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Construction Mechanical Analysis and Techniques of Ultra-high Large-size Möbius Ring Structure

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Abstract The Xi'an Silk Road Tower is a special-shaped steel tower, which stands approximately 140 meters high. Given its small diameter, the tower was divided into several segments, which were assembled on the ground, and then lifted using a heavy-duty tower crane attached. Based on the design codes and standards of the tower crane, safety assessment principles were proposed for the attachment of the heavy-duty tower crane to ultra-high slender structures, which was verified safe, feasible and easy to operate in practice. Additionally, a prefabricated inner support was designed for the installation of a large-scale Möbius ring. The designed inner support structure offered superior operating convenience and construction safety. Furthermore, an ICP algorithm for UAV scanning data correction was developed to measure the shape and position of the assembled structure at up to hundred meters high, and the scanning accuracy was significantly improved after correction.

Keywords Steel tower, Construction mechanical analysis, Möbius ring, Crane attachment, UAV scanning

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1. Introduction

The Xi'an Silk Road Tower is located at Xi'an, Shanxi Province, China, which is the landmark building of the Silk Road Paradise. The top elevation is 139.21 m with a very recognizable shape, as shown in Figure 1, rendering it extremely difficult to be constructed.

The project team conducted comprehensive investigations on special-shaped steel towers to solve the technical difficulties during construction. Ultimately, a thorough set of construction techniques obtained from existing engineering was proposed to solve the challenges, such as the narrow space limitation, difficulties of the large-scale Möbius ring and inner temporary support construction, and the high requirements for segment jointing, which provided valuable references for similar engineering practices.



Figure 1. Architectural scene.

2. Structural profile

The Xi'an Silk Tower is a special-shaped steel tower, which is comprised of an inner cylindrical frame, an outer cylindrical shell, an overhanging wheel-shaped skirt truss, a Möbius ring at the top, and an outer silk truss, as illustrated in Figure 2. Q355B material is used for the main structural system. The steel tower uses the core-in-core structural system containing the inner cylindrical frame, the outer cylindrical shell, and the link between to withstand horizontal actions.

2.1. Inner cylindrical frame

Diameter of the inner cylindrical frame is 7.3 m, and the top elevation is 104.08 m. There are ten columns, several beams, and bracings in the inner frame, as shown in Figure 3. The cross-section of the beam is H-shaped steel, while the others are pipe-shaped. Steel links are arranged at 25 m, 50 m, 70 m, and 93 m high to connect the inner and outer cylindrical steel structure.

2.2. Outer cylindrical shell structure

Top elevation of the outer shell is 94.781 m, which is a bi-directional rhombic crossing lattice. There are 20

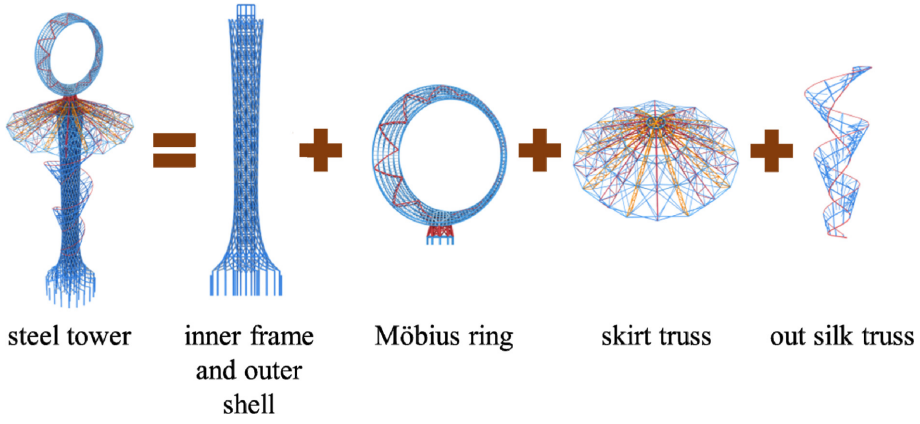


Figure 2. Breakdown diagram of the steel tower.

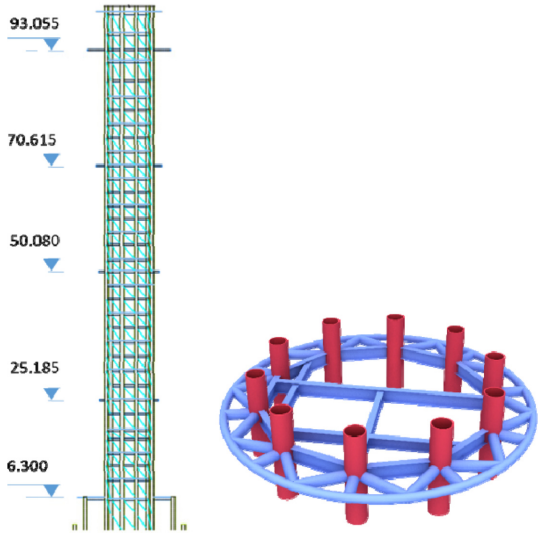


Figure 3. Inner tube illustration.

primary and 20 secondary members respectively, and the cross-section ranges from P325x36 to P600 × 30. All the members are spatial curved pipes. Diameter of the outer cylindrical shell measures 17.362 m at its base, and gradually narrows as it rises. At a height of 30.785 m, the diameter reaches its narrowest point of 9.12 m, and from this point upward, the diameter gradually increases, reaching 13.25 m at the top of the outer cylinder ultimately.

2.3. Möbius ring structure

Top elevation of the Möbius ring is 139.210 m, and consists of six ring plane trusses and diagonal trusses, as illustrated in Figure 5. Width of the ring varies from 4.8 m to 7.5 m, and has a diameter of 37 m approximately. Spacing between plane truss is 0.9 to 1.5 m, and the plane truss measures 1.0 meter high. Cross-section of all the members are pipes, while the maximum chord member is P500 × 25, and the maximum web member is P159 × 10. The main members are all spatial bi-directional curved pipes, and the entire ring is connected to the inner cylindrical frame through the cast steel support at the top.

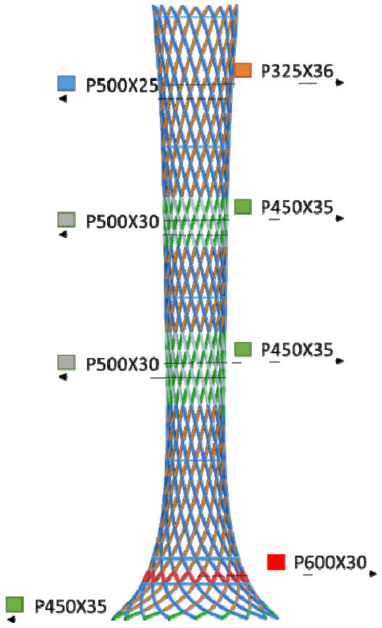


Figure 4. Elevation view of the outer cylindrical shell.

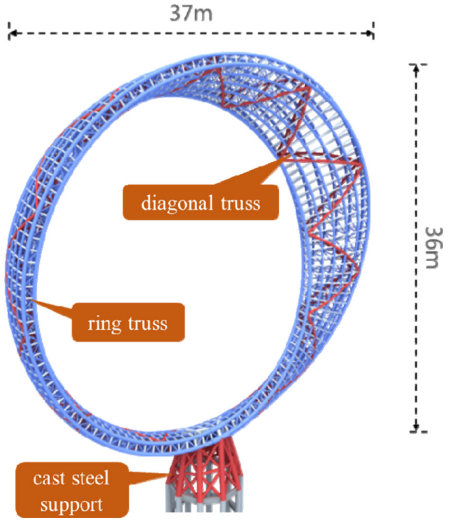


Figure 5. Axonometric drawing of the Möbius ring structure.

3. Technological difficulties and construction conditions

3.1. Narrow space limitation

Since the tower located at the core area of the amusement center, which was surrounded by already constructed buildings, thus rendering very limited space available for construction. Additionally, large members were also not able to be delivered due to the surrounding traffic conditions. Therefore, the steel tower was divided into several segments to be assembled on the ground first, and then lifted by a heavy-duty tower crane to be jointed at high altitude.

3.2. Flexible tower attached by heavy-duty crane, which requires special analysis

Though the tower is a core-in-core structure, the height of the tower without ring reaches 104 m, while the minimum diameter is only 9.12 m, resulting in a relatively large aspect ratio. The horizontal stiffness is relatively small, thus the steel tower is too flexible to control the deformation under horizontal loads.

In this project, a ZSL750-50T heavy-duty tower crane was used for hoisting, and three additional arms were attached to the steel tower to fix the crane firmly. However, there were no design codes or standards available for reference regarding the construction safety of attaching heavy-duty tower crane to flexible tower.

3.3. Difficult construction

Given the dimensions of the Möbius ring, skirt truss and the silk truss, tower crane was used combined with the trunk crane to assemble every individual segment of the tower on the ground. The overall installation procedure was as follows: (1) inner cylindrical frame hoisting, (2) outer cylindrical shell hoisting (combined with the installation of the inner cylindrical frame), (3) Möbius ring hoisting, (4) skirt truss hoisting, and (5) silk truss hoisting.

Especially, except the base cast steel support, there were no other supports to prop up the Möbius ring. Furthermore, the position of Möbius ring is too high to be propped up by temporary supports erected from ground.



Figure 6. Aerial view of the scene.

4. Construction mechanical analysis and safety assessment principles of the heavy-duty tower attached to ultra-high flexible steel tower

4.1. Load condition of tower crane attachment

A ZSL750-50T tower crane was erected adjacent to the steel tower, as shown in Figure 7 and Figure 8. The tower crane was connected to the outer cylindrical shell by three arms, which located at elevation heights of 35.3 m, 65.3 m, and 95.3 m, respectively.

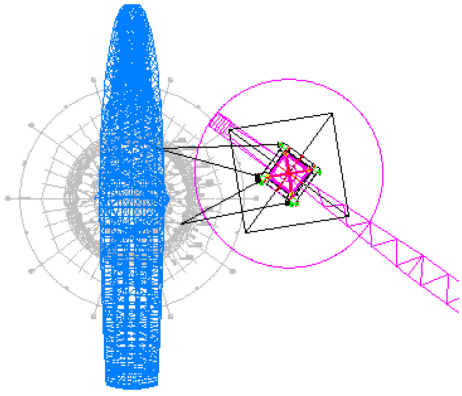


Figure 7. Layout of the tower crane.



Figure 8. Attachment of the tower crane

4.2. Safety assessment principles of the heavy-duty tower attached to ultra-high flexible steel tower

Tower cranes generally attach to structures with high horizontal stiffness, such as frame wall structures, steel frames or braced frames with large plan size. Nevertheless, there are no design codes or standards available for references regarding the construction safety of attaching a heavy-duty tower crane to a flexible steel tower.

Current Chinese codes and standards about tower cranes give the following requirements:

(1) According to the tower crane code (GB/T 5031-2019), when attached to the primary structure and at the design elevation height, horizontal displacement at the attached point and below should not exceed $2h/1000$, where h is the height at the attached point.

(2) According to the tower crane code (GB/T 5031-2019) and (GB/T 13752-2017), horizontal displacement at the top of the tower crane should not exceed 1.34% of H, where H is the height of the cantilever part of the tower crane.

However, the above requirements are only used to control the deformation of the tower crane, rather than the steel tower. To assess the feasibility of attaching a heavy-duty tower crane to a flexible steel tower, according to relevant regulations of tower cranes, the following safety assessment principles were presented:

(1) Under the most unfavorable load condition during construction, horizontal deformation sum of the highest tower crane attached point and the installation error of the steel tower, should not exceed 0.2% of h, where h is the height at attached point.

(2) Under the most unfavorable load condition during construction, horizontal deformation at the top of the tower crane should not exceed 1.34% of the cantilever part height.

(3) Members of the primary structure should meet the safety requirements under the loads from tower crane attachment.

4.3. Mechanical analysis of the flexible tower and the attached tower crane

In this section, the steel tower and the tower crane were modeled in total during construction. The following two load cases were considered:

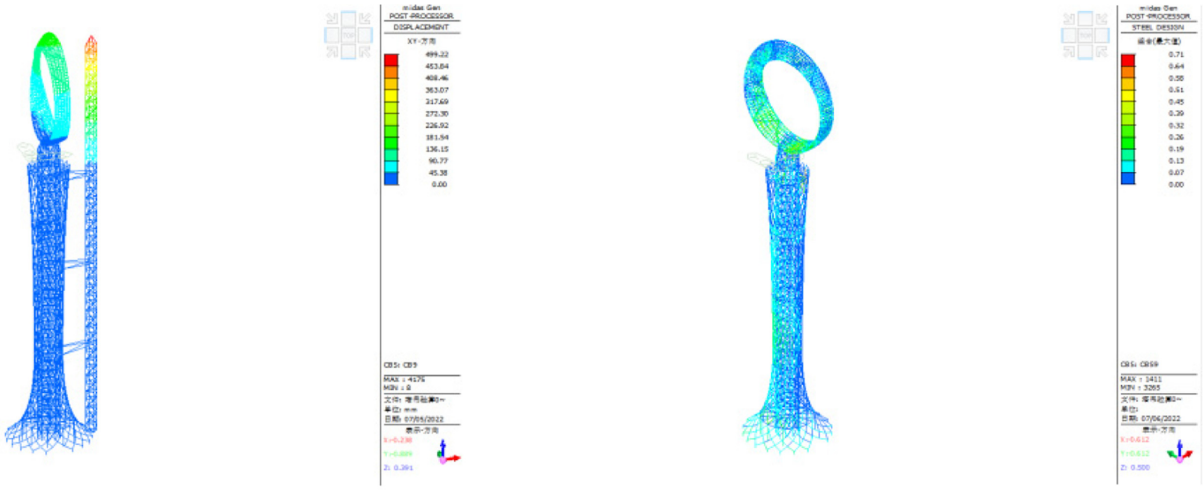
(1) Load case 1: full load of the tower crane, and the wind load considered reached grade 5 of the Beaufort scale. Direction of the wind load was the same as the horizontal force acted on the steel tower from the tower crane.

(2) Load case 2: empty load of the tower crane, and the wind load considered reached grade 9 of the Beaufort scale.

Figure 9 and Figure 10 illustrate the results of load case 1 and load case 2 respectively. As shown in Figure 9 (a) and Figure 10 (a), horizontal displacements at the top of the tower crane in load case 1 and load case 2 were 499.0 mm and 439.0 mm, respectively. Given the installation error was about 50.0 mm, therefore the total displacements at the top of the tower crane were 549.0 mm and 489.0 mm, while the deformation limit is 558.78 mm, as presented in Equation (1), that the horizontal deformation at the top of tower crane met the design requirements.

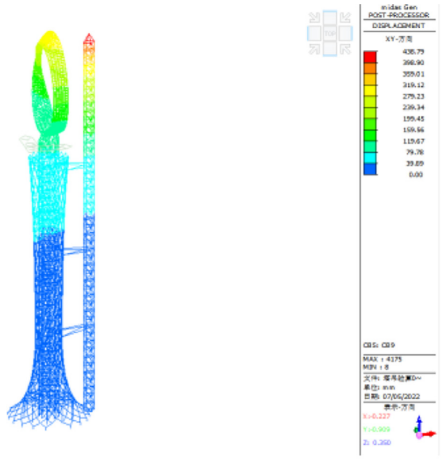
$$\Delta_1 = \frac{1.34H}{100} = \frac{1.34\times 41700}{100} = 558.78\text{mm} \tag{1}$$

Horizontal displacements at the highest attached point in load case 1 and load case 2 were 37.4 mm and 76.8 mm, respectively. Given the installation error was about 50.0 mm, the total horizontal displacements were 87.4 mm and 126.8 mm, while the deformation limit is 192.60 mm, as shown in Equation (2), that the horizontal deformation at

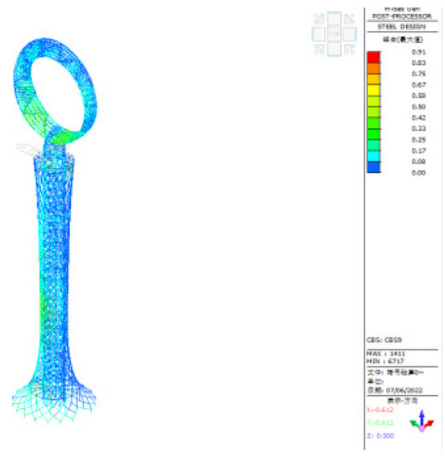


(a) Horizontal displacement (mm) **(b) Stress ratio**

Figure 9. Results of load case 1.



(a) Horizontal displacement (mm)



(b) Stress ratio

Figure 10. Results of load case 2.

the highest attached point also met the design requirements.

$$\Delta_2 = \frac{2h}{1000} = \frac{2\times 96300}{1000} = 192.60\text{mm} \quad (2)$$

Figure 9 (b) and Figure 10 (b) show the stress ratios of the two load cases, which were 0.71 and 0.91, respectively. In both load cases the stress ratios were less than 1, indicating the bearing capacity all met the design requirements.

4.4. Bearing capacity verification and strengthening of the attached point

The bearing capacity of the steel tower met the design requirements, but stress ratio of the members adjacent to the attached point still exceeded the stress ratio limit, and the out-of-plane deformation was also relatively large. To this end, additional pipe members were installed at the attached point to strengthen the connection between the inner cylindrical frame and the outer cylindrical shell. There were four reinforcing members added at each attached point to improve the bearing capacity and lateral stiffness of this joint, as shown in Figure 11.

Benefitting from the comprehensive analysis above and the on-site measurements of the tower crane during construction, the heavy-duty tower crane performed well under the aforementioned safety assessment principles.

5. Construction of the Möbius ring

5.1. Overview of the construction techniques

Total weight of the Möbius ring is about 250 ton, and was divided into eight segments, as illustrated in Figure 12. The maximum weight of individual segment is 38 ton, which was assembled on the ground and then lifted by the tower crane to hundred meters height for jointing.

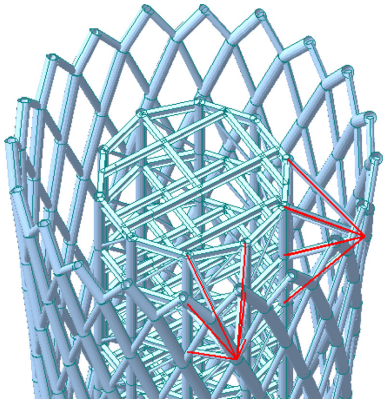


Figure 11. Schematic diagram of strengthening the position of the tower crane's attached arms.

During the hoisting process of the segments, temporary supports must be introduced. However, challenge was that the skirt truss below had not been assembled yet, thus the vertical distance from Möbius ring to ground exceeded 100 meters, rendering it unfeasible to erect supports from ground. Thus, a temporary inner support was designed, which was comprised of lattice frames and temporary links between lattice frames and ring segments. During construction, the base of the ring was assembled first, and the other segments were lifted to design position on both sides, to reduce the non-uniform deformation during construction process.

5.2. Design of the inner support structure

The Möbius ring was divided into eight segments. Two segments were comprised of three plane trusses and the links between, and the other six segments were comprised of six plane trusses and the links between, as shown in Figure 13.

The inner support structure was comprised of lattice steel frames and the link members, and the following key

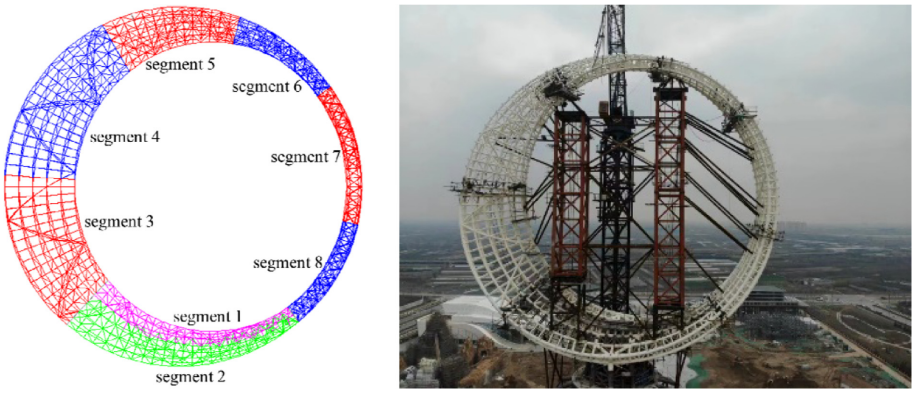


Figure 12. Construction scene and segment illustration of the Möbius ring.

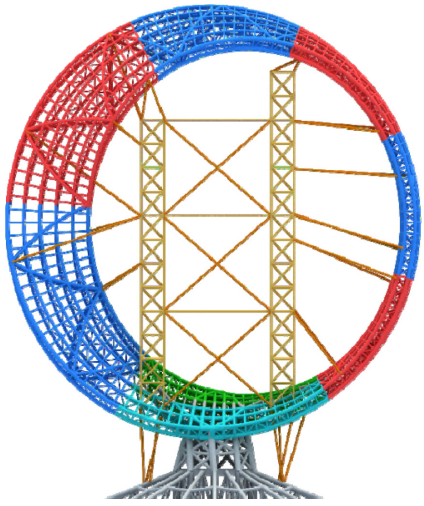


Figure 13. Schematic diagram of Möbius strip segments and temporary supports.

points should be considered during design process:

(1) The Möbius ring was relatively high, thus the inner support structure (lattice frames and link members) should be easy to assemble and dismantle.

(2) The in-plane stiffness of the inner support structure should be large enough to control the deformation of the Möbius ring segments during hoisting.

(3) The lattice steel frames were the primary horizontal resisting structural system, therefore it was necessary to appropriately increase the wall thickness of the frame members, and check whether the local bearing capacity at connections met the design requirements.

Prefabricated design concept was introduced in the design of inner support structure. Ultimately, two standard lattice frames and several crossing members between frames were used to build the inner support structure. Pin-jointed connections were used to facilitate assembling and dismantling. Higher horizontal stiffness was obtained by increasing the spacing between two lattice frames. Connections between the column of lattice frames and the link members were strengthened by attaching plates locally, to improve the local bearing capacity.

5.3. Integrated design of the inner support structure based on whole process simulation analysis

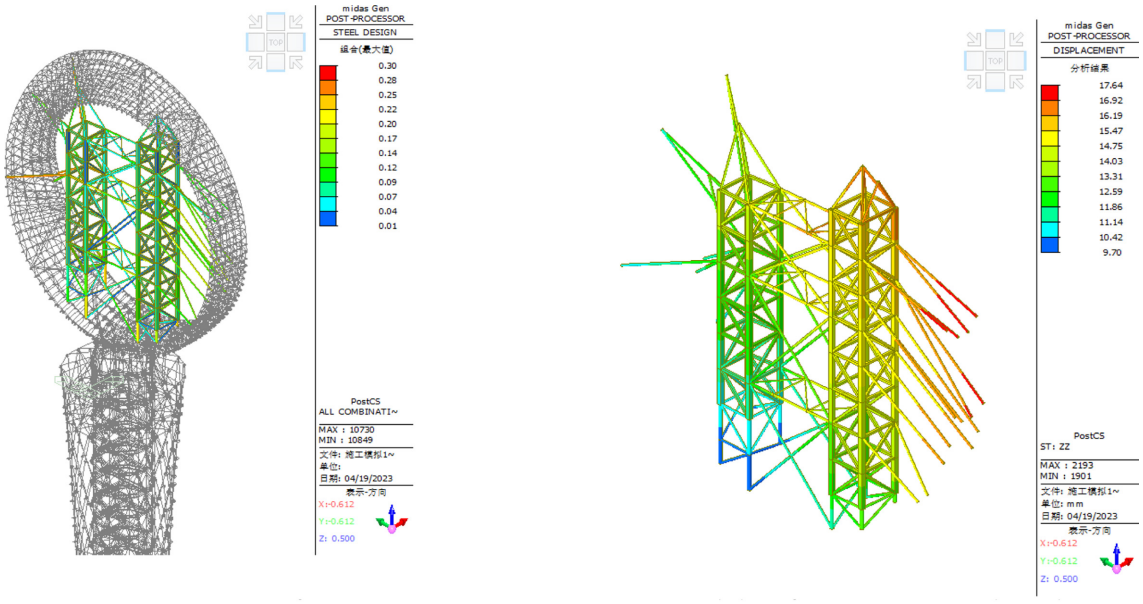
During the hoisting process of the Möbius ring, and the assembling and dismantling process of the inner support structure, the entire structure was anticipated to exhibit complex dynamic actions. To investigate the stress and deformation of the structural members, an integrative simulation of the entire construction process was conducted for both the primary Möbius ring and the secondary inner support structure. Stress and deformation variations were assessed in detail to direct the application of construction process.

In the analytical model, total weight was scaled by 1.1 to take the node weight into consideration. And during the finite element analysis, web members, crossing members between different lattice frames, and link members between lattice frames and Möbius ring were modeled by truss elements, while the other members were modeled using beam elements.

Figure 14 shows the results of the inner support structure. The most unfavorable load condition for the inner support structure was when the assembling of Möbius ring finished, and the maximum stress ratio reached 0.30. The maximum stress ratio of the Möbius ring was 0.61, which was smaller than 1.0 and met the safety requirements. Final deformation at the end of construction was 17.64 mm < H/400 = 90 mm, which also satisfies the code requirements.

5.4. Construction control based on UAV scanning measurement

During the installation of the Möbius ring, in order to control installation errors, the UAV (unmanned aerial vehicle) scanning measurement technology based on oblique photography was employed for precision detection and high-altitude position measurement of large segments. A DJI Phantom 4 RTK drone and its supporting software were used to perform 3D scanning and reverse modeling. Reflective sheets were sticked on the Möbius ring segments at the center of each chord member's end and the sidewall of the pipes on both sides, as shown in



(a) Stress ratio **(b) Displacement (mm)**

Figure 14. Calculation results of inner support system.

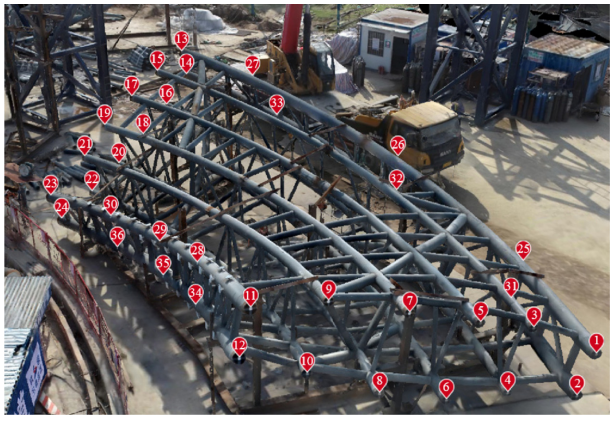


Figure 15. Schematic diagram of reflective sheet placement.



Figure 16 Scanning of the assembled segment.

Figure 15. These reflective sheets served as the control points for data comparison and processing during UAV scanning, as shown in Figure 16.

To improve the scanning accuracy, an ICP (iterative closest point) algorithm was developed for precise point cloud registration. Figure 17 compares the deviation values of the control point coordinates before and after correction between the results from 3D model and total station.

Before correction, the maximum control point coordinate deviation in X direction between 3D model coordinates and total station coordinates was 22.73 mm, with an average of 7.44 mm. The maximum deviation in Y direction was 18.83 mm, with an average of 8.45 mm, and the maximum deviation in Z direction was 13.01 mm, with an average of 5.43 mm. The total deviation in terms of spatial coordinates was 23.89 mm, with an average of 14.11 mm.

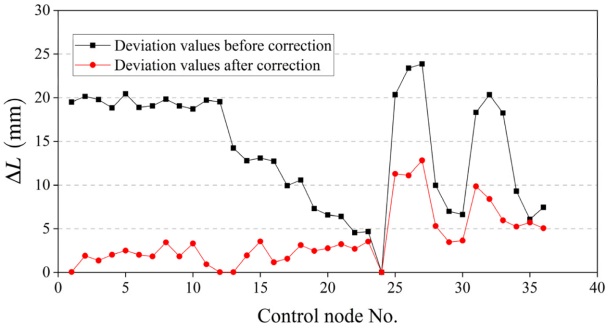


Figure 17. Deviation values before and after correction.

After correction, the maximum control point coordinate deviation in X direction between 3D model coordinates and total station coordinates was 11.52 mm, with an

average of 2.73 mm. The maximum deviation in Y direction was 6.00 mm, with an average of 1.64 mm, and the maximum deviation in Z direction was 3.29 mm, with an average of 1.08 mm. The total deviation in terms of spatial coordinates was 12.85 mm, with an average of 3.76 mm.

The corrected results indicated that the average jointing interface distance between high-altitude assembled Möbius ring segments and ground assembled segments was 23.89 mm, while the minimum deviation distance was 11.82 mm. According to the analyzed coordinate data during construction, modifications were made when assembling the ring segments on the ground before lifting, ensuring an extremely high installation accuracy at high altitude. The corrected drone scanning pre-assembly deviation detection can provide guidance for on-site installation.

6. Conclusions

Based on the results presented herein, the main findings and conclusions of this study are summarized as follows:

(1) This study introduces the technical challenges and construction conditions of the Xi'an Silk Tower. A segment hoisting process using a heavy-duty tower crane attached to an ultra-high flexible tower was proposed, which successfully ensured the completion of this project.

(2) According to relevant codes and standards for tower cranes, safety assessment preinciples were proposed for the attachment of the heavy-duty tower crane to ultra-high slender structures, which was verified safe, feasible and easy to operate in practice.

(3) An inner support structural system for the installation of large-scale Möbius ring at high altitude was designed based on the prefabricated concept, ensuring the construction safety while facilitating the assembling and dismantling process.

(4) An ICP algorithm for UAV scanning data correction was developed to measure the shape and position of the assembled structure at up to hundred meters high. The scanning accuracy was significantly improved after correction.

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