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The New Structural Design Process of Supertall Buildings in China

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Abstract

By the end of 2014, the number of completed and under-construction supertall buildings above 250 meters in China reached 90 and 129, respectively. China has become one of the centers of supertall buildings in the world. Supertall buildings in China are getting taller, more slender, and more complex. The structural design of these buildings focuses on the efficiency of lateral resisting systems and the application of energy dissipation. Furthermore, the research, design, and construction of high-performance materials, pile foundations, and mega-members have made a lot of progress. Meanwhile, more and more challenges are presented, such as the improvement of structural system efficiency, the further understanding of failure models, the definition of design criteria, the application of high-performance materials, and construction monitoring. Thus, local structural engineers are playing a more important role in the design of supertall buildings.

Keywords: Super-tall buildings, Building's profile, Structural system, Mixed structure, Composite member, Energy dissipation

1. Introduction

During the last ten years, China's super-tall buildings have boomed, which attracted the focus of the whole world. By the end of 2014, 90 tall buildings above 250m were completed and 129 under design and construction. It is predicted that the amount of super-tall buildings above 250m in China will reach 258 by 2018, 90% of which adopt the steel-concrete hybrid structures (Ding et al., 2012). CTBUH 2012 and 2014 International Conference were held in Shanghai. In April, 2015, CTBUH Asia headquarter was established in Tongji University, Shanghai.

The height record of tall building was constantly broken. The proposed Suzhou Zhongnan Center will exceed 700 m and higher buildings have been planned. The main functions of super-tall buildings include office, residence, hotel, and apartment. The location of super-tall buildings shifts gradually from eastern area to mid-west area. Structural lateral resisting system mainly adopts composite moment frame with RC core-tube. New systems such as diagonal braced tube, diagonal mesh tube and steel shear plate wall, and seismic energy dissipation technology have been applied widely. In a tall building above 600 m, its mass exceeds 0.8 million tons and its natural period approaches 10 s, the consumption of steel material is more than 100,000 tons. High performance structural materials were used. Relevant regulations and standards on materials, structural design and construction of super-tall buildings have been gradually established. Estate owners paid much more attention to the structural economic and sustainability, and introduced the peer reviewer. Local and overseas architecture and structure partners cooperate closely. The number of super-tall buildings originally designed by local structure engineer increases and the height exceeds 400 m.

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2. Height and Profile

Shanghai World Financial Center (SWFC, 492 m), has been the highest tall building in China since 2007. With the completion of Shanghai Tower (632 m), and the construction of Tianjin Goldin Finance 117 Tower (597 m), the height of China's super-tall buildings has been continuously renewed. The height of crown also increases, such as Dalian Greenland Center (518 m) with a 118 m high crown. Virtual height of the tower crown takes up more than 20% of the total height of the tower. The wind load on the crown shall not be ignored in areas with strong wind. In addition, the tower becomes tender, such as KingKey Financial Center with an aspect ratio of 10. Both high percentage crown and slender tall buildings bring great challenges to wind resisting and lead to substantial increase of material consumption.

Tower profile tends to become more complex, such as tapering profile and connected buildings. Tapering building is a combination of architectural function and structure optimization (Wang et al., 2014). According to differ-

ent functions of tall buildings, the space reserved for lift shaft becomes smaller and smaller. The tapered shape can take full advantage of structural materials and reduce wind load, especially the dynamic response of cross wind. The tapered profile can effectively improve structure's lateral stiffness, overall structural stability and shear resisting capacity of perimeter frame. Tapering profile of tall buildings is classified as follow: Staged symmetrical tapering (Shanghai Center, structural system), Staged non-symmetrical tapering (Dongjiadu Tower of the Bund), Continuous tapering (Tianjin Goldin Finance 117 Tower), Cutting regular geometry (Shanghai WFC), and Irregular torsional tapers (Shanghai Center, facade).

Suzhou Gate of the Orient is the highest twin towers with link in the world. Nanjing Gold Eagle World and Wenzhou Trade Center are triple linked towers. The former adopts rigid linking with a six-floor height. In the latter, the cantilever of the tallest tower slides on the second tower, which has a sky-bridge linking the third tower. In Chongqing Raffels City, four towers are linked together by a sky-bridge supported on friction pendulum bearings at the top.

3. High-Efficiency Structural Systems

With the increase of China's super-tall buildings in structural height and aspect ratio, more attentions are paid to the efficiency of structural systems. The structural systems of 300 m and taller buildings are characterized by the efficiency of material, such as member peripherization, braced system and composite structure. The main structural systems include: mega frame with RC core-tube, mega diagonal braced tube with RC core-tube, diagonal mesh tube with RC core-tube, and some derivative new systems such as Michell truss tube and steel plate shear walls (Zhou et al., 2014).

3.1. Mega frame with RC core-tube

Shanghai Tower (632 m, 124 stories) was topped out at the end of 2013. The mega frame is composed of 8 mega SRC columns, 4 corner columns and 8 two-story high belt trusses. The core-tube is made up of composite steel plate and concrete shear walls, and 6 outrigger trusses are used to connect the core and mega frame along the height to maximize the structural efficiency (Chunyu et al. 2012).

3.2. Mega diagonal braced tube with RC core-tube

Goldin finance 117 (597 m, 117 stories) is in Tianjin with the aspect ratio 9.5. The mega diagonal braced tube is composed of 4 mega special-shaped columns with area of 45 m^2, 9 belt trusses and mega X-braces. The core-tube is made up of composite steel plate and concrete shear walls which is 1400 mm thick at the bottom.

3.3. Diagonal mesh tube with RC core-tube

Guangzhou west tower (432 m, 103 stories) adopts the



Figure1. Shanghai Tower.



Figure 2. Tianjin Goldin finance 117.



Figure 3. Guangzhou West Tower.



Figure 4. Kunming Junfa Dongfeng Square.



Figure 5. Tianjin Jinta Tower.

structural system of diagonal mesh tube with RC core-tube. The diagonal mesh tube is composed of 30 CFTs with the maximum diameter of 1800 mm and 35 mm thick steel pipe. It is 27 m long between two intersected nodes.

3.4. Michell truss tube with RC core-tube

Michell truss tube with RC core-tube is proposed in Kunming Junfa Dongfeng Square (456 m, 75 stories). The exterior tube is composed of Michell truss in 3 elevations. Each Michell truss is made up of 2 mega columns and 6 curved X-braces in the middle. The brace angle is gradually changed to maximize the efficiency of transferring the lateral loads and minimize the use of structural materials.

Table 1. Embedded depth of foundation of typical super-tall buildings

Project	H (m)	h (m)	H/h
Shanghai WFC	492	21.35	23.0
Tianjin Goldin Finance 117	587	25.85	22.7
Guangzhou West Tower	432	20	21.6
Taipei 101	448	22.3	20.1
Hongkong IFC	484	25.5	19.0
Shanghai Tower	580	31.4	18.4
Burj Dubai Tower	828	15	55.2

H: Structure height, h: Embedded depth of foundation.

3.5. Steel plate shear walls

Tianjin Jinta Tower (337 m, 75 stories) is the tallest building which uses the steel plate shear walls considering the tension field effects in China. The structural system is composed of the CFT frame, the steel-plate shear walls core-tube and outriggers. The interior core tube is made up of CFT columns and wide-flange steel beams filled with steel plates, with thickness varying from 18 mm to 32 mm. The steel-plate shear walls can remain elastic under the small earthquake force, and are allowed to buckling to resist lateral force with the use of tension field effect under the medium and large earthquake.

4. Foundation Design

The foundation of super-tall building should meet the higher demands on bearing capacity for its big weight and sensitivity to differential settlement. Geotechnical conditions vary widely for sites of ultra-tall buildings in China. Except for cities in eastern China such as Dalian and Qingdao having reachable bedrock, most sites are soft soil, which bring great difficulties in the design and construction of deep foundation.

When pile or caisson foundations are used, the embedded depth of tall building foundation should not be less than 1/18 of the structural height in accordance with the Chinese codes. But it is difficult to meet the requirement for the building with structural height exceeding 400 meters or no requirements for multi-story basement. It brings much challenge in the construction of foundation system and adds the cost of underground earthwork and the retaining structures of deep foundation. The embedded depth of foundation of some super-tall buildings worldwide listed below reflects this trend.

The thick mat foundations supported by ultra-long piles or caissons with large diameter are common for super-tall buildings in soft soil areas. For Tianjin 117 as an example, 3 types of piles or caissons (bored pile, steel pipe and concrete barrette) were studied in the schematic design. Finally, the bored pile was selected in considerations of safety, economy and construction feasibility.

The piles are 1000 mm in diameter, 76.5 m in length, and the bearing capacity is 16500 kN. The mat thickness

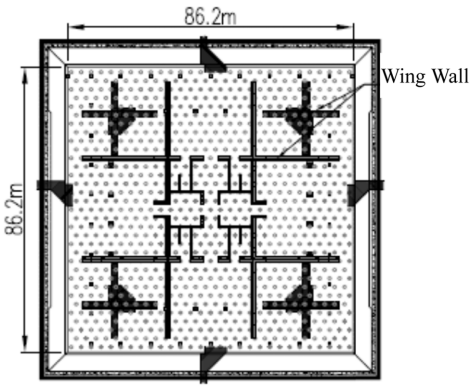


Figure 6. Piles and Mat Layout of Tianjin Goldin 117.

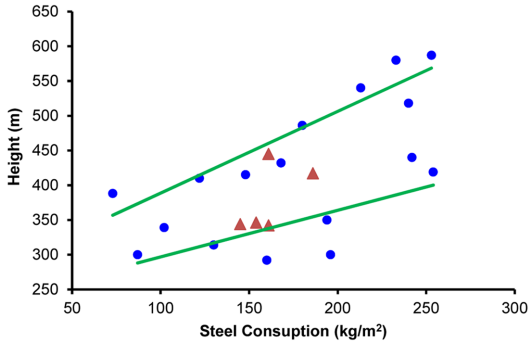


Figure 7. Steel Consumption of Super-Tall Buildings.

is optimized to 6.5 m. To distribute the vertical load more uniformly to the mat and piles, wing walls are set between the mega columns and the core-tube below B1 story. It also can improve the mat's punching capacity and bending stiffness. As far as the rigidity of superstructure is concerned, the maximum foundation settlement is 162 mm.

5. Structural Materials

5.1. High performance material

Structural material with high strength and high ductility has been used in the super-tall buildings. C70 and C60 (cube strength) concrete was adopted in the SRC column and shear wall respectively in the structure with moment frame and concrete core. No higher grade concrete has been used, since insufficient ductility of them was mainly concerned about. However, C100 concrete was utilized in the CFT or CFRT columns. The self-compact concrete was used in the elements with dense rebar considering poring convenience. The high strength concrete mix was designed to be delivered to height over 600 m.

Except for the conventional Q235 (yield point) and Q345 (yield point) steel, the extensive use of high strength steel plate including Q390 (65-ksi yield point) is practical in the elements of super-tall buildings, such as outriggers. Cast and forged steel are also used in the complex joints. For example, cast steel was used in Shanghai WFC, as well as forged steel was used in Dalian Greenland Center in the joint connecting outrigger with concrete core wall. The weldability and ductility are also taken into account when using the high strength steel. In the same time, the new connecting detail needs to be studied, such as high strength bolt with high friction coefficient.

5.2. Analysis of steel consumption

Fig. 7 illustrates the steel consumption of super-tall buildings that completed or under construction in China (Shown as dots; the steel weight excludes the weight of reinforcement per unit area of the building). These super-tall buildings, with height of 300 m and above, are mainly used for offices, hotels, or apartment. Since over 90% of current super-tall buildings in China are steel and reinforced concrete hybrid structure, the data used in this article are mainly gathered from this type of buildings. In comparison, Fig. 7 also illustrates the steel consumption of super-tall building in North America with similar heights (shown as triangles). However, unlike the hybrid structures in China, the structures in North America are mostly built with steel. The following conclusions can be drawn (Wang et al., 2012).

1) The steel consumption per unit area is dispersed wildly and ranges from 100 kg/m^2 to 250 kg/m^2. This distribution index is closely related to the height of the building, the height to width ratio, and the type of lateral force resistant system utilized.

2) According to the statistics of limited data, the steel usage of frame columns (pillars) and outrigger and ring trusses account for 30% and 15% of the total structure steel consumption, respectively. The shape of the column and the steel consumption of column within the frame have one of the greatest impacts on total steel usage.

3) The amount of steel usage for super-tall building greatly varies in different regions, which indicates that wind and seismic loads are major factors that affect the amount of structural steel used. Generally, wind loads are much higher in coastal areas, so the steel usage of super-tall buildings in Shanghai is much higher than those in inland cities such as Wuhan, Chongqi and Wuxi. A high usage of steel is found in Tianjin and Beijing because these cities are within high seismic load zones.

4) Super-tall buildings in China use a hybrid structure of steel and reinforced concrete rather than the pure steel structures that are used in North America. However, the steel usage of buildings in China is close to or even higher than that in North America.

6. Technology of Energy Dissipation

Wind and earthquake are two main lateral loads on super-tall buildings. The structural responses arising from wind and earthquake decrease with increasing damping.

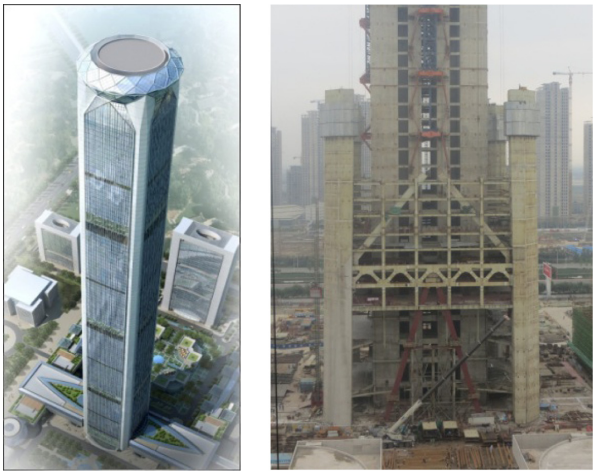


Figure 8. BRB in Tianjin Goldin 117.

However, the intrinsic damping of the super-tall building is low and uncertain. Adding supplementary damping system to a building will increase the dependable structural damping, so that the structural dynamic response will be virtually eliminated.

Displacement dependent dampers, velocity dependent dampers and tuned mass dampers are three types of dampers often used in the high rise buildings.

Displacement dependent dampers such as buckling restrained brace (BRB), shear panel damper, show high efficiency to seismic mitigation of structure. Viscous dampers (VD) dissipate energy under small deformation, and are capable of reducing lateral design forces and assuring occupant comfort (Jiang et al., 2014). Tuned mass dampers (TMD) at the top of building can be used to reduce wind-induced accelerations.

6.1. Tianjin Goldin Finance 117

6.1.1. BRB

The length of V shape braces in the lobby is about 48m. The traditional brace was replaced with BRB to solve buckling problem of the super-long brace. Therefore, the enormous unbalanced force and moment in the horizontal bar are avoided.

The steel core of ultra-long BRB consists of yielding section and non-yielding section, which are made of low yielding steel and low alloy steel respectively. The yielding capacity of BRB is 36000 kN.

6.1.2. Replaceable coupling beams

In the reinforced concrete core, replaceable coupling beams are creatively used to enhance the capability of dissipating energy. Meanwhile, structural reparation after intense earthquake will be convenient (Lu et al., 2013).

6.2. Urumqi Greenland Center

Urumqi Greenland Center consists of twin towers with

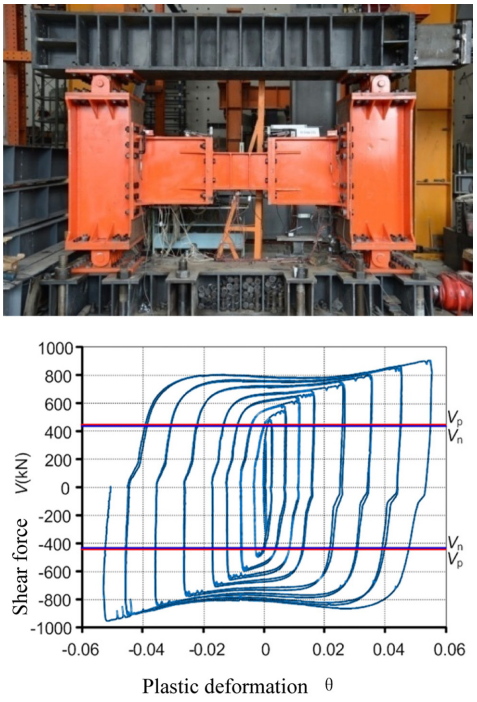


Figure 9. Replaceable Coupling Beams

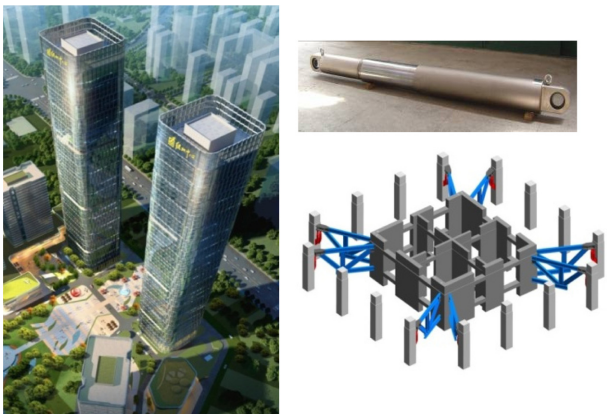


Figure 10. VD in Urumqi Greenland Center.

260 m height and 57 levels. As located in 8 degree-earthquake fortification zone, the towers may be subjected to strong lateral motions in earthquake. 48 viscous dampers are installed on three refugee floors at the end of cantilever trusses.

Analysis results show that the structural dynamic responses under small earthquake, medium earthquake and large earthquake will be reduced by 20%, 15% and 10% respectively, and the supplemental damping will be 4.5%, 2.8% and 1.9%, respectively.

6.3. Shanghai Tower

To enhance the occupant comfort of Shanghai Tower, a

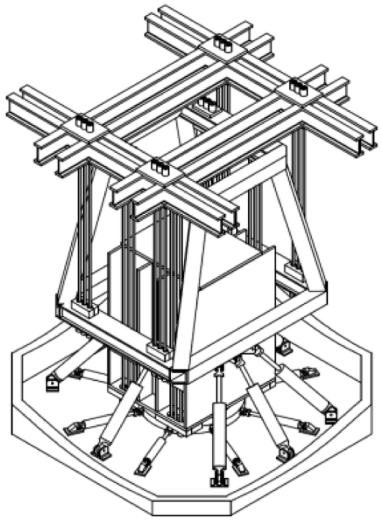


Figure 11. TMD in Shanghai Tower.

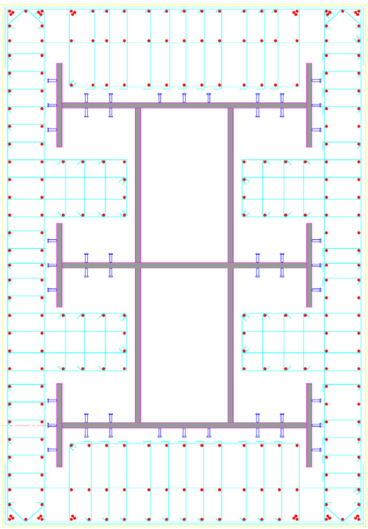


Figure 12. Mega SRC in Shanghai Tower.

tuned mass damper system was installed at the top of the tower. The TMD consists of pendulum frame, TMD mass, viscous damper devices, electromagnetic damping devices and snubbing system. The TMD was capable of reducing acceleration induced by wind with 10-year return period felt at the top floor from 11.4 gal to 6.2 gal.

6.4. Suzhou IFC Tower

Suzhou IFC Tower is 450 m high with 93 stories above the ground. Tuned liquid damper is placed at the top of the tower to assure occupant comfort. The fire water pool of the building is used as TLD tank, which can provide a total water of 593 tons. With TLD, the wind induced acceleration under 10 years returned wind will be reduced from 17 gal to 12 gal.

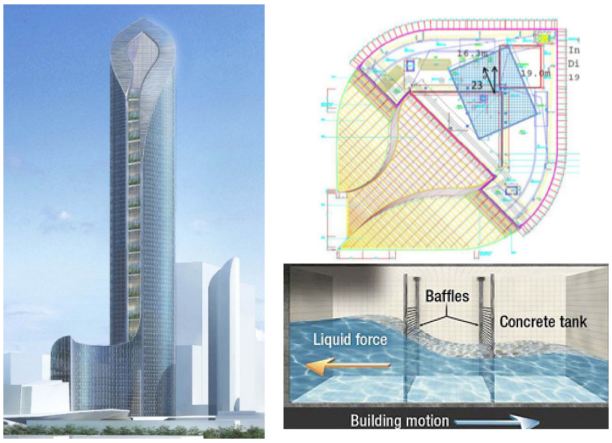


Figure 13. TLD in Suzhou IFC Tower.

7. Mega Composite Components

As described above, the building width can be fully utilized to improve the ability of resisting overturning in mega-frame with RC core-tube system or mega braced tube system, where the huge tension forces caused by the overturning moments in mega columns can be balanced by the transferred gravity loads.

It's inevitable to apply mega elements to super-tall buildings due to the high demand for capacity and axial stiffness, and composite members will be a logical choice.

Three types of composite sections (SRC, CFT and CFRT) have been widely used which vary in performance of capacity, ductility, detailing, constructability, fireproofing and economy. But none is dominant, to some extent depending on the engineers' experience. CFT and CFRT are more popular in Southern China.

Shanghai Tower and Wuhan Greenland Center adopt mega SRC columns with section area of about 20 m^2 and steel ratio of 4~6% (Fig. 12). For reliable connection of outrigger truss elements, belt truss elements or braces to SRC columns, steel sections shall be placed separately. Due to possible poor seismic performance, latticed steel sections are not acceptable in Chinese code. Usually steel webs are used to connect separate steel sections to form solid web steel columns, which will increase the difficulty of closing stirrup and add much construction cost. Limited by transportation and hoisting, segmentation is necessary for solid web steel columns. In spite of low efficiency, uncontrolled welding deformation and residual stresses, sometimes site welding is the only possible solution for steel column splicing. On the contrary, the idea of latticed steel sections in SRC forwarded in Dalian Greenland Center can avoid the above problems. For wide engineering application of SRC with latticed steel sections and sponsored by CTBUH seed funding, a series of test program are being carried out by China Academy of Building Research (CABR) to study the ultimate load-carrying capacity

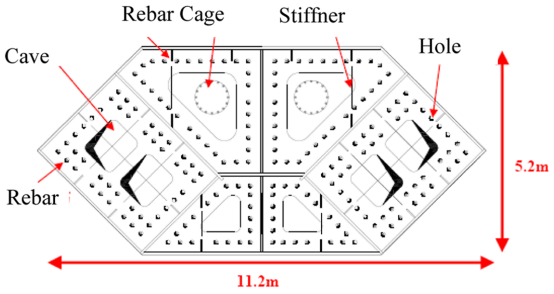


Figure 14. Mega CFRT in Tianjin 117.

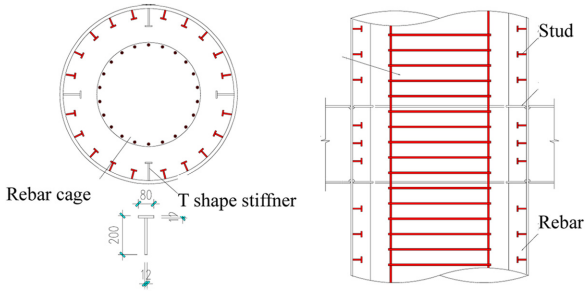


Figure 15. Mega CFT in Wuhan center.

and failure mechanism.

Special-shaped mega CFRT with multi-caves has been used in Tianjin Goldin Finance 117. Its section area is 45 m^2 and its steel ratio is 6%. For its first application in practice, in-depth studies on capacity, column foot, welding detail and fireproofing have been developed. Complete penetration weld and partial penetration weld have been respectively used for perimeter and inner plates assemble. In column foot connection, high-strength rods have been embedded to resist the huge tension forces under rare earthquake.

Mega CFT in Wuhan Center has a diameter of 3 m and the maximum tube thickness is 60 mm. Experimental study on connection of perimeter beams and outrigger truss diagonals to CFT has been conducted. Base on the experimental results, the details shown in Fig. 14 have been used in design. The ring stiffner inside the tube plays a primary role to transfer the beam shear force. Shear studs, T-shaped longitudinal stiffening ribs and reinforcement cages can reduce the adverse effects due to concrete shrinkage and creep.

8. Role of Local Structural Engineers

Super-tall building design in china has undergone 3 phases: design by overseas engineers in the late 1980s, cooperating with overseas engineers in 1990s, and by local designers in the 21st century.

Foreign architects and engineers have brought new ideas and technologies when they entered into China. Chinese engineers have made great progress during the cooperation. Taking their advantage and combing with domestic conditions, they have made innovations in the key technology, which has enhanced construction feasibility, shortened the construction period, and reduced the cost.

For instance, as the preliminary design of Tianjin Jinta Tower, vertical load is only carried by frame columns in the core, and not by steel plate shear wall (SPSW). So SPSW should not be installed until the top out of the superstructure. Local engineers adjusted the installation order of SPSW. The SPSW of the 1st floor was proposed to be installed when the erection of the 15th floor had ended. In order to avoid buckling under vertical loads, the SPSW was thickened and vertical stiffeners were added. This optimization has shortened 6 months of construction period, saved nearly 10 million RMB Yuan. In the case of Tianjin 117, considering the rigidity of superstructure, the thickness of the raft was reduced from 7.5 m in preliminary design to 6.5 m by local engineers. In addition, the 8 conventional mega braces in the lower lobby were replaced by BRB to improve seismic performance of the bracing system.

Nowadays, the cooperation between foreign architects and Chinese engineers from the phase of conceptual design turns out to be more and more common. For example, by the end of 2014, the number of super-tall buildings above 300 m designed by East China Architectural Design & Research Institute (ECADI) has reached 46. Among them, more than 50% projects such as Dalian Greenland Center (518 m) and Wuhan Center (438 m), were participated by ECADI from structural conceptual design. Local engineers cooperated with foreign architects including KPF, HOK, WOODS Bagot, and etc. In the project of Hefei Baoneng IFS (the tallest tower higher than 600 m), all the design work will be done by ECADI.

9. Prospect

- Building shape, structural system, material and construction programs should be considered in the structural design of super-tall buildings to improve the economy. Wind tunnel test is proposed in the design of super-tall building for its sensitivity to wind.
- In order to optimize the structure, further studies on structural design criteria such as inter-story drift, stiffness-weight ratio, shear-weight ratio and shear-resistant capacity of perimeter frame need to be carried out.
- Since the existing hybrid super-tall structures haven't experienced the real earthquake so far, the seismic performance of this kind of structural system needs to be studied furthermore. In high seismic intensity area, steel-concrete hybrid structure system and outriggers should be carefully used. Hybrid structural systems with energy dissipation devices or structure steel systems are advised.

- The use of mega members has brought new challenges for structure design and construction. The design method, joint detail and construction feasibility of mega columns need to be proved by more tests and practice.
- Some research needs to be done in the feasibility of high-strength concrete such as C70 and higher grades in core shear wall in order to reduce the thickness of shear wall, lighten the structural weight, and improve the floor efficiency.
- Considering the long construction period, large amount of investment in super-tall building construction, parts of a building could be occupied before the entire building is completed. Correspondingly, the post-cast strip between the tower and the podium need to be poured in advance, and construction simulation analysis and construction program should be adjusted.
- Structural monitoring system is advised to establish in the super-tall building construction. The monitoring data including structural dynamic properties, foundation settlement, strain and deformation of key members, can be used to validate and improve the structural design.

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