Research on Key Problems and Optimization Based on Structural Design of Super High-rise Buildings

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Abstract. At present, complex super high-rise buildings and super high-rise buildings are emerging all over China, but there are still many problems to be solved in the design of super high-rise structures. For example, the wind pressure and earthquake risk of high-rise buildings, fire safety issues and personnel evacuation issues, earthquake will produce greater inertia force and bending force in high-rise buildings, wind load and wind pressure effect will be more significant, these are the parts that need to be carefully considered to ensure the safety and stability of the building structure. Therefore, it is necessary to analyze and optimize the problem of high-rise buildings. Taking a super high-rise building in Luohu District of Shenzhen City as an example, this paper analyzes the basic structure of super high-rise building, analyzes the key problems of structural design, and discusses the optimization method. This paper puts forward the optimization design method of building structure for seismic problem of super high-rise building structure, puts forward the solution to wind resistance problem, and puts forward the optimization layout method of building fire protection.

Keywords: Super High-rise Buildings, Structural Design, Optimization Methods, Key Problems.

1. Introduction

In recent years, high-rise buildings continue to emerge in China. However, as the "heart" of high-rise buildings-core tube of high-rise buildings, there are few related studies. Therefore, Jiang Yong discusses in detail the area of core tube of high-rise buildings, utilization rate of marked floors, structural form, elevator system, safety evacuation system, equipment tube shaft and auxiliary rooms, and summarizes the general method of optimization design of core tube [1]. At the same time, the rapid development momentum of high-rise buildings in China, high-rise building firefighting as a worldwide problem, Zhang Qingyu adopted the high-rise building fire safety evaluation index system fuzzy comprehensive evaluation method, to evaluate the building fire safety status [2]. High-rise buildings are very sensitive to wind loads, and wind-resistant design is a key problem in their design, construction and operation. Wind effect of high-rise or super-high buildings under strong or typhoon action has always been a hot issue in the field of structural wind engineering. Wu Ming comprehensively adopts two basic methods of field measurement and wind tunnel test to study the structural dynamic characteristics and wind-induced response characteristics of super-high buildings, focusing on the characteristics of modal parameters of high-rise buildings varying with amplitude under medium and high amplitude vibration and the influence of Reynolds number (Re) effect on wind effect of arc-section super-high buildings [3]. For the seismic, wind resistance and fire safety problems of high-rise buildings, this paper analyzes the structure of a high-rise building in Shenzhen, and puts forward optimization methods for the core tube of the building, so that the building has sufficient seismic performance. At the same time, the wind-resistant performance of super-high buildings is analyzed, and the optimization scheme is proposed. For the fire safety problem, this paper puts forward solutions in the aspects of building layout and material use to ensure the safety of high-rise buildings in the later period.

2. Overview of structural design of super high-rise buildings

2.1. Characteristics of super high-rise building structure

Super-tall buildings generally refer to buildings with a height of more than 100 meters, and can even reach hundreds of meters or more. In the structural design of high-rise buildings, because of the diversity of height and shape of high-rise buildings, the structural design is often more complex, the structure needs to bear a lot of gravity and wind loads, and the rational use of the internal space of the building needs to be considered. At present, there are more and more high-rise buildings. While reflecting the aesthetic feeling of the building, ensuring the safety of the structure is the first consideration of engineers, and meeting certain comfort. At the same time, the building needs to be able to respond to certain emergencies, set up reasonable evacuation channels, firefighting facilities, etc. In addition, high-rise buildings cannot ignore the impact of earthquake and wind loads on the structure, because the height of the building makes the building more susceptible to earthquake and wind effects, so the structural design needs to take into account these external forces. It is necessary to improve the safety performance of building structures through various considerations [4].

2.2. Type of super high-rise structure system

2.2.1. Shear wall structure

Shear wall structure is a building structure in which a large number of concrete walls are set up. Under the action of lateral force, these walls resist and disperse lateral force through their own rigidity and strength, thus improving the stability and seismic performance of the building. Due to the large number of concrete walls, the high-rise shear wall structure has good structural stability, which can effectively resist various external loads on the building and ensure the overall stability of the building. However, shear wall structure design needs to consider the impact of the wall on the building space, which may limit the flexibility of the internal layout of the building, and the construction cost is relatively high.

2.2.2. Frame structure

Frame structure is relatively traditional in its structural form. It mainly relies on the rigidity and strength of columns, beams and frames to bear lateral forces, thus improving the stability and seismic performance of buildings. The frame structure has strong adaptability, which makes the space planning and layout of the building more flexible and diverse, and at the same time, the use space is large, which can provide a wider use space. But in the super high-rise building, the load is large, easy to occur lateral displacement, so the structure has a certain safety hazard.

2.2.3. Frame-shear wall structure

Frame-shear wall structure is a combination of frame structure and concrete wall structure to meet the requirements of structural rigidity, stability and earthquake resistance of high-rise buildings. This structure is usually used for high-rise buildings with a height of more than 150 meters to ensure structural stability and safety under external forces such as wind loads and seismic loads. Due to the frame structure, the column and beam size of the building is relatively small, so that the space utilization rate of the building is increased, and the indoor space is more flexible and spacious. In the structural design, shear wall structure should be reasonably designed, the number of shear walls need to be reasonably controlled, too much will increase the construction cost, otherwise it will make the lateral force resistance of the structure weakened, reduce the stability of the structure. Therefore, reasonable arrangements are required in structural design to ensure that the building structure is safe and reasonable [5].

2.3. Necessity of structural optimization of super high-rise buildings

Based on various successful optimization cases, it can be found that structural optimization can effectively improve the resource utilization efficiency of high-rise buildings, including personnel, materials, space and other resources. Through reasonable structural design and optimization, the paper can reduce the use of materials, improve the space utilization rate of the building, reduce the construction cost, speed up the construction progress, and reduce the impact on the environment. Therefore, structural optimization is very necessary in the design and construction of high-rise buildings. Structural design optimization is generally achieved by adjusting the shape, material, layout, etc. of the structure to achieve the best performance, and to improve and further optimize the deficiencies and defects of the design scheme. For example, in the design of steel structure buildings, optimization can reduce the section size of steel columns and steel beams, reduce the weight of the structure and improve the economy of the building. Therefore, scientific structural optimization is conducive to improving the safety and utilization of high-rise buildings.

3. The establishment of simulation model

3.1. Analysis of experimental results

In recent years, earthquakes occur frequently in our country, so it is very important to design aseismic structures to reduce the harm of earthquake activities to buildings and personal safety. However, in practice, there are still some problems in the seismic design of our country.

Although the seismic design standard value of our country is constantly upgraded, there is still a certain gap compared with the international standard, and the standard is not strict enough. At the same time, due to the lack of practical application experience, there is a certain gap between the design and practical application, resulting in some buildings in the earthquake in accordance with the seismic design code, but still suffered serious damage. Therefore, it is necessary to build a building with enough seismic performance, and further improve the seismic design is conducive to strengthening the overall stability of the structure.

3.2. Design of Windproof Structures

Wind load has great influence on the structure of super high-rise buildings because of its high height, so the accuracy of wind load calculation is very important. The structure needs to fully consider the structural vibration and deformation caused by wind load to prevent the structural wind resistance from being insufficient and causing certain safety hazards. In the structural design, the maximum wind speed should be used as the calculation basis to obtain the wind load on the structure. Wind tunnel tests can be carried out to check the wind resistance of high-rise buildings. For wind-resistant design of high-rise buildings, it is necessary to obtain more measured data about wind field, wind pressure and structural acceleration response of high-rise buildings. However, the accumulation of measured wind pressure data is still relatively small.

3.3. Fire protection design of buildings

Due to the high height of the super high-rise building, many floors and more personnel, the internal pipeline layout is more complex. In case of accidental incidents such as fire, it is difficult to evacuate personnel, which will pose a great threat to personal safety. Therefore, high-rise buildings are generally used as office space, apartments and hotels, and their use functions are limited to some extent [6].

Once a large fire accident occurs in a super high-rise building, it is difficult to control the fire scene due to the high floor. The factors affecting the firefighting level are as follows:

(1) The layout of circuit equipment inside the super-high-rise building is relatively complex, and in the event of an accident, each line may be short-circuited, causing certain harm.

(2) There are many people in super high-rise buildings, the flow of personnel is large, the number of floors is high, and the corridor is limited, so the evacuation speed of personnel is slow, which is not conducive to rescue.

(3) When a fire breaks out in a super high-rise building, due to the high number of floors, the configuration of firefighting facilities is limited, which is not conducive to fighting. At the same time, due to the high number of layers, it also caused certain obstacles to the fire fighting vehicles.

(4) There are many vehicles in the underground garage and the oil storage capacity is large, which will indirectly cause or expand the fire.

The above are important factors affecting the fire protection of high-rise buildings. In addition, there are potential safety hazards in the construction process. In the construction process, some combustible materials are piled up in a concentrated way, and the electricity consumption on site is relatively large, so it is easy to cause fire. In addition, in the construction process of super-high buildings, the fire protection facilities are insufficient, the fire passage is not opened, and the water source is insufficient. If there is a large fire, it will not be effectively controlled, resulting in greater losses. At the same time, due to the high number of floors of high-rise buildings, evacuation is more difficult when accidents occur. The design of evacuation passage of some super high-rise buildings is unreasonable, such as insufficient width of passage, blockage of passage and so on, which affects the efficiency and safety of evacuation. At the same time, some high-rise floors have complex structures, such as staggered floors and irregular floors, which greatly increase the difficulty of evacuation.

4. Optimization of design problems for super high-rise structures

4.1. Construction case Engineering overview

The case building is located in the south of Shennan East Road and the west of Beidou Road, Luohu District, Shenzhen City. Above the ground, it consists of a tower and podium. There is no structural joint between the tower and podium, which is a structural unit. There are 5 basement floors below the tower floor. The tower has 42 floors above the ground, the roof height is 195.45m, and the curtain wall height above the roof is 12m. The upper standard floor of the building is approximately rectangular in plan, with a length of about 51.3m, an equivalent width of about 28.58m, and a structural aspect ratio of about 6.84. The first floor of the building is 6m high, the standard floor is 4.5m high, the refuge floor is 6m high, and the apartment floor is 3.6m high. The podium has seven floors above ground, the commercial floor height is 5.4m, the office floor height of large space is 4.5m, and the conference room is 4.5m. The multi-function hall located on the seventh floor is combined with the roof shape of the podium to form a high space.

Due to the need of architectural culture modeling, the plane outline of the middle and lower parts of the building shrinks inward, and the structure adopts inclined column method to solve the elevation change, resulting in more inclined outer frame columns in the middle and lower parts. The core tube runs vertically along the height of the building. The outer periphery of the core tube is about 28.1m long and 11m wide. The ratio of height to width of the core tube is 17.77. The design service life of the structure is 50 years, the building safety level is Class II, and the foundation design level is Class A [7].

4.2. Seismic performance optimization

In order to make the structure have enough seismic resistance, according to the latest revised Code for Seismic Design of Buildings, it is mentioned in the code that the mode decomposition response spectrum method can be used for building structures. For Class A buildings, the time history analysis method can be used to supplement the calculation of multiple earthquakes, thus enhancing the seismic performance of the structure.

At present, the seismic system often used in the field of architecture is "ductile structure system". Ductile structure system can produce a certain degree of deformation under the action of external forces such as earthquake, so as to reduce the stiffness of the structure, absorb and disperse earthquake energy, reduce the impact of earthquake on the building, and make the building reach the state of "cracking but not falling"[8]. It greatly improves the seismic performance of buildings. It is a seismic method with development prospects. It is a very good seismic design measure for high-rise buildings. The case building adopts frame-core tube structure, ordinary reinforced concrete beams and slabs are used inside the core tube, and composite floors are used outside the core tube. Along the height of the building, two stiffening stories containing ring trusses and outrigger trusses and one stiffening story containing ring trusses are provided. The core tube is continuous, as shown in Fig1.

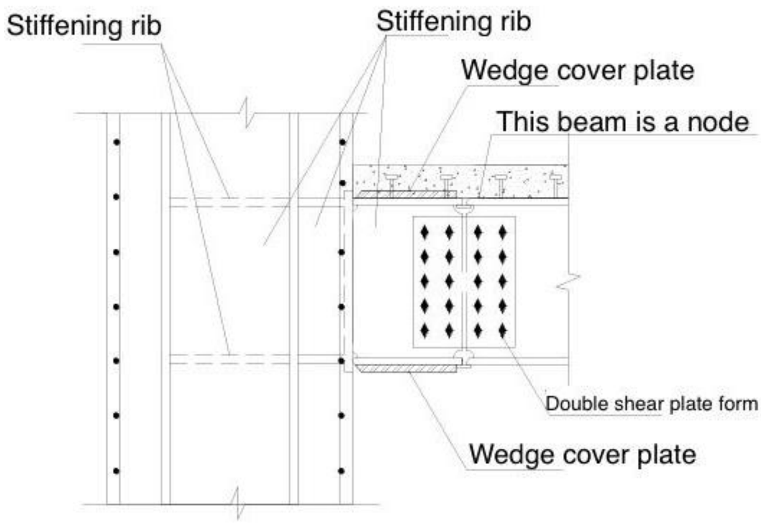

Figure 1. Schematic diagram of rigid joint between steel column and steel beam in core tube shear wall

According to the structural design requirements, the internal wall thickness of the core tube is designed to be 800mm. At the same time, most of the external frames have different degrees of inclination, some inclined columns are one-way inclined, some are two-way inclined, and the nodes at the turning points are shown in Fig 2. The core tube provides the longitudinal bearing capacity of the building, while the outer frame structure provides lateral seismic support. This structure can effectively improve the overall stability and seismic performance of buildings.

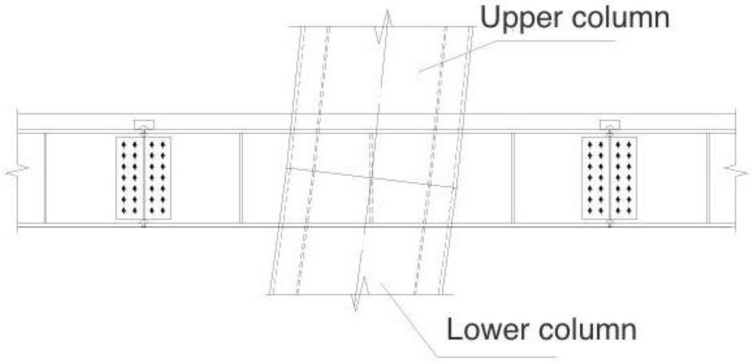

Figure 2. Frame column turning point

Based on the case building structure, carbon fiber material can be added to the outside of the core tube to increase the strength of the core tube. Carbon fiber has the advantages of high strength, high modulus, light weight and corrosion resistance, which can significantly improve the seismic performance and structural stability of the core tube. By using carbon fiber reinforced materials in the core tube design, the amount of materials used can be reduced, the weight of the structure can be reduced, and the seismic performance of the structure can be improved, so that more economical and efficient building design can be realized.

Multiple seismic lines can be established, and the structural system composed of outer frame columns, core tubes, ring trusses and outrigger trusses can act together through the floor to resist earthquake action. At the same time, it is necessary to strengthen the seismic grade of the outer frame column, the strengthened floor and the outer frame straight column above and below the structure to Special Grade I. The outer frame inclined column and the frame beam connected with the outer frame inclined column are designed according to Special Grade I to increase the safety reserve of the component system. Thickening the thickness of the floor properly, analyzing the stress of the floor and calculating the reinforcement ratio of the floor. For the node position of the building, strengthen the strength of the node area, increase its thickness, achieve the seismic requirements of strong nodes and weak members, and make the node force transfer more effective and direct. Through the above measures, the seismic performance of high-rise buildings is guaranteed, making them more stable and safe.

4.3. Windproof structure optimization

Because of its high height, super high-rise buildings will be affected by large wind loads, which will affect the service life of the structure. Therefore, in the structural design, people should analyze the influence on the structure and the maximum wind load received by the building according to the local maximum wind pressure, and adopt appropriate structural forms and materials to ensure the wind resistance performance of the structure. The wind tunnel test can be carried out in the design stage of the case building to simulate and verify the wind conditions of the building under different wind speeds and winds, to detect the wind resistance performance of the top structure, to strengthen the components such as columns and rigid structures, to enhance the rigidity of the building, and to enhance its wind resistance performance[9]. At the same time, the shape design of the building will also affect the wind resistance. The case building adopts streamlined design to reduce wind resistance, and at the same time, the building is inclined to reduce the wind invasion area and disperse the wind force. It not only provides certain wind resistance performance, but also makes the building have enough ornamental.

When wind tunnel test is carried out for super high-rise buildings, it is necessary to consider the size of wind tunnel and various parameters of buildings, etc., which can be deduced based on fluid motion equation:

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=f_i-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+v\frac{\partial}{\partial x_i}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)(i,j=1,2,3) \tag{1}$$

Where $v=\frac{\mu}{\rho}$ is the dynamic viscosity of air. The relationship between physical quantities of building prototype and model is expressed by this formula, C_t, C_l, C_u, C_P, C_f, C_v and C_p are the ratios of time, geometry, velocity, pressure, additional external force, dynamic viscosity and density respectively, all of which are constants, and are respectively:

$$C_t=\frac{t}{t^*},\ C_l=\frac{xi}{l^*},\ C_u=\frac{ui}{ui^*},\ C_p=\frac{p}{p^*},\ C_f=\frac{f}{f^*},\ C_v=\frac{v}{v^*},\ C_\rho=\frac{\rho}{\rho^*} \tag{2}$$

Among them, those with * are defined as model variables, and the rest are original variables. Simplifying the parameters such as area and volume can be obtained as follows:

Area:

$$C_A=\frac{A}{A^*}=\frac{l^2}{l^{*2}} \tag{3}$$

Volume:

$$C_v=\frac{v}{v^*}=\frac{l^3}{l^{*3}} \tag{4}$$

Substituting the above formula for further derivation, the paper can finally obtain the following formula:

$$\frac{\partial u^*}{\partial t^*}\frac{C_l}{C_uC_t}+u_j^*\frac{\partial u_i^*}{\partial x_j^*}=f_i^*\frac{C_fC_l}{C_u^2}-\frac{1}{\rho^*}\frac{\partial p^*}{\partial x_i^*}\frac{C_p}{C_\rho C_u^2}+\frac{\partial}{\partial x_j^*}\left(\frac{\partial u_i^*}{\partial x_j^*}+\frac{\partial u_j^*}{\partial x_i^*}\right)\frac{C_v}{C_uC_l} \tag{5}$$

It is expressed as the fluid motion equation of the hypothetical model, because to make the original motion model similar to the motion equation of the hypothetical model, the two equations are compared, where the physical quantity needs to satisfy the following conditions:

$$\frac{C_v}{C_uC_t}=\frac{C_l}{C_uC_t}=\frac{C_\rho}{C_\rho C_u^2}=1 \tag{6}$$

Thus, the expression for Reynolds number is obtained:

$$\mathrm{Re}=\frac{ul}{v} \tag{7}$$

Re is a dimensionless quantity describing the flow state of fluid, which is related to the velocity, density, viscosity and other factors of fluid. Reynolds number can be used to describe wind flow in wind-resistant design of super-tall buildings. When the wind speed is low, the Reynolds number is small, and the wind flow state is laminar, at this time, the wind force of the building is small, and the wind resistance ability is strong; when the wind speed is high, the Reynolds number is large, and the wind flow state is turbulent, at this time, the wind force of the building is large, and the wind resistance ability is weak.

Therefore, in the structural design of high-rise buildings, wind tunnel test and Reynolds number calculation should be carried out to make the structure meet the wind resistance design, while considering the building shape, etc., to design the shape conducive to wind resistance, such as streamlined design, reducing corner design, reducing cross-sectional area, reasonable control of cantilever structure after structural analysis and calculation, etc. So that the super high-rise structure has stronger wind resistance.

4.4. Fire protection design optimization

4.4.1. Reasonable layout and fire prevention zones

In the case of building design, the distance between the building and the surrounding buildings should be controlled. On this basis, the general floor plan should be reasonably designed. In the reasonable fire compartment, each fire compartment should be equipped with a fire shutter door. At the same time, the automatic opening and closing device of the fire door should be installed. When there is a fire, the shutter door can work automatically in time to prevent the fire from expanding and achieve the purpose of fire prevention. When installing the rolling shutter door, pay attention to not leaving a gap with the wall beam. At the same time, it can also be equipped with automatic sprinkler system, which can put out fire quickly in case of fire.

4.4.2. Ensure fire resistance of buildings

The fire resistance performance of super high-rise buildings is very important to prevent the progressive collapse caused by structural collapse when fire occurs. Therefore, in the design of high-rise buildings, people should strictly abide by the fire rating requirements of high-rise buildings, and use refractory materials such as refractory concrete, refractory glass and refractory coatings in the structure and decoration process of high-rise buildings to improve the overall fire resistance of buildings, reduce the damage of fire to buildings, and provide sufficient time for personnel evacuation.

4.4.3. Reasonable design of smoke exhaust system and evacuation passage

When a fire occurs, the influence of smoke is very serious, so it is necessary to do a good job in smoke exhaust system in high-rise buildings. Shenzhen Case Building is an office building integrating office, commerce and business. It is densely populated and has a large flow. If there is no good smoke exhaust system, it will pose a great threat to the personal safety of personnel in case of fire. Therefore, buildings need to set up effective smoke control and exhaust systems, including exhaust fans, exhaust pipes, etc., and also need to design smoke exhaust windows that are easy to open to prevent smoke exhaust system failure. Evacuation stairs, refuge floors and emergency exits should be reasonably set up to ensure safe and rapid evacuation of personnel in case of fire[10].

5. Conclusion

Firstly, the anti-seismic and wind-resistant design of high-rise buildings needs to consider the factors of building structure, foundation soil layer and seismic wind load. In the structural design, reinforced concrete and steel structure are combined to improve the overall seismic performance of the building by strengthening the strength of the core tube, the external frame and the thickness of the floor. At the same time, new structural measures such as dampers and shock absorbers can effectively reduce the vibration response of buildings in earthquake and wind disasters, and improve the seismic and wind resistance of buildings. Secondly, the fire protection design of high-rise buildings needs to consider the aspects of building structure, personnel evacuation and fire protection facilities. In the design of building structure, fire-proof materials and isolation belts can effectively reduce the impact of fire on building structure. In the aspect of evacuation, reasonable evacuation passage and emergency evacuation facilities can improve evacuation efficiency and reduce fire damage to personnel. In terms of fire protection facilities, the use of automatic sprinkler systems, smoke detectors and other advanced equipment can improve the fire safety performance of buildings, but also the use of fire resistant materials to strengthen buildings. Finally, the seismic and wind-resistant design and fire protection optimization of high-rise buildings need to consider the factors of building structure, material performance and design standards. In the aspect of anti-seismic and wind-resistant design, it is necessary to select appropriate structural forms and anti-seismic measures according to actual engineering conditions, and comprehensively consider external factors such as earthquake wind load, so as to check the Reynolds coefficient of high-rise buildings.

To sum up, in the design of high-rise buildings, people should carefully consider the problems existing in the design of buildings to ensure that the building structure is safe and reasonable. Based on the seismic performance of buildings, wind resistance and fire performance, the optimization design of high-rise buildings can make high-rise buildings safer.

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