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Design of Supertall Structures with Connected Towers the Structural Solution to the Development of Sky Cities

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Abstract

Three cases of supertall connected structures are presented and each of them represents a quite style. The first case is a strong-connected structure. The coupling function of towers and connector contributes a lot to the structural stiffness and stability. Its special construction scheme had great impact on the construction quality and the structural safety, and must be accurately considered. For the second case which is a weak-connected structure, the influences of different connecting modes to the structural dynamic characteristic were explained. Then the combined bearings were proposed to achieve the design presume. In the third case which represents the multi-supported structures, the structural distinctive mechanical properties were discussed. For the structural state during construction process is quite different from that in final service condition, two construction procedures were simulated to get an optimal one. Although there are great challenges to designers, the advantages of the supertall connected buildings are obvious. Further work is needed in this area to adapt to the development of future cities.

Keywords: supertall connected structures, Coupling effects, Construction simulation, Seismic design

1. Introduction

High-rise buildings in high-density cities are developing rapidly. It is an important direction for urban development that the resources of different buildings should be coordinated and planned as a whole to satisfy the new demands. Since the 9/11 incident, the researches on structural safety have focused on three key aspects (Antony Wood, 2012): structural systems, fire protection systems and evacuation systems. In recent years, connected structures have been increasingly used. The particular form provides new thoughts about fire protection and evacuation.

In order to meet the structural stability requirements, sufficient dimension of the width of the supertall buildings are needed. When the width is too large, the ratio of useable room area is low and the structural weight is too heavy. It has an adverse effect on seismic design. Therefore, the traditional design method encounters bottlenecks in the balance of utilization and structural performance when the height of the structure exceeds a certain level.

As a kind of mega-structures, connected structures provide a solution to this problem (Kyoung Sun Moon, 2019). Based on topology optimization theory, inefficient parts can be gradually removed from a large cantilever solid beam. Finally, the efficient main frame can be obtained as a ideal connected structure (See Fig. 1).

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Compared to single towers, connected structures have more advantages in structural stiffness and stability. Different towers bundled together by connectors can help each other to achieve better structural performance through rational design. So the towers in connected structures can break the limitations of aspect ratio, plane and elevation regularity, which enable structures to present more variability.

In 1990s, Shanghai BOCOM Financial Tower was designed by East China Architectural Design and Research Institute (ECADI) and ABB+OBERMEYER. In detail, the main structure consists of the north tower with height of 230.35m and the south tower with height of 197.55m (See Fig. 2). The planes of towers were trapezoid and the width of the bottom short edge was only 5.4m. So each single tower is unstable. Three steel trusses were set to connect two towers at 13th floor, 26th floor and 39th floor respectively, which made the whole structure stable.

Beijing Lize SOHO (shown in Fig. 3), designed by Zaha Hadid Architects and China Academy of Building Research, was divided into two parts by the subway tunnel and twisted with its height increasing. The atrium in the center of the structure extended from the top floor to the ground with the height of 190m, connecting two separate towers. Two antisymmetric single towers were connected by 4 cambered belt trusses with the span from 9 to 38m.

Supertall connected structures are not only an architectural choice for the development of sky cities, but also a reasonable structural solution.

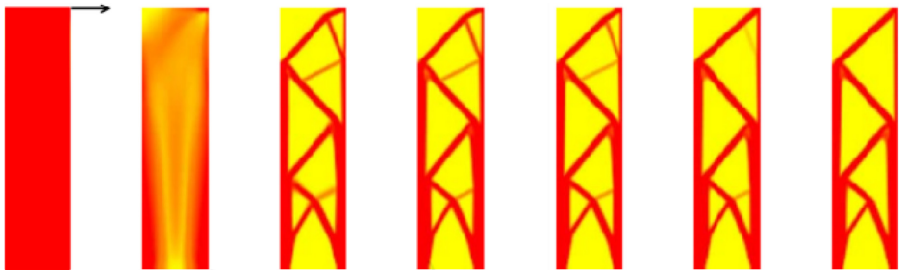


Figure 1. Optimization of cantilever beams.



Figure 2. Shanghai BOCOM Financial Tower.

2. Mechanical properties of connected structures

Connected sections in connected structures lead to serious interaction among towers. The structural performance is influenced by many factors under vertical and horizontal forces, resulting in more complicated dynamic properties. It is shown in several aspects as follows (East China architectural design & research institute, 2013):

Complicated dynamic properties: The stiffness relationship between the connector and towers and the location of the connector are both have significant impact on the structural dynamic properties. They cause complex vibration modes in connected structures. The reverse or asynchronous movements of towers in vibration modes are basic properties of connected structures.



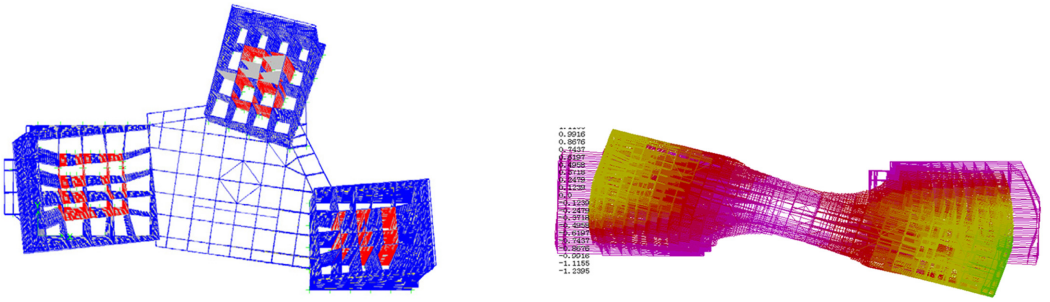
Figure 3. Beijing Lize SOHO.

Distinct torsional effects: There is always a large structural torsional displacement due to the phase differences in movement of towers, which leads to a more obvious coupling effect of the translation and the torsion as shown in Fig. 4 (Bao et al., 2015).

Abrupt changes in storey stiffness: There are sharp changes between connected storeys and adjacent ones. It always bring complicated stress conditions like stress concentration.

Wind loads: The wind loads acting on towers in connected supertall structures are interfered with each other. The researches in this field were rare up to date. Comparatively reliable method to obtain the wind loads is still wind tunnel experiments and corresponding vibration analysis based on experimental results.

Special construction scheme: It results in complete different structural mechanical model from construction state to final service state (Shown in Fig. 5). The design work is firmly connected to the construction and assembling schemes. The construction simulation is very important in connected structures (Wang et al., 2008).



(a) Nanjing Golden Eagle Plaza (b) The Gate of the Orient (Zhang et al., 2008)

Figure 4. Twist response of structures.

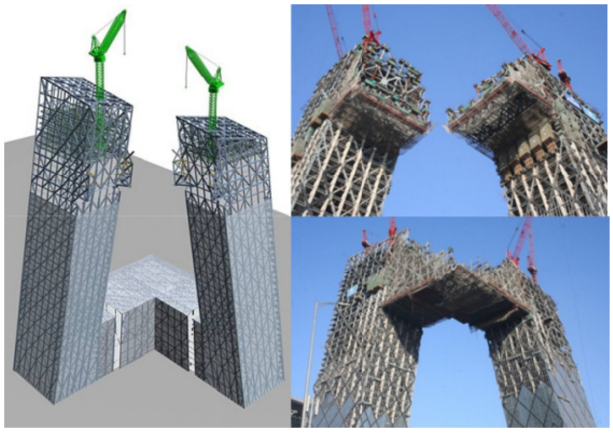


Figure 5. Construction simulation.

Usually, there is relatively weaker stiffness of connector compared to towers. So the vibration control of the connector is very importance. In addition, adopting energy dissipation measure to make the connected structure more efficient and economical is also a significant topic.

The following are three cases of structures for supertall connected buildings.

3. Nanjing Golden Eagle Tiandi Plaza

3.1. Project overview

Golden Eagle Tiandi Plaza locates in Nanjing city. It is composed of three diverse towers of Tower A (368m), Tower B (328m) and Tower C (300m). The triplet towers are connected with each other by a 6-storey sky lobby at the elevation of 192m~232m (See Fig. 6). Typical plan of the connected floor is shown in Fig. 7.

3.2. Structural arrangement

The three towers are hybrid structures of SRC columns and concrete core. Additional belt trusses and outrigger trusses are set up in equipment layers to strengthen lateral stiffness of the towers, as shown in figure 8. The lower part of the concrete core was reinforced with steel plate to improve ductility and reduce wall thickness.

The height of the sky lobby is over 40m and the span



Figure 6. Golden Eagle Tiandi Plaza.

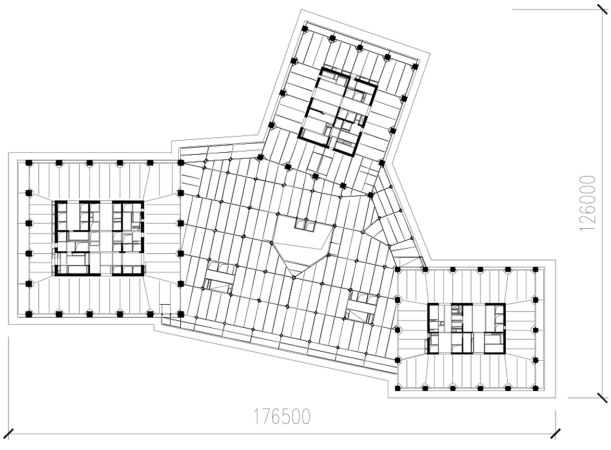


Figure 7. Typical plan of the connected storeys.

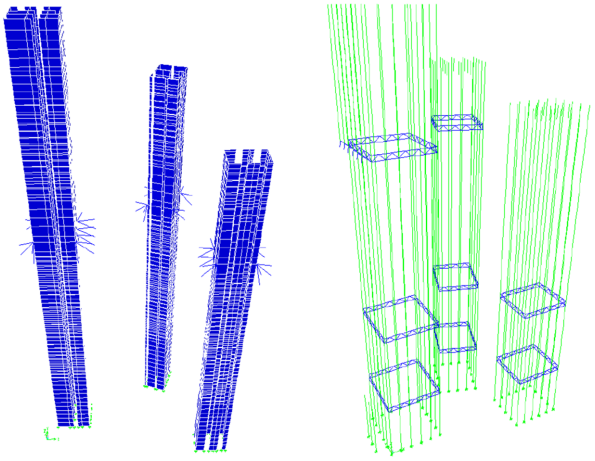


Figure 8. The structural arrangement of Golden Eagle Tiandi Plaza.

is over 70m. The sky lobby and the towers are connected by a 5-storey high main connecting truss. The main connecting truss joined the belt trusses (See Fig. 9(b)) surrounding three towers, coordinating the inconsistent deformation and strengthen the structural stiffness. The bottom storey of the sky lobby is equipped with orthogonal transfer trusses to bear the vertical loads of the whole platform (See Fig. 9(c)).

3.3. Coupling effect of towers and connector

The location of the lobby is of approximately 1/2 to 2/3 elevation of Tower A, 2/3 of Tower B and 3/4 of Tower C respectively. Analysis revealed that the lower the connected storeys placed, the weaker the lateral stiffness of the connected structure was. At the same time, the structural torsional response enhanced and the whiplash effect of the storeys above the connected part intensified. It means that the seismic performance of the connected structure is improved when the connector is placed at the upper elevation of the tower.

According to the analysis on the overturning moment of the connected structures under earthquakes listed in Table 1, the local overturning moment resisted by every single tower decreased, while the proportion of the whole overturning moment resisted by the axial forces of towers

Table 1. The overturning moment of the connected structure / (10^7kN·m)

Direction	Total	Local	Whole	Whole/Total
X	1.986	1.500	0.486	24.4%
Y	1.806	1.327	0.479	26.5%

was up to 24.4% and 26.5% in X and Y direction respectively. The local and whole overturning moment are defined as shown in Fig. 10. The result shows that the connected structure combined of three towers works effectively as a whole structure. The proportion of the whole overturning

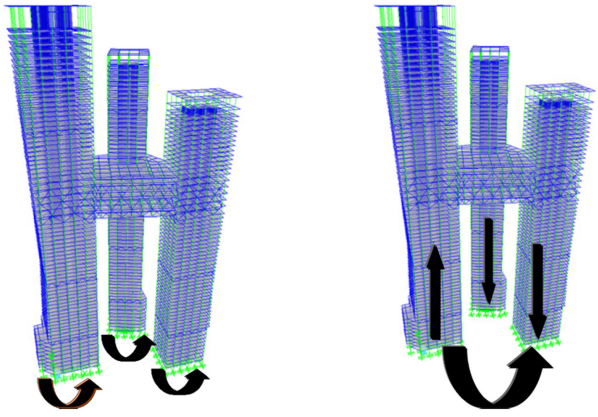


Figure 10. Definition of local and whole overturning moment.

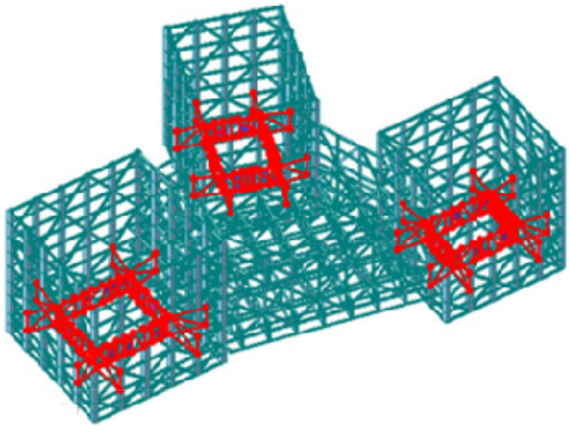
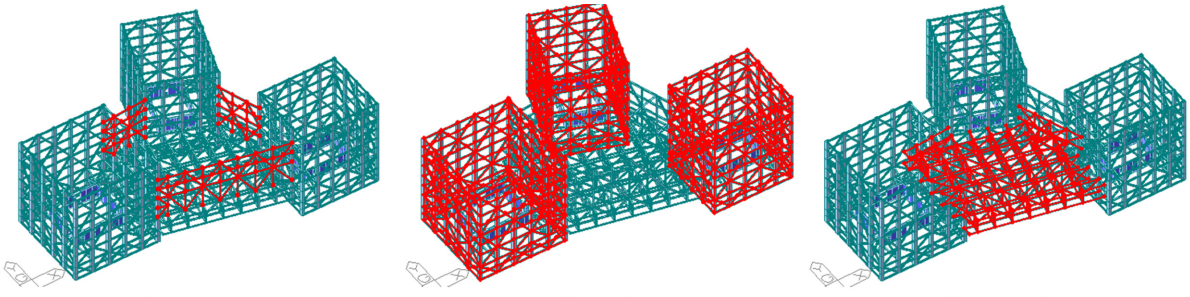


Figure 11. The outrigger truss.



(a) The main truss **(b) The belt truss** **(c) The transfer truss**

Figure 9. The trusses of sky lobby.

moment is a key index to evaluate the integrality of the connected structure.

So there is only one layer of outrigger trusses in every tower to meet the needs of the structural stiffness. Fewer outrigger trusses are beneficial for reducing the construction time and cost.

3.4. Influence of the construction scheme

The orthogonal transfer trusses were assembled in advance on the podium roof, and lifted integrally to the designed location (Wang et al., 2018) by 12 jacks (shown in Fig. 12). Then a construction platform formed when concrete slabs on the transfer trusses was poured and meet the design strength. The rest part of the sky lobby could be fixed on this platform.

The construction processes have great influence on the design of the transfer trusses. If loaded at once, the trusses are rigidly connected to the towers bearing all vertical loads, as shown in Fig. 13. In practice they are actually loaded in two steps, shown in Fig. 14. The ends of trusses were hinge while trusses were under lifting. The load was just the weight of transfer trusses. When trusses were fixed with the towers, the supports turned to rigid connections to bear the rest vertical and lateral loads.

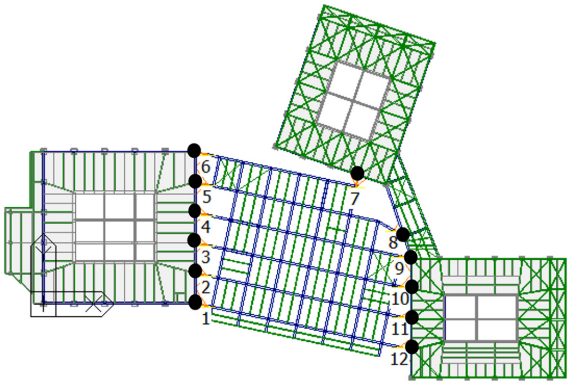


Figure 12. Location of the lifting jacks.

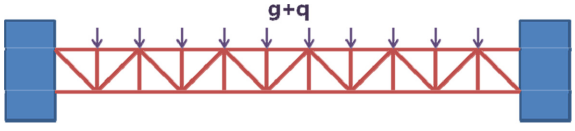


Figure 13. Loading at once.

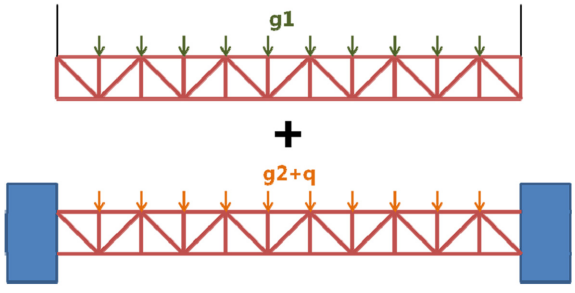


Figure 14. Loading in two steps.

Table 2. Vertical deformation of the transfer trusses

Condition	Truss 1	Truss 2
Loading at once	42mm	74mm
Loading in two steps	72mm	92mm

Table 2 showed the deflection of two trusses under different conditions. The results show that the deflection of two trusses was increased by 30mm and 18mm respectively considering the construction simulation in normal service stage. The optimal pre-camber values of trusses should be equal to the deflection under the weight of trusses and concrete floors, so the actual thickness of concrete floors is uniform. The influence of construction process must be accurately considered.

When the transfer trusses were lifting, the outer frame of tower A was constructed to the 46th floor and tower B and tower C were both topped off, shown in Figure 15. The tension force of each lifting point caused additional overturning moment to towers, causing deformation in X direction and making the distances between towers reduced. Analysis results indicate the maximum lateral deformation is about

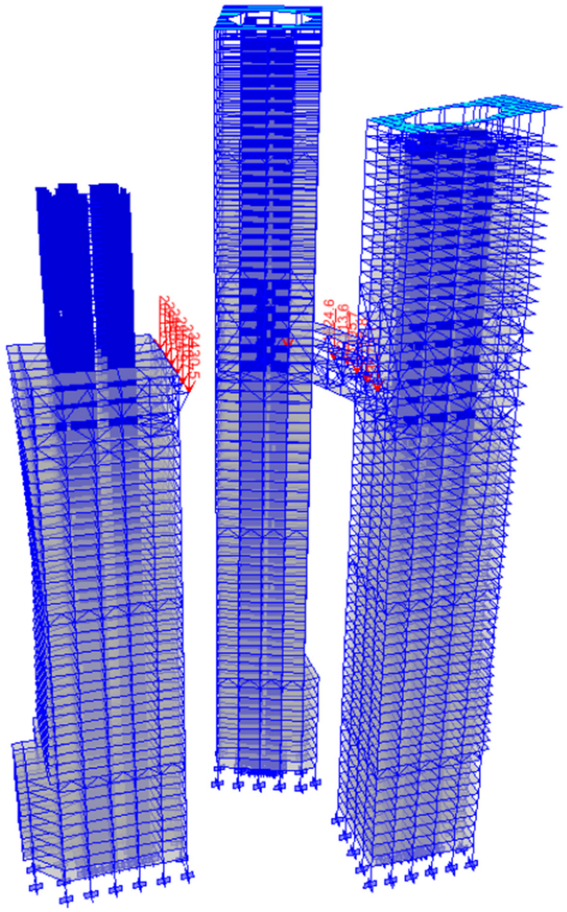


Figure 15. Construction simulation.

10mm. The deformation should be considered in the construction of trusses to ensure the verticality of cables during lifting process and the installation accuracy of trusses.

4. Wenzhou Center Tower

4.1. Project overview

Wenzhou Center Tower (shown in Fig. 16) was located in Wenzhou, Zhejiang Province. The height of Tower A1, Tower A2 and Tower A3 were 280m, 164m and 164m respectively. Tower A1 and Tower A2 were connected at elevation 128~136.5m and Tower A2 and Tower A3 were connected at elevation 138.5~164m, forming 'urban balcony'. The overall planar is shown in Fig. 17.



Figure 16. Wenzhou Centre Tower.

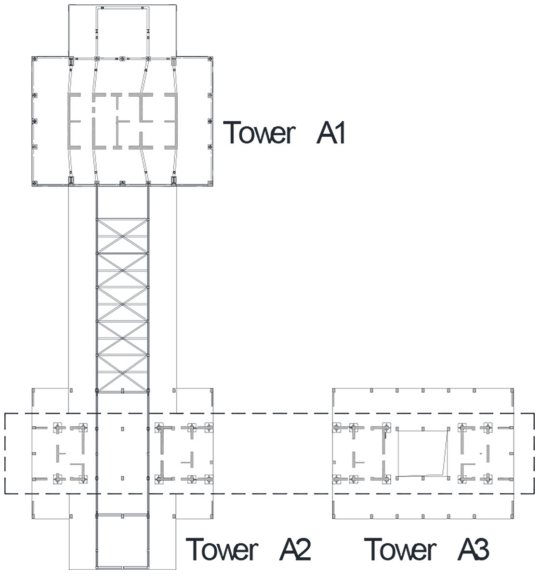


Figure 17. Overall plan.

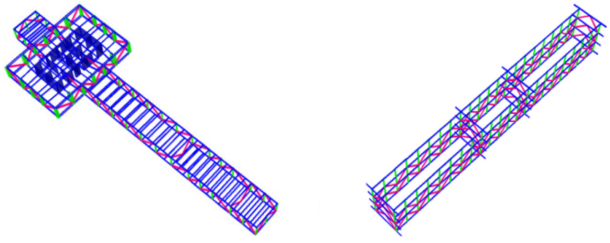
4.2. Structural arrangement

Tower A1 are hybrid structures of SRC columns combined with concrete core. Tower A2 and Tower A3 with lower height and similar stiffness are both concrete structure with concrete frame and shear wall.

The connectors between towers are long-span steel trusses, shown in Figure 18. The connector between Tower A1 and Tower A2 (named Connector 1) is one storey high. One end of Connector 1 was rigidly connected to Tower A1 and the other placed on the roof of Tower A2 through isolation bearings (shown in Fig. 19). The connector between Tower A2 and Tower A3 (named Connector 2) was three-floor high. Two floors at the bottom of Connector 2 were main trusses and the top floor was steel frame. Connector 2 was supported on the shear wall of Tower A2 and Tower A3 (shown in Fig. 19).

4.3. Schemes of connection between Towers

Connection between connectors and towers determined the basic dynamic characteristics of the whole structure. Connection schemes should be based on the stiffness relationships between towers, functions of the connector



(a) Connector 1 **(b) Connector 2**

Figure 18. Structural arrangement of connectors.

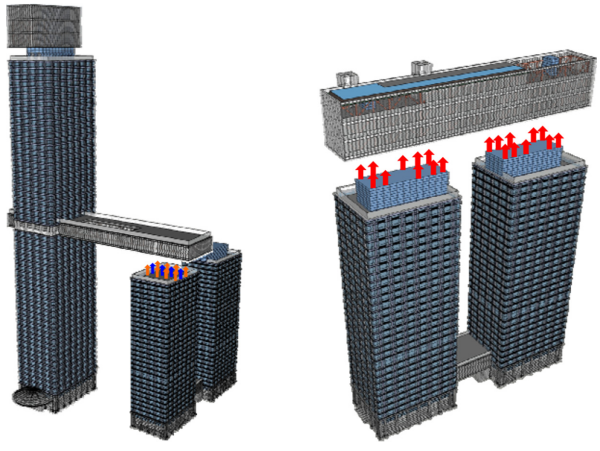


Figure 19. Relationship between connectors and towers.

Table 3. Summary of connection schemes on towers

Connector 1		Connector 2	
On Tower A1	On Tower A2	On Tower A2	On Tower A3
Rigid connection	bi-directional sliding	bi-directional sliding	Fixation at long side and elasticity at short side
	Sliding at long side and elasticity at short side	Sliding at long side and elasticity at short side	Fixed hinge
		Fixed hinge	

and other factors. In this project, Tower A1 and Tower A2 were quite different in height and stiffness, and with lower stiffness, Connector 1 could not fit the deformations of Tower A1 and Tower A2. In this case, sliding or isolation bearings were reasonable. Based on this, feasible connection schemes between towers are listed in Table 3.

However, if the bearing stiffness of Connector 1 at the end of A2 in X direction was lower, the slip became larger and the requirement for bearing deformation and the width of seismic joint were both strict, so the bearing stiffness should be determined by comprehensive factors.

Connector 2 had three floors to coordinate the deformations of connected towers. However, the connection between Connector 2 and two towers required a certain amount of lateral stiffness or fixed at short side (Y direction) to reduce torsion effects. Besides, Connector 2 was placed on the shear wall at the top of Tower A2 and Tower A3. If movable bearings were used, it was difficult to connect bearings and shear walls. Hence, considering the structural height, plane arrangement and lateral stiffness of Tower A2 and Tower A3 were the same, fixed connection is feasible. It can reduce the complexity of structural system and simplify the structural bearing connection.

Finally, connector 1 was rigidly connected with Tower A1 and elastic connected with Tower A2 in X direction, and glidingly connected in Y direction. Connector 2 was fixed hinged with Tower A2 and Tower A3 in both directions.

4.4. Design of bearings

12 bearings on the roof of Tower A2 are shown in Figure 20. Two main trusses of Connector 1 were put on the eight bearings (1# bearing) on two sides respectively. The eight bearings were designed as bi-directional sliding hinged bearings to bear vertical loads and the other four bearings (2# bearing) in the middle to bear horizontal loads.

1# bearing is bi-directional sliding hinged bearing and 2# bearing was designed as a combined one with a rubber bearing and a unidirectional strip slider, to perform the boundary condition of sliding in Y direction and elasticity in X direction. Both of the bearings were shown in Figure 21. Through calculation, the lead rubber bearings with a diameter of 1100mm were used, and the deformation demand is about 150mm under a rare earthquake. The deformation demand of sliding bearing was about 350mm.

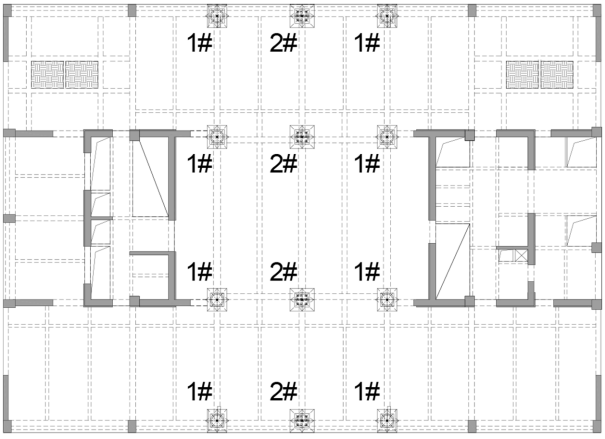


Figure 20. Bearing arrangement of the connector between Tower A1 and Tower A2.

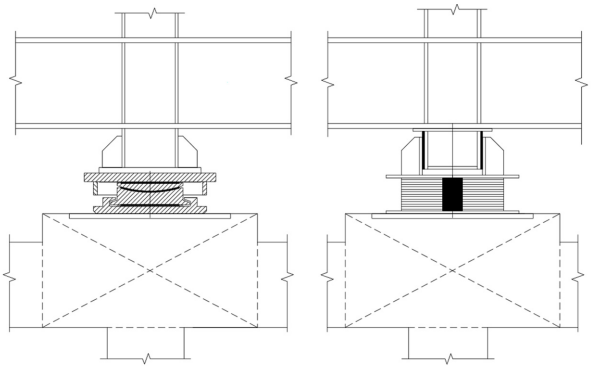


Figure 21. Bearings of the connector between Tower A1 and Tower A2.

Inhibiting devices were respectively set at 200mm in X direction (elastic constraint direction) and 400mm in Y direction (sliding direction).

Ten bearings of Connector 2 were installed at the top of Tower A2 and Tower A3 each (shown in Figure 22), using seismic spherical steel bearings with fixed hinges. Some of the horizontal shear of spherical steel bearings under vertical dead loads could be eliminated by the delayed fixation of bearings. Designed according to the combined internal forces under rare earthquakes, the bearings were guaranteed with sufficient structural safety.

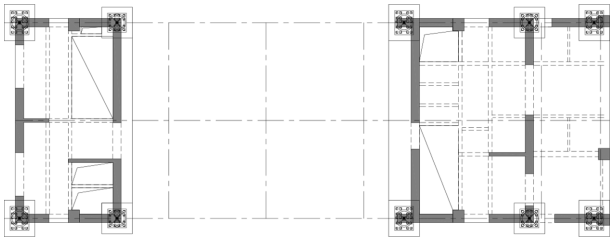


Figure 22. Bearing arrangement of the connector between Tower A2 and Tower A3.

5. Shanghai Shimao Chasm Intercontinental Hotel

5.1. Project overview

Shimao Chasm Hotel is located in a geologic chasm and was constructed along cliff. The main building of the hotel consists of the aboveground part, the underground part and the underwater part. There are two floors above the ground with the height about 10 meters. There are 14 floors from the underground to the water surface with the height of nearly 60 meters. The underwater part is two floors with the height of about 10 meters. The architectural renderings are shown in Fig. 23.

5.2. Structural arrangement

Two storeys above ground is fixed with ±0.000 floor. The main building within the chasm is located on the weakly weathered rock at the bottom with box foundation; meanwhile, the structure is also supported on the pit rock at the top of the quarry through huge steel trusses, obtaining constrains in both vertical and horizontal direction

The main structure adopts the braced steel frame structural system with concrete-filled steel tube column (Wang et al., 2011), as shown in Fig. 24.Concrete filled steel tube and steel structure are used to better adapt to the complex architectural surfaces. In the weaker radial direction, the steel brace hidden in the partition wall is set to reduce stiffness differences between two directions. The top hinged support is used to increase the structural rigidity and constrain horizontal displacement under self-weight.



Figure 23. Architectural rendering of the hotel.

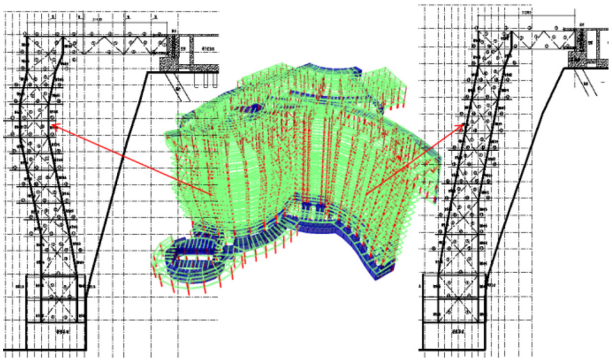


Figure 24. Braced steel frame structural system with concrete-filled steel tube column.

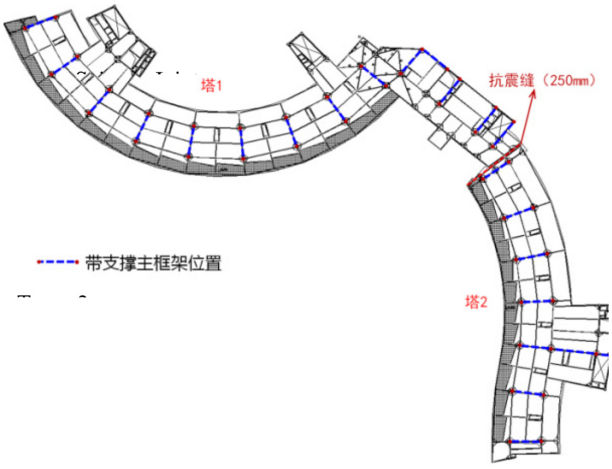


Figure 25. Typical structural plan of the hotel.

The central part of each floor of the building was used for vertical traffic (elevator and staircase), and hotel rooms are arranged on both sides. The typical hotel plan is long and narrow, so the 14 floors from the underground to the water surface are divided into two relatively regular structural units by the anti-seismic joints, as shown in Fig. 25. Therefore, the underground to the water surface part becomes a multi-tower structure, while it is integrated into a whole above the ground.

5.3. Overall structural characteristics of the hotel

The hotel structure has two upper and lower supports, so its structural characteristics are quite different from conventional single point supporting structures. The deformation of the hotel structure under horizontal load is characterized by fixed constraint at one end and fixed hinge support at the other end. The structural characteristics of normal structures are similar to cantilever beams. The deformation characteristics of a cantilever beam model under horizontal load is bending deformation, though the storey drift angle is larger, there is more harmless part in the whole storey drift. While the hotel structure is similar to one end fixed, one end fixed hinge beam model, its deformation characteristics under horizontal load is shear deformation,

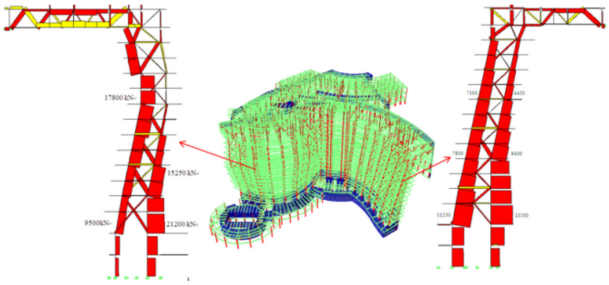


Figure 26. Axial force of the main frame column and brace under gravity load.

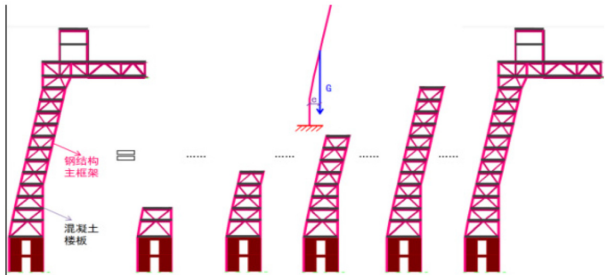


Figure 28. Condition 2: Floor-by-floor construction of the main structure.

and the storey drift is relatively smaller, but there is more harmful part.

The axial force distribution of the main frame column under gravity load is shown in Fig. 26, the red area means compression and the yellow is tension. The axial force transmission characteristic of the main frame column is: the main steel frame with brace is similar to a inclined column, the axial force of frame columns on both sides is quite different. There is tension forces on some members under gravity load because of the inclined shape.

5.4. Study on variation law of internal force of the structural members under different construction sequences

The tower is constrained by the upper and lower supports under normal use state. However, during construction, the upper support does not exist until the main steel frame is installed above the ground. That is to say, before the crossing truss is installed, the curved main frame in the chasm is a cantilever structure, which is quite different from the structure after construction completion. Therefore, study on variation law of internal force of the structural members under different construction sequences is very important.

The one-way inclined main frame in Figure 27 and 28 is taken as an example. Variation law of internal force of some typical members under different construction sequences is studied. The research results show that, compared to structural design condition that structural stiffness is formed and structural load is added simultaneously, internal force of the frame columns at the side leaning against the cliff will be increased and force of columns at another side will be decreased under both construction condition 1 and 2. Considering the gravity load, variation of internal forces of structural column is very large under construction condition 2, the maximum column axial force is increased by 50%, so the construction condition 2 is not accepted by structural designers. To the construction condition 1, the maximum axial force increase under gravity load is 20%, and the total internal force considering gravity load, wind load and earthquake load increases by no more than 13%.

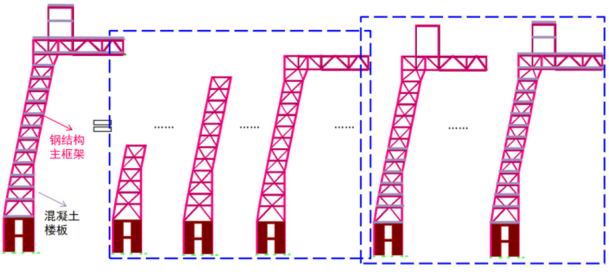


Figure 27. Condition 1: Concrete slabs are constructed after the trusses are finished.

To reduce the influence to the internal force due to the construction sequence, the actual construction sequence is as follows: First 3 floor slabs were constructed initially; and all the other concrete slab can be poured only when the chief trusses and upper support were finished. During structural design, the influence to the structural members due to the actual construction sequence is taken into consideration through fine construction simulation analysis. Moreover, different technical method such as deformation compensation and on-site monitoring technology are adopted to effectively reduce the construction influence to the structural members.

6. Conclusions

Antony Wood, executive director of CTBUH, pointed out that the shortcomings of high-rise buildings focused on the fact that they were designed as stand-alone icons. Even though owning remarkable gravitational elevation, they were not unable to “connect to each other at any level other than the ground plane”.

Connected supertall buildings extend the connections among structures from the ground to the upper air, significantly expanding the space and efficiency of cities. The development of connected supertall buildings is still ascendant, when there is architectural scheme of the building up to 700 meters (shown in Fig. 29), and more intensive researches of related topics are needed. Connected supertall buildings, although triggering enormous challenges for structural design, are entitled with advantages where single-tower buildings are incomparable in either architectural or structural aspect.

Some conclusions of the three supertall connected structures here may provide references to researches and designing



Figure 29. Scheme for connected supertall building.

works in this area. But in realistic projects, comprehensive analysis should be carried out according to characteristics of each project to foster advantages and circumvent disadvantages, making the connected structures exhibit the superiority that "one plus one is better than two".

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