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Research on wind resistance principles and design of super high-rise buildings

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Abstract. Due to the high and flexible characteristics of super high-rise buildings, the structure is very sensitive to wind loads, and wind vibration effects and comfort are issues that cannot be ignored in the structural design of super high-rise buildings. The paper mainly introduces the problems in wind resistance design of super high-rise buildings. Including wind load values, wind vibration effects, and vibration control methods and applications. The result show that the wind induced vibration effect and comfort of the structure are often determined through wind tunnel tests. For super high-rise buildings with complex structural forms. There are two methods for controlling wind-induced vibration in high-rise buildings: Optimizing structural form through architectural methods; Take structural control measures. At the same time, with the cost of high-performance materials and engineering technologies, it is a challenge to find building materials and technologies that can meet wind resistance requirements while keeping costs in check. However, as computational technology continues to evolve, the wind-resistant design of tall buildings will benefit from more accurate wind-tunnel simulations and computational modelling, which will help to better predict and address wind-resistance challenges. Scientists and engineers will continue to research novel materials and structural designs to improve the wind resistance of tall buildings and reduce costs.

Keywords: Super High-Rise, Wind Resistant Design; Wind Vibration Effect, Vibration Control.

1. Introduction

With the progress of science and technology and the development of society, high-rise buildings and high-rise structures continue to emerge and develop towards high-strength and lightweight directions. The stiffness and damping of structures are constantly decreasing, making the natural vibration period of current high-rise building structures closer to the natural wind speed, and the impact of wind on high-rise buildings is increasing [1].

Wind loads are generated by the irregular movement of air and have strong destructive effects on structures. According to statistics, wind disasters account for the largest proportion of all-natural disasters, with annual economic losses caused by wind disasters in China reaching billions or even tens of billions of yuan. Although the amplitude of wind load on the structure is not as large as that of earthquake load, its frequency of action on the structure is relatively high. In addition, the stiffness of super high-rise building structures is relatively small, which may cause significant wind vibration response of the structure. Once the wind-induced vibration response of a building structure exceeds the

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ultimate bearing capacity of the structural components, it will cause deformation or even damage to the structure, which we cannot accept. Secondly, wind loads often lead to the damage of decorative structures such as glass curtain walls, which may cause the detachment of the wall plaster layer. Therefore, it is necessary to study the wind-induced vibration response of super high-rise building structures [2].

Under the architects' requirements for building appearance, how to reduce the impact of wind on high-rise buildings while increasing height and lightweight materials, optimize the safety of high-rise buildings, and increase the upper limit have become the key issues that need to be studied. This article mainly introduces the calculation method of wind load and wind vibration effect and through these calculations optimize building methods or structural methods to reduce the impact of wind loads on buildings.

2. Development process of super high-rise buildings

Super high-rise buildings originated in the United States and have a history of over 120 years, and the super high-rise buildings in the United States. Architecture has always been at the forefront of the world in terms of quality and height. At the end of the 20th century, super high-rise buildings in countries such as Canada, Malaysia, and China rose rapidly and gradually became the center of gravity for the construction of super high-rise building structures worldwide. The emergence of super high-rise buildings is an inevitable product of social development and has become a symbol of a country's economic development level. In addition, the development of high-rise buildings not only reflects the national level of building technology, material industry, and comprehensive technology but also serves as the most intuitive standard for measuring the modernization of a city [2]. For example: 632m high Shanghai Tower of 632m high; Burj Khalifa Tower of 828m high; 1 World Trade Center of 541m high.

Figure 1. Shanghai Tower [3].

Figure 2. Burj Khalifa Tower [4].

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3. Research Method for Wind Load on Super High Building Structures

In the 1960s, Professor Davenport [5, 6] applied buffeting theory to the analysis of high-rise building structures. In terms of wind-induced response, a theoretical method for solving the wind-induced vibration response of high-rise building structures has been proposed, laying the foundation for the discipline of structural wind engineering. More and more scholars have begun to study the wind-induced effect of wind loads on high-rise building structures. Currently, considerable research results have been achieved in this field and have been reasonably applied to some typical high-rise buildings. There are four main methods for studying the wind effects of high-rise building structures: on-site measurement, wind tunnel testing, numerical wind tunnel testing, and theoretical analysis [7].

3.1. On-site measurement

The on-site measurement is directly measured using equipment such as wind speed and direction sensors, wind pressure sensors, and acceleration sensors. Wind field characteristics around the structure wind vibration response data of the structure, and further modification of the measured raw data. In order to obtain more accurate results. Field measurement is a direct method for studying the wind-induced effects of super high-rise building structures. The data can provide an important scientific basis for correcting experimental models and numerical calculation models.

3.2. Wind Tunnel Testing

The conventional approach to wind-resistant structural optimization of supertall buildings relies on the utilization of wind tunnel test technology, which enables the provision of reasonably precise wind-induced structural response and equivalent static wind load for the purpose of structural design [8].

3.3. Numerical wind tunnel test

The numerical wind tunnel is based on the principles of Computational Fluid Dynamics and to assume that natural wind is an incompressible viscous fluid, an air turbulence model that is close to the actual environment is selected, and the simulation results are intuitively reflected through numerical calculation methods and certain image display techniques. Compared to wind tunnel testing methods, numerical simulation has advantages such as low cost, fast calculation time, and intuitive and rich information. It has the ability to simulate the real wind environment of structures and can conduct full-scale simulations of structures [9]. With the rapid development of computer technology, numerical simulation calculations have been used as supplementary tools for wind tunnel tests or separately in practical engineering.

3.4. Theoretical studies

Due to the complexity of the mechanism of wind action on structures, it involves a wide range of disciplines, including meteorology, aerodynamics, aerodynamics, aeroelastic mechanics, structural dynamics civil engineering, etc. At present, structural wind engineering is still mainly an experimental discipline. At present, structural wind engineering is still an experimental discipline [10, 11]. In recent years, with the deepening development of related research fields and the continuous improvement of test methods, the theoretical study of structural wind engineering has achieved many results, providing basic parameters and approximate wind load and vibration analysis means for the design of structural wind resistance.

4. Research Method for Wind Vibration Effect on Super High Building Structures

Due to the high and flexible characteristics of super high-rise buildings, wind vibration effects (downwind wind vibration, crosswind wind vibration and torsional wind vibration) have become a problem that cannot be ignored in the structural design of super high-rise buildings. Currently, the commonly used calculation methods are the frequency domain method and the time domain method.

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4.1. Frequency Domain Method

Engineers use frequency domain analysis to research control systems. A synthesis of sinusoidal signals with various frequencies can be used to express the signals in a control system. The frequency characteristic, which reflects how well the system responds to sinusoidal signals, is a mathematical model that describes the relationship between a control system's steady-state output and input signals under the influence of different sinusoidal functions. Frequency domain analysis is the term used to describe the traditional approach of using frequency characteristics in the study of linear systems. The 1930s saw the development of the useful engineering technique known as frequency domain analysis.

Using frequency features to investigate linear systems graphically is called frequency domain analysis. Transfer functions and frequency characteristics can both be used to illustrate a linear system or link's dynamic qualities. The time-domain analysis technique's drawbacks are made up for by the frequency-domain approach of control system analysis, which has a wide range of applications. The complex ratio of a system's frequency response to a sinusoidal input signal is known as its frequency characteristics. The steady-state component of a linear system's output under the influence of a sinusoidal input signal is called the frequency response [12].

4.2. Time Domain Method

It is a direct dynamic method, based on taking the time-dependent wind load as the input data, the damping, stiffness, and mass distribution of the structure as the objects of calculation, and solving the differential equations of motion directly to obtain the dynamic response data. The time-domain analysis is a direct dynamic method, which is based on taking the time-varying wind load as the input data and solving the differential equations of motion directly to obtain the wind vibration response of the structure.

Compared with the time-domain method, the frequency-domain method is easy to use, fast, and most of the current engineering in the frequency domain range of structural wind analysis, but the frequency-domain method has the following shortcomings. It cannot effectively consider the geometric nonlinearities, and material nonlinearities on the structural wind performance. It cannot be effectively considered in the structure of the time-dependent impact of the surface loads, is not applicable to high-rise building comfort and local fatigue analysis, is not conducive to the study of structural vibration control problems, and is not conducive to the analysis of structural vibration control problems. In order to carry out a more accurate and in-depth analysis of high, flexible, and important building structures, it is necessary to apply the time-domain method. In addition to making up for the above deficiencies of the frequency-domain method, the time-domain method, in the absence of actual measurements or experimental data, can be compared with various simplified computational methods and accurate time-domain analysis methods for verification. Although time-domain analysis is more complicated and time-consuming than frequency-domain analysis, with the continuous development of computing technology, this problem has been gradually solved [13].

5. The current research on wind-resistant design methods

Currently, more widely used wind design methods can be divided into two types: 1) architectural methods, architectural methods refers to base on engineering experience or wind tunnel tests, numerical simulation results, selection of aerodynamically more reasonable building cross-section shape or the overall shape of the building to inhibit the generation of vortex shedding, so as to reduce the crosswind wind load and reduce the wind vibration response; 2) structural methods, structural methods refers to strengthening the building structural system or the use of additional energy-consuming vibration damping devices to improve the wind resistance of the building. Refers to the strengthening of the building's structural system or the use of additional energy-consuming vibration-damping devices to improve the wind resistance of the building. A typical example is the Taipei 101 building where the design was optimized by using the corner-cutting method on the original square cross-section of the building, and the sectional shrinkage method along the height on the façade, which reduces the wind load by about 25% compared with the original scheme [13]. In addition, a tuned mass damper, a 660-ton gold-colored steel sphere, is suspended between the 88th and 92nd floors to dampen the vibration

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of the building. In this paper, the former (corner-cutting and segmental section shrinkage) is classified as the architectural method while the latter (additional dampers) is classified as the structural method.

Figure 3. Taipei 101 building [14].

Figure 4. Tuned Mass Damper [15].

5.1. *Architectural Method*

In 1971, Davenport [17] verified the effect of building shape on wind loads by means of aeroelastic modeling, which provided a feasible idea for the wind-resistant design of buildings. With the prosperous development of super high-rise buildings in the 1990s, aerodynamic means such as corner correction, setback, opening and twisting of buildings have been proven to be effective in reducing the transverse wind loads of buildings [18-21].

Jieming Xie [22] divided the building methods into two categories according to the magnitude of the optimization of the building shape:1) aerodynamic modifications (aerodynamic modifications); 2) aerodynamic design methods (aerodynamic designs). The former refers to methods that optimize the shape of a building's cross-section but do not change the overall shape of the building, including rounded corners; cut corners; recessed corners; grooves, etc... This type of method allows localized adjustment of aerodynamic characteristics after the architect has completed the building plan. Aerodynamic design methods, on the other hand, often require full communication and coordination with the architect at the early stage of design to make the overall shape of the building have better aerodynamic properties, such as taper; recession; openings, torsion, etc. Normally, the aerodynamic design method needs to determine the taper ratio, torsion angle and other specific design parameters through a large number of wind tunnel tests.

5.2. *Structural method*

Although architectural methods are effective in reducing crosswind wind loads, the final shape of a building is usually determined by architectural aesthetics rather than by aerodynamic considerations. The use of structural methods has become the primary means of controlling structural vibration in cases where wind tunnel tests have shown that the wind vibration response is not adequate after the completion of the architectural program and the preliminary structural design.

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Structural methods can be divided into two categories: reinforced structural systems and additional energy-consuming vibration-damping devices, among which additional energy-consuming vibration-damping devices can be categorized into active control, passive control, semi-active control, and hybrid control according to the need for external energy. According to the specific form of the damper, the structural method can be divided into the following types: Tuned Mass Damper (TMD),Tuned Liquid Damper (TLD or TSD),Extended arm damping technology, Distributed damping technology,New damping technology.

5.3. Discussion

Reducing wind loads and wind effects on buildings by changing the shape of the building is a common and very effective measure and can be combined with building design. Based on the mechanism of wind action on high-rise buildings, it is possible to minimize the wind loads and wind effects on the structure at the source.

The wind loads are resisted by increasing the wind resistance of the structure itself, i.e., by increasing the strength and stiffness of the structure itself, and by storing and consuming the wind vibration energy in order to resist the wind loads. This traditional approach to wind design is not necessarily safe, is not economical, loses the advantages of lightweight, high-strength materials, and is used only in the design phase of a structure.

Reducing the wind response of a structure by adding an auxiliary damping system to the main structure can also improve the seismic performance of a building. TMD is an effective damping device in controlling structural vibration. It is simple, reliable, effective, and low-cost, and is widely used in the vibration control of high-rise and civil engineering structures, especially in the wind-resistant design of high-rise buildings, television towers, and bridge structures.

As the height of high-rise buildings increases, the structures become more sensitive to wind loads, and in many areas, wind-resistant research and design have become a key factor in controlling the safety and performance of structures. In addition, the international engineering community also attaches great importance to the wind speed and wind pressure testing of super high-rise buildings, and in some of the world's most famous super high-rise buildings, there are anemometers, vibrometers, and long-term wind vibration work, which has accumulated a certain amount of data. But at the same time, we also need to continue to explore to build more beautiful and safer high-rise buildings, we must start from the characteristics of high-rise building structures, to carry out reasonable and effective wind design work, and then improve the design level of high-rise building structures.

6. Conclusion

In this paper, through reviewing a large number of national literature and data, we comprehensively review the previous wind vibration response analysis of high-rise buildings and some of the wind-resistant designs of high-rise buildings in use today. The main points are summarized as follows:

There are four main methods to study the wind effect of high-rise building structures: on-site measurement, wind tunnel test, numerical wind tunnel test and theoretical analysis.

There are two main methods to study wind vibration effect on super high building structures: frequency domain method and time domain method. Calculations of the wind vibration effect can help in the design of wind-resistant high-rise buildings.

The design of wind-resistant high-rise buildings can be categorized into architectural and structural methods. The architectural and structural methods are in fact the product of a conflict and compromise between the aesthetic requirements of the building's appearance and the requirements of wind resistance.

For high-rise building structures, wind load is a very important load, with the complexity of its building type and the application of vibration control equipment, the wind vibration analysis research for the design of wind-resistant structures is of great significance. However, due to the limitations of time and my own level, there is still a lot of work to be further improved.

The specific formulae for the calculation of wind loads and wind vibration effects have not been introduced and studied. This reduces the authority of the article's description, whereas accurate theoretical calculations are the best way to study wind loads and wind vibration response, and have an extremely important impact on the design of future buildings

High-rise buildings need to maintain structural strength and stability under extreme weather conditions such as strong winds, typhoons or tornadoes to ensure the safety of the building and its occupants. In high-rise buildings, wind pressure is not uniformly distributed because wind speed and direction change at different heights and locations. Designers need to take this factor into account to prevent damage to the structure from uneven wind pressure. Tall buildings are susceptible to lateral wind vibration due to their greater height, which may cause discomfort and structural fatigue in the building. Vibration control and damping techniques are essential. Finding building materials and technologies that meet wind resistance requirements while controlling costs is a challenge. The cost of high-performance materials and engineering techniques is usually high. Modern high-rise buildings need to meet sustainability criteria, including reduced energy consumption and environmental impact. This may require the use of renewable energy and green building technologies to be considered in wind-resistant designs.

But as computational technology continues to evolve, the wind-resistant design of tall buildings will benefit from more accurate wind-tunnel simulations and computational modelling, which will help to better predict and solve wind-resistance challenges. Scientists and engineers will continue to research novel materials and structural designs to improve the wind resistance of tall buildings and reduce costs. Intelligent systems, such as wind speed monitoring, vibration control, and wind power generation, will be more widely used in tall buildings to enhance their wind resistance and sustainability. Wind-resistant design of tall buildings is a global issue and international co-operation will become more important to share best practices and experiences to ensure wind-resistant performance of buildings. Overall, with the continuous advancement of technology and development of engineering techniques, more opportunities and innovations in wind-resistant design of high-rise buildings will be available to meet the construction needs of future cities. At the same time, sustainability and international co-operation will become important developments to ensure the reliability and safety of tall buildings in risky environments.

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