Study on the Conversion Scheme of Steel-Concrete Composite Girder Self-Anchored Suspension Bridge System

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Abstract. Different system conversion schemes can affect the reasonable completion state of self-anchored suspension bridges. To determine a reasonable system conversion scheme for self-anchored suspension bridges, a double tower steel-concrete composite beam self-anchored suspension bridge is taken as an example. Based on the construction process characteristics of beam first and cable later, Midas Civil is used to calculate and analyze the two schemes for system conversion of this bridge. The two suspension cable tensioning schemes, "from the main tower to the side pier" and "from the side pier to the main tower", are compared. The stress-free state method is used to simulate the suspension cable tensioning process, and a dual element model is established to simulate the suspension cable tensioning process, which can effectively control the changes in suspension cable force. The research results indicate that the structural stress is safer during the transformation process from the side pier to the main tower. The maximum stresses of the main beam concrete slab, secondary longitudinal beam, and main beam steel beam during the suspension cable tensioning process are 9.57 MPa, 42.94 MPa, and 33.57 MPa, respectively, and the maximum deformation of the main beam does not exceed 230 mm.

Keywords: Steel-hybrid composite girder; Self-anchored suspension bridge; System conversion; Sling tensioning; Stress-free state method

1 Overview

The construction of self-anchored suspension bridges generally adopts the construction method of beam first and cable later. After the main beam is erected on the support, the suspension cables are tensioned. The process of tensioning the suspension

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cables is the conversion process of the self-anchored suspension bridge system, which is the most critical construction stage in the construction process of this bridge type.

Due to its unique structural characteristics of self-anchoring, self-anchored suspension bridges are difficult to construct. Many scholars have conducted extensive research on the system conversion process, Yang Chengzhi[1] et al, proposed a numerical simulation method for the stress free state of suspension cables based on the fact that the stress free length of the cables only changes during tension and does not vary with changes in load; Li Zhijun[2] et al, proposed a three-stage implementation plan for suspension rod tensioning using the theory of stress free state method and alternating tension method; Lu Wei[3] et al. proposed a three-stage, 2-wheel tensioning suspension system conversion scheme by adjusting the main cable saddle pushing and suspension rod tensioning strategies; Kim Ho-Kyung, Myeong-Jae, and Sung-Pil Chang[4-5] proposed the idea of finite element analysis of self-anchored suspension bridges by using spatially elastic suspension chain line method, using the Yong Jong Bridge in Korea as an engineering background, It was drawn up to use a maximum of 80 jacks to tension the cables of the Yong Zong Bridge, and the tensioning sequence was carried out from the mid-span of the main span and the anchored parts of the side spans to the direction of the main tower at the same time. Nonlinear finite element analysis method is the most used method in the analysis of the tension process of self-anchored suspension Bridges at present. Based on the principle of incremental superposition, this method makes use of the powerful nonlinear analysis function of finite element software to carry out formal assembly or reverse disassembly analysis in the construction stage to determine the structural response in the specific construction stage[6-7].

This article conducts finite element analysis on the transformation process of a five span double tower steel-concrete composite beam self-anchored suspension bridge system. The tension process of the suspension cable is simulated using the stress-free state method. By comparing and analyzing the stress and deformation of the main longitudinal beam, secondary longitudinal beam, and control sections of the bridge deck during the transformation process of the two systems, the optimal solution is determined through comprehensive comparison.

2 Engineering Background and Finite Element Simulation

A self-anchored steel-concrete composite beam suspension bridge adopts a five span continuous structure, with a span arrangement of (45+75+180+75+55) m. The suspension cables are numbered DS1 to DS21 and DS21 'to DS1 ' from the direction of the North Ring Road to the South Ring Road, with a total of 42 pairs of suspension cables. The bridge layout is shown in Figure 1. Considering the structural safety of composite beams, Figure 1 mainly lists the stress results of several typical composite beam cross-sections for comparison and analysis. The measurement points at half of the end span are numbered 1 and 9, the measurement points at the main tower are numbered 2 and 8, the measurement points at 1/8 of the main span are numbered 3 and 7, the measurement points at 1/4 of the main span are numbered 4 and 6, and the measurement points at the mid span of the main span are numbered 5.

The total width of the stiffening beam is 43.5m (including the cable area), using a steel-concrete composite beam form. The main longitudinal beam adopts a steel box beam with a single box and single chamber section; Five I-shaped secondary longitudinal beams are arranged between the main longitudinal beams, with a center distance of 4m between adjacent secondary longitudinal beams. The standard cross-section of the composite beam is shown in Figure 2.

The full bridge model was established using the bridge finite element software Midas Civil, as shown in Figure 3. The main beam and tower are simulated using beam elements, the cable structure is simulated using cable elements, and the bottom of the tower is constrained by consolidation; The tower beam is directly connected with elastic connections to limit displacement in three directions; The main cable is constrained by a rigid connection with the main tower; The anchoring method of the main cable on the beam also adopts rigid connection; General supports are used at both ends of the main beam to release longitudinal displacement and angle constraints along the bridge direction; Temporary piers are simulated using only compression elastic connections with a certain degree of stiffness.

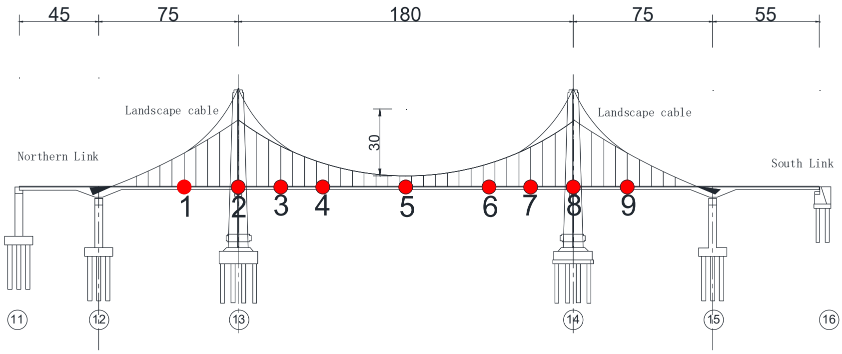

Fig. 1. Bridge Elevation View (Unit: m)

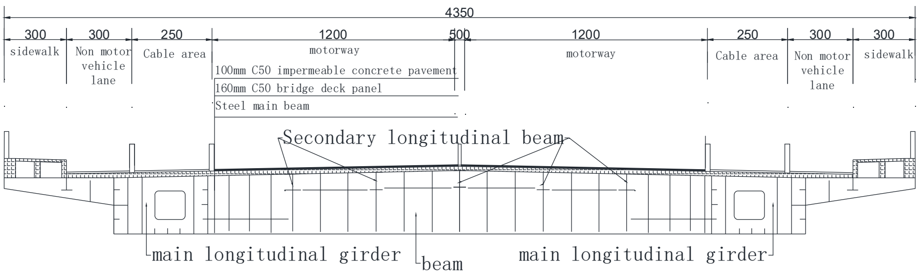

Fig. 2. Standard Cross-Section of Steel-Concrete Composite Girder (Unit: m)

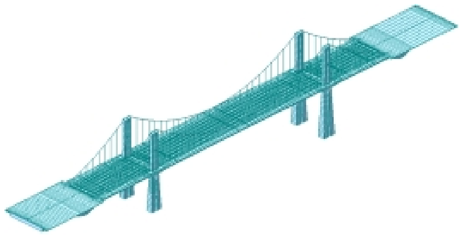

Fig. 3. Finite Element Modeling of Self-Anchored Suspension Bridges

3 Finite Element Analysis and Comparison of Sling Tensioning Programs

3.1 Tensioning Option 1 "From Main Tower to Side Piers"

Plan 1: Tensioning all suspension cables from the tower to the auxiliary pier direction in a total of 13 steps. Four pairs of suspension cables with different numbers are tensioned in each stage. During the later mid span tensioning, eight pairs of suspension cables are tensioned simultaneously. In actual tensioning, up to 64 jacks are required to work simultaneously. The specific construction sequence is shown in Table 1. The maximum cable force during the tensioning process of the sling is 2455kN, and the safety factor is greater than 2.0.

Table 1. Sling tensioning program 1 construction sequence

Construction Stages	Construction Steps	Contents of construction
Sling before tensioning	1to5	Erection of Main Towers, Main Girders, and Main Cables
Sling tensioning process	6to12	Tensioning four pairs step by step from 8, 9 (8', 9') to 1, 10 (1', 10').
	14	A sling 17, 18 and (17', 18')
	15	A sling 19, 20 and (19', 20')
	16	One sling 21 and (21')
	17	Two slings 17, 18, 19, 20 and(17', 18', 19', 20')
	18	Two slings 21 and (21')
After sling tensioning	19to20	Removal of Temporary Supports and Second-Stage Pavement Installation

As shown in Figure 4, during the entire cable tensioning process, the compressive stress in the concrete deck of the main girder is relatively small. At the main tower, the stress in the concrete deck of the main girder increases significantly, reaching 9.71 MPa. As the cable tensioning progresses, the compressive stress in the concrete deck at the mid-span of the main span gradually decreases. For the other sections, the compressive stress in the concrete deck shows an increasing trend, with the maximum compressive stress in the concrete deck being 5.46 MPa.

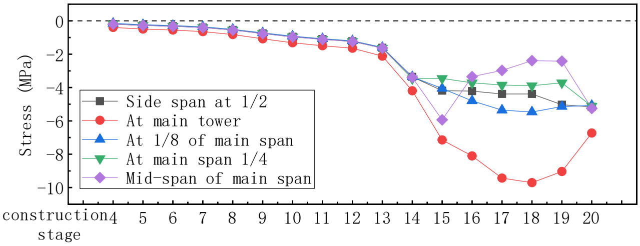

Fig. 4. Concrete slab stress in typical section of main longitudinal beam during tensioning process

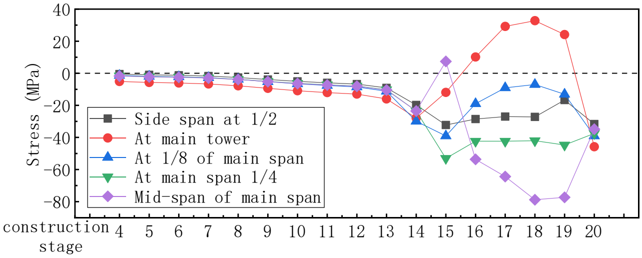

Fig. 5. Typical cross-section stress of main longitudinal beam during tensioning process

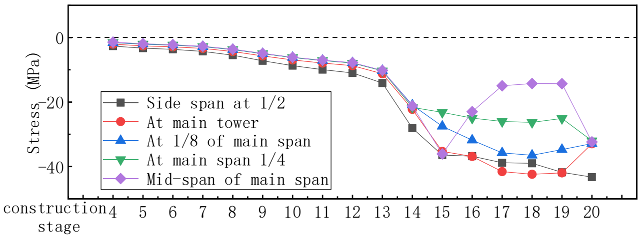

Fig. 6. Stress of the typical cross-section of the main longitudinal girder during the tensioning process

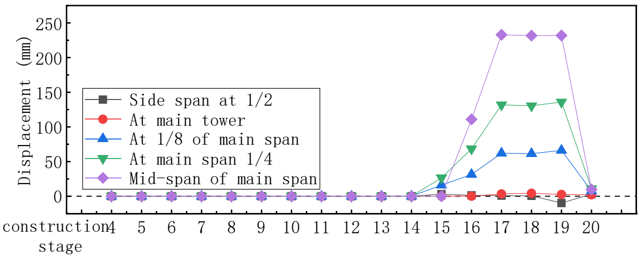

Fig. 7. Displacement changes of main beam during tensioning process

According to Figure 5, in the later stage of tensioning, the main longitudinal beam and steel beam generate tensile stress at the section of the main tower and the mid span of the main span. The maximum tensile stress value at the lower edge of the steel beam occurs in stage 18, which is 32.79 MPa. In stage 15, due to the inadequate tensioning of the suspension cable at the mid span of the main span, the steel beam generates tensile stress; According to Figure 6, during the tensioning process, the stress of the secondary longitudinal beam in the mid span of the main span first increases and then decreases. The maximum compressive stress occurs in stage 15, with a maximum value of 36.11 MPa. The compressive stresses of other sections show an increasing trend. In stages 14 and 15, the stress of the secondary longitudinal beam suddenly increases, and the change in cross-sectional stress is relatively small in the later stage of tensioning; As shown in Figure 7, in the initial stage of tensioning, the displacement of the main beam is basically zero. In the later stage of tensioning, the main beam is lifted due to the staged tensioning of the suspension cable. The maximum displacement during the tensioning process reached 232 millimeters, occurring in the 17th stage. At the completion stage of the bridge, the shape of the main beam is basically close to the design shape.

3.2 Tensioning Scheme 2 "From the Side Pier to the Main Tower" Tensioning Sling

Plan 2 involves 17 steps of tensioning all the suspension cables from the auxiliary pier towards the cable tower. Four pairs of suspension cables with different numbers are tensioned in each stage, and 32 jacks are used for actual tensioning. The specific tensioning plan is shown in Table 2. The maximum tension process of the sling is 2438kN, with a safety factor greater than 2.0.

Table 2. Sling tensioning program 2 construction sequence

Construction Stages	Construction Steps	Contents of construction
Sling before tensioning	1to5	Erection of Main Towers, Main Girders, and Main Cables
Sling tensioning process	6	Tension sling 21 (21')
	7to10	Tension four pairs of hangers step by step starting from the midspan, from 20, 19 (20', 19') to 15, 2 (15', 2').
	11to13	Each group consists of four pairs of hangers: 14, 3 (14', 3'), 13, 4 (13', 4'), and 5, 6 (5', 6').
	14	Two slings 3, 4 (3', 4')
	15to16	Step-by-step tensioning of one hanger: 7 (7'); 11, 12 (11', 12').
	17	Two slings 14, 13 (14', 13')

	18	One sling 10 (10')
	19	Two slings 11, 12 (11', 12')
	20	One sling 9, 8 (9', 8')
	21to23	Step-by-step secondary tensioning of: 5, 6 (5', 6');10, 7 (10', 7');9, 8 (9', 8').
After sling tensioning	24to25	Removal of Temporary Supports and Second-Stage Pavement Installation

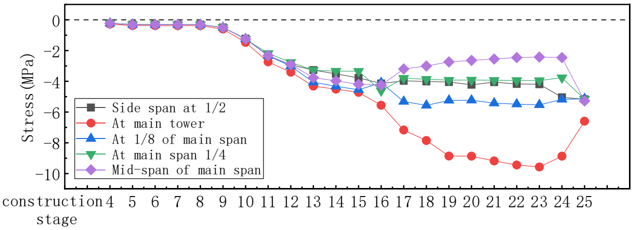

Fig. 8. Concrete slab stress in typical section of main longitudinal beam during tensioning process

As shown in Figure 8, during the entire cable tensioning process, the compressive stress in the concrete deck of the main girder is relatively small. The most significant change in the concrete deck stress occurs at the main tower, with a maximum value of 9.57 MPa. Throughout the cable tensioning process, the compressive stress in the concrete deck at 1/4 of the main span and at the mid-span of the main span first increases and then decreases. For the other sections, the compressive stress in the concrete deck shows an increasing trend, with the maximum stress values reaching 4.91 MPa. In Stage 16, due to the first tensioning of the sling near the main tower, there is a sudden increase in the compressive stress in the concrete deck at the mid-span of the main span.

As shown in Figure 9, in the later stage of tensioning, tensile stress is generated in the main longitudinal beam steel beams of the main tower section and the 1/8 section of the main span. The maximum tensile stress of the lower flange of the steel beam is 33.57 MPa, which occurs in the section of the main tower. As shown in Figure 10, in the 1/8 section of the main span, a tensile stress of 3.42 MPa was generated in the 18th stage. For other parts, only compressive stress is generated throughout the entire process, which meets the requirements of the specifications. As shown in Figure 11, in the initial stage of tensioning, the displacement of the main beam is basically zero. In the later stage of tensioning, due to the high tension of the sling and graded tensioning, the main beam is lifted. The deformation of the main beam at the main tower and side span is relatively small. The maximum deformation during the tensioning process occurred in stage 23, with a maximum deformation of 229 millimeters at the mid span of the main span. At the completion stage of the bridge, the shape of the main beam is basically close to the design shape.

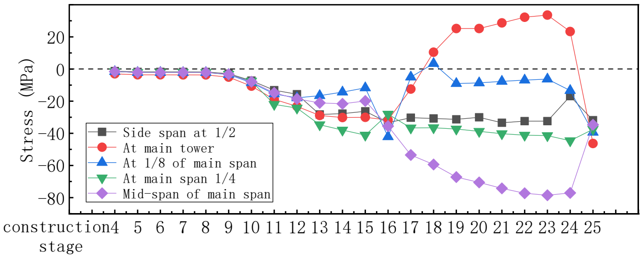

Fig. 9. Typical cross-section stress of main longitudinal beam during tensioning process

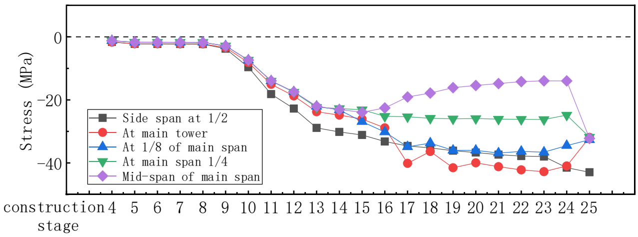

Fig. 10. Stress of the typical cross-section of the main longitudinal girder during the tensioning process.

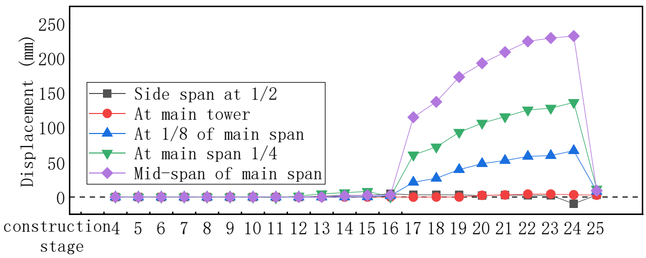

Fig. 11. Displacement changes of main beam during tensioning process

4 Conclusion

This paper uses a finite element model to simulate the system transformation of the bridge. Based on the principle of the unstressed state and the characteristics of construction control, different cable tensioning schemes are used to control the displacement and stress of the composite beam, while ensuring that the error between the cable tension force and the target control value during the construction process remains within the specified range. By implementing two tensioning schemes, Scheme 2 ensures safer structural stress during the system conversion process and better meets the construction control requirements of the bridge. The use of the stress-free state method in the system conversion process can clearly obtain the length and force of the suspension cables during the tensioning process. This method fills the gap of the inability to obtain accurate cable forces in conventional simulations and provides more precise construction control for self-anchored suspension bridges during the tensioning process.

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