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Research Article

Analysis on Mechanical Behavior of Relay Vertical Rotation for Steel Arch Tower

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The vertical rotation method is a special option for steel tower construction in fabricated bridge. The tall tower is prefabricated on the ground and then pulled to its designed position using steel wires. Traditional vertical rotation method always uses a taller temporary structure to provide an upward pull force to lift the rotation member; however, the temporary structure would spend much time, cost, and work high above the ground. For instance, the Jinwu Bridge tower's weight was so heavy that the ordinary rotating method was not feasible. Therefore, a relay traction system with two auxiliary struts was employed to rotate the tower. The chief strut was first rotated to an inclined angle of 60° by an assistant strut to decrease the lateral component force of tension. Then, the tower was pulled from horizontal to vertical by the chief strut. Furthermore, a numerical model was established to analyze the mechanical behavior of the inner force, stress, and deformation of the chief strut, assistant strut, and tower. The study identified critical conditions such as the reverse of axial force for the assistant strut, intervention of back cables, and release of cable tension. The relay traction system effectively reduced initial pulling stress, spending less cost and time. Besides, the analysis method can be an innovate reference for other vertical rotating projects.

1. Introduction

Bridge rotation construction method (BRM) is an innovative technique to build bridge structures, particularly for superstructure rotation. The superstructure is fabricated on ground with a hinge device and then rotated to the designed position by a dynamic system's pulling or pushing force. Compared to traditional construction methods like cast-in-place method and cantilever method, BRM is faster and safer. In China, it has become one of the preferred bridge types for crossing large spans over rivers and valleys, especially when minimizing impact on existing traffic is a priority [1, 2].

BRM can be divided into horizonal rotation method (HRM) and vertical rotation method (VRM). HRM involves the rotation of arch bridge ribs, cable-stayed bridge beams, or T-shape rigid frame bridges in a horizonal plane. Siwowski and Wysocki [3] proposed a 148 m long tied-fixed arch steel structure, which was entirely rotated by 90° via floatation on barges. To conduct an optimum design for the tension force of traction system, Feng et al. [4] considered seven different load conditions during the rotating construction process of high-speed railway swivel arch bridge. As spherical hinge is the key element of horizonal rotation of swivel arch bridge, a complete design and analytical solution to determine the relationship of radial stress and upper load were present in details [4]. For T-shape curve rigid frame bridge, Shao et al. [5] proposed construction methods, which consist of installation process of ball joint, design of traction system, accuracy control method, and rotation control strategy. In addition to the vibration, which emerged at the spherical hinge and was amplified at the girder end of superstructure cantilever, Wang et al. [6] made a scaled model to test the vibration during the rotating process of HRM. To accurately simulate the dynamic construction environment, Tian et al. [7] integrated the building information modeling (BIM) and unmanned aerial vehicles (UAVs) to control construction monitoring of rotation process.

In this regard, HRM has been matured in techniques and widely adopted for construction of bridge superstructure. Different to HRM, VRM is challenging and risky because

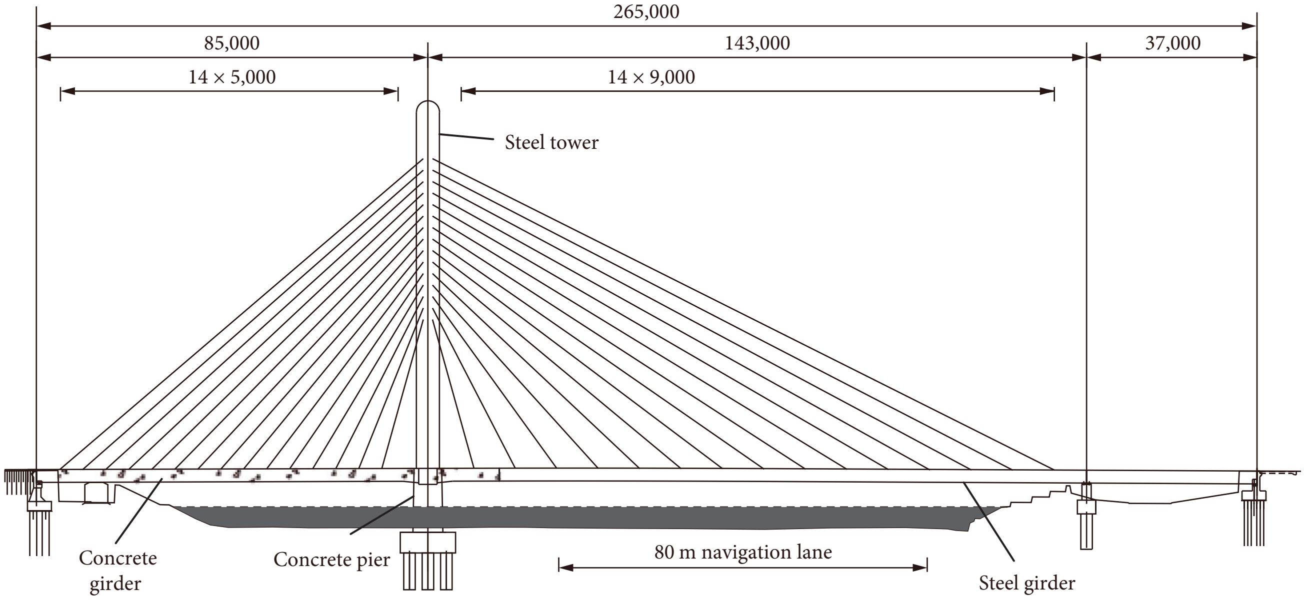


FIGURE 1: Elevation view of Jinwu Bridge (unit: mm).

the force of the rotating system varies due to the position change of superstructure. Finite element method (FEM) is a useful tool to simulate stress and deformation during construction process and analyze the strength and stability of various bridge components [8–12]. Ma et al. [13] simulated the rotating structure in three dimensions of a concrete-filled steel tube concrete basket arch bridge, and the most unfavorable stress conditions were determined. Li et al. [14, 15] studied a negative angle vertical rotating construction method in China and analyzed the vertical pouring, rotation, closure process, and other key construction processes. Also, he proposed a dynamic unstressed FEM to simulate bridge construction of vertical rotation through the whole rotation process. Li et al. [16] conducted numerical analysis to clarify the strength and stability of the arch ribs and tower in the vertical rotation of steel tube arch ribs. Sun and Wu [17] studied the transverse synchronization control of two main arch ribs during vertical rotation, based on FEM software Midas. The above rotating system always contained a strong temporary tower to lift the superstructure of bridge. However, the temporary structure would spend much building cost, time, and work high above the ground [18]. Thus, an economic, safe, and fast VRM needs to be put up.

Jinwu Bridge is cable-stayed bridge with a steel box arch tower, which was built by VRM. The rotation angle of tower was 90° from horizontal to vertical position, and the total rotating weight was 2,530 tons, creating the largest vertical rotation weight of steel bridge tower in China. The paper presents three aspects of the research: (1) the steps of relay pulling by two pressing struts for vertical rotation, (2) the mechanical behavior of the relay traction system basing on Midas Civil, and (3) the mechanical behavior of the rotating process of steel tower and the critical loading conditions. Compared to traditional vertical rotating method, which uses a taller temporary structure to provide an upward pull force to lift the rotation member, the proposed method in this paper effectively reduces temporary structures, construction cost, and risky work high above the ground. Also, mechanical behavior for the relay traction process is studied to guarantee construction safety. The relay traction system and analysis method presented in this paper can be an innovate reference for other large vertical rotating projects.

2. Project Description

2.1. Bridge Information. Jinwu Bridge is a prominent cable-stayed bridge situated in the heart zone of Jinhua, Zhejiang province. Its total length is 265 m and comprises three spans with length of 85, 143, and 37 m, and its width is 40 m. The primary bridge is a single tower cable-stayed bridge with a permanent connection between the tower and beam. To balance the gravity of different spans, the primary bridge features a 143 m span of steel box girder and an 85 m span of concrete box girder. Additionally, an 80 m navigation lane is located beneath the 143 m span. A detailed bridge elevation drawing is presented in Figure 1.

The primary tower of Jinwu Bridge is an arch tower column, with each pier located on the separation zone between the vehicles and bicycles lanes. The tower's structure below the deck is of reinforced concrete and its height is 13.511 m. The structure above the deck is composed of steel box and reaches a height of 82.404 m. The steel tower is comprised of 12 sections from T0 to T11, with T5 to T9 serving as cable anchor sections, T11 as the top beam of the tower, and T0 as the steel–concrete mixed segment. The bridge tower boasts a unique box-shaped section with an elliptical curve on the outside. The tower's height of 72.283 m follows a parabolic line, while the arch beam at the top of bridge tower utilizes an oval line, as illustrated in Figure 2.

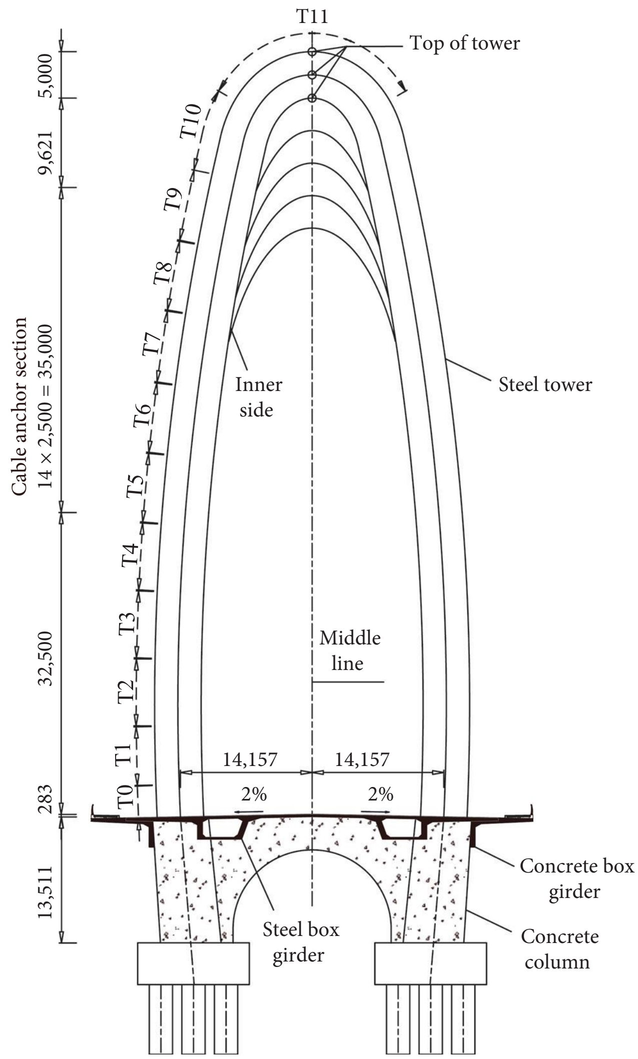


Figure 2: Structure of tower (unit: mm).

2.2. Rotation Process. The steel section of tower was located above T0, and the rotating hinge was set on the upper side. The vertical rotation process involved turning the assembled steel tower from a horizontal position to a vertical position, with a total weight of 2,150 tons. To ensure safety, linear control feasibility, and construction convenience, the overall vertical rotation process was chosen for construction.

The rotating construction method was developed using a relay mode with two struts. The proposed method is compared with traditional method, as shown in Table 1, giving improvement and advantages of relay vertical rotation. First, for traditional method, a temporary tower should be made on the ground to provide an upward pull to the steel tower [14–16]. As the steel tower is rotated to vertical position at last, the temporary tower should be taller than the steel tower. Thus, a big and strong structure is necessary. The proposed method introduces a rotating chief strut, which not only can provide an upward pull, but also have a smaller size. Comparing with the temporary tower, mass of temporary structure and amount of work high above the ground are significantly reduced.

Second, the chief strut should be initially placed at an oblique state, so that a vertical component of force can be provided by the end of chief strut. In addition, the greater the angle between the chief strut and the horizontal plane, the smaller the initial tension of steel wire is. This meant that the chief strut would be installed at an oblique initial state with higher supporting structures. In this regrad, the proposed method gives an assistant strut to lift the chief strut up first. In this way, massive temporary structure and construction cost are all successfully reduced.

In all, this relay rotating method could effectively reduce temporary structures, thus reducing construction cost and time. Moreover, the tension force of steel wire is comparatively smaller and the work high above the ground is less, making the construction safer.

In details, the chief strut and assistant strut were manufactured on supporting structures with angles of 13° and 30°, respectively (Figures 3(a) and Figure 4). The assistant strut was lifted to a vertical position using a crane before rotating and then the chief strut was lifted by the assistant strut through a junior tie and junior cable (Figure 3(b)). After the chief strut was rotated to 60°, a senior cable was used to drag between the jack and anchor to pull the chief strut instead of junior cable, and the assistant strut was disassembled to realize force conversion (Figure 3(c)).

The chief strut, made of a steel truss structure, was adopted as a dragging transition bar, and a senior tie was set on the vertical belly of the tower by the cable anchor point. The chief strut, senior tie, and tower formed a triangular force transfer structure (as shown in Figure 3(d)), so that the tension of jack was transferred to the tower anchor and provided a large enough vertical force to lift the tower. The back cable, as shown in Figure 3(d), was applied to provide an opposite force for ensuing stability. The number of senior cables was gradually reduced according to the rotating angle to ensure that the cable maintained sufficient stiffness, as shown in Figures 3(e) and 3(f). The total rotating weight in the entire facility was 2,530 tons.

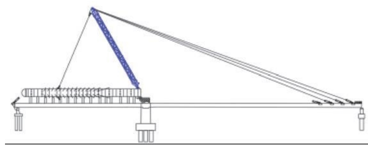
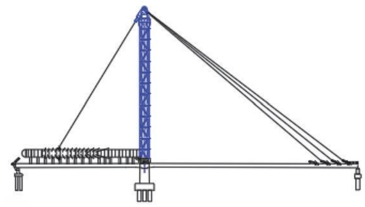
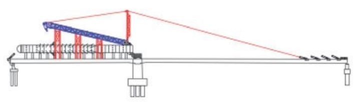
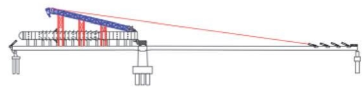
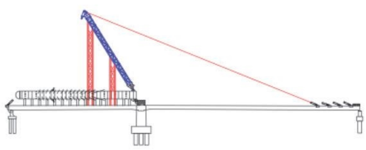
2.3. Model Establishment. The large rotation angle causes force changes in multiple working conditions. In addition, the deformation of tower and struts should be monitored during rotating process to ensure safety. Therefore, it is necessary to obtain the inner force and deformation of members by model analysis before the construction is set on.

The Midas Civil program was used for modeling. Beam unit is chosen for struts, and truss unit was adopted for cables and ties. The hinge adopts rigid connection for boundary and elastic connection for rotating. In order to take in second-order effect, geometric nonlinearity is enabled in the analysis, and the node coordinates of strut model are corrected according to the initial defects, which are considered as follows:

$$\delta_0 = e_0 \sin\frac{\pi x}{l}, \qquad (1)$$

where x is distance between support, l is the span length, and δ_0 is the initial bending deformation at position x, $e_0 = l/350$ [19].

Table 1: Comparison between proposed method and traditional method.

Rotating member	Proposed method	Traditional method	Improvement
Tower			(1) Mass of temporary structure is reduced (2) Amount of work high above the ground is reduced
Chief strut			(1) Tension force is significantly reduced
			(1) Mass of support structure is reduced (2) Amount of work high above the ground is reduced

Note: The blue member is temporary structure used in rotating tower, and the red member is temporary structure used in rotating chief strut.

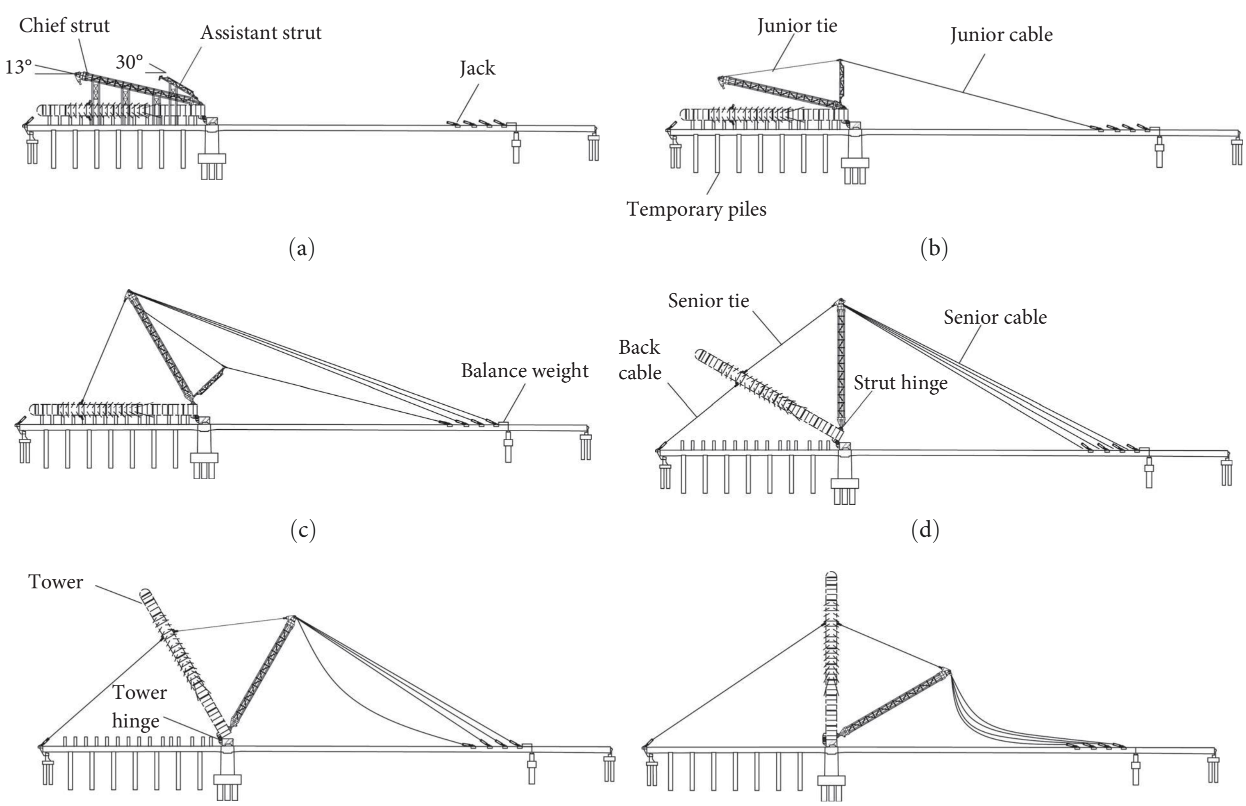


Figure 3: Step of the vertical rotating structure of steel tower. (a) Preparatory phase, (b) initial state, (c) 0°, (d) 30°, (e) 60°, and (f) 90°.

The main bridge adopts Q355qD steel, and the plate thickness is 16–28 mm. Grades of temporary structural steel are Q235 and Q355. Other properties are listed in Table 2. All the materials are behaved within the elastic deformation range in order to ensure safety of traction system, thus only main properties like yield strength and Young's modulus are given. During the construction period, the design wind speed is 15 m/s, and the height of tower top above the water surface is about 95.965 m.

Details of FE models for chief strut rotation and tower rotation are provided in the below section, respectively.

Figure 4: Preparing phase of chief strut and assistant strut.

Vertical load is arranged according to actual construction situation. Structural strength and deformation stability are to be checked under basic load combination, which contains gravity and wind load. A standard combination with load factors of 1.0 is adopted to calculate structural deformation, and a basic combination with load factors of 1.32 and 1.4 for gravity and wind, respectively, is to calculate structural strength.

3. Rotation of Chief Strut

The chief strut, standing at a height of 60 m and weighing 303.1 tons for vertical rotation, was constructed as a portal space truss structure with two columns of upper and lower truss beams. Each column comprised of four tubular trusses. The lifting of the chief strut was facilitated by the assistant strut, as illustrated in Figure 5. The traction system for the chief strut was designed with two groups of stranded wires consisting of 31 steel wires with a diameter of 15.2 mm, with the anchor point located at 48.8 m from the base of chief strut. The assistant strut was raised to the vertical position using a truck crane, which lifting process is an ordinary method. Thus, details of the process are not discussed in this paper.

Figure 6 illustrates the analysis model used for the rotation of the chief strut. The chief strut and assistant strut are modeled using beam elements with rigid connections to simulate the weld joints. Truss elements are used for the junior tie and cable, as they only experience tension during the rotation process. The junior cable is hinged on one end of the assistant strut and fixed on the other end. The traction system is rotated around the strut hinge, which is fixed to the ground.

To ensure the safety of the rotation process, the vertical rotation of the chief strut is divided into six working conditions based on the angle, ranging from 13° to 60° around the bottom hinge. An analysis is performed to calculate the normal stress of each section, bending deformation, tension of junior tie and cable, and axial force of the assistant strut. The rotation process is closely monitored and controlled based on these calculations.

3.1. Stress and Deformation. The maximum normal stress experienced by the chief strut section during rotation can be seen in Figure 7. Additionally, stress cloud diagrams for the 13° and 60° positions are presented. It should be noted that the normal stress for the chief strut section is a combination of bending and axial forces. As the axial force is compressive, the maximum normal stress for the section is also compressive and is, therefore, presented as a positive value for comparison purposes. As the chief strut rotates from 13° to 60°, the effective span under gravity decreases, leading to a gradual reduction of the maximum normal stress experienced by the cross-section. The most unfavorable position occurs at the initial 13°, where the maximum stress (91 MPa) is compressive stress on the upper edge of the strut. However, this stress level is still lower than the yield strength of steel. From 50° to 60°, the decrease in maximum normal stress is more rapid, and the maximum stress position of the member transfers below the anchor point. As a result, the speed of rotation needs to be reduced to accommodate faster stress changes during actual construction.

Figure 8 shows the maximum bending deformation that occurs in the span (from the anchor point to the rotation center) during the rotation of the chief strut. Additionally, the location of the maximum value is shown in the vertical deformation cloud diagram at a horizontal inclination of 13°. As the rotation angle increases and the effective span decreases, the maximum bending deformation at each rotating angle decreases linearly. At the initial position of 13°, the maximum deformation value in the span is 45 mm, which is less than the safety limit of 97 mm (48,800 mm/500) as specified in the regulation [19]. This indicates that the bending deformation is well within the allowable range, and no additional measures are needed to control the deformation of the chief strut during rotation.

3.2. Junior Tie and Cables. Although the stress and deformation of the chief strut are under control, it is important to consider the mechanical behavior of the traction members. Specifically, we need to verify the strength of the junior tie, which connects the chief strut to the assistant strut, and the strength of the junior cable, which connects the assistant strut to the jack. These components provide the pulling force to resist the moment generated by the gravity of the chief strut. As the elevation of the chief strut increases, the moment generated by gravity decreases, and the pulling force of the junior tie and cable decreases accordingly (see Figure 9). In addition, during the rotation of the chief strut, the pulling force changes evenly with no sudden changes. Our calculations show that the maximum tensile stress on the steel strands in the junior tie and cable is 458 MPa, which is below the yield strength of the most vulnerable strand position (13°). Therefore, the mechanical properties of the junior tie and cable are safe during the rotation of the chief strut.

3.3. Assistant Strut. The triangular force balance system comprising of the assistant strut, chief strut, and junior tie undergoes rotation under the influence of the pull force exerted by the junior cable. During the rotation process, the assistant strut experiences only axial force, as depicted in Figure 10. As the angle of the assistant strut changes from 90° to 127°, the axial force reduces gradually. At approximately 127°, the reduction rate slows down and becomes zero. However, beyond 127°, the axial force begins to decrease rapidly, ultimately turning into a tension force of 270 kN at an angle of 137°. The stress cloud diagram reveals that the columns are under tension, while the beam between the two vertical columns is under compression at an angle of 137°. During the

Table 2: Material properties used in bridge.

Material	Grades	Component	Yield strength (MPa)	Young's modulus (MPa)	Poisson's ratio	Weight (kN/m^3)
	Q355qD	Tower	355	2.06×10^5		
Steel	Q355 [20]	Chief and assistant strut	355	2.06×10^5		
	Q235 [21]		235	2.06×10^5	0.3	78.5
Alloy steel	40Cr [22]	Pin roll	550	2.06×10^5		
Steel wires	1,860 [19]	Cable and tie	1,860	1.95×10^5		

Figure 5: Rotation of chief strut by assistant strut.

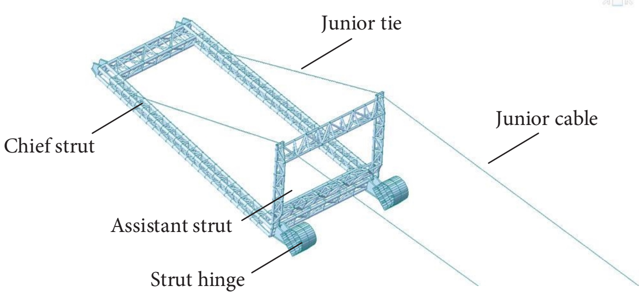


Figure 6: Analysis model of chief strut.

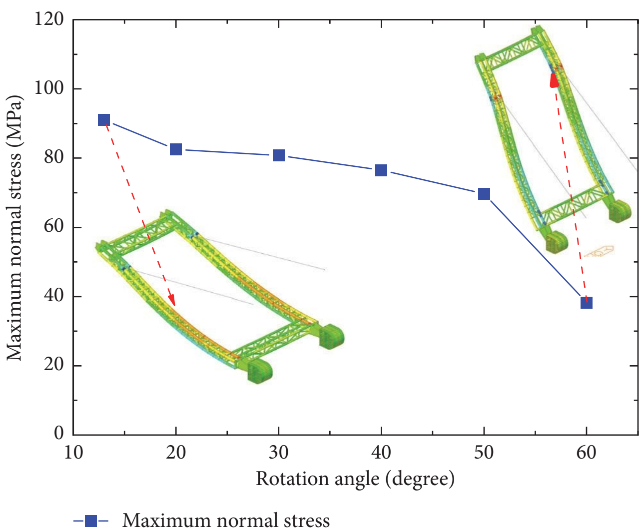


Figure 7: Normal stress of chief strut.

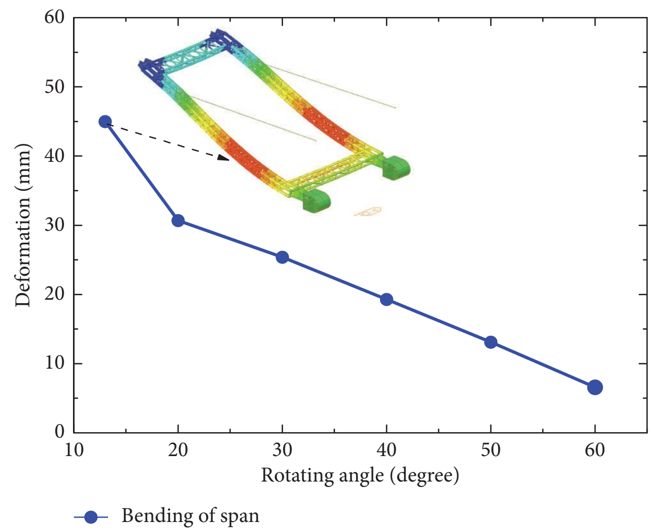


Figure 8: Deformation of chief strut.

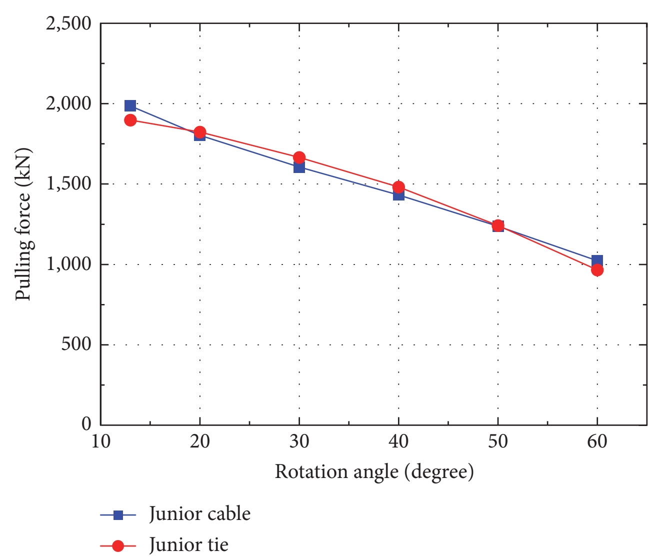


Figure 9: Pulling force of junior tie and cable.

transition from compression to tension, the plastic deformation of the strut, such as the deformation of connection, disappears instantly, leading to structural internal force mutations. Therefore, to accommodate such a change, the rotation speed needs to be slowed down and even held for a certain time between 127° and 137° to ensure complete structural deformation.

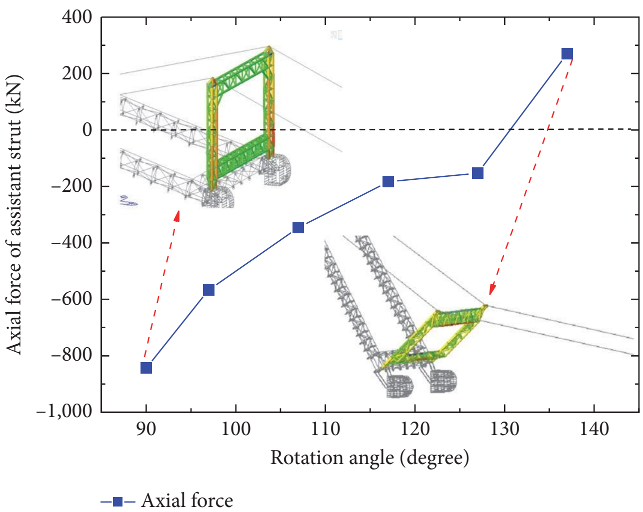


Figure 10: Axial force of assistant strut.

Figure 11: Process of rotation for tower.

4. Rotation of Tower

After the chief strut is rotated to an angle of 60°, the senior cable and tie are tensioned to support the weight of the chief strut. At this point, the assistant strut is removed from the rotation system along with the junior tie and cable. The triangular force balance system is then comprised of the chief strut, senior tie, and tower, which are rotated under the pulling force of the senior cable. This process is illustrated in Figure 11.

The senior cable was comprised of eight groups of stranded wires, with each group containing 31 steel stranded wires that had a diameter of 15.2 mm. The senior tie was composed of two sets of flexible steel tie, each of which contained four groups of 37 steel stranded wires that had a diameter of 17.8 mm. At a tower position of 30°, two back cables were tensioned with a force of 50 tons to prevent the tower from overturning. The back cable was comprised of two groups of 31 steel stranded wires with a diameter of 15.2 mm, which provided a reverse pull. At a tower position of 60°, two groups of stranded wires were released to ensure that the other senior cables had enough tension force and sufficient stiffness.

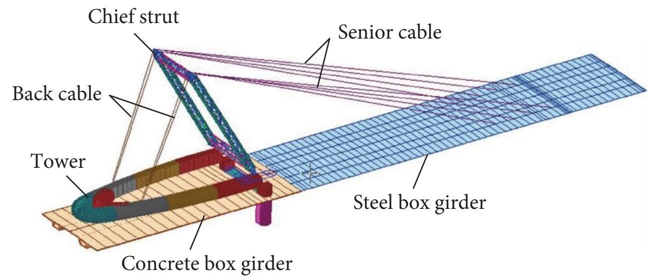


Figure 12: Analysis model of tower.

Table 3: Working conditions of rotation for tower.

Rotation angle (°)	Back cable	Number of senior cables
0	/	8
15	/	8
30	/	8
30	Tension	8
45	Tension	8
60	Tension	8
60	Tension	6
75	Tension	6
90	Tension	6

The axial force, section stress, and deformation occurring during the 0°–90° rotation are analyzed using a FE model, as shown in Figure 12. The back cable and senior cable are modeled using truss elements, similar with the junior cables. The senior cable is hinged at the chief strut and the top of the steel box girder. The arch tower is modeled using beam elements with a length of 1–3 m for T0–T11 parts and refined in the curved sections. The steel box section is applied to the beam element of the tower. The beam element length for the concrete box girder is set to 5 m and that for the steel box girder is 3 m. The bridge structure is placed on the columns, which are modeled as being fixed to the ground. The tension control process is shown in Table 3.

4.1. Stress and Deformation. During the rotation process, the maximum stress is observed at the initial 0° moment, which is the tensile stress of the tower body cross-section above the anchor point. This stress is shown in Figure 13. The reason is that the anchor point of the main tower is located at a height of 57.4 m, and the remaining 25 m is a cantilever beam. The cantilever length is 0.30 times the length of the tower, which is different from that of the chief strut, which length is 0.19 (11.2/60) times the entire length. As a result, the bending moment of the cantilever root is larger, and the maximum value of the normal stress at the root is listed in Figure 13 for angles from 0° to 90°. As the cantilever root moment decreases, the vertical component of gravity transforms into axial pressure of the tower. Therefore, the normal stress of the section tends to reduce from tension of 43.2 MPa to compression of −66.8 MPa. The stress curve shows that the stress is not affected by the tensioning of the back cable (at 30°) or the release of the senior cable (at 60°).

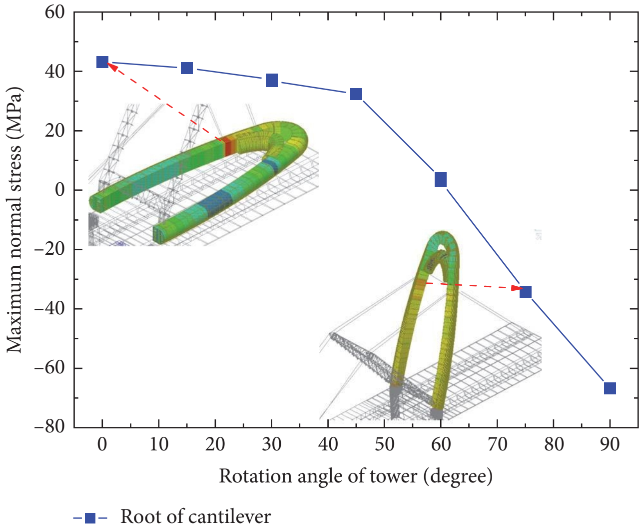


FIGURE 13: Maximum normal stress of root of cantilever.

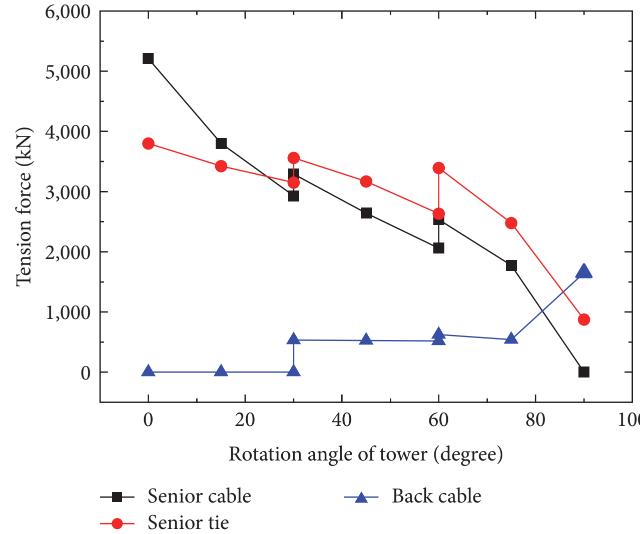


FIGURE 15: Curve of tension for cables.

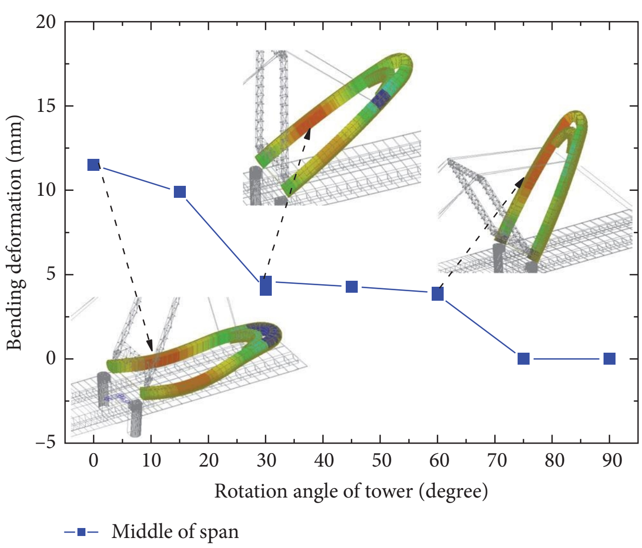


FIGURE 14: Bending deformation in the span.

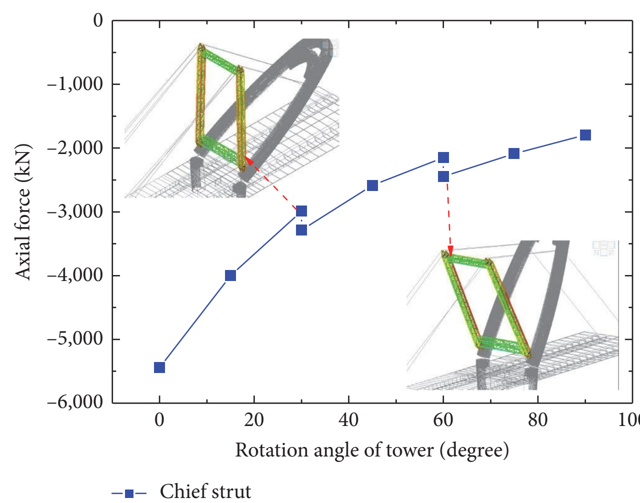


FIGURE 16: Axial force of chief strut.

Figure 14 shows the bending deformation in the middle of span of the tower during rotation. The maximum bending deformation of 11.5 mm occurs at the initial position of 0°. Although the tower body has a larger cross-section and greater bending stiffness compared to the chief strut, the tower still experiences obvious deformation. The bending deformation decreases as the effective span reduces and after 75°, the bending deformation in the middle of the span is almost zero. The tensioning of the back cable at 30° and the releasing of the senior cable at 60° have a negligible effect on the tower deformation.

4.2. Senior Tie and Cables. The simulation results demonstrate that the tower's stress and deformation during rotation are minimal, ensuring its strength and stiffness. This is due to the tower's large cross-section and high strength, specifically designed to resist tension from the bridge cables. However, the tower's larger cross-section also increases its gravity, placing high demands on the strength of senior cable and tie. As depicted in Figure 15, the tension of the senior cable and tie at the initial horizontal position is 5,210 and 3,800 kN, respectively. As the tower is lifted, the rotational moment decreases, reducing the tension in the cables and ties. When the back cable intervenes in the system at 30° with a tension force of 500 kN, the tension in the senior cable and tie simultaneously increases to balance the reverse pull. The tension in the senior cable and tie decreases as the angle increases until 60°, while the back cable tension remains at 500 kN. At the tower position of 60°, two groups of stranded wires drop out, and the tension in the remaining cables increases by almost 1.3 times. Finally, as the angle approaches 90°, the tension in the senior cable decreases to zero, while the back tension increases to 1,650 kN, mainly to resist the gravity of the chief strut. During construction, careful attention must be given to changes in cable and tie forces, and the simulated results could serve as a useful guideline.

4.3. Chief Strut. As shown in Figure 16, the chief strut experiences pressure instead of tension like the assistant strut during the entire vertical rotation process of the tower. At the initial 0° position, the maximum pressure on the chief strut is 5,440 kN. As the tension of senior cable and tie decreases, the pressure on the chief strut gradually decreases. However, at the 30° and 60° moments, the pressure on the chief strut increases due to the tensioning of the back cable and the increase in tension of the senior cables, respectively. Finally, the chief strut is disassembled from its bracket and the cables and ties are removed in a proper order.

5. Conclusions

Based on the large rotating engineering of Jinwu Bridge, this study proposed a relay traction system for the VRM. This system consists of two rotating struts, of which the chief strut is initially pulled by an assistant strut. This method effectively reduces the initial tension by using a larger initial traction angle. Compared to traditional VRMs [13–16], the relay rotating method, in which the tower was built on ground, could significantly reduce risky work high above the ground. Moreover, two rotating struts replaced the strong temporary tower in the traditional way and save cost and time.

However, the rotation process in the proposed method was more complex than that in the traditional way. Thus, FE models were established to study the mechanical behavior of the chief strut and steel tower during the whole rotating process. By analyzing the internal force change of each structure member, the following conclusions are obtained:

(1) During the rotation process, both the strength and deformation of the structure are under control.
(2) The position of maximum stress will change with increasing of rotating angle, thus multiple locations need to be arranged strain gauge and tracked throughout the whole process.
(3) Some critical conditions were pointed out for guiding construction, such as the axial force of assistant strut change from press to pull, and cables are unstretched as cable stiffness decreases.

The following topics need to be addressed to ensure broad applicability of the method:

(1) Try to avoid the strut to be tensioned by controlling the rotating angle in future engineering.
(2) More superstructure types need to be applied and verified.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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