Design and Construction

Study on Key Technology of Assembling Installation of Long-Span Composite Girder Cable-Stayed Bridge

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Abstract: The Nanxi (Xianyuan) Yangtze River Bridge in Yibin is a composite beam cable-stayed bridge with twin towers and double cable planes and a main span of 572 m. The superstructure is erected by the assembly method. In order to ensure the precise installation and control of internal forces for steel girders and bridge deck slabs of composite beams while also considering the construction efficiency of composite beams, a control method for the installation and erection of the superstructure has been proposed. This method is based on optimizing the internal force and geometric states of segments throughout the entire process, achieved by establishing finite element calculation models for both the full bridge and segmented sections and combining these with comparative studies of on-site monitoring data. With the installation stress and precision of composite beams properly controlled, construction efficiency has been enhanced through the optimization of the pouring process for wet joints between steel girders and concrete bridge deck slabs, as well as the tensioning process for stay cables. The equivalent tension method is applied to the tension process of the stay cable, thus ensuring the uniformity of the cable force of the steel strand. The relevant conclusions are applicable to the same type of composite girder cable-stayed bridge erection construction.

Keywords: cable-stayed bridge; composite beam; erection method; steel strand cable; equivalence tensioning method

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1. Introduction

The design of the Yibin Nanxi (Xianyuan) Yangtze River Bridge adopts a double tower-double cable plane composite beam cable-stayed bridge with five spans of 280 m + 572 m + (72.5 + 63 + 53.5) m. Refer to the bridge layout plan in Figure 1. The main span and the north bank side span both adopt composite beams, while the south bank side span adopts concrete beams. A combination section of composite beam and concrete beam is set near the tower on the south bank side. The composite beam has a width of 30.5 m, a height of 3.5 m, and a standard beam length of 13.5 m, with a lifting control weight of 62 t. Q370C steel is used for the composite beam, which is a double-sided I-beam structure connected by steel cross beams in the middle. The bridge deck slabs adopt C60 high-strength concrete, with a standard slab thick-ness of 26 cm. The stay cables adopt epoxy-coated steel strands.

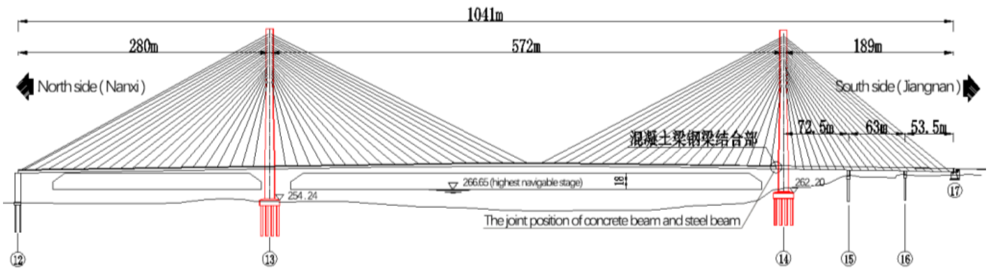

Figure 1. Layout of cable-stayed bridge

The superstructure of the bridge is constructed using a prefabricated assembly and erection method. The steel girders and concrete bridge deck slabs are processed and prefabricated in the factory. The bridge deck crane is used to lift the steel girders and deck slabs to the designated positions, and then the wet joints are poured on-site to form the composite beam. The installation of the cables and adjustment of cable forces are carried out according to their corresponding construction stages.

Construction of cable-stayed composite beam bridges of the same type involves the following key points: (1) reasonable control of the internal forces and geometric states of the I-steel girders and bridge deck slabs during construction to achieve a reasonable bridge target; (2) reasonable optimization of the segment installation process and improved work efficiency to meet the requirements of the construction period; and (3) selection of appropriate cable tensioning methods to ensure even stress distribution among steel strands inside the cable. To address these technical challenges, this study proposes an optimized control method based on the internal force and geometric state throughout the entire process by integrating finite element calculation with field construction control, thus presenting a comparative study.

2. Finite element model

The space model is established by MIDAS software, and the fishbone beam model is adopted. The main beam nodes and the stay cable nodes are rigidly connected. The pylon and girder are simulated using spatial beam elements, taking into account the influence of shear deformation, while the cables are simulated using truss elements, taking into account the influence of sag. The calculation model takes the longitudinal direction of the bridge as the X axis, the transverse direction of the bridge as the Y axis and the vertical direction as the Z axis. The bridge deck crane cantilever assembly method is adopted for the construction of the main beam.

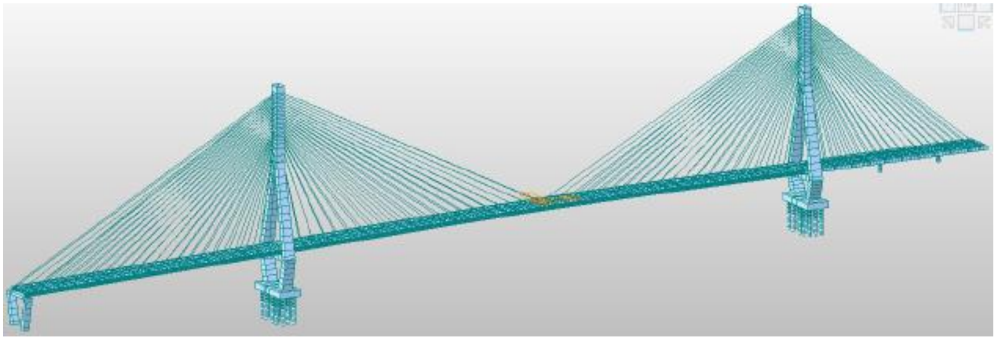

Figure 2. The MADSA spatial model

3. Optimization of the assembly method for the superstructure

3.1. Reasonable completed bridge state control

Stress control of composite beam: (1) During the whole construction process, the stress of the top plate of the main steel girder should be between 140.5 MPa (compression) and 41.3 MPa (tension), the stress of the bottom plate of the steel girder should be between 105.6 MPa (compression) and 130.2 MPa (tension), and the stress of the concrete bridge deck slabs should be between 14.13 MPa (compression) and 1.24 MPa (tension). (2) Completed stage: the maximum compressive stress of top plate of the main steel girder is 110.8 MPa, the maximum compressive stress of bottom plate of the steel girder is 72 MPa, the maximum compressive stress of concrete bridge deck slabs is 12.2 MPa, and the minimum compressive stress is 2.7 After the completion of 10-year concrete shrinkage and creep, the maximum compressive stress of the top plate of the main steel girder is 141 MPa, the maximum compressive stress of the bottom plate is 105 MPa, and the maximum compressive stress of the concrete bridge deck slabs is 9.9 MPa, and the minimum compressive stress is 2.4

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MPa under the dead load condition. The stress control of the composite beam can be realized by controlling the shape of the main beam, the pylon and the cable force.

Pylon and beam deformation control: (1) Deformation of towers: The horizontal displacements of towers top at the completion stage are 94 mm and 134 mm, respectively (both toward the shore side), and the horizontal displacements of the tower top at the completed stage (after shrinkage and creep) are -6 mm and 80 mm, respectively. (2) Deformation of the main beam: During the segmental installation of the composite beam, the main beam will produce vertical deflection and horizontal displacement due to its own weight and the tension of the stay cables. The horizontal displacement of the side span is between 267 and 0 mm and that of the midspan is between 167 and 0 mm. The vertical displacement of the side span ranges from -3867 mm to 0 mm, and the vertical displacement of the middle span ranges from -2455 to 0 mm. The above pylon towers and beam deformation need to be accurately monitored during construction, and the design target alignment shall be finally achieved by controlling the manufacturing alignment and installation alignment.

3.2. Optimizing construction procedure to improve segment installation efficiency

3.2.1. Optimization of the main beam installation scheme

The concrete bridge deck slabs of composite beams are divided into two parts: precast slabs and cast-in-place wet joints. The precast slabs shall be stored for 6 months after the completion of prefabrication in the prefabrication yard. When precast slabs are hoisted and placed in positions, the wet joints concrete shall be poured to connect them with the steel beams to form a composite beam. There are two types of stress modes in the construction process of composite beams: one is the stress of the concrete slab and steel beam as a whole (mode 1), and the other is the stress of concrete slabs and steel girder independently (mode 2). Mode 1 refers to the bridge deck slabs and steel girder forming a composite beam by pouring wet joints during the construction stage and then bearing all temporary construction loads (such as bridge deck crane, beam transport vehicle, etc.) during construction stage; Mode 2 refers to the situation where the wet joints between the bridge deck panels and steel girders are not cast during the construction stage, and each of them respectively bears all the temporary construction loads during the construction stage. Because of the different mechanical mechanisms of the two modes, the influence on the mechanical state of the steel girder and the bridge deck slab is also different. The wet joints can be poured after the crane is moved in "Mode 2", which can greatly shorten the installation period (shorten the installation period of one standard segment main beam) compared with the method of "Mode 1", which must wait until the wet joints are poured and the composite beams are formed before moving the crane. Three installation schemes are compared and analyzed in this project. Scheme I corresponds to construction mode I, and Schemes II and III correspond to construction mode II. The difference between Scheme II and Scheme III is that Scheme II lags behind one segment to pour wet joints to form a composite beam, while Scheme III lags behind two segments to pour wet joints to form a composite beam.

Table 1. Main beam installation procedures comparison

construction procedure	**Scheme I**	**Scheme II (single-cycle construction)**	**Scheme III (double-cycle construction)**
1	Hoisting n# steel girder segment	Hoisting n# steel girder segment	Hoisting n# steel girder segment
2	1st cable tensioning for the n# beam segment	1st cable tension for the n # beam segment	1st cable tensioning for the n# beam segment
3	Hoisting n# beam segment concrete slab	Hoisting n# beam segment concrete slab	Hoisting n# beam segment concrete slab

construction procedure	Scheme I	Scheme II (single-cycle construction)	Scheme III (double-cycle construction)
4	2nd cable tensioning for the n# beam segment	2nd cable tensioning for the n# beam segment	2nd cable tensioning for the n# beam segment
5	Pouring wet joint of n# beam segment	Crane moves forward	Crane moves forward
6	3rd cable tensioning for the n# beam segment	Pouring wet joint of n-1# beam segment	Pouring of wet joints of n-2# and n-1# beam segments
7	Crane moves forward	3rd cable tensioning for the n# beam segment	2nd cable tensioning for the n-2# and n-1# beam segments
Construction period for one segment	9 days	8 days	7.5 days
Total construction period	189 days	168 days	158 days

By comparing and analyzing three construction scenarios, it was found that the lagged pouring of wet joints on the bridge deck has a more significant impact on the stress of the steel girder, while its impact on the compressive stress of the concrete bridge deck slab is not significant. As the number of segments with lagged pouring of wet joints increases, the stress on the steel girder also increases. The stress on the steel girder follows the order of lagging pouring of wet joints for two segments > lagging pouring of wet joints for one segment > non-lagging pouring of wet joints. For more detailed analysis and conclusions, please refer to Table 2.

Table 2. Main beam stress comparison (Unit: MPa)

	construction procedure	Scheme I	Scheme II	Scheme III
steel girder	Compressive stress during construction	141	174	200
	Compressive stress in operation stage	167	198	229
concrete slab	Compressive stress in operation stage	15.1	15.6	15.8

Through the comparison and demonstration of construction schemes, Scheme II is recommended for construction, that is, the construction process of lagging a segment to pour wet joints. Under the premise of effectively controlling the stress of the main beam, the construction efficiency is greatly improved, and the construction period is saved for 21 days.

3.2.2. Optimization of the stay cable tensioning scheme

The main purpose of cable force control is to control the internal force and alignment of the main beam and towers simultaneously. The main reason for adjusting the cable tension during the construction process of cable-stayed bridges is that cable-stayed bridges are statically indeterminate structural systems. The structural system of cable-stayed bridges during construction is different from that after completion. Through appropriate cable force adjustment, the requirements for deformation and stress control in each stage can be satisfied. Additionally, cable adjustment can eliminate the influence of construction error and make the actual construction coincide with the design goal. In order to reduce the influence of different tensioning sequences of stay cables on the deformation and stress of the main beam, the construction control method of the nonstress state is adopted; that is, the theoretical elongation of stay cables is calculated by the target state, and then the tension is controlled according to the theoretical elongation.

The cable tension of a conventional composite girder cable-stayed bridge usually adopting four-times tensioning scheme, which is the first tensioning when the steel main girder is installed, the second tensioning when the concrete bridge deck slab is installed, the third tensioning after the wet joint pouring of the bridge deck slab, and the overall adjustment of the cable force (the fourth tensioning) after the second-stage dead load is applied. Since the total weight of wet joints and second-stage dead loads generally do not exceed 25% of the total weight of the main beam, according to the construction control method of the non-stress state, the three-times tensioning in the installation of the main beam segment can be adjusted to two-times tensioning. That is, after the precast bridge deck slabs are hoisted, the wet joint and the second-stage dead load are taken into account in the second tensioning of the stay cable. Under the premise of reaching the control target state, the construction process is simplified. See Figure 3 and Figure 4 for a comparison of the stress and deformation of the main beam in the two tensioning schemes.

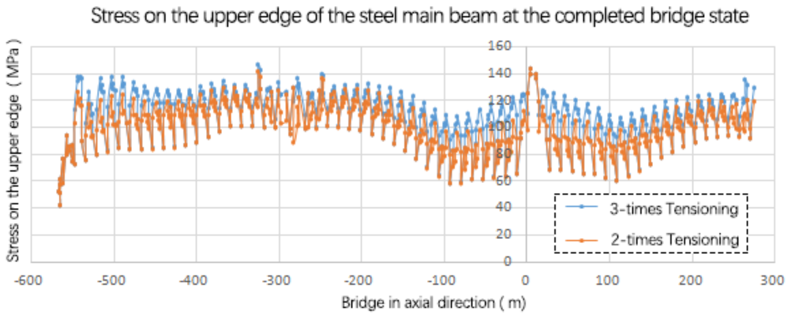

Figure 3. Comparison of stress on the upper edge of the main beam at the completed bridge state

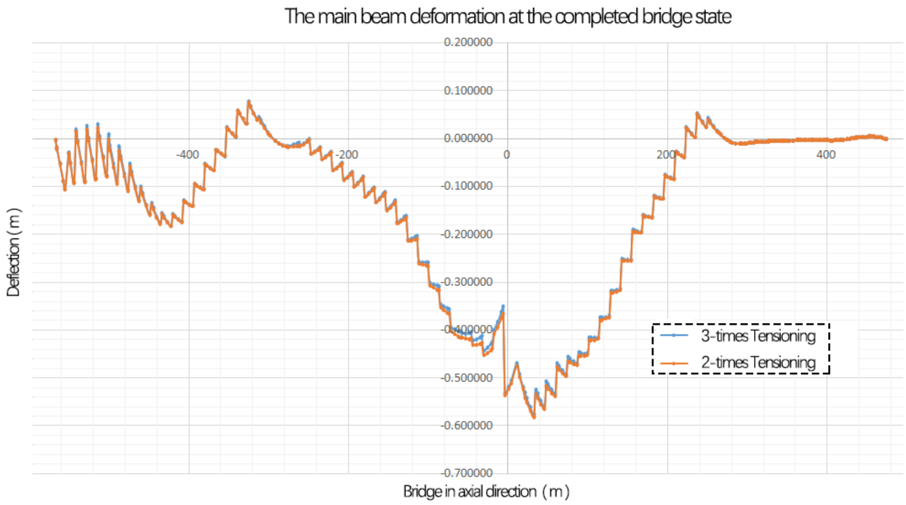

Figure 4. Comparison of the main beam deformation at the completed bridge state

Through the comparison and demonstration of the stay cable tensioning schemes, the stress and alignment of the main beam corresponding to the two tensioning schemes can be well controlled. Therefore, the scheme of twice tensioning is adopted in the construction, which greatly improves the construction efficiency and saves 15 days of construction.

3.3. Uniformity control of cable tension

To ensure uniform tension in each cable strand, the equivalence tensioning method is employed for cable tensioning. The working principle of this method is to install a pressure sensor at the tensioning end of a reference steel strand and tension it to a certain level. When tensioning the subsequent individual steel strand, considering the influence of structural deformation or temperature change, the error between the tension value of the subsequent individual steel strand and the existing cable force of the reference steel strand does not exceed ± 1%.

Figure 5. On-site tensioning of a single strand

Figure 6. On-site overall tensioning of cables

The tension value of a single steel strand of the stay cable is taken as T_i, and the calculation method is shown in equation 1.

$$T_i = \frac{N}{n} + \frac{E_C \times A \times (\delta \times \sin\alpha + \varepsilon)}{l} \tag{1}$$

where: N is the tension control force of stay cable, n is the number of steel strands, δ is the theoretical values of vertical displacement of main beam anchor points before and after installation of cable stays (determined by on-site monitoring values), α is the design elevation angle for cables, ε is the anchorage deformation and clip retraction (5 mm on site), E_c and A is the elastic modulus of steel strand and section area, l is the length of the stay cable.

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The cable force value of the ith cable is taken as $T_i = T_{i-1} - \Delta_i$, where Δ_i is the change value of the sensor corresponding to the first cable when the ith cable is installed.

When tensioning a single steel strand, the reference strand force is corrected based on the average strand tension force of the entire cable bundle and the deformation of the main beam and tower. This method can make the tension force after installation close to the design tension force, but there is still a certain margin of error. In order to ensure that the actual total force of the cable meets the design requirements, the cable force must be adjusted as a whole after the complement of single tensions. After the overall cable adjustment is completed, the error between the actual cable force value and the design target cable force value shall be controlled within 5% (Figure 7). At the same time, the linear error of the composite beam shall be controlled within 40 mm (Figure 8), which meets the design requirements.

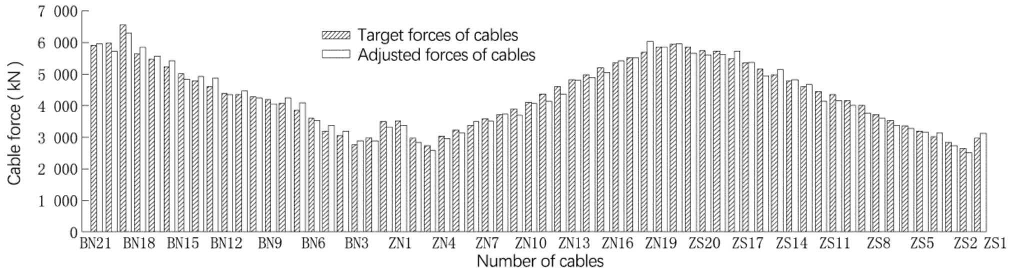

Figure 7. Comparison of cable force after cable adjustment

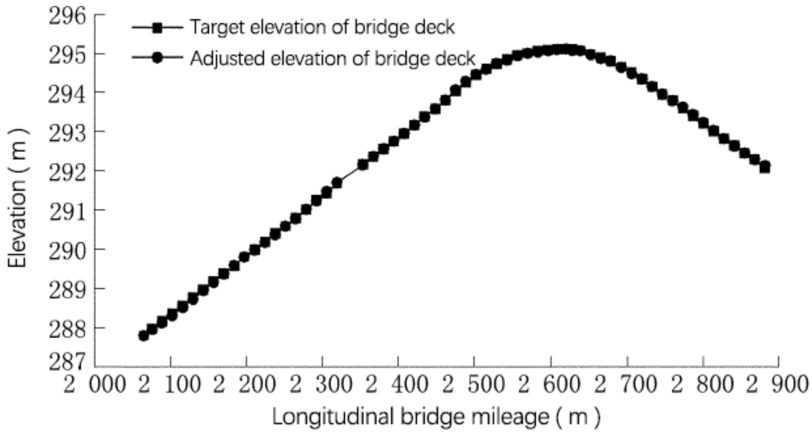

Figure 8. Linear Comparison of Composite Beam after Cable Adjustment

4. Conclusion

Regarding the technical difficulties encountered during the installation of the segmented combined beams of the Yibin Nanxi (Xianyuan) Yangtze River Bridge, finite element analysis was used along with on-site construction control methods to study the main beam installation and cable tensioning process. Based on the optimization of the segment's overall target state, a combined beam assembly method was proposed. The study showed the following:

The main beam installation scheme adopting a single-cycle process, which can effectively shorten the construction period and optimize the construction process.

Based on the construction control method of the non-stress state, through moderate over-tensioning of the stay cable, reduce the number of tensioning times of the stay cable;

The equivalence tensioning method is used to control the uniformity of the strand force, which effectively ensures the bridge alignment and cable force of the cable-stayed bridge and improves the construction efficiency.

The technology solutions presented in this paper have been successfully applied to the construction of the Yibin Nanxi (Xianyuan) Yangtze River Bridge and Yibin Yanpingba Yangtze River Bridge. While shortening the construction period, better control over the bridge's alignment, internal forces, and cable tension has been achieved. This has significant reference value for the design and construction of similar bridges in the future.

References

1. Ministry of Transport of the People's Republic of China JTG/T 3365-01—2020 Specifications for Design of Highway Cable-stayed Bridge. 2020.
2. Sichuan Highway Planning Survey Design and Research Institute Ltd *Yibin Nanxi Yangtze River Highway Bridge construction drawing design document*; 10/2015 2015.
3. Shan, D.; Zhang, X.; Gu, X.; Li, Q. Cable Force Adjustment for Long Span Cable Stayed Bridge Based on Multilayer Perceptron Deep Learning. *Bridge Construction* **2021**, *51*, 14-20.
4. Wei, L.; Cao, M.; Cui, B.; Xiong, W. Study of Construction Method for Lnstalling Superstructure of Wangdong Changjiang River Highway Bridge. *Bridge Construction* **2019**, *49*, 119-124.
5. Zhang, Y.; Li, Q.; Tang, L. Study on Cable Force Control of Zhumba Jinsha River Bridge in Yibin. *Railway Standard Design* **2005**, 27-30, doi:10.13238/j.issn.1004-2954.2005.08.011.
6. Yuan, R.; Qin, S. Application of Unstressed State Method to Construction of Steel Strand Stay Cable. *Bridge Construction* **2012**, *42*, 75-79.

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