Design and Construction

Design and Analysis of a Partially Cable-Stayed Bridge over the Mingyue Qujiang River in Guang'an

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Abstract: The long bridge over the Mingyue Qujiang River in Guang'an, Sichuan, China is a prestressed concrete partially cable-stayed bridge with a main bridge span arrangement of (110+210+110) m constructed with a pier-girder-tower fixed system. The girder features a single-box three-chamber section, measuring a width of 23 m, a height of 7.5 m at the main pier top, and a height of 1.6 m at mid-span. The girder is reinforced with prestressed steel bars in three directions and constructed using the cast-in-place cantilever method. The main tower is a reinforced concrete structure with a rectangular cross-section and a height of 32.05 m. The bridge has a total of 56 pairs of stay cables in a single plane. Sleeve cable saddles are adopted with two-way anti-slip keys arranged on both sides of tower wall. The findings in this study serve as a reference for the design of similar projects in the future.

Keywords: partially cable-stayed bridge; girder; stay cable; tower; saddle

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1 Introduction

Continuous girder bridges are highly cost-effective bridge structures offering several benefits, including excellent structural integrity, minimal presence of expansion joints, and a smooth driving experience. By fixing the pier and the girder, a continuous rigid frame bridge can be formed. The fixed connection between the pier and the girder creates a rigid framework, resulting in a more balanced distribution of internal forces within the structure. Additionally, this design eliminates the need for bearings and avoids the complexity of system conversion during construction. Therefore, this type of bridge is particularly suitable for spans ranging from 100 to 300 m. Nevertheless, in recent years, continuous rigid frame bridges with main spans exceeding 150 m have faced significant challenges, primarily related to the development of cracks in prestressed concrete girders and excessive deflection at the mid-span [1]. In response, engineers have adopted various improvement measures. For instance, they have utilized lightweight and high-strength concrete, as seen in the Stolma Bridge in Norway; alternatively, they have replaced a section of the girder at the mid-span with steel box girders, as demonstrated by the double-line Yangtze River bridge at Shibanpo in Chongqing, China. Such modifications aim to reduce the dead weight of girders and enhance the load-bearing capacity of the bridges [2]. Nevertheless, these improvement measures do not lead to a substantial improvement in the load-bearing performance of the bridges. As an alternative, transferring some of the prestressed force within the girder near the supports can be employed. In such cases, the continuous rigid frame bridge evolves into a partially cable-stayed bridge. Since the cable distance from neutral plane of the girder is significantly greater in a Partially cable-stayed bridge compared to conventional internal cables, this characteristic allows for a significant improvement in the load-bearing performance of the girder [3]. Using the partially cable-stayed bridge over the Mingyue Qujiang River in Guang'an, Sichuan, China as a case study, this study examines the design approach for partially cable-stayed bridges. The findings can be used as a reference for future projects of a similar nature.

2 Project Overview

Positioned approximately 250 m downstream from Mingyue Ferry in Mingyue Town, Huaying, the long bridge over the Mingyue Qujiang River stretches across the Qujiang River. Upstream from the bridge site, at a distance of 2.5 km, is the Huangmadu Qujiang Bridge. Downstream, at distances of 8.6 km and 28.1 km, respectively, are the Yujiazui Qujiang Bridge and the Fuliutan Junction. The river segment within a 4-kilometer range upstream and downstream of the bridge area forms a pronounced "U"-shaped bend. The bridge is situated in the middle portion of the bend, where the main current of the river runs near the right bank, with the left bank being occupied by the Mingyue Reef Beach measuring approximately 5 m in length and nearly 150 m at its widest point. At the bridge location, the river segment exhibits an asymmetrical, narrow, and deep U-shaped river valley, where the river width is approximately 300 m. The Qujiang River experiences its flood season from May to October each year, while the dry season occurs from November to April of the following year. The flood season represents approximately 86.1% of the total annual runoff, whereas the dry season corresponds to around 13.9% of the annual runoff. The bridge location is designated as a Class III waterway in river segment planning.

The predominant geological formations in the project area include a Quaternary Holocene artificially filled soil layer (Q4me), Quaternary Holocene residual slope deposit (Q4dl+el), Quaternary Holocene alluvial deposit (Q4al+pl) silt, and clay with gravel in the alluvium of the Pleistocene in the fourth series (Q2al). The underlying bedrock primarily consists of sandstone, sandy mudstone and mudstone interbedded with unequal thickness in the Upper Shaximiao Formation of the Middle Jurassic (J2s).

The automobile load rating is classified as Highway Class I, while the peak acceleration of seismic motion measures 0.05g; the bridge's seismic fortification category is class A [4].

3 Structural Design

3.1 Bridge Span Arrangement

The main bridge is constructed as a prestressed concrete cable-stayed bridge with a span of (110+210+110) m, while the approach bridges on both sides are prestressed concrete continuous T-girder bridges with a span of 40 m each. The bridge consists of a combination of 5 spans measuring 40 m each, followed by a section measuring 430 m (110+210+110 m), and then 4 more spans measuring 40 m each; the total length of the bridge is 799 m. The elevation layout of the bridge is shown in Figure 1.

The main bridge is constructed using a tower-girder-pier consolidation system, and at the junction piers (piers #5 and #8), both vertical bearings and horizontal limit stops are arranged.

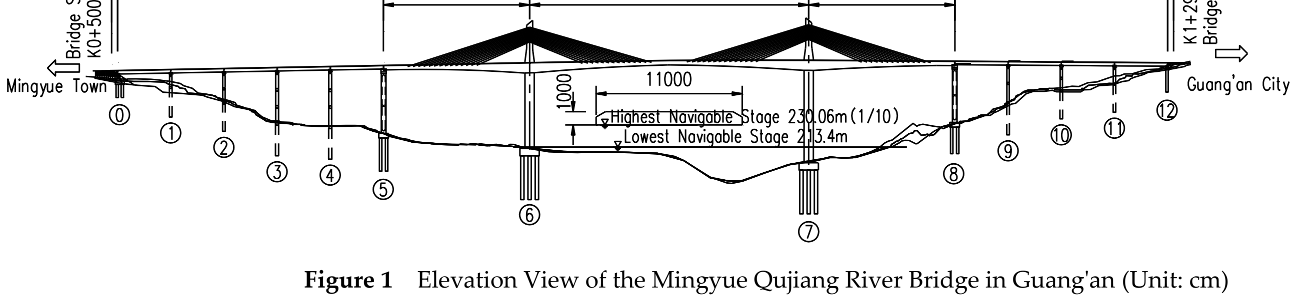

Figure 1 Elevation View of the Mingyue Qujiang River Bridge in Guang'an (Unit: cm)

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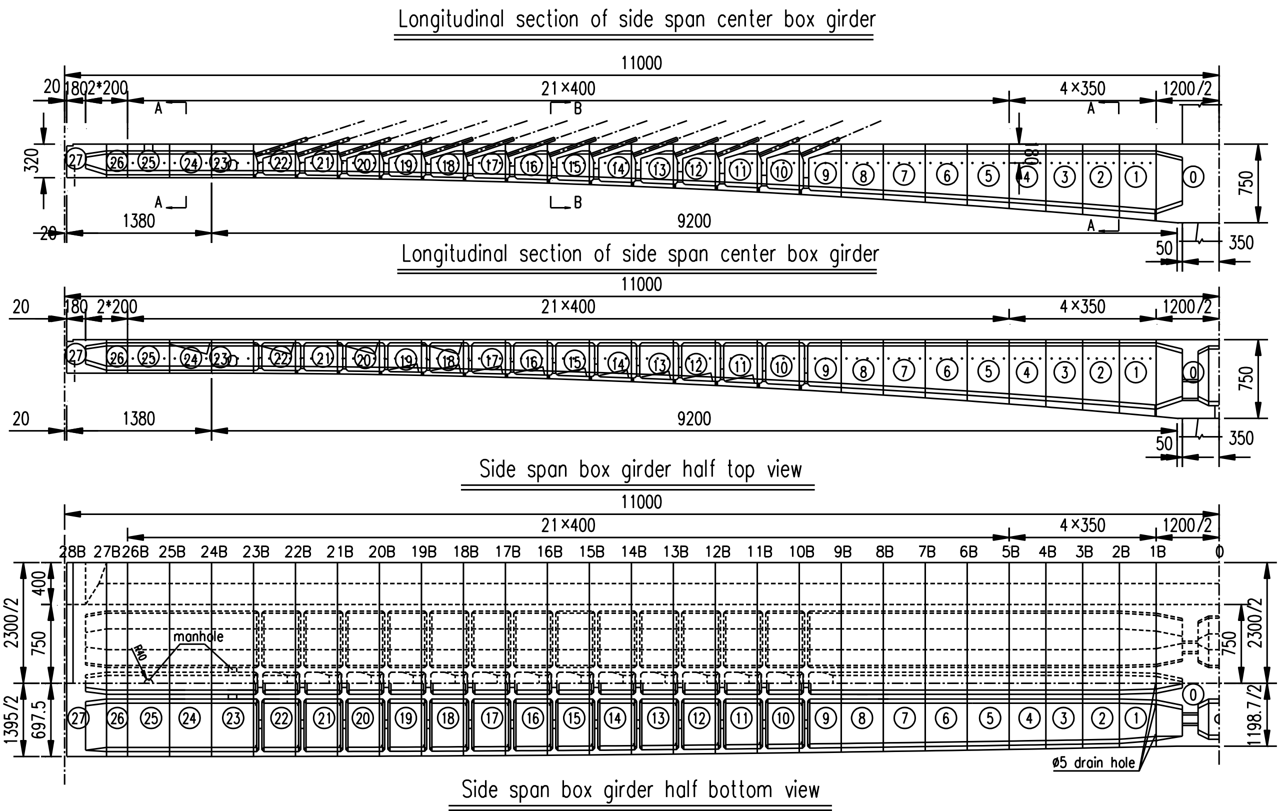
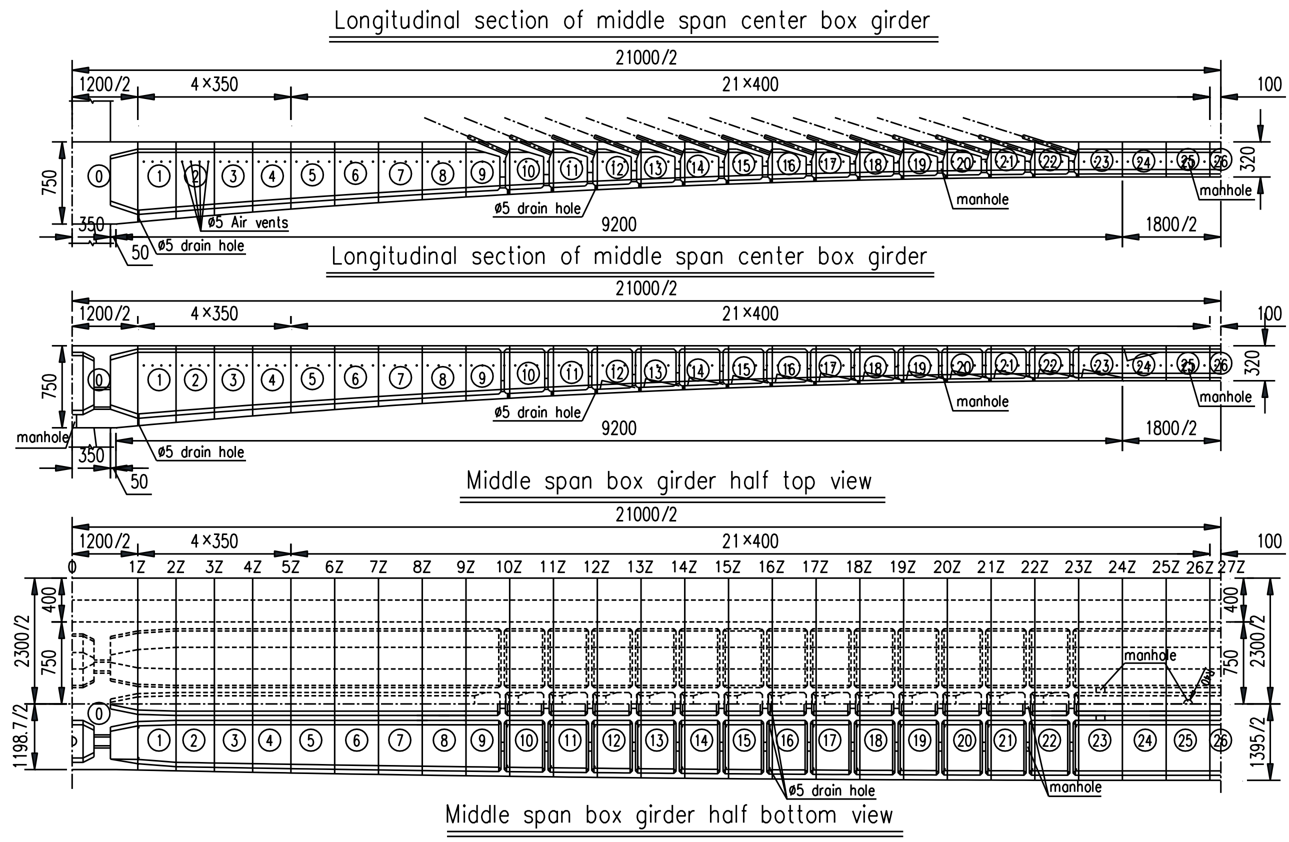
3.2 Girder Design

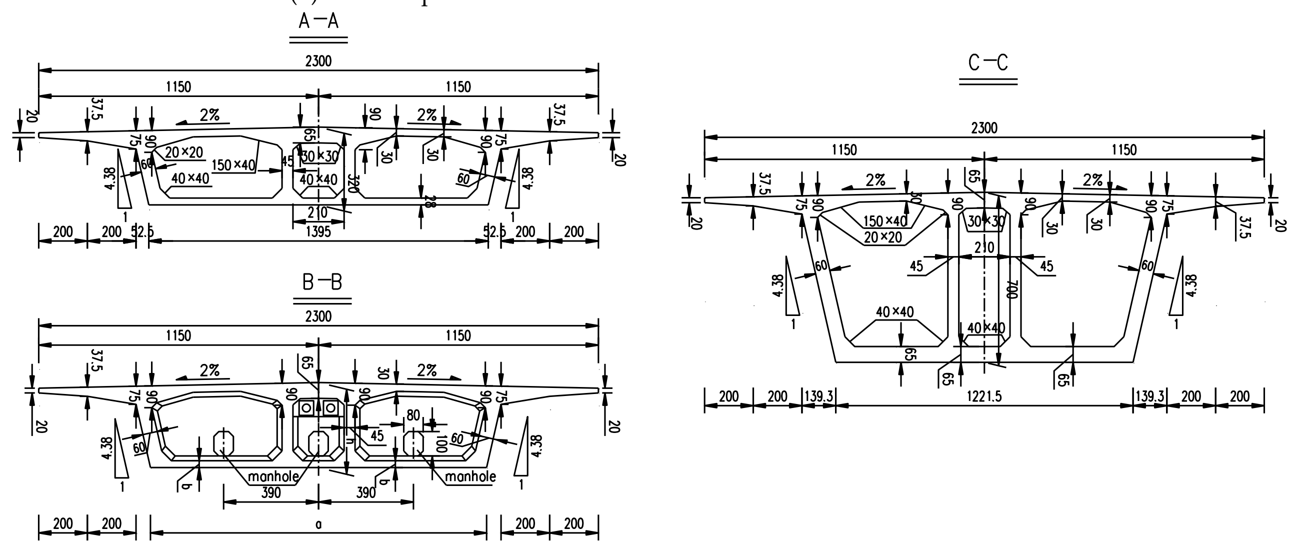
The girder is designed as a fully prestressed element featuring a variable-height single-box three-chamber section. The side webs are configured as inclined webs, and three-directional prestressed tendons are incorporated within the girder. C60 concrete is used for the construction. The girder features a bottom curve shaped like a second-order parabola, with a straight section length of 18.00 m for the middle span and 13.80 m for side spans. The top deck of the girder measures 23.0 m in width, and the cantilever length of the deck measures 4.00 m in length; the height of the girder at the mid-span is 3.20 m, and the girder height at the main pier top is 7.50 m. The top deck is 30 cm thick, whereas the bottom deck thickness increases from 28 cm at the mid-span to 70 cm at the top of the pier; the side webs have a thickness of 60 cm, and the middle web is 45 cm thick. The thickness of the cantilever board is 20 cm at the end, 37.5 cm in the middle, and 75 cm at the root. Transverse diaphragms are installed at the top of the pier and at the anchorages of the stay cables, with manholes incorporated on these partitions. The transverse diaphragm in the central chamber has a thickness of 50 cm, while the transverse diaphragm in the side chambers has a thickness of 30 cm. The thickness of the end beam is 180 cm. The bottom deck of the girder is horizontally level, whereas the top deck features a bidirectional slope of 2%. The zero block of the girder measures 12 m in length, and the standard segment lengths for cantilever construction are available in two options: 3.50 m and 4.00 m. The bridge has 3 closure segments, each measuring 2 m in length; the maximum weight allowed for the cantilever construction segments is 3201 kN. The general structural diagram of the girder is shown in Figure 2.



(a) Side Span



(b) Middle Span



(c) Girder Sections

Figure 2 General Structure of the Girder (Unit: cm)

Figure 3 shows the types of longitudinal prestressed tendons used in the box girder, which include five different specifications of high-strength and low-relaxation steel strands: 12 ϕ^s 15.2, 15 ϕ^s 15.2, 17 ϕ^s 15.2, 19 ϕ^s 15.2, and 22 ϕ^s 15.2. These tendons are designated for different purposes within the structure. Specifically, "T" refers to the tendons for the top slab of segmental cantilever, "W" refers to the tendons for the bottom slab of segmental cantilever, "ST" refers to the tendons for the top slab of side spans closure, "SB" refers to the tendons for the bottom slab of side spans closure, "CT" refers to the tendons for the top slab of mid spans closure, "CB" refers to the tendons for the bottom slab of mid spans closure, "Z" refers to the tendons in the mid-web slab, and "B" refers to the tendons in the side-web slab.

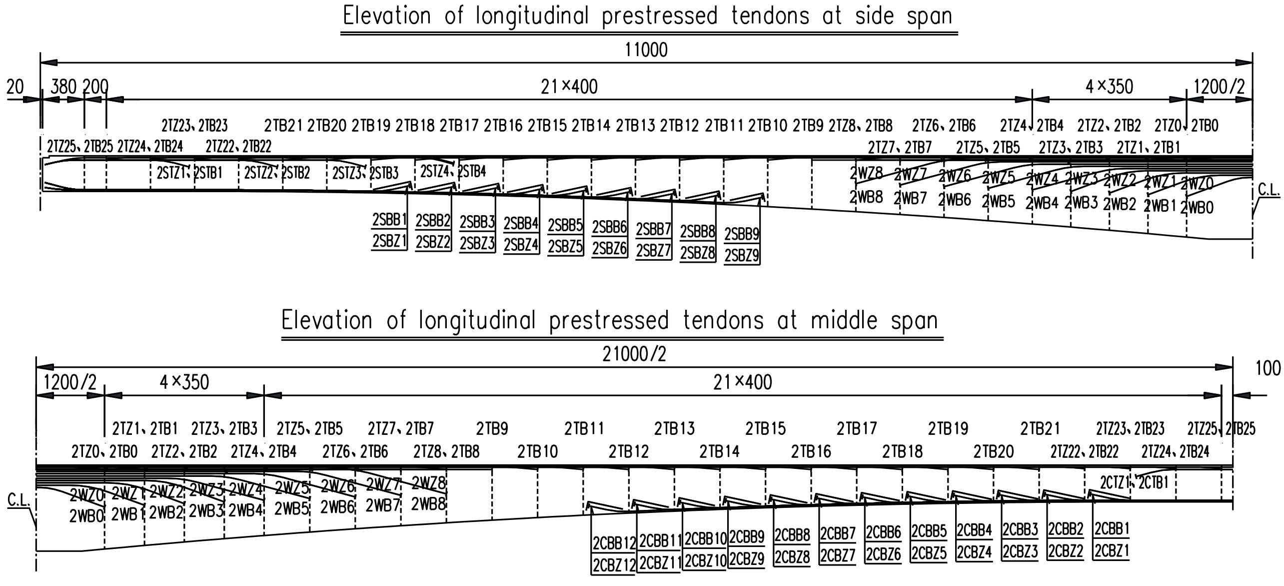


Figure 3 Layout Diagram of Longitudinal prestressed Tendons in the Girder (Unit: cm)

Table 1 Specifications for Girder Tendons

Middle Web Plate	WZ0-WZ8	TZ0-TZ8	TZ22-TZ25	STZ1-STZ4	SBZ1-SBZ9	CTZ1	CBZ1-CBZ12
Side web plate	WB0-WB8	TB0-TB12	TB13-TB25	STB1-STB4	SBB1-SBB9	CTB1	CBB1-CBB12
Specification	$15\phi^s 15.2$	$15\phi^s 15.2$	$19\phi^s 15.2$	$17\phi^s 15.2$	$12\phi^s 15.2$	$12\phi^s 15.2$	$22\phi^s$ 15.2

The girder adopts a three-dimensional prestressed system. Except for segment zero and the transverse prestressed tendons inside the end beam, which are 10 ϕ^s 15.2 strands, the vertical and transverse prestressed tendons in the remaining segments are all 5 ϕ^s 15.2 strands. The utilized tendons are high-strength low-relaxation steel strands with a flat anchorage system that exhibits low shrinkage. In the box girder, vertical prestressed tendons are arranged along the longitudinal web at approximately 50 cm intervals, alternating with the longitudinal web tendons within the web.

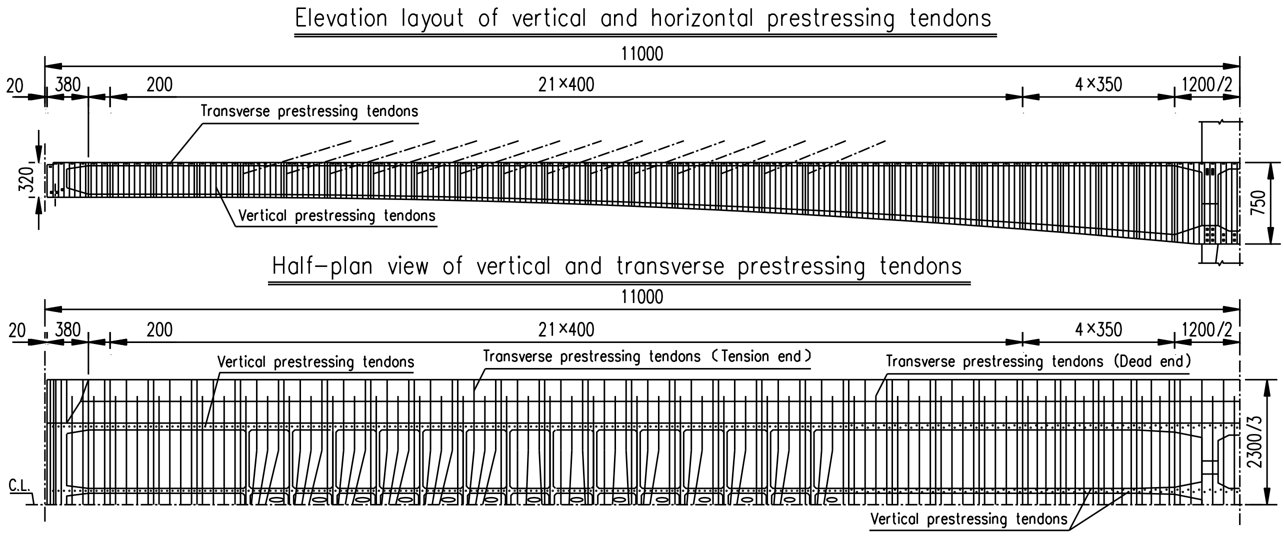


Figure 4 Layout Diagram of Transverse and Longitudinal Prestressed Tendons in the Girder (Side Span) (Unit: cm)

3.3 Main Tower

The main tower is a reinforced concrete structure with a rectangular cross-section on the central median strip. The main tower has a width of 2.5 m in the transverse direction and a gradually increasing width in the longitudinal direction from 4.5 m in the cable section to 7.0 m at the base of the tower. The tower has a height of 32.05 m. The anchoring method for the stay cables at the top of the tower utilizes a sleeve saddle structure. The main tower is constructed using C50 concrete, as shown in Figure 5.

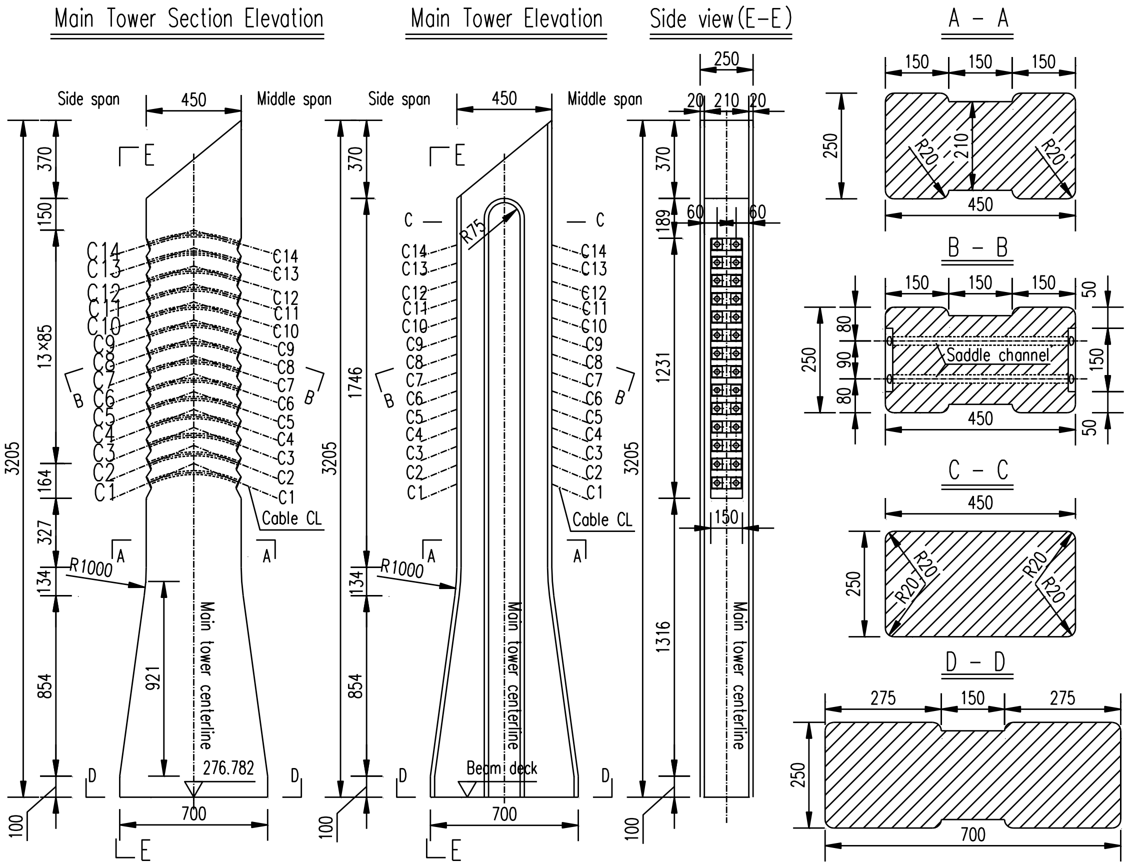


Figure 5 General Structure of the Main Tower (Unit: cm)

3.4 Stay Cable and Saddle Design

The bridge is furnished with 56 pairs of single-plane dual-row cables on the central median strip. The non-cable segment length of the girder near the base of the main tower is 36.00 m; the cable spacing on the girder is 4.00 m, while the cable spacing at the top of the tower is 0.85 m. The stay cables are constructed using high-strength epoxy-coated steel tendons. The specifications for cables C1 ~ C8 are 37 ϕ^s 15.2, while the specifications for cables C9 ~ C14 are 43 ϕ^s 15.2. The nominal strength of the steel tendons, also known as f_{ptk}, is 1860 MPa. For design purposes, the strength is typically taken as 0.55 times the nominal strength, which in this case would be 1023 MPa.

The cable saddles adopt a sleeve structure, where each steel tendon passes through its corresponding guide tube, creating a separate arrangement that does not interfere with each other. Anti-slip anchor cages are installed at both ends of the saddle on the tower, and special formula high-strength epoxy grout is poured after anchoring to resist the unbalanced cable forces on both sides of the tower saddle.

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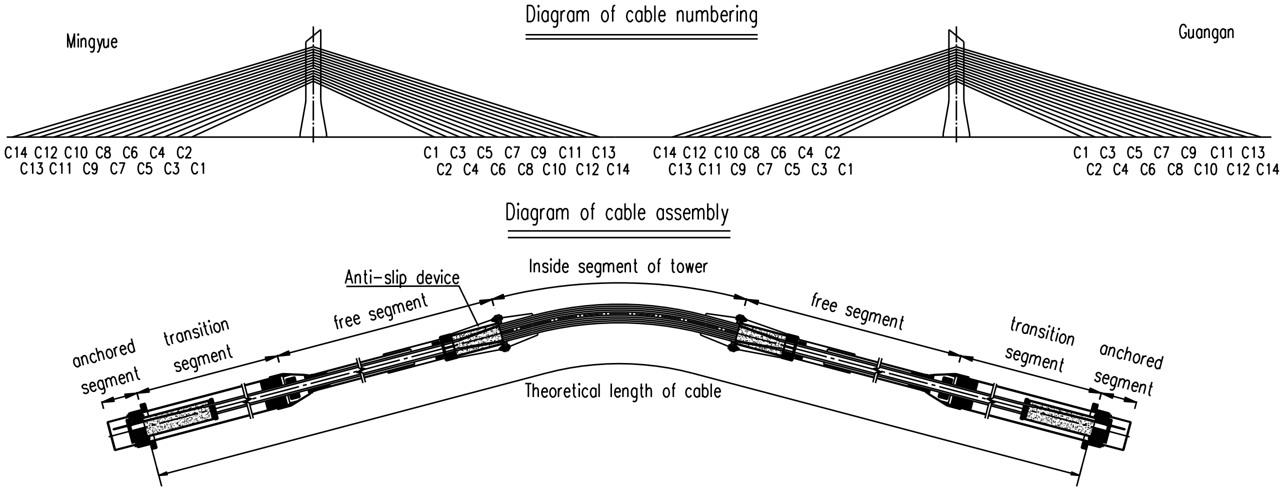

Figure 6 General Construction of Cables

Table 2 Cable Specifications and Design Cable Forces

Cable No.	Cable Specification	Saddle Type	Cable Length (m)	Cable Force (kN)
C1	37-ϕ^s15.24	M250AT-37	86.223	4487
C2			94.295	4553
C3			102.384	4599
C4			110.486	4632
C5			118.598	4651
C6			126.719	4669
C7			134.847	4685
C8			142.983	4693
C9	43-ϕ^s15.24	M250AT-43	151.123	4698
C10			159.269	4715
C11			167.418	4729
C12			175.575	4749
C13			183.728	4775
C14			191.888	4795

4 Main Bridge Calculation

4.1 Material Properties

The physical property parameters of the main materials used in the structural analysis of the main bridge are shown in Table 3 [6].

Table 3 Physical Property Parameters of Each Material

Material	Parameters	Value	Units
Concrete C50	Elasticity modulus	3.45 E+04	MPa
	Poisson's ratio	0.2	/
	Design value of compressive strength	22.4	MPa
	Standard value of compressive strength	32.4	MPa
	Design value of tensile strength	1.83	MPa
	Standard value of tensile strength	2.65	MPa

Material	Parameters	Value	Units
Concrete C60	Elasticity modulus	3.60 E+04	MPa
	Poisson's ratio	0.2	/
	Design value of compressive strength	26.5	MPa
	Standard value of compressive strength	38.5	MPa
	Design value of tensile strength	1.96	MPa
	Standard value of tensile strength	2.85	MPa
Steel strands	Elasticity modulus	1.95 E+05	MPa
	Nominal strength limit value	1860.0	MPa
	Poisson's ratio	0.3	/
	Density	8005	kg/m^3
Reinforcing bar	Elasticity modulus	2.00 E+05	MPa
	Design value of tensile strength	330.0	MPa
	Poisson's ratio	0.3	/
	Density	7850	kg/m^3

4.2 Load Conditions

The main tower of the main bridge is a concrete structure, and the box girder is designed as a fully prestressed concrete component. The static analysis of the construction stage and the completion stage is carried out by using a single girder model.

4.2.1 Permanent Effects

Permanent effects include structural gravity, prestress, cable force, foundation displacement, concrete shrinkage and creep. The detailed parameters are as follows:

(1) The bulk density of the main structure concrete is proposed to be 26.5 kN/m^3, and the bulk density of the pavement concrete is 25 kN/m^3;
(2) For the second phase, the dead loads such as bridge deck pavement and guardrails should be calculated based on their actual weight;
(3) The prestressed tendons and cable forces should be determined based on the design values;
(4) Uneven settlement: The main piers should be calculated with a settlement of 2 cm, while the junction piers should be calculated with a settlement of 1 cm;
(5) Concrete shrinkage and creep should be calculated based on the specifications [5].

4.2.2 Variable Effects

Variable effects include vehicle loads, crowd loads, temperature effects, etc. In the calculations, the construction loads during the construction (e.g. hanging baskets) and the structural internal forces, stresses, and displacements caused by the lane load during the service phase are taken into account. The parameter values for variable effects are as follows:

(1) Vehicle load class: Highway Class I; the vehicle loads are considered for a four-lane configuration in both directions, taking into account longitudinal reduction, transverse reduction, and the effect of eccentric loading; the transverse distribution factor for vehicle loads is taken as 3.484;
(2) The calculation of car braking forces follows the specifications outlined in the General Specifications for Design of Highway Bridges and Culverts (JTG D60-2015) [4], using a two-lane configuration in the same direction;
(3) The crowd load is determined based on the General Specifications for Design of Highway Bridges and Culverts (JTG D60-2015) [4], with a value of 2.5 kN/m^2.

(4) The design closing temperature range is set between 15 to 18°C, considering the following temperature effects: System warming by 25°C and system cooling by 25°C;

(5) The temperature gradient is determined based on the specifications outlined in the General Specifications for Design of Highway Bridges and Culverts [4], specifically Section 4.3.10. For the given case, T1 is taken as 14°C, and T2 is taken as 5.5°C;

(6) During the calculation, the dead weight of the hanging basket, including the formwork, is considered as 1600 kN; if there are any changes in the weight of the hanging basket, it is necessary to recalculate the internal forces and elevations depending on the actual conditions.

4.3 Static Calculation Results of Main Bridge

The calculation results for the girder during the construction are shown in the diagram below, where tensile stress is represented as positive values and compressive stress is represented as negative values. It can be seen that the maximum compressive stress during the girder construction is -20.5 MPa, located at the lower edge of the mid-span; the maximum tensile stress is 0.5 MPa, located at the anchor position of the C1 cable girder end; the stress calculation results comply with the Code [6].

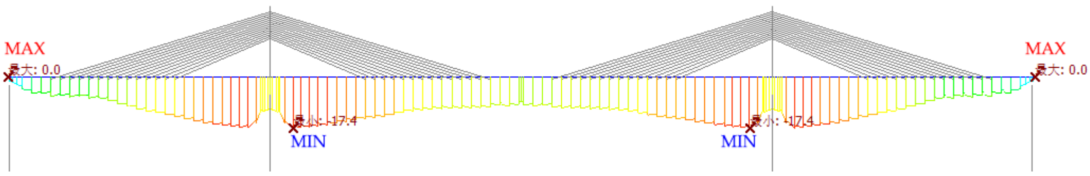

Figure 7 Minimum Stress on Top Edge of the Girder (Unit: MPa)

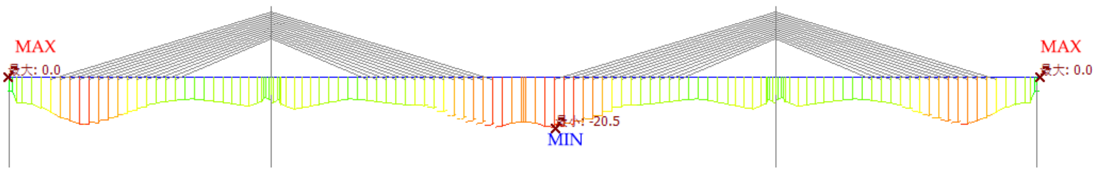

Figure 8 Minimum Stress on Bottom Edge of the Girder (Unit: MPa)

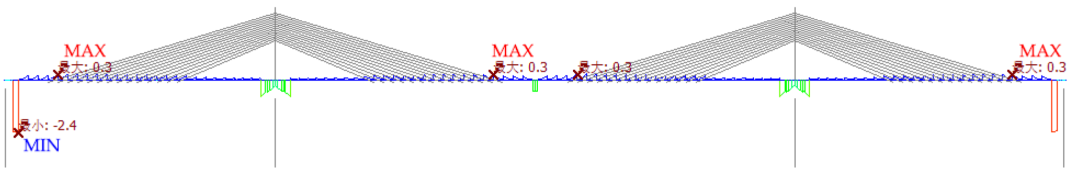

Figure 9 Maximum Stress on Top Edge of the Girder (Unit: MPa)

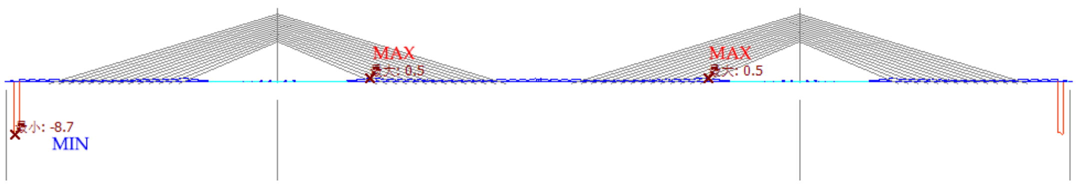

Figure 10 Maximum Stress on Bottom Edge of the Girder (Unit: MPa)

The girder's load-bearing capacity includes its bending load-bearing capacity and shear load-bearing capacity. The envelope diagram below shows that both the bending moment and shear force of the girder are smaller than its load-bearing capacity, which meets the requirements of Code [6].

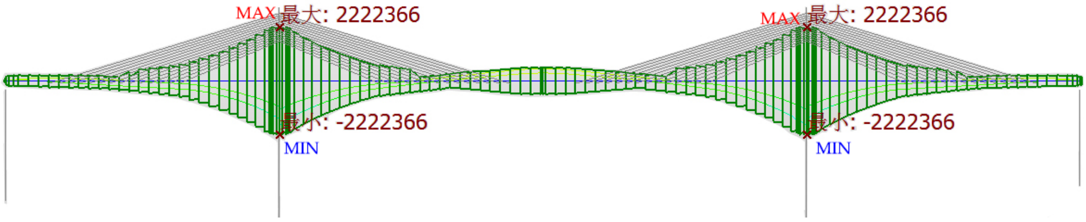

Figure 11 Bending Torque Envelope of the Load-bearing Capacity of the Girder (Unit: N*m)

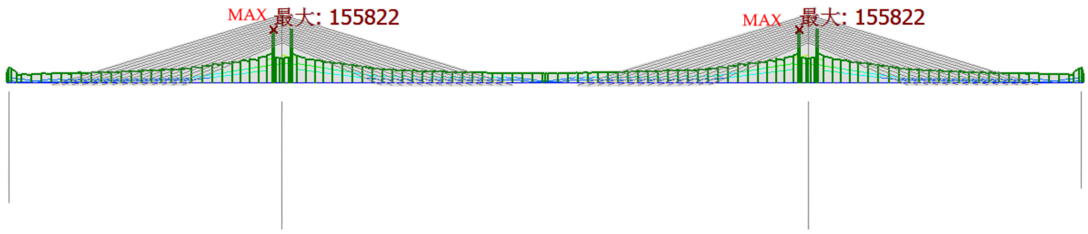

Figure 12 Shear Envelope of the Load-bearing Capacity of the Girder (Unit: kN)

The check calculation results of crack resistance in the limit state of the normal use of girder are shown in the figure below, where tensile stress is represented as positive values and compressive stress is represented as negative values.

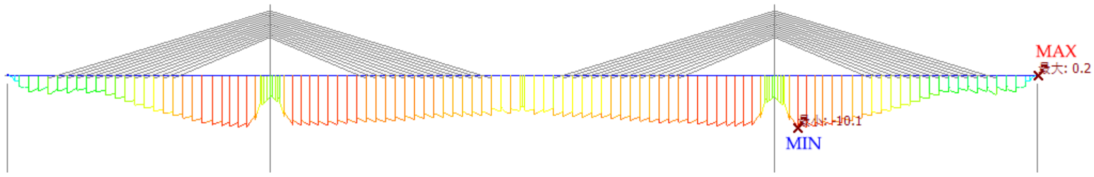

Figure 13 Top-edge Stress Envelope Diagram of the Girder (Unit: MPa)

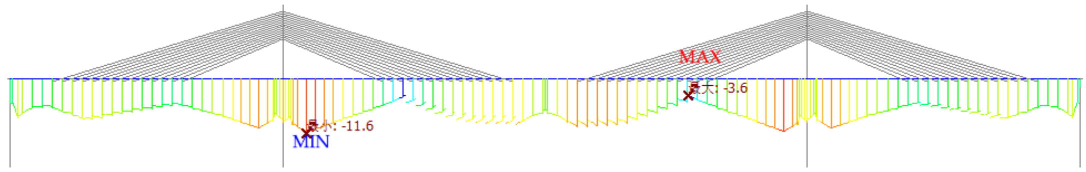

Figure 14 Bottom-edge Stress Envelope Diagram of the Girder (Unit: MPa)

The check calculation results of stress in limit state of the normal use of girder are shown in the figure below, where tensile stress is represented as positive values and compressive stress is represented as negative values.

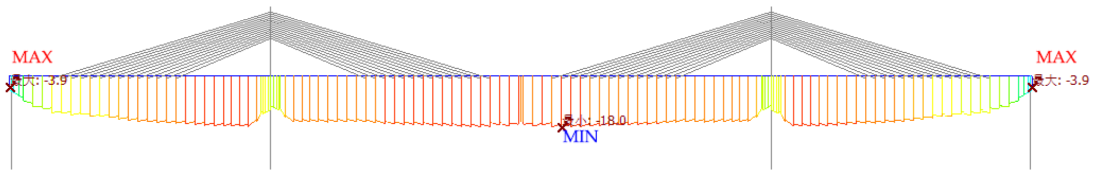

Figure 15 Top-edge Stress Envelope Diagram of the Girder (Unit: MPa)

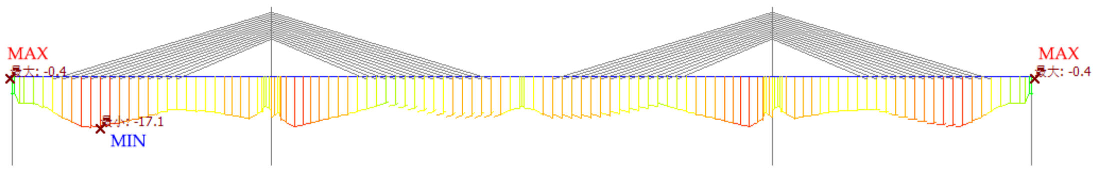

Figure 16 Bottom-edge Stress Envelope Diagram of the Girder (Unit: MPa)

4.4 Calculation of Stay Cable Forces

The calculation results for cable stresses are presented in the following table:

Table 4 The results of cable stresses

Side Span (Unit: MPa)				Main Span (Unit: MPa)			
Cable No.	**Max Stress**	**Min Stress**	**Stress Amplitude**	**Cable No.**	**Max Stress**	**Min Stress**	**Stress Amplitude**
No. 1	800.4	725.1	75.3	No. 1	825.9	747.9	78.0
No. 2	822.9	746.6	76.3	No. 2	847.9	769.7	78.2
No. 3	842.0	764.3	77.7	No. 3	866.6	787.9	78.7
No. 4	860.4	780.8	79.6	No. 4	882.9	803.4	79.5
No. 5	878.5	797.0	81.5	No. 5	898.2	817.7	80.5
No. 6	898.0	814.3	83.7	No. 6	914.0	832.6	81.4
No. 7	918.6	832.5	86.1	No. 7	930.3	847.8	82.5
No. 8	939.7	850.7	89.0	No. 8	946.1	862.5	83.6
No. 9	835.2	742.8	92.4	No. 9	835.4	750.7	84.7
No. 10	859.0	762.8	96.2	No. 10	853.5	767.6	85.9
No. 11	884.7	784.3	100.4	No. 11	872.0	784.9	87.1
No. 12	912.5	807.4	105.1	No. 12	892.0	803.8	88.2
No. 13	943.8	833.4	110.4	No. 13	913.9	824.5	89.4
No. 14	983.4	867.0	116.4	No. 14	944.8	854.3	90.5

The maximum stress in the stay cable is 983.4 MPa, which is below 0.55 times the standard strength of 1023 MPa. This satisfies the requirements specified in the Code [5], and the minimum safety factor is 1.89.

4.5 Stability Analysis

Taking into account the influence of construction and operational wind loads, the calculation results are as shown in the following table:

Table 5 Stability Factors for Various Conditions:

Condition	Maximum Double Cantilever Stage	Maximum Single Cantilever Stage	Service Stage (With Vehicles)	Service Stage (Without Vehicles)
1	32.8	31.1	36.9	38.0
2	33.5	43.1	38.3	39.4
3	65.2	63.6	38.3	48.2

Elastic Eigenvalue Stability Analysis Table: During the construction of the main bridge, the minimum safety factor for stability is 32.8. During the bridge completion, the minimum safety factor for stability is 36.9. Both values are greater than 4, satisfying the requirements specified in the Code [6].

4.6 Seismic Analysis

A three-dimensional finite element model of the entire bridge was constructed to calculate internal forces and deformations under seismic loads. Taking into account the design code requirements and utilizing available geological data, seismic ground motion input was reasonably determined. Time history analysis was employed to calculate the effects under different seismic motions.

The calculation results indicate that under both E1 and E2 seismic actions, the bridge meets the requirements outlined in the "Seismic Design Code for Highway Bridges.

5 Conclusion

The Mingyue Qujiang Bridge features a prestressed concrete cable-stayed main span with a length of (110+210+110) meters. The girder section of the main pier top has a height of 7.5 m, while the mid-span section has a height of 3.2 m. Compared to continuous rigid-frame bridges with similar spans, this design significantly reduces the girder height, resulting in an improvement in main girder stress.

Compared to cable-stayed bridges with similar spans, this bridge requires fewer stay cables, and the cable stress amplitudes are low. Additionally, the safety factor requirements have been reduced from 2.5 to 1.5. This bridge design is highly competitive for main spans ranging from 200 m to 300 m.

The outcomes of this study can be used as a reference for the design of partially cable-stayed bridges with similar spans.

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