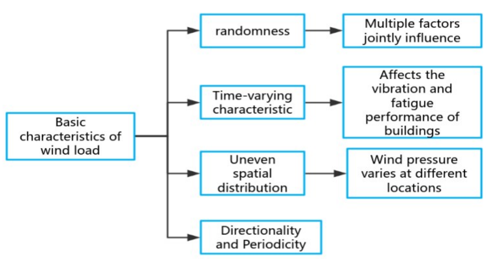

Figure 1 Wind load characteristics

2 Dynamic response analysis of different civil engineering structures under wind load

2.1 Dynamic response of high-rise building structures

High rise buildings are highly sensitive to the dynamic response of wind loads due to their towering height and elastic characteristics. On high-rise buildings, the influence of wind is diverse, covering average wind pressure, fluctuating wind pressure, and vortex induced vibration[3]. The wind characteristics endured by these buildings interact with their structural styles, exterior contours, and the properties of the building materials used, thereby affecting their dynamic response. Under wind load, the dynamic response of high-rise buildings mainly manifests as horizontal movement and vibration. The stable horizontal displacement caused by average wind pressure is usually determined by the wind direction pressure and the wind resistance strength of the building structure, while fluctuating wind pressure leads to dynamic vibration of the building structure. Especially in the low-frequency part of wind pressure fluctuations, it may coincide with the natural vibration frequency of high-rise buildings, triggering resonance effects and causing significant velocity increases and deformation expansions. In order to explore the dynamic effects caused by wind loads, finite element analysis methods in the field of structural dynamics can be applied to comprehensively consider the distribution properties of wind and the geometric shape and material characteristics of buildings. The displacement response u (t) of high-rise buildings under horizontal vibration can be calculated using the following simplified model:

$$m\frac{d^2u(t)}{dt^2}+c\frac{du(t)}{dt}+ku(t)=Fw(t) \tag{1}$$

In formula (1), m is the equivalent mass of the building and c is the damping coefficient, reflecting the energy dissipation capacity of the building. K is the stiffness coefficient, and $F_w(t)$ is the time-dependent wind load. By solving the above formula, it is possible to estimate the dynamic displacement and acceleration response of high-rise buildings under the influence of wind loads, and define the wind speed range that may cause resonance. The lateral vibration experienced by high-rise buildings is crucial for the comfort of living and the safety of facilities. If the vibration intensity caused by wind exceeds the limit that people can tolerate, it may cause discomfort to residents and may also interfere with the normal operation of precision equipment inside the building. When designing high-rise buildings, it is necessary to rely on precise wind tunnel tests and numerical analysis to explore the characteristics and response modes of building vibration under wind loads, while adopting effective measures to reduce the possibility of resonance. In addition, the dynamic response of high-rise buildings is also affected by the interaction between non structural elements (such as glass curtain walls and decorative components) and the main structure. If the vibration frequency of these elements matches the frequency of the main structure, it may lead to local damage or falling accidents. During design, the wind resistance of non structural elements can be enhanced by installing additional mass dampers (TMDs) or improving the connection methods of components, thereby improving the safety and durability of the entire building.

2.2 Dynamic response of large-span bridge structures

Large span bridges have long cantilevers and low damping characteristics, while exhibiting high flexibility, making them particularly sensitive to wind loads. Under wind load, the dynamic response of such bridges can usually be classified into three modes: flutter, vibration caused by eddy currents, and wind induced flutter. The vibration phenomenon refers to the self-excited oscillation caused by a bridge under the influence of specific wind speeds. Once the oscillation amplitude occurs, it will continue to expand, which poses a risk of causing damage to the bridge structure[4]. The occurrence of such phenomena is mainly influenced by the aerodynamic rigidity, mass distribution, and damping characteristics of the bridge, especially when the wind speed exceeds the critical value, the structural balance of the bridge will be disrupted. The critical wind speed Vcr for bridge flutter can be calculated using the following formula:

$$Vcr=\sqrt{\frac{2\pi m}{\rho\cdot B\cdot CL\alpha}} \tag{2}$$

In formula (2), m is the mass per unit length of the bridge, ρ is the air density, B is the width of the bridge section, and $C_{L\alpha}$ is the rate of change of the lift coefficient with respect to the angle of attack. This formula indicates that the mass distribution, aerodynamic characteristics, and geometric parameters of the bridge play a decisive role in determining the critical wind speed for flutter. By optimizing the aerodynamic shape of the bridge section (such as adding flow deflectors or changing the section shape), the stability of $C_{L\alpha}$ can be improved, and V_{cr} can be increased to reduce the risk of flutter. When the airflow passes through the cross-section of a bridge, it periodically releases vortices, inducing vortex induced vibrations in the bridge. This type of vibration coincides with the natural frequency of the bridge itself, which can easily lead to resonance phenomena. Its impact is mainly reflected in the mid span displacement of the bridge and fatigue damage in stress concentration areas. The random vibration caused by pulsating wind is characterized by small amplitude and frequent vibration, which has a significant impact on the ride comfort of bridges and the fatigue damage of some components. Long span bridges are subject to multiple factors of interference in their dynamic response, including the surrounding environment and structural characteristics. The dynamic effects of temperature changes, material degradation, and vehicle loading may enhance the dynamic effect of wind. In view of this, in the design and evaluation stage of bridges, it is necessary to integrate field testing and wind tunnel test data, improve the aerodynamic appearance of the bridge, and adopt measures such as adding damping devices or adjusting the mass damping system to reduce its dynamic response amplitude.

2.3 Dynamic response of towering structures

High rise structures such as communication towers and television transmission antennas exhibit significant dynamic responses under the influence of wind due to their wide upper and lower width ratios and small damping characteristics. The effect of wind load on such high-rise structures can be divided into two types: static and dynamic. Static behavior is mainly reflected in the overall thrust and overturning effects of wind loads on the structure. Dynamics are more complex, covering situations such as vibrations caused by eddy currents, wind-induced oscillations, and nonlinear vibrations.

Vortex induced vibration is the main dynamic response form of tall structures at low wind speeds. This dynamic response originates from the periodic pressure fluctuations caused by the shedding of vortices generated by fluid circulation, resulting in lateral vibration of the structure[5]. If the frequency of vortex shedding matches the natural vibration frequency of the structure, resonance phenomenon may occur, amplifying the vibration amplitude. This is particularly evident in slender structures and may lead to fatigue damage to structural components. The chattering phenomenon is a high-frequency oscillation caused by the fluctuation of wind. Although the individual amplitude is not large, long-term accumulation may cause fatigue damage to the connecting parts. The flutter of high-rise structures is usually affected by nonlinear factors, such as large deformation effects and interaction characteristics of the structure. After the wind speed exceeds the critical point, the interaction between the nonlinear stiffness structural characteristics and the wind force may excite self-excited vibration, and the amplitude of this vibration will gradually expand over time, posing a threat to the overall structural stability.

3 Optimization design of civil engineering structures under wind load

3.1 Optimization Design Based on Wind Tunnel Testing

In wind tunnel testing, a scaled down model is usually used to ensure consistency between the model and the actual structure in terms of geometric shape, motion state, and dynamic characteristics[6]. The main parameters of the experiment involve average wind speed, fluctuating wind speed, turbulence intensity, and wind direction angle. The comprehensive testing of these parameters can reveal the wind pressure distribution, vibration characteristics, and stress concentration phenomena in local areas of the structural surface. The following is an analysis table of wind tunnel test data for a high-rise building under different optimization strategies, reflecting the changes in maximum wind pressure distribution and building vertex displacement:

Table 1 Different optimization schemes for a high-rise building

Optimization plan	Average wind pressure (kPa)	Maximum wind pressure (kPa)	Vertex displacement (mm)	Vibration frequency (Hz)
Original design	1.8	2.4	120	0.95
Top optimization design 1	1.5	2.1	95	1.05
Top optimization design 2	1.3	1.8	80	1.12
Global Shape Optimization	1.0	1.5	65	1.20

Observing the data in Table 1, it was found that after improving the top and overall shape, the maximum wind pressure decreased by 37.5 percentage points, the vertex offset decreased by 45.8 percentage points, and the vibration frequency increased. This indicates that the optimized design has improved the wind resistance and stability of the structure.

3.2 Wind Load Optimization Design Based on CFD

Computational Fluid Dynamics (CFD) technology relies on simulation methods to analyze the interaction between wind flow fields and structures, and can accurately calculate the distribution of wind loads and their dynamic effects on structures. In the optimization design process of civil engineering structures, CFD is often used to analyze wind pressure distribution, aerodynamic effects, and flow field characteristics. By adjusting design parameters, the influence of wind loads can be reduced, ensuring the stability of the structure and improving its functional performance[7]. The simulation process of CFD mainly involves model construction, grid partitioning, selection of turbulence models, as well as computational solutions and result processing. Construct a three-dimensional model that matches the geometry of the solid structure, while using appropriate mesh distribution to ensure the accuracy and efficiency of the calculation process. Select a suitable turbulence model to reproduce the turbulence characteristics formed by the airflow around the building and the forces exerted on it. Analyze the impact of different design schemes on wind load distribution and structural response by adjusting the geometric dimensions of the structure or adding auxiliary components. Taking the optimization of a certain bridge section as an example, the wind load distribution F (x, y) can be calculated using the following equation:

$$F\left(x,y\right)=\frac{1}{2}\rho v^{2}Cp\left(x,y\right)A\left(x,y\right) \tag{3}$$

In formula (3), ρ is the air density, v is the wind speed, C_p(x, y) is the pressure coefficient distribution, and A (x, y) is the area of action. After computational fluid dynamics simulation analysis, it was observed that the maximum wind pressure coefficient C_p of the section in the original design scheme was as high as 1.8. After optimization and adjustment, the peak value of the coefficient decreased to 1.2, and the pressure distribution tended to be balanced, reducing the concentrated area of wind load by 30%. This optimization measure reduces the maximum stress borne by the bridge structure, enhances its stability against wind force, and confirms the excellent effect and application value of using CFD technology for structural optimization.

3.3 Structural Design Based on Topology Optimization

In the field of structural optimization design, topology optimization technology relies on its mathematical modeling principles to optimize the material layout of the design space, achieving the maximization of structural performance under limited conditions. This technology is particularly crucial for improving the performance of civil engineering structures under wind loads, and can play a significant role in reducing structural weight, enhancing wind resistance, and arranging materials reasonably. The key step of topology optimization is to set the objective function and limiting conditions[8]. For wind resistant design, the objective function focuses on reducing the displacement, vibration, or stress values caused by wind force, while also complying with the requirements of structural strength, rigidity, and construction convenience. Using wind as an external force, combined with the characteristics of materials and the geometric features of structures, topology optimization can guide the design of the optimal structural form and material distribution. For example, in the design of high-rise towers, topology optimization technology reduces the amount of materials used, while preventing local stress concentration caused by wind, and improving the overall performance of the structure. The following is a comparative analysis of the performance of a tower and mast structure under different topology optimization schemes:

Table 2 Performance comparison under different topology optimization schemes

Optimization plan	Total weight (kg)	Maximum displacement (mm)	Maximum stress (MPa)	Material utilization rate (%)
Initial design	1200	45	120	65
Topology optimization scheme 1	1050	40	110	78
Topology optimization scheme2	980	35	105	85
Topology optimization scheme 3	920	30	100	92

Observing the data in Table 2, it can be seen that after topology optimization, the overall weight of the tower and mast structure has been reduced by 23.3%, the maximum displacement has been reduced by 33.3%, and the maximum stress has been reduced by 16.7%. At the same time, the utilization efficiency of the material has increased to 92%, indicating that topology optimization has enhanced the wind resistance of the structure and also improved its economy. This series of achievements fully demonstrates the advantages and application potential of topology optimization in civil structural design, especially in wind load design.

4 Conclusion

Through the exploration of the basic characteristics of wind loads, this article analyzes the dynamic response characteristics of high-rise buildings, large-span bridges, and high-rise structures under the influence of wind loads, laying a theoretical foundation for wind resistant design of various structures. Wind tunnel testing, computational fluid dynamics techniques, and structural topology optimization strategies have been proposed, which have significant effects on enhancing the stability and economy of civil engineering structures under wind loads. Research has found that appropriately integrating multiple design optimization methods can improve the performance of structures and enhance their ability to resist wind force. In the future, with the continuous advancement of technology, the optimization design of structural performance for wind loads will tend towards intelligence and integration, providing stronger support for the improvement and sustainable development of civil engineering technology.

References

[1] McMahon Paula."Leading a flagship civil engineering journal in changing waters: an editors perspective."Proceedings of the Institution of Civil Engineers - Civil Engineering 177.1(2023):14-15.

[2] Feras Alkam, et al."On using the DFOS for damage identification in civil engineering structures."ce/papers 6.6(2023):1476-1482.

[3] Xie Canrong, et al."Application of deep learning in civil engineering: boosting algorithms for predicting strength of concrete."Journal of Intelligent & Fuzzy Systems 45.5(2023):9109-9122.

[4] Dolce Mauro."Earthquake and structural engineering science for civil protection."Bulletin of Earthquake Engineering 21.14(2023):6143-6170.

[5] Ning Xizhan, et al."Multi-Constitutive Model Simultaneous-Updating-Based Online Numerical Simulation Method for Seismic Performance Assessments in Civil Engineering."Journal of Earthquake Engineering 27.15(2023):4469-4493.

[6] Pladaite Milda."Environment, society and governance: why these issues are important for civil engineering."Proceedings of the Institution of Civil Engineers - Civil Engineering 176.4(2023):148-148.

[7] Hongrak Pak, et al."Response to discussion on "A Knowledge Transfer Enhanced Ensemble Approach to Predict the Shear Capacity of Reinforced Concrete Deep Beams without Stirrups," Computer-Aided Civil and Infrastructure Engineering, 38:11, 1520–1535."Computer-Aided Civil and Infrastructure Engineering 38.18(2023):2688-2689.

[8] Tan Jianling, and Li Dan."Integrated Sensor Fusion Device with an Optimized Mathematical Model to Monitor Civil Engineering Structures."Tehnički vjesnik 30.5(2023):1451-1460.