Design and Construction

Structural Design and Static Analysis of the Cable-stayed Bridge on Xuefu Road

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Abstract: The cable-stayed bridge on Xuefu Road is a single-pylon spatial double-cable-plane cable-stayed structure with a main span of 160 m. The main girder is a PK-section flat steel box girder, while the main pylon is made from reinforced concrete. With a width ranging from 46.1 to 57.5 m, it is currently the widest single-pylon cable-stayed bridge with steel box girder in China. A comprehensive review has been conducted on the structural design and static analysis of the cable-stayed bridge on Xuefu Road, which can provide a reference for future projects of a similar nature.

Keywords: single-pylon cable-stayed bridge; steel box girder; structural design; static analysis

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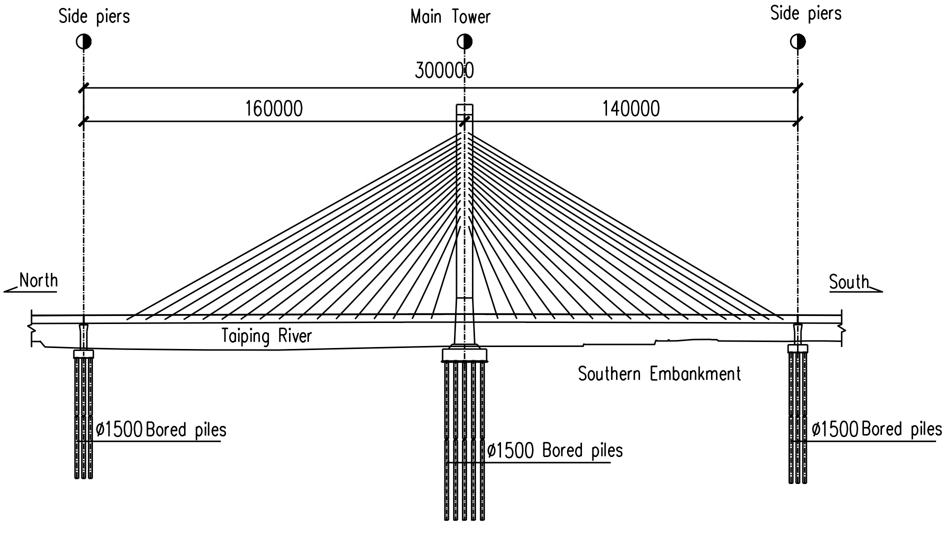
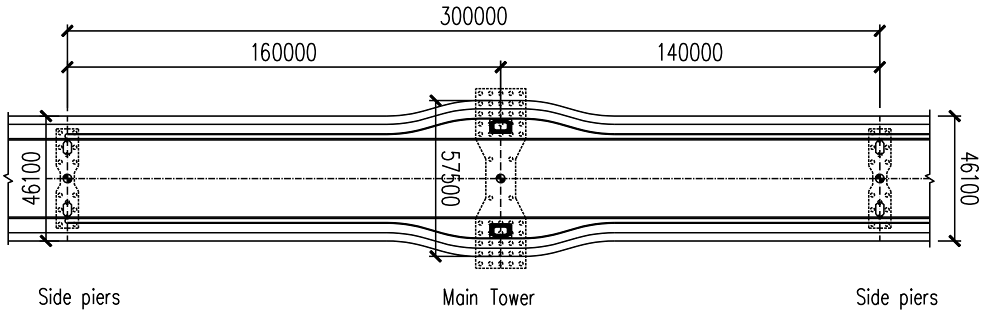
1 Project Overview

A cable-stayed bridge is a structural system composed of three fundamental components: pylon, girders and cables [1,2]. With the rapid growth of large-span bridge development in China, cable-stayed bridges have swiftly evolved and gained popularity thanks to their visually appealing designs and excellent spanning capacity, particularly single-pylon cable-stayed bridges, which have emerged as highly competitive options for urban bridges ranging from 100 to 300 m in length [3,4].

The cable-stayed bridge on Xuefu Road in Shijiazhuang starts at Cuiping Road in the north and extends southward, crossing the Taiping River. The main bridge is a single-pylon spatial double-cable-plane cable-stayed structure with a span of 160+140 m (see Figure 1). The main span crosses the deep-water area of the Taiping River channel, and the side span crosses the southern embankment. The width of the bridge ranges from 46.1 m (standard segment) to 57.5 m (widest point around the pylon). The main girder is constructed as a PK-section flat steel box girder, the main pylon is a reinforced concrete structure taking on the form of a standing person in the transverse direction, and the lower structure is supported by ϕ1.5 m bored cast-in-place piles.



(a) Elevation



(b) Plan

Figure 1 General layout of the cable-stayed bridge on Xuefu Road (Unit: mm)

2 Technical Specifications

The main technical specifications are as follow:

(1) Road class: Urban arterial road.
(2) Design speed: 50 km/h.
(3) Bridge design safety level: Class 1.
(4) Bridge design load: Urban - Grade A; design values for non-vehicular live loads are subject to the Code for design of the municipal bridge (2019 edition).
(5) Bridge design base period: 100 years.
(6) Seismic design class: A; seismic design intensity: VII; peak ground acceleration: 0.10 g.
(7) Design flood frequency: 100 years.
(8) Design basic wind speed: V10 = 27.9 m/s (with a recurrence interval of 100 years).
(9) Environmental class for durability design: I.

3 Main Bridge Design

3.1 Structural System Design

The cable-stayed bridge on Xuefu Road has a span arrangement of 160+140 m and features a single-pylon spatial dual-cable-plane design, creating a semi-floating system. The main girders are constructed as PK-section steel box girders with fixed bearers, lateral wind-resistant bearers and longitudinal blocks arranged at the main pylon; movable bearers and lateral stoppers are arranged at the side piers. All bearers are spherical steel bearers, and the side spans of the girders are furnished with concrete weights.

3.2 Main Girder Design

The main girders are PK-section flat steel box girders made of Q345qD structural steel suitable for bridge construction; the cable area is equipped with single-box double-chamber enclosed side girders, and the side girders are connected to the whole structure through the crossbeams. The width of the standard segment of the bridge is 46.1 m (excluding the wind faring); the girder height is 3.315 m at the road center line, the top deck is designed with a 1.5% bidirectional slope, and the bottom deck remains horizontal (see Figure 2). U-rib orthotropic steel deck slabs are arranged within the roadway area to minimize the fatigue stress, and I-rib orthotropic steel deck slabs are arranged within the non-vehicular area to lower costs.

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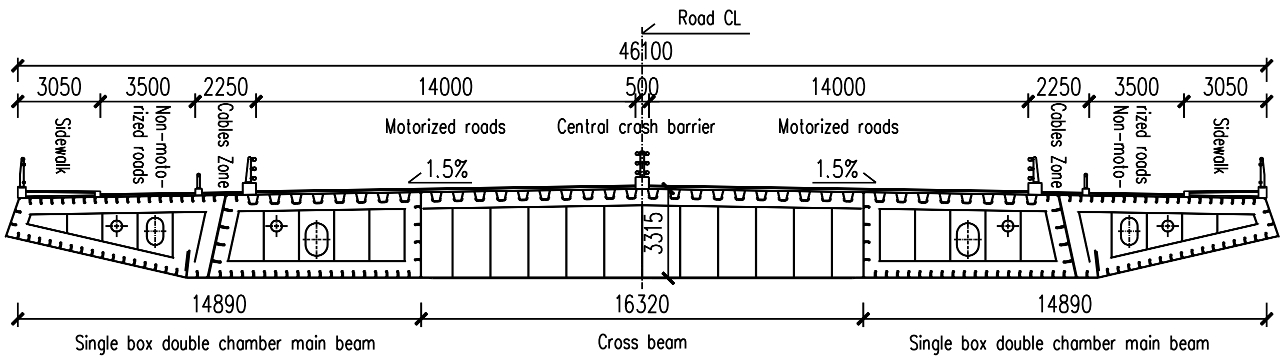

Figure 2 Cross-section of a standard segment of the cable-stayed bridge (Unit: mm)

Approximately 42 m from the bridge pylon, the main girder progressively widens from 46.1 m at the standard segment to 57.5 m (the widest) around the pylon through a circular curve. The pylon runs through the bridge deck from the preset area around the pylon, the girder height at the center line of the road is 3.324 m, and the bearer spacing is 27.94 m (see Figure 3).

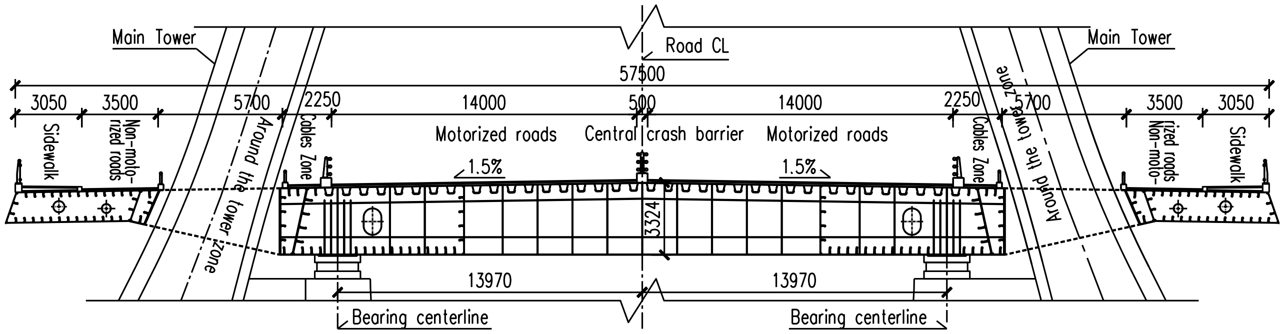

Figure 3 Cross-section of the around-pylon segment of the cable-stayed bridge (Unit: mm)

Considering the requirements for girder fabrication and construction, all steel box girders for the bridge are divided into six major categories, namely A to F; category D is located at the widening point of the girder body and falls into six subcategories, namely D1 to D6; overall, the bridge comprises a total of 37 segments. Segments A and F are at the end of the girder area and are 9.11 m long; segment C is a standard segment and is 8.0 m long; segments B and E are transition segments and are 6.0 m long; segments D1 to D6 are widening segments, with D1 to D4 being 8.0 m long and D5 and D6 being 10.0 and 13.5 m long, respectively (see Figure 4).

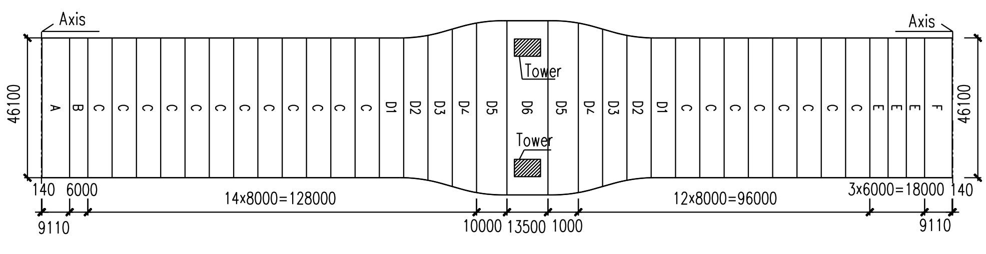

Figure 4 Segmentation of steel box girder for the entire bridge (Unit: mm)

3.3 Main Pylon Design

The main pylon is a spatially shaped cable pylon fabricated from C55 reinforced concrete, taking on the form of a "人" shape in the transverse direction of the bridge. The total height of the main pylon is approximately 102.75 m, and the height above the bridge deck is 88 m. From top to bottom, it is divided into five parts: a pylon crown, upper pylon column, middle pylon column, lower pylon column, and pylon pedestal (see Figure 5). A transition beam is arranged at a height of 57.9 m to progressively merge the lower bifurcated double-leg column into a whole structure. Within the 88 m area of the main pylon above the bridge deck, the transverse section is 4.3 m of equal width, and the width gradually increases to 7.5 m within the 11.5 m area below the deck. Along the central axis of the bridge, the area approximately 19.45 m away from the pylon pedestal is 6.8 m of equal width, and it gradually increases to 8.5 m within the 19.45 m area.

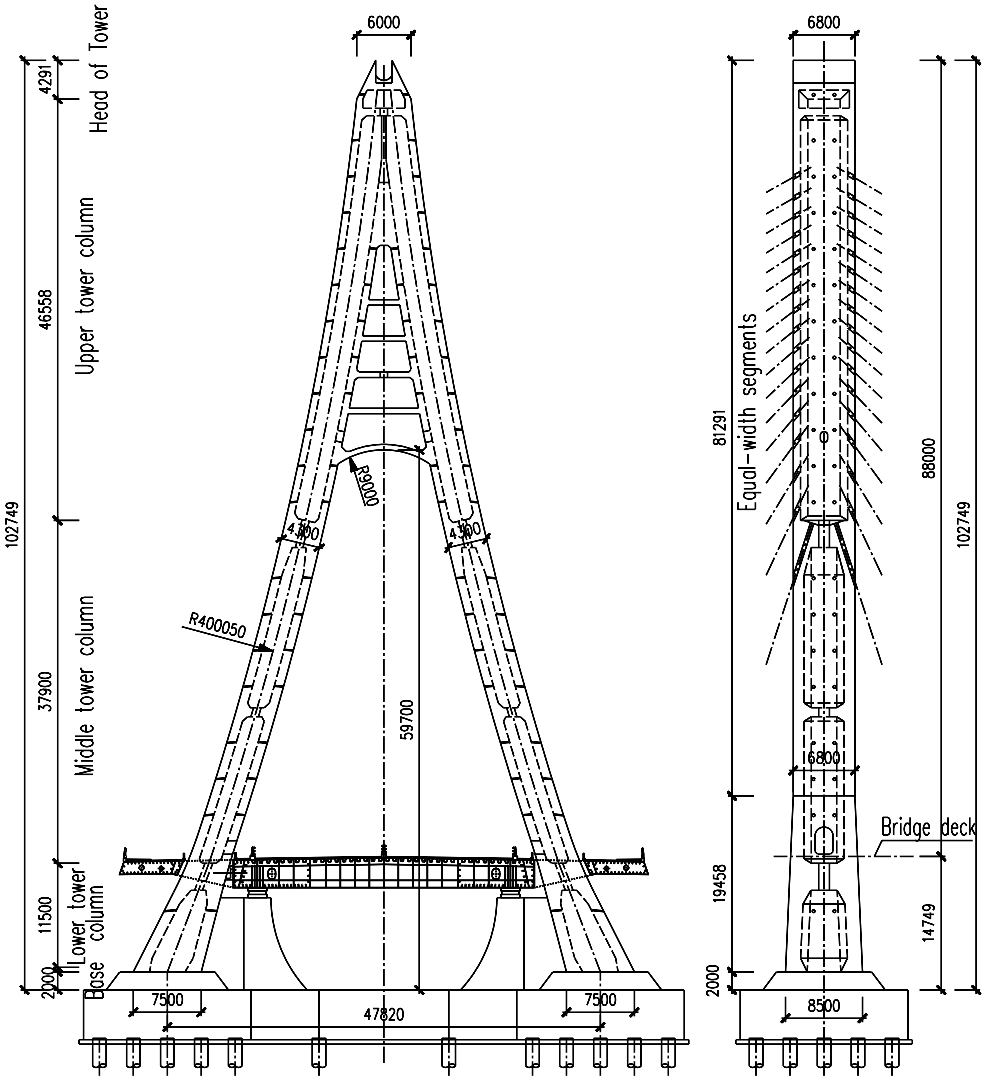

Figure 5 Structural view of the main pylon (Unit: mm)

3.4 Foundation Design

The foundation for the main pylon is composed of bored cast-in-place piles and dumbbell caps. Under each pylon are 25 ϕ 1.5 m bored cast-in-place piles, whose toes reach into the pebble layer. With a plane size of 18.5 (axis direction of the bridge) × 66.32 m (transverse direction of the bridge) and a thickness of 5.5 m, the caps are constructed of C40 concrete; on the caps are 2.0 m-thick C40 pedestals, and below the caps is 0.5 m-thick C25 bottom-sealing concrete (see Figure 6).

The caps are made of mass concrete, and 5 layers of cooling water pipes are arranged evenly in along the height; 36 ϕ^s 15.2–19 1860 MPa high-strength low-relaxation steel strands are arranged in the transverse direction of the bridge to resist the force component on the pylon in the transverse direction of the bridge, thereby improving the stress in the pile caps.

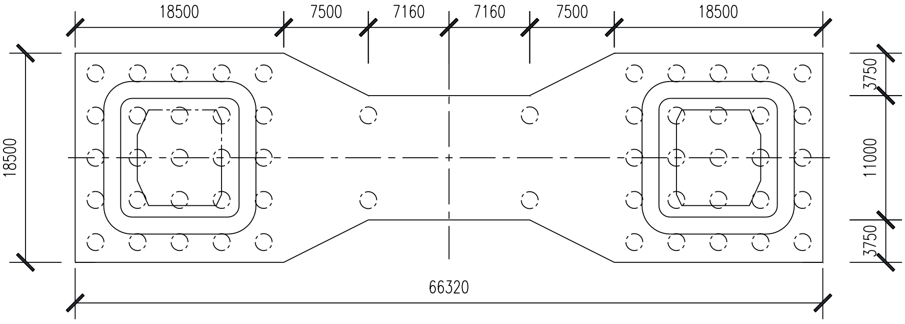

Figure 6 Plan of the pile-cap foundation for the main pylon (Unit: mm)

The side pier is a detached vase pier constructed of C40 concrete, and its structural size is 3.0 (axis direction of the bridge) × 5.0 m (transverse direction of the bridge). The cap is a dumbbell cap built of C35 concrete with a plane size of 8.2 (axis direction of the bridge) × 36.6 m (transverse direction of the bridge); below each pier are 8 ϕ 1.5 m bored cast-in-place piles.

3.5 Stay Cable Design

The stay cable for the main bridge employs a spatial double-cable-plane layout; the cable spacing on the main pylon is 2.3~3.4 m; the standard cable spacing on the main girder is 8.0 m, and the girder-end cable spacing on the side span is 6.0 m. A total of 34 pairs and 68 stay cables are arranged throughout the bridge; the stay cables are designed with a horizontal inclination of 28~70° and a maximum length of approximately 163 m. The maximum tonnage of a single cable is approximately 650 t, and the safety factor is not less than 2.5.

The stay cables are made of high-strength galvanized steel wires, featuring a strength of 1860 MPa. The steel tendons are furnished with dual-layer PE sheaths, and the stay cable specifications are PES7-211, 223, 253, 313 and 337; the anchors are chill-cast anchors. Built-in dampers are installed at both ends of the stay cable to absorb energy and alleviate shock; the outer surface of PE sheath is threaded to reduce the effect of rain chatter.

The stay cables are anchored into the built-in steel anchor box of the main pylon, and the steel anchor box is connected with the concrete pylon wall through welded pins; they are anchored onto the cantilever steel anchor box at the middle web of chamber on the main girder, and the steel anchor box is welded to the middle web.

4 Static Analysis

4.1 Analytical Model

An overall space bar system analysis model was built for the stayed-cable bridge on Xuefu Road using the large general-purpose finite element analysis software Midas Civil (Figure 7). The main girder, main pylon, and piers were subjected to girder element simulation; the stay cables were processed only through tensioned truss element simulation; the pile foundation was simulated through spring elements; the section size is based on the actual size, and the deck widening is simulated with equivalent stiffness; the whole bridge consisted of 846 elements and 707 nodes.

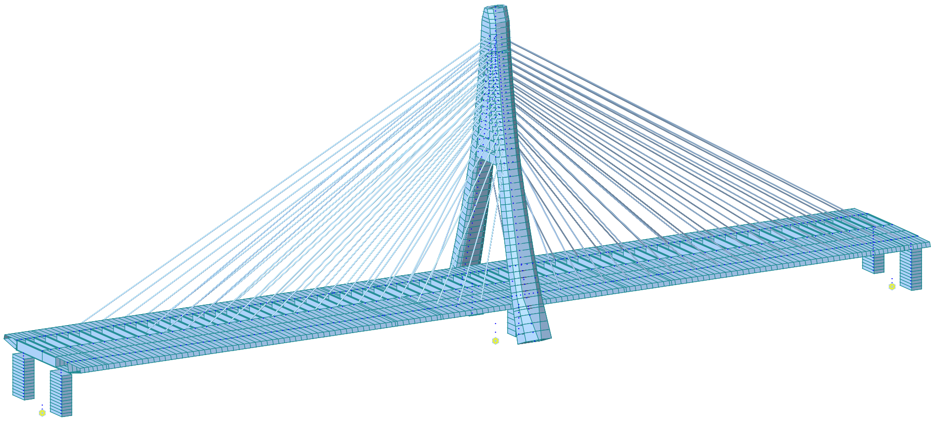

Figure 7 Overall analysis model

4.2 Stay Cable Analysis

The optimization methods for cable-stayed bridges' cable forces can be categorized into four types: the Influence Matrix Method, Constrained Optimization Method, Specified State Method, and Unconstrained Optimization Method [5]. The Influence Matrix Method is based on the linear superposition principle, which allows for the determination of the numerical relationship between cable forces and internal forces and displacements. This method enables the establishment of objective functions and constraints based on internal forces and displacements, facilitating the reverse calculation of reasonable cable forces.

The structural strain energy of a bridge includes the summation of three types of strain energy: bending, tensile/compressive, and shear. In this bridge, minimizing the structural strain energy is chosen as the optimization objective for determining cable forces. The impact of shear strain energy is neglected for this purpose. To achieve this optimization, a program is utilized to generate the influence matrix, which describes how each unit of cable force affects the bending moments and axial forces at various sections. This forms the basis for the optimization objective function with 34 pairs of cable forces as independent variables.

The constraints are primarily focused on three aspects:

(1) Main Girder Alignment After Bridge Completion: Vertical displacements at specific locations on the main girder are restricted. These constraints are as follows:
   (a) Vertical displacement at $L/4$, $L/2$, and $3L/4$ of the main span: 80 mm $\leq D_{Z1} \leq$ 80 mm.
   (b) Vertical displacement at $L/4$, $L/2$, and $3L/4$ of the side spans: 70 mm $\leq D_{Z2} \leq$ 70 mm.

(2) Tower Top Displacement: The vertical displacement of the tower top is constrained with the following limits: 0 mm $\leq D_Y \leq$ 20 mm (positive values indicate a deviation towards the side span).

(3) Cable Forces (N) Constraints: The cable forces (N) are subject to the following constraints: $0.25\ R_k A_s \leq N \leq 0.45\ R_k A_s$.

Here, R_k represents the standard tensile strength of the cables (1860MPa). A_s is the cross-sectional area of a single cable.

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The process for determining the cable forces is illustrated in Figure 8, and the final cable forces after bridge completion are presented in Table 1.

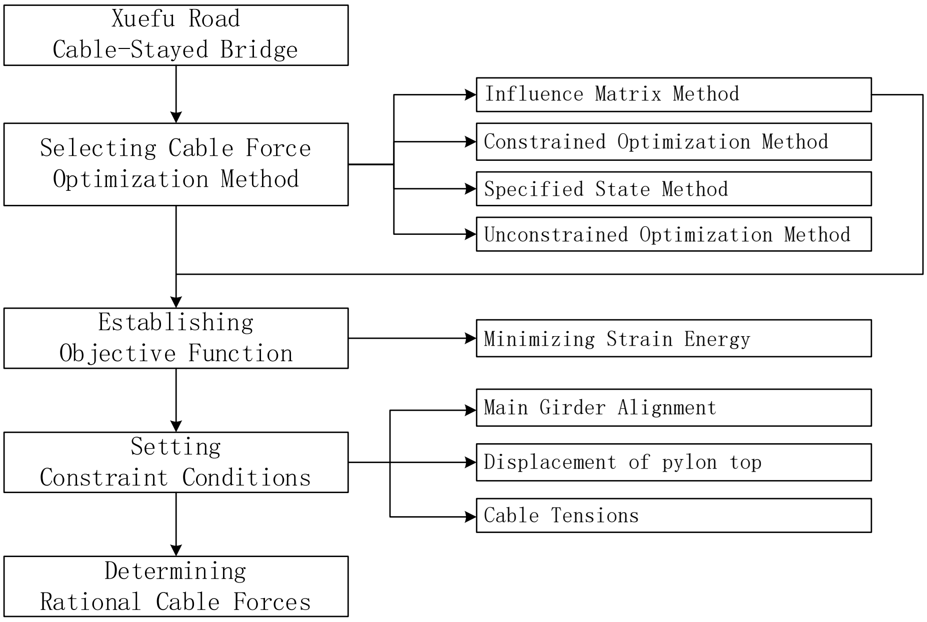

Figure 8 Flowchart for rational cable force determination

Table 1 Cable forces after bridge completion (Unit: kN)

Cable No.	Cable Force Main Span	Cable No.	Cable Force Main Span	Cable No.	Cable Force Side Span	Cable No.	Cable Force Side Span
S1	6176.23	S10	3901.15	S1‘	6605.15	S10'	3902.18
S2	4378.16	S11	3517.57	S2’	4598.10	S11'	3509.68
S3	5997.84	S12	4537.85	S3'	5500.68	S12'	4555.54
S4	4829.20	S13	3029.43	S4'	5386.27	S13'	3018.00
S5	4712.31	S14	1815.23	S5'	5205.39	S14'	1816.46
S6	4556.34	S15	3678.14	S6'	5292.94	S15'	3681.70
S7	4388.76	S16	3557.50	S7'	4362.76	S16'	3601.49
S8	4233.42	S17	4585.98	S8'	4224.14	S17'	4504.39
S9	4050.30	/	/	S9'	4054.97	/	/

Note: S1 and S1’ represent the longest cable of main span and side span, respectively.

After determining the rational cable forces as per the above-mentioned method, the safety verification of the stay cables is conducted using the limit state method in accordance with the requirements of the Specifications for Design of Highway Cable-stayed Bridge (JTG/T 3365-01-2020), Section 7.2.4.

The stress range for the stay cables was 255 ~ 771 MPa under the bearing capacity combination; the maximum stress was observed at the girder-end stay cable at the side span, while the minimum stress was observed at the fourth stay cable at the side span away from the main pylon (see Figure 9). The maximum stress was approximately 771 MPa, which is less than the design value of 1860 MPa for the tensile strength of a stay cable; hence, the design meets the specification requirements and contains a certain safety margin.

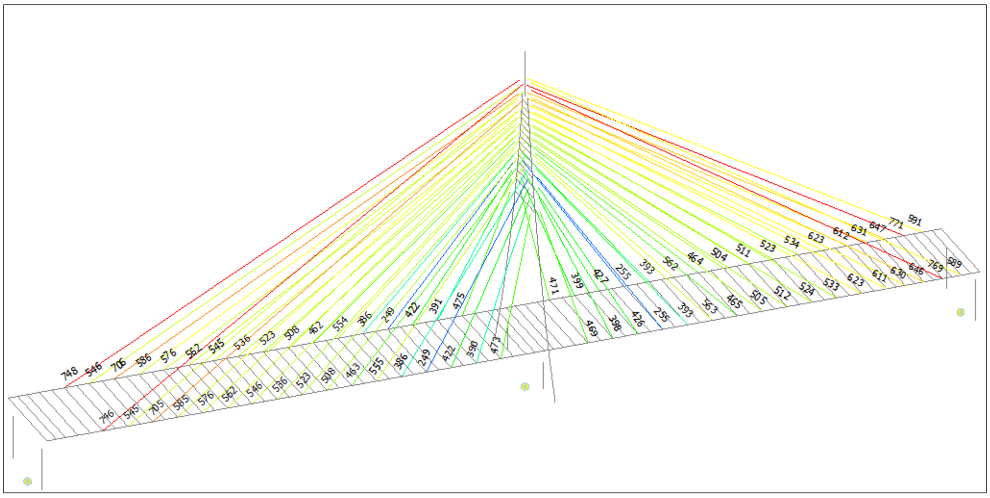

Figure 9 Stress diagram of stay cable under the bearing capacity combination (Unit: MPa)

4.3 Main Girder Analysis

Under the combined bearing capacity, the maximum tension stress in the main girder is approximately 114 MPa, while the maximum compressive stress is approximately 144 MPa, indicating that the stress is even in the main girder; due to the fact that the horizontal component of the stay cable is gradually transferred to the main girder, the full section of the main girder near the main pylon is compressed (see Figure 10). The maximum stress in the main girder is always less than 270 MPa, which is lower than the strength design value of a steel girder; that is, the requirements stated in Section 3.2.1 of the Design Specifications of Highway Cable-stayed Bridges (JTG D64-2015) are met.

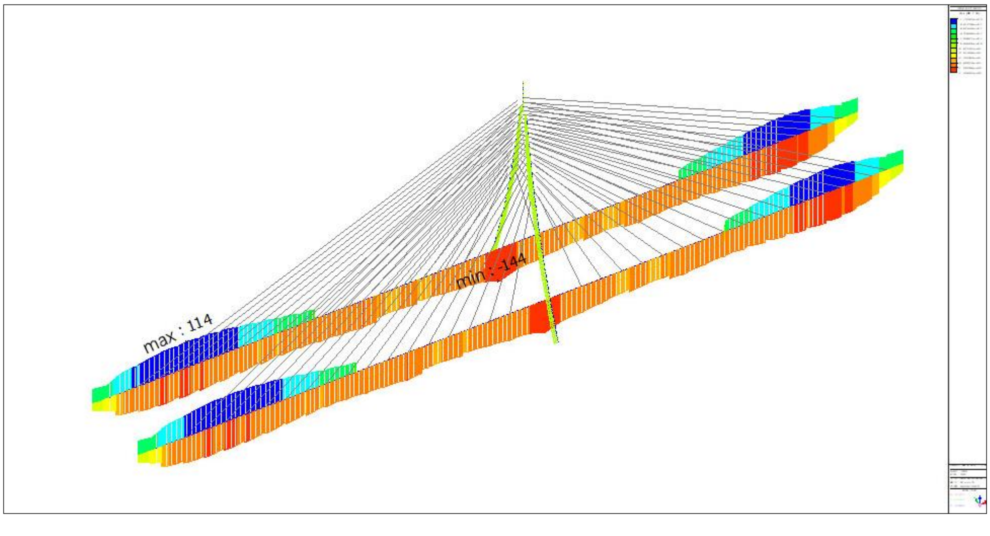

Figure 10 Stress envelope diagram of the main girder under the bearing capacity combination (Unit: MPa)

4.4 Main Pylon Analysis

Under frequent combination, the full section of the main pylon is compressed; the maximum compressive stress is approximately 14 MPa, and this is observed at the lowest beam of the main pylon; the minimum compressive stress, which is approximately 0 MPa, is observed at the pylon top (see Figure 11); hence, the stress in the main pylon is deemed to meet the specification requirements.

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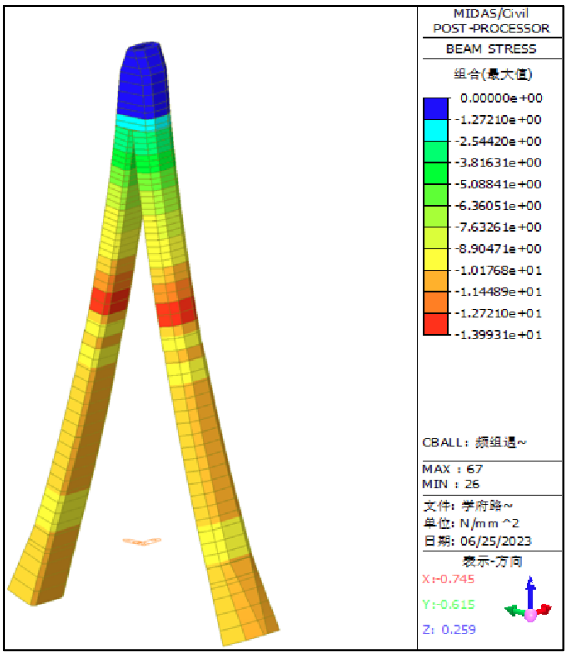

Figure 11 Stress diagram of main pylon under frequent combination (Unit: MPa)

5 Conclusion

The stayed-cable bridge on Xuefu Road is the widest single-pylon cable-stayed bridge featuring steel box girders in China. Featuring a rational structural system and safe and reliable stress, its design embodies the successful implementation of an ultra-wide cable-stayed bridge built at home and abroad. This paper summarizes its structural design and static analysis for use as a reference in the design of ultra-wide single-pylon cable-stayed bridges.

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