The Typical Case Analysis of Special Ultra-high-rise Building

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Abstract: Based on the definition of “ultra-high-rise building” in the world, this paper first puts forward the definition of “special ultra-high-rise building”, and then the data of 28 typical special ultra-high-rise buildings (including some 300m~400m representative ultra-high-rise buildings) which have been built in the world is collected. Through statistical analysis of the data regarding the structure form, the overall and core tube height-width ratio, the facade change and foundation, this paper draws some regularity results: (1) the overall and core tube height-width ratio is not closely related to the building height;(2) the elevation change should be simple, regular, tapered and continuous;(3) the 7 main structure types are ranked according to the using height;(4) the suggested raft thickness is given by its relationship to the total storeys.

1. Introduction

With the economic development, the high-rise buildings develop dramatically. There are many reasons for this:

(1) The development of material. The emergence of high-strength concrete and steel makes it possible to choose suitable materials to construct higher buildings.

(2) The improvement of structural theory. The stages of one-dimensional bar theory, two-dimensional plain theory and three-dimensional space theory lay a theory foundation for the more efficient lateral resistant system.

(3) The innovation of computer technology. The explosion of computing power increases the ability to cope with the analysis of the complicate high-rise buildings, thereby providing a reliable basis.

(4) The development of construction technique is the material basis of the high-rise buildings, which makes new structural system be a reality.

There are many outstanding advantages of high-rise buildings, including an effective use of space, a smaller land demand, which alleviate the shortage of land resources, traffic jam and housing issues. According to the relevant material, as the building height doubles, the building density reduces by about 30%, and the municipal facilities fee declines by 30%~40%.

2. The definition of “special ultra-high-rise building”

There is no unified standard to define high-rise building, and the building height requirement updates constantly.
2.1. The high-rise building

The Chinese code <Code for design of concrete structures> [1] (JGJ3-2010) shows that the residential buildings with 10 and above stories or with a height more than 28m and the other civil concrete high buildings with a height of more than 24m are “high-rise building”.

2.2. The ultra-high-rise building

The Chinese code <general principles of civil building design> [2] (GB50352-2005) stipulates that "the civil buildings with a height over 100m" are "super high-rise buildings".

The CTBUH recommends that "the buildings with a height over 300m are super tall buildings".

The definition of ultra-high buildings ("skyscraper") is different in other countries, such as, the 152 m (500 ft) in the United States and the 60m in Japan, and France.

Although the height requirement of "ultra-high building" is not uniform in the worldwide, the value will inevitably rise with the increase of construction height of ultra-high building.

2.3. The special ultra-high-rise building

"The special ultra-high-rise building" is the main research subject of this paper. At present, there is no relevant literature which conducts this definition. Combined with the foregoing provisions, and according to China's current super high-rise building height and the current level of social and economic development, the definition of special ultra-high-rise building is the buildings with height over 400m (in this paper, several typical super-tall buildings between 300 and 400m are introduced). According to <technical specification for concrete structures of tall buildings> (JGJ3-2010), these buildings belong to the B-level high-rise buildings.

3. The cases of “special ultra-high-rise building”

To some extent, special ultra-high-rise buildings can reflect the comprehensive economic and technological strength of a country or a region. Therefore, such buildings are often built in some developed countries or regions and the height of the skyline is refreshed, constantly. As a result, the owner of "the world's tallest building" changes frequently.

In this paper, data collection and statistics is carried out on 28 special ultra-high buildings (including some 300m~400m representative super-tall buildings) which have been built in the world. As shown in table 1, there are 19 buildings constructed in China, 3 buildings in the United States, 2 buildings in Japan, 1 building in South Korea, 1 building in the United Arab Emirates, 1 building in Saudi Arabia and 1 building in Malaysia. To date, 5 of the 10 tallest buildings in the world are built in China. Based on the data of building height distribution, the building height can be divided into five grades: >800m, 600m, 500m, 450m, 400m and subordinate (figure 1). There is only one building in the first class, namely burj khalifa, which is 31% higher than the second Wuhan Greenland center, occupying the absolute height advantage. The 600m class accounts for 21%. The 500m class accounts for 32% and the 450m class makes up of 21%; the 400m and the junior class account for 21%.

| Building name                        | Country       | City          | Height(m) |
|--------------------------------------|---------------|---------------|-----------|
| Khalifa Tower                        | The united Arab emirates | Dubai        | 828       |
| Wuhan Greenland center               | China         | Wuhan         | 636       |
| Tokyo Sky Tower                      | Japan         | Tokyo         | 634       |
| Shanghai center                      | China         | Shanghai      | 632       |
| The royal bell tower hotel           | Saudi Arabia  | Mecca         | 601       |
| Pingan Financial Center              | China         | Shenzhen      | 599.1     |
| Tianjin 117                          | China         | Tianjin       | 597       |
Figure 1. The height distribution of 28 special ultra-high-rise buildings
4. The building shape
The parameters of architectural form of special ultra-high-rise buildings mainly include aspect ratio, elevation variation and plane shape. The reasonable building type can effectively reduce the wind load, seismic force, so as to reduce the cost of the structure.

4.1. The overall height-to-width ratio
The height-to-width ratio of high-rise building structure is the macro-control of structural stiffness, overall stability, bearing capacity and economic rationality. This ratio mainly affects the economic rationality of structural design.

The relationship between the overall height-width ratio and the structural height is shown in figure 2. It can be seen that 50% of these buildings have a height-width ratio which exceed the limit of the tube structure in Chinese code JGJ3-2010. In addition, the value of height-to-width ratio has little correlation with the height of the structure.

4.2. The height-to-width ratio of core tube
For frame-core tube structure, article 9.2.1 of Chinese code JGJ3-2010 stipulates that core tube should be as tall as the building. The width of the core cylinder should not be less than 1/12 of the total height of the cylinder (as shown in table 2).

To the tube-in-tube structure, article 9.3.3 of the Chinese code JGJ3-2010 shows that the width of the inner tube can be 1/12~ 1/15 of the height.

The size of the core cylinder should meet the code requirements, and in general, when it achieves, the floor displacement of the structure can also meet the requirements. When various conditions are limited and the plane size of the core tube is small, it is necessary to meet the requirements of the structural displacement index through other means (such as adding extension truss and other measures), and the project cost may also cause a large increase.

Table 2. The specification recommendations for core tube height-to-width ratio

| The structural system | Limit of core height-to-width ratio |
|-----------------------|-----------------------------------|
| Frame - core tube     | 12                                |
| Tube-in-tube          | 12~15                             |

Note: the ratio of height-to-width of core cylinder refers to the ratio of the total height of the cylinder to the minimum size of the cylinder plane.

The relationship between the ratio of height-to-width of core tube and the height of the structure is drawn according to the case statistics, as shown in figure 3. It can be seen that all the ratio of the height-to-width of core tube exceeded the limit of the Chinese code JGJ3-2010. Only one case meets the limit of the ratio of height-to-width of the core tube structure, and the ratio is in the range of 15~20. Therefore, it can be seen that the building’s demand for core cylinder area is not completely proportional to the building height. The owner or architect wants to obtain more usable floor space at the expense of cost.

Figure 2. The overall height-to-width ratio

Figure 3. The core tube height-to-width ratio
According to the data statistics of some domestic developers on their own development projects, the relationship between core tube area and building height is shown in the table 3.

### Table 3. The relationship between core tube area and building height

| Height       | The core tube area ratio |
|--------------|-------------------------|
| 200–250m     | 18%–25%                 |
| 250–300m     | 24%–30%                 |
| 350–500m     | 30%–35%                 |

#### 4.3. The facade change

The selection principle of special ultra-high-rise building facade can be summarized as: simple, regular, conical and continuous.

Simple, regular and continuous facade can avoid sudden change of stiffness and concentration of elasto-plastic deformation of vertical components, which is beneficial to the overall wind resistance and earthquake resistance.

As the wind pressure gradually increases along the height of the house, the main purpose of the tapered facade is to reduce the upper windward area, so as to reduce the total wind load. Moreover, the center of the building mass can be lowered to reduce the overturning moment caused by wind load and earthquake. In addition, the study shows that the width of the plane decreases with the increase of the building height, and the critical wind speed that generates vortex-induced resonance also decreases. The wind profile in the boundary layer indicates that the wind speed increases with the increase of height, which makes the vortex-induced resonance effectively controlled.

Most of the case buildings can meet the three characteristics of "simplicity, regular and conical". About 65% of the buildings are "continuous". Typical case elevations are shown in figure 4.

![Figure 4. The typical vertical change](image)

(a) Tianjin chow tai fook binhai center  
(b) Jin MAO tower

#### 5. The structure system

According to the statistical analysis of the cases of special ultra-high buildings, the selection rules related to the structural system and the building height are obtained as shown in figure 5. The structural system that is adopted in large quantities must be a relatively efficient structural system that meets the requirements of all parties through comprehensive comparison and selection.

According to the above analysis, special-high-rise structure’s common structure system can be divided into seven types: frame-core tube, tube-in-tube (including box tube-core tube, oblique net tube - core tube), giant column-core tube-cantilever truss, giant column-giant brace-core tube, giant column-giant brace-core tube-cantilever truss, beam tube structure, core barrel buttress.

The lowest height of the various structural system increase according to the transverse direction, for the "giant column - giant brace – core tube" structure without cantilever truss, its lowest high level is higher than the "giant column - giant brace - core tube - cantilever truss" with cantilever truss. This may be related to other structure design conditions (e.g., aspect ratio, core barrel ratio, site category, the basic wind pressure, seismic intensity, etc.).
6. The foundation

Statistics of cases show that the majority of super-high building foundations use the form of "pile foundation + raft". Some cases, such as T1 tower of Changsha national gold centre (IFS), adopt the natural "raft foundation" because the basement is located in the weathered rock with high bearing capacity and compression modulus. The stiffness of pile should be determined by test pile. When the local engineering experience is mature, the joint work of pile and soil can be considered. The strength grade of the bottom concrete is generally C35–C45, and impermeable concrete is used. As shown in the figure 6–7, the thickness of the bottom plate under the tower is positively correlated with the structural height and buried depth.

After removing the data of natural raft, as shown in the figure 8, the relationship between the number of building layers and raft thickness was established, and the linear relationship curve between them was made. The thickness of raft could be estimated by 0.044 times the number of building layers. A estate developer in China has made statistics on the completed projects with 40 to 100 floors, and the conclusion is that the thickness of raft can be estimated at 0.05 times the number of floors, which is not different from the statistical results in this paper.
Figure 8. The correlation between the thickness of slab and the number of building floors

7. Conclusion
Through data collection and statistics of 28 special ultra-high-rise buildings built in the world, this paper summarizes some characteristics of special ultra-high buildings. The main conclusions are shown as following.

(1) Special ultra-high-rise buildings have developed rapidly in recent years, especially in China, which accounts for an increasing proportion of the world's highest buildings.

(2) The overall building height-to-width ratio and core tube height-to-width ratio have little correlation with the structural height. The demand of core tube area is not directly proportional to the building height.

(3) Facade selection is characterized by simplicity, regularity, tapering and continuity.

(4) There are 7 main types of commonly used structural system: frame - core tube, tube in tube (including box tube - core barrel, oblique net tube - all the core tube), giant column - core barrel - cantilever truss, giant column - giant brace - core barrel, giant column - giant brace - core barrel - cantilever truss, beam tube structure, buttress core barrel. The order is according to the minimum using highly respectively.

(5) Most of the Special ultra-high-rise building’s foundations use the form of "pile foundation + raft". The thickness of the bottom plate is positively correlated with the height and depth of the structure. Raft thickness can be estimated by 0.044 times the number of building floors.

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