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Research on Key Construction Techniques for Giant and Complex Suspension Steel Structures

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Abstract The structural form of a project in Shenzhen, Guangdong Province, China adopts a "frame support structure with hanging frame", consisting of two towers. Each tower is composed of a steel core tube and six asymmetric staggered giant hanging steel structure outer frames. For different installation sequences, finite element analysis software is used to simulate and analyze the entire construction process and calculate deformation. Based on the software calculation results, the reverse pre-deviation of the steel structure core tube and the pre-lifting of the suspended outer frame steel structure are achieved to control the deformation of tower construction. Meanwhile, based on comparative analysis of construction simulation calculations, the optimal support unloading scheme is selected to achieve overall deformation control of the structure. After the completion of the project, the deformation values of the structure and key components before and after unloading were basically consistent with theoretical calculations through total station retesting.

Keywords Suspension structure, Construction simulation, Pre-deformation, Uninstall, Deformation control

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1. Project Overview

1.1. Project Introduction

A project in Shenzhen, Guangdong Province, China is a super high-rise twin tower with a full steel structure. The tower structures are heights of 193.1m with 44 floors and 211.6m with 47 floors respectively. The total amount of steel used in the project's steel structure is about 55000 tons, of which 23000 tons are used for the outer frame. There are six hanging frames arranged asymmetrically on the east, west, and south sides of the core tubes of the two towers, with two hanging frames on each side above and below, as shown in Figure 1.

The structural form and outer frame layout of the two towers are basically similar. This article takes the West Tower as an example to explain. The core tube size of the West Tower is 25.35 m × 34.40 m, and the hanging outer frame dimensions of South Hanging Wing1is 31.75 m × 18.05 m, West Hanging Wing2 is 31.75 m × 15.75 m, and East Hanging Wing3 is 21.25 m × 18.1m, as shown in Figure 2. The starting floor height of each side of the overhanging wing varies, with the starting floors of the lower overhanging wing being 6F, 7F, and 9F respectively, and the starting floors of the upper overhanging wing being 20F, 22F, and 27F respectively. The asymmetric arrangement of the giant suspension outer frame will cause a certain torsional effect on the core tube. Therefore, deformation control and early pre-processing during the construction process are particularly important for the accuracy of tower installation.

1.2. Introduction to Construction Plan

Taking into account the overall construction period and cost investment of the project, the installation of the main structure of the tower adopts a phased handover of the working face to organize on-site construction. The tower support measures are composed of bottom frame support, middle support column, and upper temporary truss layer from bottom to top, as shown in Figure 3.

The construction steps for the main steel structure of the tower are as follows:

1) Construction of core tube steel structures on floors L1 to L10.

2) Insert bottom support measures, include bottom distribution truss, bottom support tire frame for construction. As shown in Figure 4.

3) Synchronous construction of the lower wing and core cylinder. As shown in Figure 5.

4) Middle support installation.

5) Temporary truss layer installation. As shown in Figure 6.

6) After the installation of the temporary truss layer is completed, first remove the middle support column, and then remove the bottom support measures. As shown in



Fig. 1. Tower rendering.

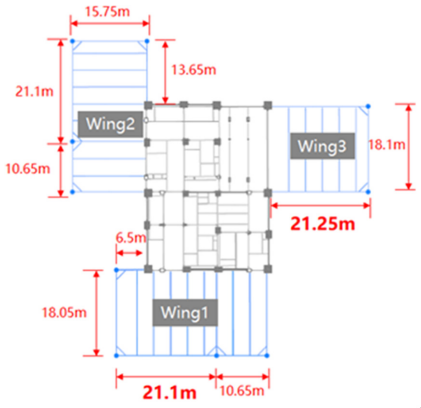


Fig. 2. The tower plan.

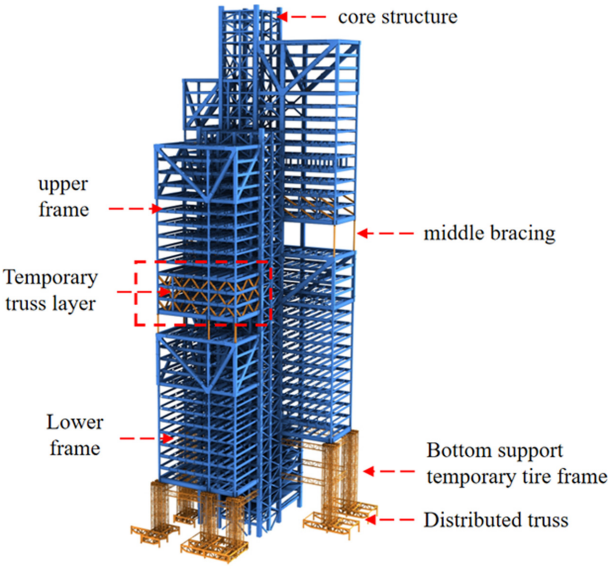


Fig. 3. Support arrangement plan.

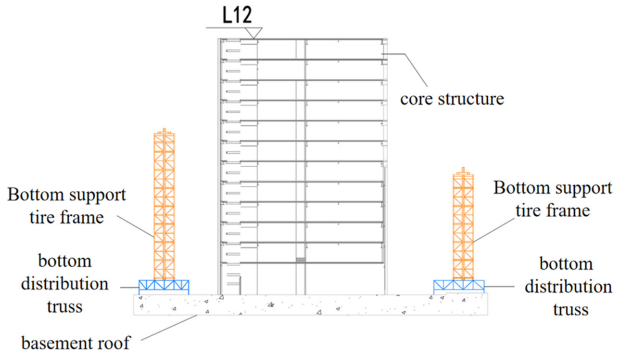


Fig. 4. Construction procedure②.

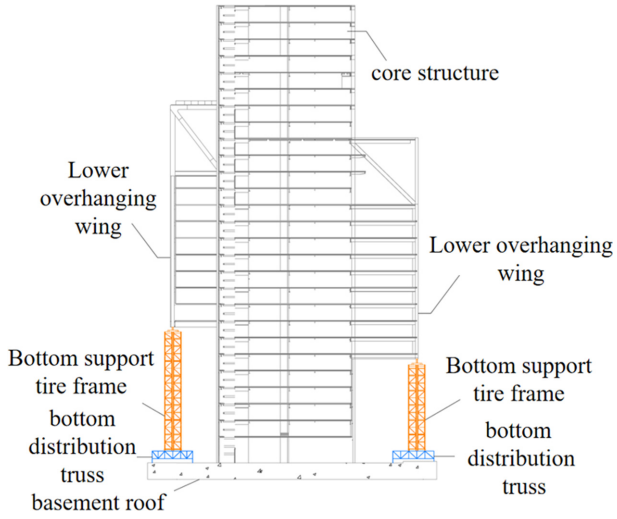


Fig. 5. Construction procedure③.

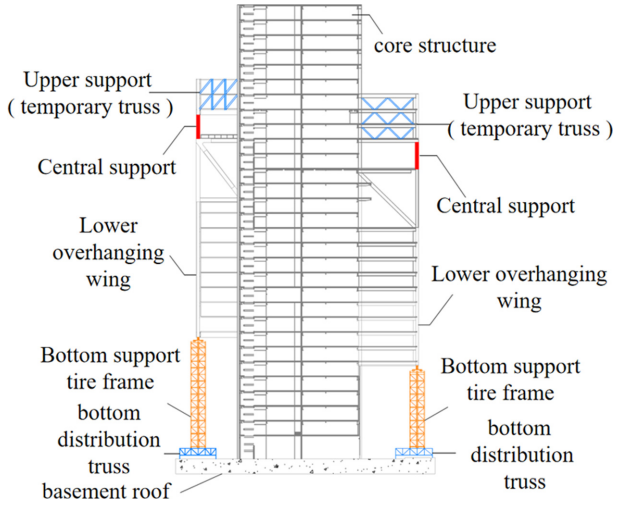


Fig. 6. Construction procedure⑤.

Figure 7. After the completion of this stage of construction, the lower suspension wing can be handed over to other units for construction, and the steel structure of the upper suspension wing can be synchronously organized for construction, shortening the overall project duration.

7) Using temporary truss layers as vertical support platforms to support the construction of suspended wings. As shown in Figure 8.

8) After the construction of the upper suspension wing is completed, the temporary truss layer measures will be removed. Complete the installation of the main steel

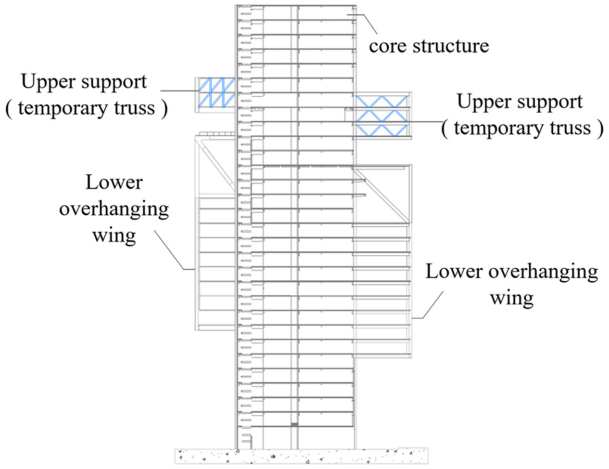


Fig. 7. Construction procedure⑥.

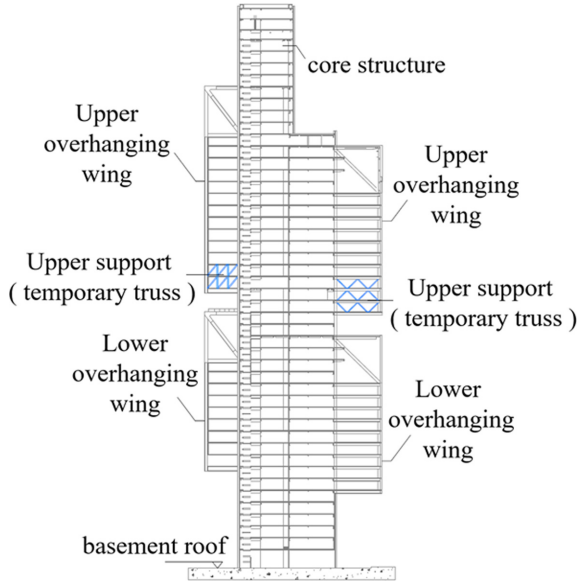


Fig. 8. Construction procedure⑦.

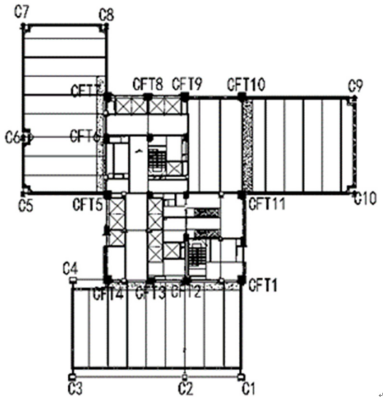


Fig. 9. Serial number diagram of davit and internal frame column of core tube.

structure of the tower.

Based on the construction plan of this project and the characteristics of the tower structure, the key points for deformation control during the construction process of the main steel structure of the tower include the following three points.

1) The core tube is pre-biased in the horizontal direction. Under the full load of construction simulation, the asymmetric arrangement of the giant outer frame has an impact on the core tube, and the installation and positioning of the core tube should be pre-biased in advance.

2) Suspend the outer frame and columns for pre-lifting. Under the action of gravity, the hinge joint between the steel beam and the core tube steel column will generate a rotation angle. It is necessary to pre-lift the outer frame circular pipe suspension column C1-C10 in advance (as shown in Figure 9), and under the final load, the outer frame steel beam will return to the horizontal.

3) Comparison of unloading sequences for supporting measures. By comparing and analyzing the construction simulation, select the unloading sequence that has the least impact on the deformation of the core structure steel column.

2. Calculation of Construction Deformation

2.1. Load Selection

Considering the on-site construction situation of this project, the calculated load values for tower construction deformation are as follows:

1) The self weight load of tower steel structure and concrete floor slab is automatically considered by the software. The concrete load and floor bearing plate load of tower are added to the steel beams according to the line load.

2) The first floor considers the driving load and construction stacking load.

3) The live load value for steel structure floor construction is 1.5 kN/m^2.

4) The wind load on the tire frame is calculated as $w_k = \mu_s\mu_z w_0$, w_0 is the wind pressure of 0.75 kN/m^2 with 50 year return period, and the shape coefficient μ_s is 2.7, height variation coefficient μ_z is 1.52.

5) During the construction process of the tower steel structure, curtain wall construction is not carried out, and the wind load has little impact on the main steel structure.

2.2. Load combinations

1) Load combination conditions for deformation calculation: 1.0D (constant load)+0.5L (live load during normal use).

2) The load combination conditions for calculating the bearing capacity of temporary measure components are: 1.2D (dead load)+1.0L (live load)+1.4w_k (wind load).

2.3. Analysis of calculation results

According to the construction steps of the tower, the upper structure construction simulation analysis under

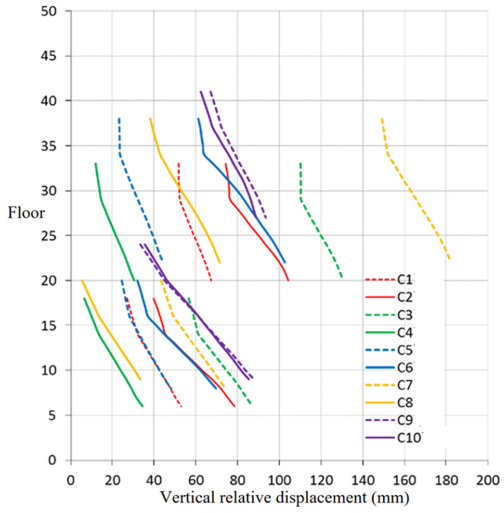


Fig. 10 Vertical relative displacement of davit floor joints.

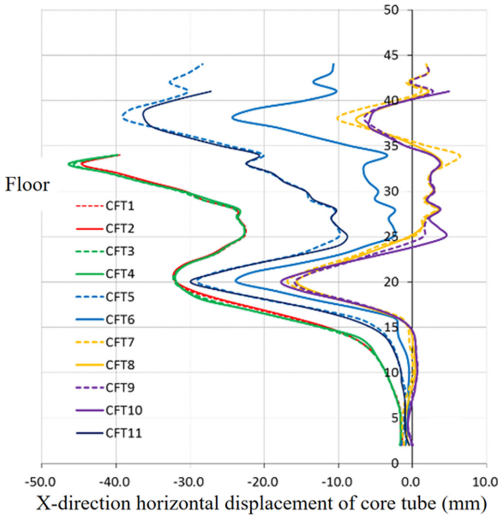


Fig. 12. Horizontal X - direction displacement of floor steel tubular columns.

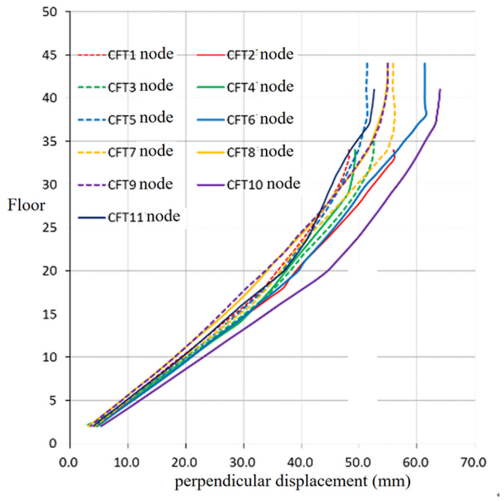


Fig. 11. Vertical displacement of floor joints of steel tubular columns

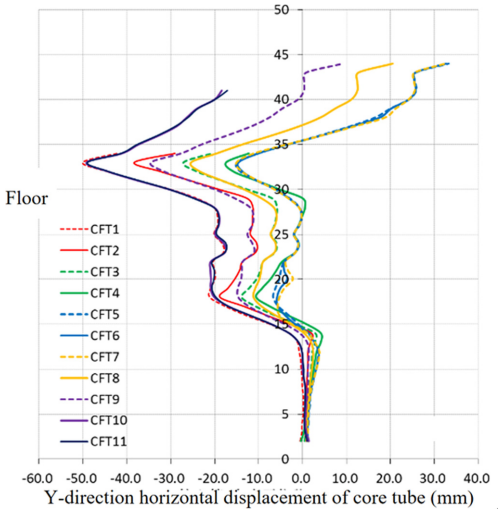


Fig. 13. Horizontal Y displacement of floor steel tubular columns.

full load is considered. The finite element construction simulation analysis results are shown in the following figure (Figure 10~13).

Based on the simulation analysis results, the following conclusions are formed:

1) During the construction phase of the outer frame steel structure of the West Tower, the vertical displacement of the suspension columns C7 and C8 was the highest at the 22nd floor, with maximum vertical displacements of 182.3 mm and 71.5 mm respectively. The vertical displacement of the core tube steel column CFT7 at the 22nd floor was 38.5mm. The deflection of suspension column C7 relative to suspension column C8 is 1/142 (span 15.75 m), and the deflection relative to the adjacent core tube steel column CFT7 is 1/145, the span is 20.85m, considering the straight-line distance from the nearest core tube steel column CFT7.

2) The maximum vertical displacement of the square steel tube concrete column inside the core tube is 64.0 mm. The maximum horizontal displacement in the X direction is 46.4 mm, and in the Y direction is 50.1 mm.

Based on the above calculation results, the on-site construction adopts the method of horizontal pre-deviation of the core tube steel column and vertical pre-lifting of the hanging outer frame suspension column to eliminate the adverse deformation of the structure itself in advance during the main structure construction stage. At the same time, the unloading sequence with the least impact on the tower structure deformation is selected to organize the on-site construction.

3. Construction Techniques for Pre Deformation of Structures

At present, the majority of super high-rise tower structures in China are concrete core tube with steel frame structures, with only a small number of pure steel super high-rise buildings. In addition to being an all steel structure above ground, this project also has the following characteristics:

1) The overall layout of the outer frame is completely asymmetrical, and the three overhanging wings have varying masses. The hanging wing area of the outer frame is 1.66 times the area of the core tube.

2) The outer frame facade is arranged in a staggered manner, especially the continuous staggered arrangement of the upper and lower three hanging truss layers of the outer frame;

3) The center of gravity and stiffness of the tower are unevenly distributed, resulting in a twisting effect. After construction simulation analysis, considering the load of steel structure and concrete floor slab, the maximum horizontal displacement of the core tube of the West Tower reaches 36 mm.

3.1. Horizontal pre-deviation construction of core cylinder steel columns

Based on the construction simulation analysis under full load (decoration and renovation stage), considering the influence of the outer frame on the horizontal deformation of the core tube, the steel columns of the core tube were pre-biased horizontally in advance during the construction process. The specific pre-deflection values are detailed in Table 1.

The horizontal deformation of the core tube is mainly caused by a sudden change in the range of the upper and lower suspension wing truss layers of the outer frame, so the steel columns of the core tube need to undergo reverse deformation in the area of the outer frame suspension wing truss. During the on-site steel column installation and correction stage, pre-deviation is required. After the overall structural construction is completed, the core cylinder of the tower is restored to its vertical state.

Compared to traditional steel structure super high-rise buildings, the simulation results of the entire construction process of external asymmetric hanging structures before construction are particularly important for on-site construction guidance in the later stage.

3.2. Vertical Pre-lifting Construction of Suspended Outer Frame and Suspension Column

The connection between the non-truss floor and the core tube of the tower's hanging outer frame are all pin connections with high-strength bolts. Only the main load-bearing members such as upper and lower chords and slant support of the truss floor and the core tube steel columns are welded in full section. In addition, the varying quality, height, and asymmetrical layout of each outer frame pose extremely high requirements for deformation control during the construction process of tower structures. After each suspended outer frame is rigidly connected to the core tube through the top truss layer, the lower non truss layer is “pulled” by the suspension column.

Therefore, under the action of gravity, the non-truss layer of the large-span suspension outer frame will have a certain degree of deflection relative to the same floor of the core tube. Considering the vertical compression deformation of the core tube, combined with the construction method of pre-deviation in the horizontal direction of the core tube, the calculation assumes that the construction simulation analysis is carried out under the condition of constraining the horizontal lateral displacement of the core tube and considering the effects of concrete floor slabs and decoration loads. The vertical relative displacement of the hanging outer frame suspension column

Table 1. The lower suspension wing of the west tower corresponds to the horizontal pre-deviation of the steel column installation of the core cylinder (mm)

Floor	Structure elevation Hs (m)	storey height (m)	Horizontal pre-bias value	
			X (The east is positive)	Y (The north is positive)
24	105.35	4.5	8	0
23	100.85	4.5	10	0
22	96.35	4.5	12	0
21	91.85	4.5	14	0
20	87.35	4.5	16	0
19	82.85	4.5	13	0
18	78.35	4.5	10	11
17	73.85	4.5	7	10
16	69.35	4.5	4	7
15	64.85	4.5	2	4
14	60.35	4.5	1	1

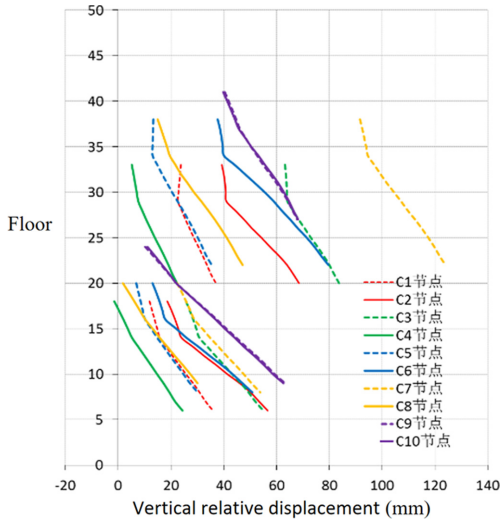


Fig. 14. Vertical relative displacement (mm) of hanging column of west tower.

(relative to the nearest core tube steel column on the same floor) is shown in Figure 14.

After pouring the floor slab, the maximum relative displacement of the outer frame circular pipe suspension column C7 is 124 mm, corresponding to a deflection of 1/168 (span 20.85 m), and a rotation angle of 0.34 degrees relative to the core cylinder steel column. During the construction process, it is necessary to carry out the reverse pre-lifting of the outer frame circular pipe suspension column in advance. During the installation and correction stage of the circular pipe suspension column, the pre-adjustment is carried out by increasing the installation elevation of the suspension column. The actual pre-lifting value on site is up to 127 mm.

After the construction of the lower suspended wing steel structure is completed, the concrete pouring will be completed after the unloading of the bottom support measures. The settlement deformation of the lower suspended wing is close to the simulated calculation value.

Therefore, for the construction of giant suspended steel structure towers, based on the results of construction simulation analysis, the external frame tension suspension columns should be pre-lifted in advance during steel structure installation to control the vertical deformation of the tower's outer frame and ensure that the stress state after tower construction is consistent with the design stress state.

3.3. Comparison of Support Measures Unloading Sequence

3.3.1. Construction simulation calculation

There are three giant asymmetric hanging frames in the tower, and different unloading sequences have varying effects on structural deformation. Therefore, when determining the unloading sequence of bottom support, middle support, and temporary truss layer, construction simulation calculations should be carried out for each unloading sequence, and the unloading sequence with the smallest unloading deformation should be selected. Taking the bottom support unloading method as an example, the initial internal force and deformation conditions for controlling different unloading sequences are the same. Construction simulation analysis is conducted on three suspended outer frames with different unloading sequences, and the X and Y displacement envelope lines of CFT columns (steel tube concrete columns) with different unloading sequences are obtained. As shown in figure 15~16.

Based on the displacement envelope of CFT columns in the X and Y directions, the following conclusions can be drawn.

1) The sequence of dismantling temporary trusses W1-W3-W2 overlaps with the minimum envelope horizontal displacement in the X-direction of W3-W1-W2, and the sequence of dismantling temporary trusses W2-W1-W3 overlaps with the minimum envelope horizontal displace-

Table 2. Vertical pre-lift value of the hanging column of the outer frame of west tower (mm)

Suspended wing area	Suspension column number	Advanced raising value	
		First layer of upper overhanging wing	First floor of lower overhanging wing
Wing1	C1	25	22
	C2	41	38
	C3	59	86
	C4	60	70
Wing2	C5	35	48
	C6	40	45
	C7	55	127
	C8	50	81
Wing3	C9	68	70
	C10	68	70

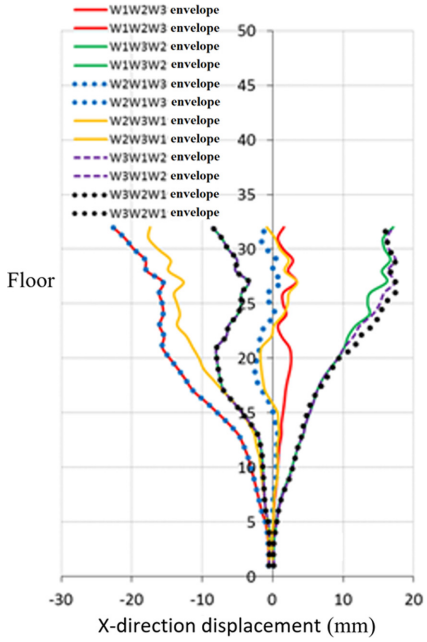


Fig. 15. X displacement of CFT column.

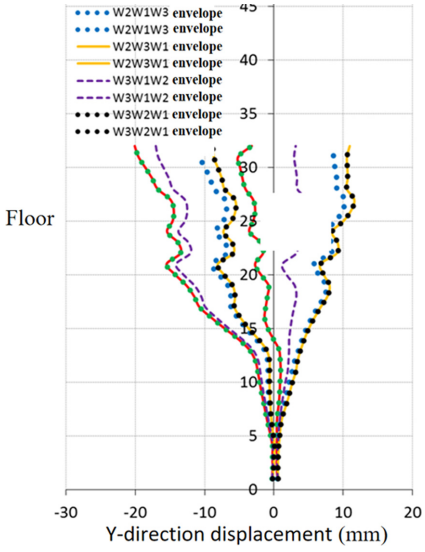


Fig. 16. Y displacement of CFT column.

ment in the X-direction of W2-W3-W1. This indicates that when the W2 cantilever wing is first or last dismantled, the dismantling sequence of W1 cantilever wing and W3 cantilever wing has little effect on the minimum envelope displacement in the X-direction.

2) The sequence of dismantling temporary trusses W1-W2-W3 overlaps with the maximum envelope horizontal displacement in the X-direction of W2-W1-W3, and the sequence of dismantling temporary trusses W3-W1-W2 overlaps with the maximum envelope horizontal displacement in the X-direction of W3-W2-W1. This indicates that when the W3 cantilever wing is dismantled first or last, the dismantling sequence of W1 cantilever wing and W2 cantilever wing has little effect on the maximum envelope displacement in the X-direction.

3) The minimum horizontal displacement in the Y direction of the temporary truss dismantling sequence W2-W3-W1 and W3-W2-W1 overlaps, indicating that when the W1 cantilever wing is finally dismantled, the dismantling sequence of W1 cantilever wing and W2 cantilever wing has little effect on the minimum displacement in the Y direction.

3.3.2. Comparison between actual displacement and construction simulation

The unloading displacement and deformation values during the unloading process of each point in the

Table 3. Maximum horizontal displacement of core tube (mm)

removal sequence	Max displacement (mm)		Min displacement (mm)		Max displacement of absolute value (mm)	
	X	Y	X	Y	X	Y
W1-W2-W3	3.4	1.0	-22.7	-20.1	22.7	20.1
W1-W3-W2	17.1	1.0	-8.6	-20.1	17.1	20.1
W2-W1-W3	1.2	10.2	-22.7	-11.1	22.7	11.1
W2-W3-W1	3.5	11.6	-17.6	-8.8	17.6	11.6
W3-W1-W2	17.4	4.7	-8.6	-17.0	17.4	17.0
W3-W2-W1	17.4	11.6	-8.6	-8.8	17.4	11.6

Table 4. Bottom support deformation of lower suspension before and after unloading(mm)

position	Calculate the settlement value	Initial unloading is completed	Uninstall completed 1 day	Uninstall completed 1 week	2 months after completion
C1	15.1	11	10	15	13
C2	23.5	18	17	21	20
C3	29.6	22	23	25	26
C4	11.0	5	8	9	10

construction simulation calculation of outer frame W1 are shown in the table below:

By monitoring the deformation of the bottom support of the suspended outer frame after unloading the bottom support, it was found that there was an difference between the theoretical calculation value and the on-site construction deformation monitoring, but the value was relatively small. Preliminary analysis shows that the reasons for the error are as follows.

1) There is an deviation in total station measurement, with an instrument deviation about 2 mm.

2) The vertical displacement of nodes caused by temperature changes varies greatly. When the structure is uniformly heated or cooled, the relative displacement of the suspension column nodes does not change much. When the structure is non-uniformly heated or cooled, the displacement of the suspension column nodes changes significantly.

The bottom support is unloaded in the order of W3-W2-W1, and the monitoring results show that the unloading deformation value of the bottom support measures is basically consistent with the construction simulation calculation value.

4. Conclusion

The successful unloading of the lower suspension wing of this project fully proves that the construction deformation control of the giant asymmetric suspension steel structure tower needs to fully utilize the data of construction simulation calculations. At the same time, it is very important that according to the structural characteristics of the tower, the core tube steel columns are horizontally pre-deviated during the construction stage, and the hanging outer frame suspension columns are vertically pre -lifted. By simulating construction and selecting the unloading sequence of supports with smaller deformation, a good deformation control effect can be achieved, providing reference for the construction of other similar suspension system super high-rise structures.

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