Effect of Load and Prospect on High-Rise Buildings

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Abstract. With the acceleration of urbanization, high-rise buildings have become the most familiar buildings in the city because of many advantages such as a small footprint and good lighting. However, due to the height of high-rise buildings, they are particularly affected by transverse loads, such as wind load and earthquake load. To have a better understanding of high-rise buildings, this paper discusses the central structural systems of high-rise buildings. And explains the influence of wind load and earthquake load on high-rise buildings. The main structural styles of high-rise buildings include frame structure, shear wall structure, frame-shear wall structure, and tube structure. Frame structure weight of small but large displacement, shear wall structure integrity but less space, frame - shear wall structure is the advantage of the two, and frame tube structure has strong ability to resist lateral but considerable weight. The randomness of wind load leads to unstable vibration of high-rise buildings. The weakest link of high-rise buildings under seismic load appears at the beam-column joints. Future high-rise buildings will pay more attention to humanistic significance while considering safety. This paper summarizes the advantages and disadvantages of several primary forms of high-rise buildings at present, and analyzes the influence of wind load and earthquake load on high-rise buildings, which has specific guiding significance for the safety research of high-rise buildings.

Keywords: High-rise building, structural systems, wind load, seismic load.

1. Introduction

With the acceleration of urbanization, high-rise buildings have become one of the most familiar buildings in urban development by their small footprint and good lighting. However, high-rise buildings also have many problems, and their fire resistance and other safety requirements are high. At the same time, the influence of some horizontal loads, such as wind load and earthquake load on high-rise buildings, cannot be ignored. Up to now, several large earthquakes have occurred in our country, which brought inestimable property loss, building collapse, and casualties. Among all kinds of hazards caused by earthquakes, the destruction of buildings and structures is the most direct manifestation of earthquake disasters. In March 1966, the Xingtai earthquake in Hebei Province destroyed 2.08 million houses. In the 1976 Tangshan earthquake in Hebei Province, 70 to 80 percent of the buildings collapsed, including 14.79 million square meters of public places and 5.3 million private dwellings, resulting in heavy casualties. The magnitude eight earthquake that occurred in Wenchuan on May 12, 2008, was one of the most devastating, widespread, and deadly earthquakes in China since the founding of the People's Republic of China. A total of 69 227 people were killed, 374 643 injured, 17 923 missing, and 3.128 million houses collapsed. 15.609 million homes were damaged; On March 10, 2011, the 5.8-magnitude earthquake in Yingjiang, Yunnan province, destroyed or destroyed more than 100,000 houses [1]. As a result, In the coming decades, the study of high-rise buildings will become a hot research direction.

The previous research mainly focused on medium and low-rise buildings, while the studies on the high-rise buildings were relatively few. Although there are many similarities between the two, there are many differences. For example, for medium and low-rise buildings, the loads that affect them are mainly vertical loads such as gravity. However, with the increase in building height, the influence of transverse loads on buildings will become more and more apparent. Especially wind load and earthquake load, these two kinds of loads on high-rise buildings are prevalent. To increase the safety performance of high-rise buildings, it is critical to understand their primary structural forms and how loads affect them [2].

This paper first summarizes four common high-rise building structure styles and analyzes their advantages and disadvantages for different structural forms. Then, the characteristics of wind load and earthquake load are briefly described, and the influence of wind load and earthquake load on high-rise buildings is explained. Finally, this paper gives the prospect of high-rise building development in the future.

2. The structural system of high-rise buildings

With the increasing need for urban construction land, people's demand for urban land becomes tenser and tenser, which leads to the accelerated development of high-rise buildings. In recent years, the advantages of high-rise buildings are becoming more and more prominent, especially the needs of high-rise residential plane and space and the requirements of the amount of lighting, the general building plane and space requirements cannot be met, so high-rise buildings have become the first choice of urban architecture, which also leads to high-rise buildings more and more by the attention of designers. To fully comprehend the mechanical properties of high-rise buildings, it is essential to understand the structural system of high-rise buildings. The central structural systems of high-rise buildings include: frame structure, shear wall structure, frame-shear wall structure, and tube structure [3].

2.1. Frame Structure

The frame structure is composed of beam and column components, the most widely used structural system in the early stage. There are a few frame structure components, which can be standardized in the construction factory or cast-in-place made by the formwork on the construction site. The members made by this method have good integrity and seismic performance. And the frame structure layout is flexible. The space is ample, can adapt to the needs more functional.

In the frame structure building, the exterior wall can use non-bearing components, so the facade design is flexible; The interior walls are made of lightweight partitions, which can be removed as needed to adapt to more diverse space needs. Moreover, using these lightweight partitions and external walls dramatically reduces the dead weight of the building and saves materials, so it is the main structural form of high-rise buildings. However, the disadvantages of frame structure are slight lateral stiffness and large lateral displacement under seismic load. When the lateral displacement is too large, the vertical load on the upper part of the frame structure will further increase the internal force of the rod and the lateral displacement of the system, which will produce serious second-order effects, and even endanger the overall stability of the frame [4]. The lateral force resistance of frame structure mainly depends on the bending capacity of the beam and column. When the number of building layers increases, the total value of lateral force increases, and to improve the bending ability and stiffness of beams and columns, only increasing the section size of beams and columns, if the section is too large, it will make the frame structure lose its economic rationality. In addition, due to the lack of stiffness of the frame structure system, the lateral displacement is prominent during the earthquake, which can easily to cause damage to non-structural components, and sometimes even the damage of the structure. The entire frame structure is generally suitable for high-rise steel structures with no more than 30 layers [5]. In short, when building tall buildings with small heights, the frame structure system performs well.

2.2. Shear Wall Structure

The shear wall structure system uses a cast-in-place reinforced wall as a structure to bear the vertical load and horizontal load. Shear wall structure has high lateral stiffness, is very beneficial to resist horizontal wind, and cast-in-place wall can also be used as a dividing member of the house. Therefore, it is suitable for small high-rise buildings, such as hotels, residential buildings, etc., and the height of the construction is much higher than the frame structure. The main body of the shear wall structure is cast-in-place reinforced concrete, which has good integrity. Throughout the world,

the earthquake damage to shear walls is relatively light, so it is suitable for promoting of construction in earthquake areas. It is worth noting that in high-rise residential buildings with a shear wall structure, part of the middle partition wall is the shear wall. This is different from the non-load-bearing lightweight partition wall in the frame structure, which must not be removed because it is also part of the load-bearing structural system. Therefore, the space use of the shear wall structure system is minimal, which cannot meet the use requirements of public buildings. Moreover, the overall cast-in-place reinforced concrete wall also causes an increase in the dead weight of the whole building, so that the amount of building materials increases, the seismic force increases, the superstructure, and foundation design will become difficult [6].

2.3. Frame-shear Wall Structure

Frame shear wall structure is a system that sets shear wall in the frame structure, also known as frame-shear structure. The frame shear wall structure combines the characteristics of the frame structure system and the shear wall structure system. Most of the horizontal load (80%~90%) is borne by shear walls, which improves the lateral stiffness of the structural design [1]. In addition to the vertical load, the frame structure can also bear a small amount of horizontal load, and improve the flexibility of space use. The deformation of the frame structure under horizontal load is shear, and the shear wall part is bending deformation. When the two components work together through the floor slab, the deformation must be coordinated and unified, so the deformation becomes a flexural shear type. The deformation of each layer will be uniform, and the total lateral displacement of the top will be reduced. Its disadvantage is the limited layout, often appear rigid center and center of mass deviation and other phenomena, at the same time make the building construction height is fixed. In addition, in this kind of structural system, concrete is used more, resulting in its more immense weight. Usually, the total size should not exceed 150m [7].

2.4. Tube Structure

If the column distance in the frame structure is reduced, the height of the beam is amplified,and a tube structure of the dense column and high beam is formed. As shown in Figure 1, the shear wall is enclosed into a cylindrical shape to create a spatial thin-walled tube. A spatial structure that uses a frame tube or a space-thin-walled tube to bear the horizontal load is called a tube structure. The connection of one or more tube structures is called a tube structure system. Common types include solid belly tube, frame tube structure, bundled tube structure, tube in tube structure, and so on [8].

Tube structure is a structured system with better force in a high-rise structure. Both inner and outer tubes can form muscular bending stiffness and jointly bear the horizontal force, which can include the effect of two seismic lines. Generally, the outer tube should hold at least 30% ~ 40% [9] horizontal force. Moreover, due to the symmetry of the tube structure, the structural system has a uniform and symmetric lateral stiffness and torsional stiffness, which can resist the sizeable overturning moment and torsional moment in any direction. It has good fexibility, and good seismic performance.

The shear lag effect of truss tube structure, tube in tube structure, and bundled tube structure system is greatly improved than that of frame tube structure system. The bundled tube structure system is composed of some tube structures with incredible stiffness, which can be combined into any shape and plane, and each tube can end at different heights, which can make the building form a stable tower structure without increasing the complexity of the frame. The super tall buildings with a unique appearance and sturdy structures can be designed by using the bundled tube structure system.

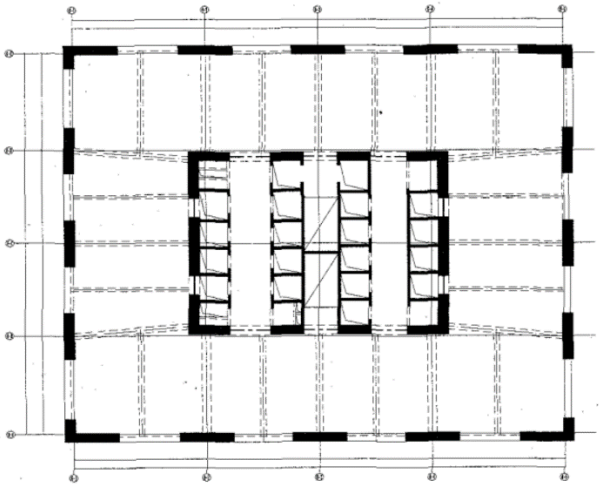

Figure 1. Tube structure standard floor plan [10]

3. Influence of different loads on high-rise buildings

The high-rise building structure is different from the low-rise and multi-story building structure. The internal force and displacement generated by the horizontal load of low-rise buildings are tiny and usually can be ignored. Therefore, the external effect of the low-rise building structure is mainly represented by the vertical load as the dead weight. In contrast, the high-rise building structure should bear both vertical load and horizontal load [11]. Design the high-level building an enormous wind and casual when the earthquake force generated by horizontal lateral force must be given priority, because with the increase of building height and the increase of aspect ratio, although the vertical load on the structure design is still essential, the level of load on the structure internal force and displacement increasing, will become the structure design of the control factors. Because the height of the high-rise building is more significant, the effect of the earthquake on it is also larger. Therefore, the key to the design of high-rise building structures is the design of lateral force resistance structure and good seismic resistance. In addition, the height to width ratio of tall buildings should be strictly controlled to ensure their stability. Make the building plane, shape, facade quality, and stiffness as far as possible to maintain symmetry [12], so that the overall structure does not appear vulnerable.

3.1. Wind Load

3.1.1 Characteristics of wind load

For high-rise buildings, the wind is a random load with a long duration. The effect of wind on the structure makes the structure vibrate, which mainly has the following three reasons [13]: (i) The downwind wind effect, which includes the average wind (static force) and the fluctuating wind (dynamic force), among which the fluctuating wind (dynamic force) causes the downwind vibration of the structure. This form of vibration should be considered in all kinds of engineering structures. (ii) The vortex behind the structure causes the transverse wind direction vibration of the structure; (iii) Vibration caused by airflow in the wake of other buildings.

3.1.2 Influence of wind load on high-rise buildings

The sound of the wind is the most direct manifestation of the wind's influence on high-rise buildings. When the sound is too large, it will cause some high-rise residents to panic. Sometimes the wind can last for hours, seriously affecting residents' daily work and rest. In addition, the wind will also impact a high-rise building in the form of wind load. Wind load is one of the most common horizontal wind loads. Under the action of the load, the structure of the high-rise building lateral will happen, causing the floor and the elevator can't play its expected role, if excessive lateral, buildings from side to side, and even damage to buildings. For example, in 1926, a strong wind caused plastic deformation of the steel frame of a 10-story building in the United States, causing severe damage to

the envelope structure; The John Hancock Building, Boston, USA, from the summer of 1972 to January of 1973, due to high winds, approximately 16 pieces of glass were broken, 49 were badly damaged, and 100 were cracked [11].

Since most high-rise buildings generally adopt complete steel frame structure and glass curtain wall, this will increase the deflection of systems and reduce the damping of the them, making the structure's natural vibration period less than the period of wind speed, wind load effects at the same time also with the characteristics of the wind, and high-rise buildings, shape, the wind and change with the change of surface area, When the high-rise building design does not meet the requirements of the code, the total effect of wind load will reach the limit of the structural bearing capacity, and then lead to the high-rise building or damage.

When the wind flows in the air, if there is no barrier, the airflow is relatively stable. Once blocked by the building, it will form a high-pressure air curtain-the greater the airflow velocity, the greater the impact on the building. In the design and calculation of the building structure, it must be calculated according to the wind pressure and wind speed. Different wind speed has different wind pressure. It can be seen from the Building Structure Load Code that the wind load is $Wk=\beta z\mu z\mu sw0$, where the primary wind pressure is w0, the wind pressure height variation coefficient is μs, the wind load body type coefficient is μz, the wind vibration coefficient at height is βz, and the standard value of wind load is Wk [14].

The wind in human lives is mainly ground flow wind, and the same is true of the wind acting on buildings. The wind on the ground will be affected by the landform and topography of the area flowing through, as well as the change of the wind itself, which leads to the disorderly and random characteristics of the wind only on the ground on the buildings. In general, fluctuating wind and average wind, are the two kinds of wind, have the most significant influence on the force of building structure, so the role of dynamic force must be considered in the structural design.

The effect of wind on the building structure will produce vibration. The main reason is that the pulsating current will cause the downwind vibration of the structure, the system will have transverse wind vibration in the upwind direction, and the air damping will also cause the building to create lateral instability vibration.

The influence of wind on building structure mainly includes four aspects: the average wind static effect, the fluctuating wind vibration effect, the vortex disturbance wind vibration effect, and the self-excited vibration effect [15].

3.2. Seismic Load

3.2.1 Characteristics of seismic load

Earthquake is a natural phenomenon. According to statistics, the earth has an average of about five million earthquakes yearly, among which there are about 1,000 earthquakes of magnitude 5 and above [10]. Among them, there were about two devastating earthquakes with a magnitude of more than eight and an epicenter intensity of more than 11 degrees, about 20 large earthquakes with a magnitude of more than seven and an epicenter intensity of more than 9 degrees, and more than 150,000 felt earthquakes with a magnitude of more than 2.5. The 7.6-magnitude earthquake that struck Taiwan in the early hours of September 21, 1999, killed 2,103 people, injured and injured more than 10,000 people, and destroyed tens of thousands of houses, causing massive damage to the earthquake and the economy [16].

3.2.2 Influence of seismic load on high-rise buildings

The seismic damage of the frame structure mainly occurs at the column end and node, while the seismic damage of the beam end is relatively small. There are several main types of seismic damage to frame columns: bending shear failure of column end, shear failure of column body, bending shear failure of corner column, and shear failure of a short column. The seismic damage of the frame beam is relatively light, mainly manifested as a vertical bending crack or oblique shear crack. Beam-column node is the critical part of connection frame beams and columns, the shear in the earthquake often

produces diagonal inclined cracks or cross diagonal crack, serious when cut up spalling of concrete column outside longitudinal reinforcement buckling drum, the damage is the main reason of the shear bearing capacity is insufficient or caused by the poor quality of construction, the shear stirrups shortage is the main reason. Figure 2 shows the beam-column joints damaged by the earthquake.



Figure 2. Damaged beam-column joints [17]

The seismic damage pattern of the frame-filled wall is as follows: the occurrence of wall oblique crack. It also cracks along the periphery of the column, produces oblique cracks or cross cracks in the corner of the end wall, window wall, or door opening, and causes more severe earthquake damage. The main reasons for these failures are: the low tensile and shear strength of the wall, small deformation ability, and lack of effective binding between the wall and the frame.

Compared with frame structure, shear wall structure and frame shear wall structure have less earthquake damage. There are two main types of shear wall failure in high-rise buildings: one is the failure at the bottom of the shear wall, which is mainly due to the narrow and high wall limb working performance similar to the cantilever beam, and the earthquake damage often occurs at the bottom. The other is the shear failure of the connecting beam. The connecting beam is a horizontal component connecting the wall limbs between the upper and lower doors and Windows. The deformation of the shear wall structure is concentrated between the wall limbs, so the connecting beam is easy to be damaged.

In the frame-shear wall structure, the frame is mainly used to bear the vertical load, and the shear wall bears most of the horizontal load. Due to its large lateral stiffness and bearing capacity, the frame-shear wall (core tube) structure shows superior seismic performance, especially compared with the frame structure in the same area. The damage of the non-structural members of the frame-shear wall (core tube) structure is much lighter [18].

4. Prospect

In today's high-rise buildings, more and more new materials and super strong materials are used. Material problem is the first problem to be solved in the technical problems of the high-rise building structure. Concrete has been from the earliest C10 to now C100, high strength and good toughness of concrete are conducive to reduce the size of structural components, reduce the weight of the structure, improve the seismic performance of the structure. In addition to concrete, another ideal material for high-rise buildings is steel, steel strength and plasticity. Now, the requirement of buildings is increasing. And the requirements for building materials are also improving, such as new fire-resistant, weathering steel, composite materials [19].

Modern architecture not only meets the use and aesthetic requirements, but also represents the level of economy and technology. Architecture is paying more and more attention to the needs of people, the humanity, ecology, and intelligence of high-rise buildings have become the critical aspects of future high-rise buildings. Some high-rise buildings become local landmarks, so future high-rise buildings need new design concepts and structural forms [20].

From the development trend of recent years, the future high-rise buildings will develop towards the direction of combining advanced technical function and perfect art. They will have a huge leap in quantity, quality and height, and the scientific and technological content will be higher and higher.

5. Conclusion

High-rise buildings are more and more common in urbanization construction, and people pay more and more attention to high-rise buildings. This paper summarizes the four main types of high-rise building structure, frame structure, shear wall structure, frame - shear wall structure, and tube structure, and compares their advantages and disadvantages: frame structure weight of small but large displacement, shear wall structure integrity but less space, frame - shear wall structure is the advantage of the two, and frame tube structure has strong ability to resist lateral but immense weight. At the same time, the influence of load on high-rise buildings can not be ignored. Earthquake and wind load are the main transverse loads affecting high-rise buildings. Both loads have great randomness, and the consequences of failure are grave. In the coming decades, high-rise buildings will continue to be the hot research direction. Future high-rise buildings should not only ensure their practical use, but also highlight their humanistic value. In the future, engineers will develop better structures to make high-rise buildings safer and more humane. The research of this paper has some specific guiding significance for the construction of high-rise buildings in the future.

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