Project Report

Downward Through-pass Cable-Stayed-Arch Composite Structural System Bridge: Yanluo Pedestrian Bridge in Shenzhen

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Abstract: The Yanluo Pedestrian Bridge has a length of 136.0 meters, a width of 11.5 meters, a main span of 108.0 meters, and a rise span ratio of 1/11.74. The bridge design introduces the innovative "Downward Through-pass Cable-stayed Inclined Arch Composite Structural System." Compared to conventional deck-type arch bridges, this composite structural system significantly enhances the load-bearing capacity of the main arch, reduces the horizontal forces on the arch abutments, and improves the stiffness of the main arch. The Yanluo Pedestrian Bridge consists of the main arch, main girder, bridge towers, main cables, back cables, vertical braces, steel pipe columns, and foundations. The construction employs minimal support in the water.

Keywords: pedestrian bridge; downward through-pass cable-stayed-arch composite structural system; mechanical performance; locator

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1 Project Overview

With the development of society, more and more cities are beginning to pay attention to and construct pedestrian bridges. Compared to simple highway bridges, pedestrian bridges serve numerous functions such as transportation, landscaping, greening, and gathering [1], thereby possessing distinctive cultural attributes. Some bridges serve both pedestrians and vehicles, cleverly integrating into the local natural landscape through design combinations, forming a beautiful urban skyline [2]. Compared to traditional bridge types, composite bridges can create aesthetically pleasing, cost-effective, and powerful structures, providing assurance for the development of urban infrastructure [3].

The Yanluo Pedestrian Bridge is an important project along the Maozhou River Greenway in Shenzhen. Situated approximately 630 meters upstream of the current Songluo Road Bridge, the bridge serves as a convenient and comfortable crossing for both sides of the greenway and adjacent plots. Considering factors such as flood safety in the river channel, the need for continuous routes on the embankment, and the passage through box culverts, the Yanluo Pedestrian Bridge adopts a single-span solution over the Maozhou River. The span arrangement is 14+108+14 meters, with a total bridge length of 136.0 meters and a width of 11.5 meters. The conceptual illustration of the Yanluo Pedestrian Bridge is shown in Figure 1, and the elevation layout as well as typical cross-sections are shown in Figures 2 and 3.

Figure 1 Renderings of Yanluo Pedestrian Bridge

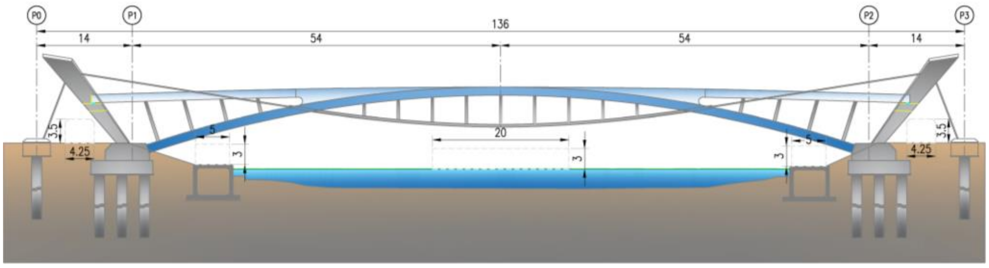
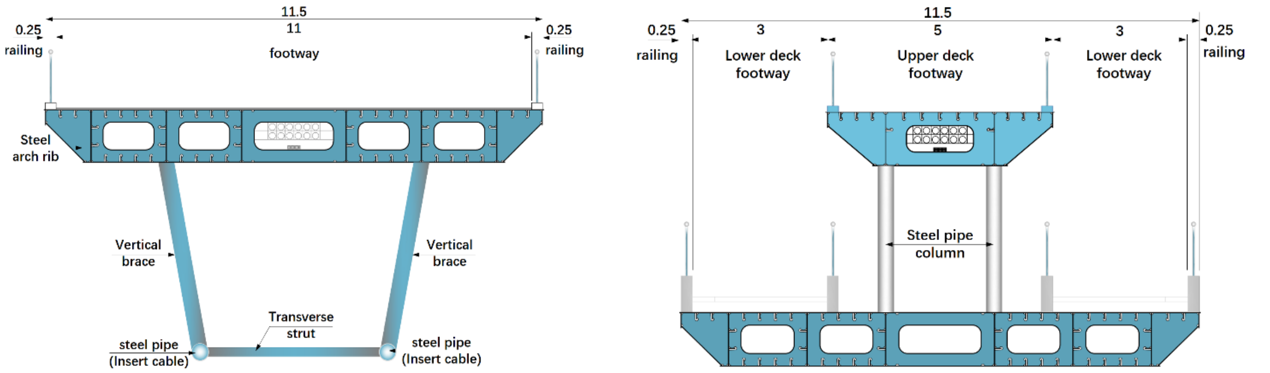


Figure 2 Elevation layout of the Yanluo Pedestrian Bridge (Unit: m)



(a) Cross-section layout diagram at midspan (b) Cross-section layout diagram of Double-Deck Bridge Deck

Figure 3 Typical Cross-sectional layout of Yanluo Pedestrian Bridge (Unit: m)

2 Key Points in Structural Design

The Yanluo Pedestrian Bridge comprises main arch, main girder, bridge towers, main cables, back cables, vertical braces, steel pipe columns, and foundations, as illustrated in Figure 4.

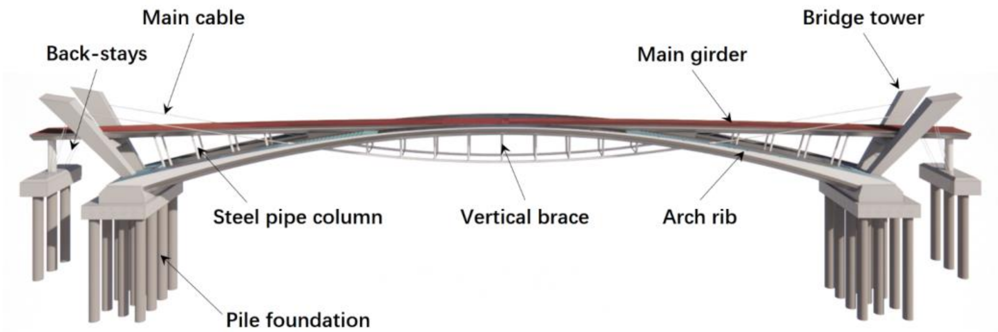


Figure 4 Structural Components of Yanluo Pedestrian Bridge

The main arch adopts a 108 m-span steel arch with a rise of 9.2 m and a rise span ratio of 1/11.74. The arch rib section employs a separated equal-height steel box with a double-box double-chamber configuration, featuring a straight web plate and a beam height of 1.2 m. The arch foot is connected to the concrete arch seat through PBL shear keys. The main beam utilizes a welded I-shaped steel beam with a height of 1.2 m. The lower flange plate of the steel beam is welded to φ350 mm steel pipe columns, and the connection to the arch rib is achieved through these steel pipe columns. The bridge towers are constructed using cast-in-place variable-section concrete inclined towers with a height of 13.04 m. A transverse beam is set 5.84 m above the tower base. The foundation is constructed using φ150 cm bored cast-in-place piles.

Each bridge tower is set with 2 main cables and 4 back cables. The cables adopt a galvanized steel wire cable system with a double-layer hot-dip HDPE sheath. The main cables use PES (C) 7-223 finished cables, anchored at both ends on the bridge

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tower. They pass through the locators on the arch ribs, then through the steel tube casing beneath the arch ribs, and are connected to the arch ribs through vertical braces. The back cables use PES (C) 7-121 finished cables, anchored at the upper end on the bridge tower and at the lower end anchored to the foundation cap through anchor tension plates. The main and back cables intersect and anchor on the bridge tower to ensure proper force distribution in the tower concrete. For the convenience of cable threading during construction, a set of locators is installed on both the upper and lower edges of each arch rib, ensuring the linear alignment of the cables during threading. During cable threading and tensioning, the longitudinal constraints of the locators are released, leaving only radial constraints. Once the cable tensioning reaches the design force, longitudinal constraints are applied, and the locators become fixed points. The "Locator Inside Steel Tube" construction of "Cable Through Arch" realizes a single uninterrupted main cable, reducing the number of cable joints, facilitating cable threading during construction, and ensuring good force transmission performance and durability.

3 Structure System Mechanics Principles and Force Analysis

3.1 Structural System Mechanics Principles

The Yanluo Pedestrian Bridge achieves a rise span ratio of 1/11.74, categorizing it as a large-span flat arch bridge. In order to reduce the horizontal forces on the arch abutments, control the size of the foundation, and propose an innovative structural solution, the "Downward Through-pass Cable-stayed-Arch Composite Structural System" is introduced. The mechanical principles of this system are as follows:

(1) Load Transfer Path of the "Downward Through-pass Cable-stayed-Arch Composite Structural System": A portion of the load is transmitted through the arch ribs to the arch abutments; another portion is transmitted through the through-pass cables to the inclined towers, forming a combined force with the tension of the back cables and transmitting it to the base of the tower; the combined force at the tower base and arch abutments is ultimately borne by the foundation.

(2) The "Main Cable-Inclined Tower-Back Cable" forms an irregular-shaped truss. The horizontal component of the combined forces from the tension in the main cable, tension in the back cables, and the self-weight of the inclined tower can balance a portion of the horizontal force on the arch abutments, reducing the size of the foundation.

(3) The main cables of the lower segment of the arch rib, through vertical braces, share the load with the main arch, improving the mechanical performance of the main arch and enhancing its stiffness.

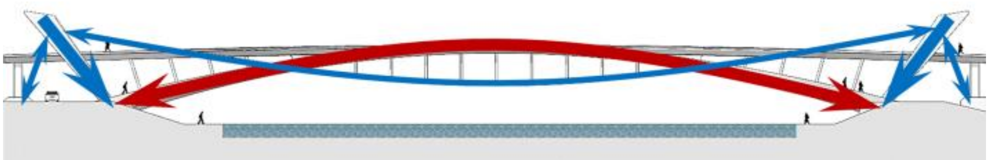


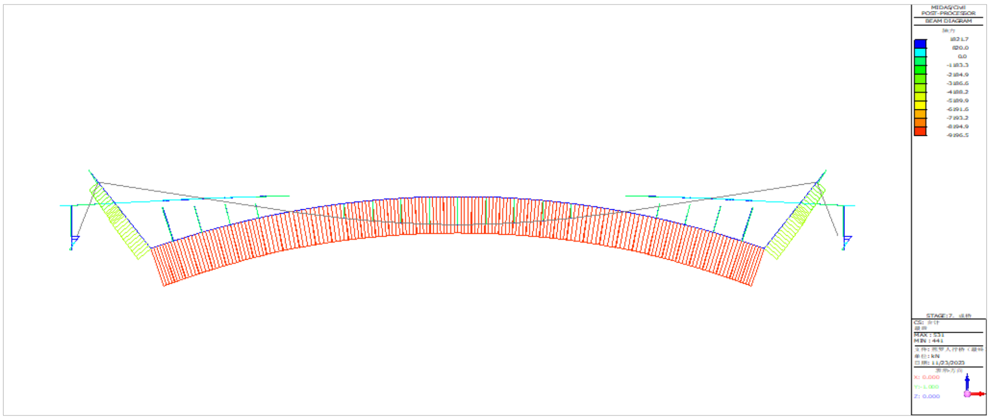
Figure 5 Mechanical Principles of the Downward Through-pass Cable-stayed-Arch Composite Structural System

3.2 Structural System Force Performance Analysis

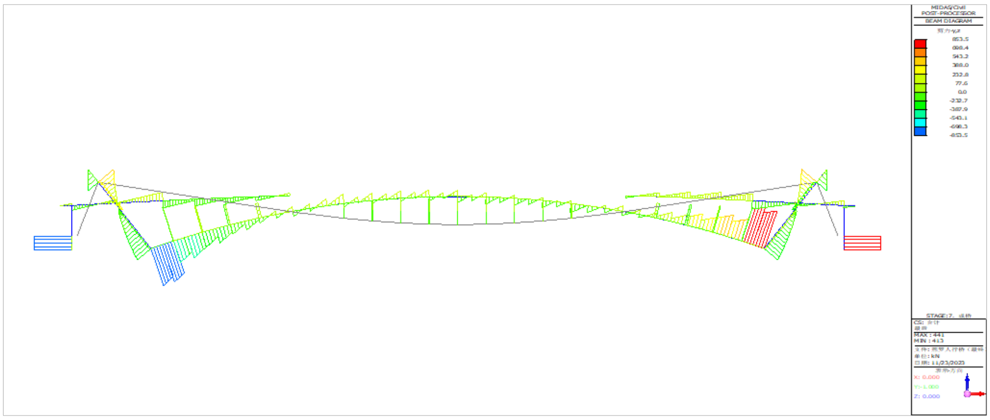
Using MIDAS software to establish a finite element model of the Yanluo Bridge and referring to the specifications of " Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts" (JTG 3362-2018), evaluate the stress performance of the Yanluo Bridge.

3.2.1 Internal Forces in the Structural System During the Bridge Completion Phase

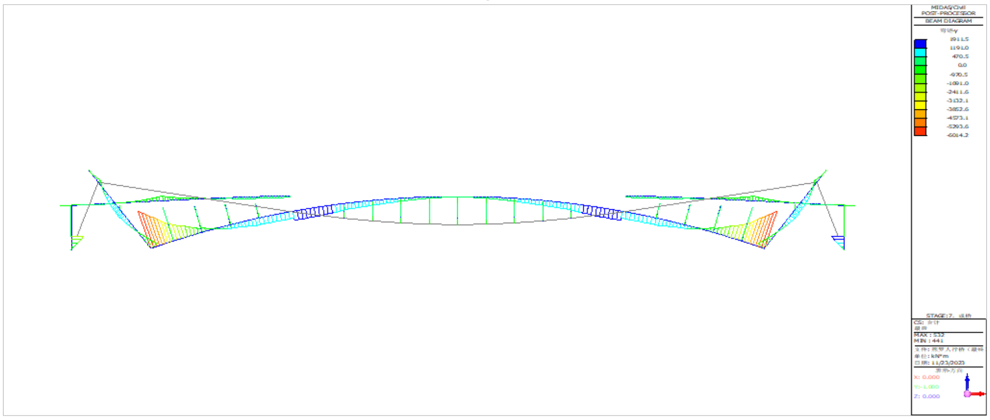
During the bridge completion phase, the forces in various parts of the structural system are as follows:



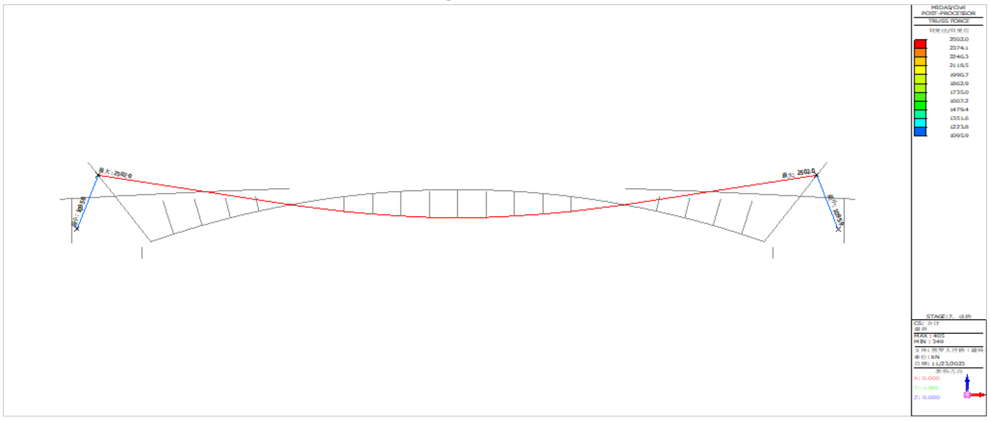
(a) Axial force (kN)



(b) Shearing force (kN)



(c) Bending moment (kN·m)



(d) Cable force (kN)

Figure 6 Forces in various parts of the structural system in the completed bridge state

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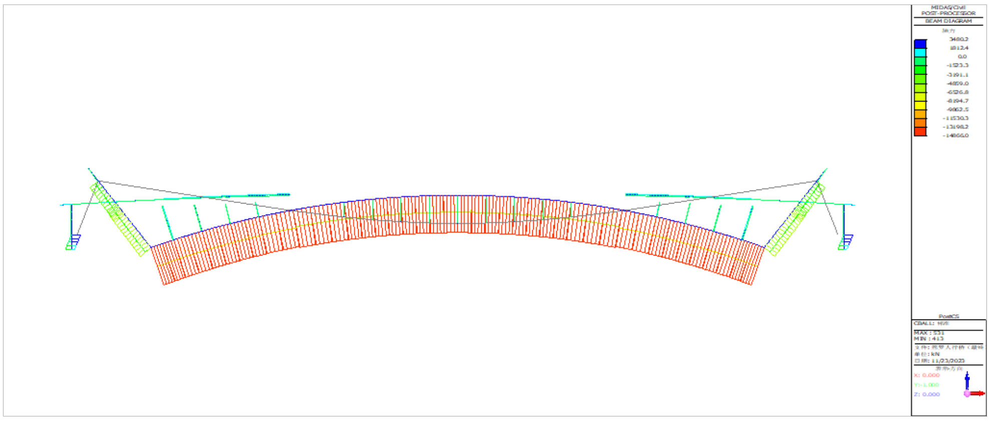
In the completed bridge state, the summarized forces in various parts of the structural system are presented in the table below.

Table 1 Forces in Various Parts of the Structural System in the Completed Bridge State

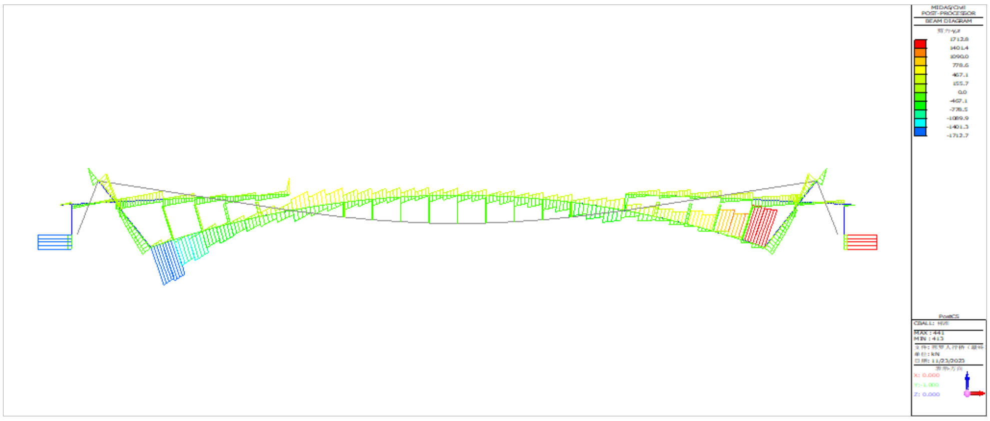
Various part of structural system	internal force of section			Cable force (kN)	Foundation reaction		
	Axial force (kN)	Shear force (kN)	Bending moment (kN·m)		Axial force (kN)	Shear force (kN)	Bending moment (kN·m)
Main arch	9196.5	853.5	6014.2	/	/	/	/
Main girder	98.1	181.3	741.1	/	/	/	/
Bridge tower	3930.7	438.3	1267.7	/	/	/	/
Main cable	/	/	/	2502.0	/	/	/
Back cable	/	/	/	1095.9	/	/	/
Vertical brace	79.4	8.6	21.4	/	/	/	/
Steel pipe column	183.1	53.6	74.6	/	/	/	/
foundation	/	/	/	/	23088.6	3550.0	8972.5

3.2.2 Internal Forces in the Structural System Under Standard Load Combinations

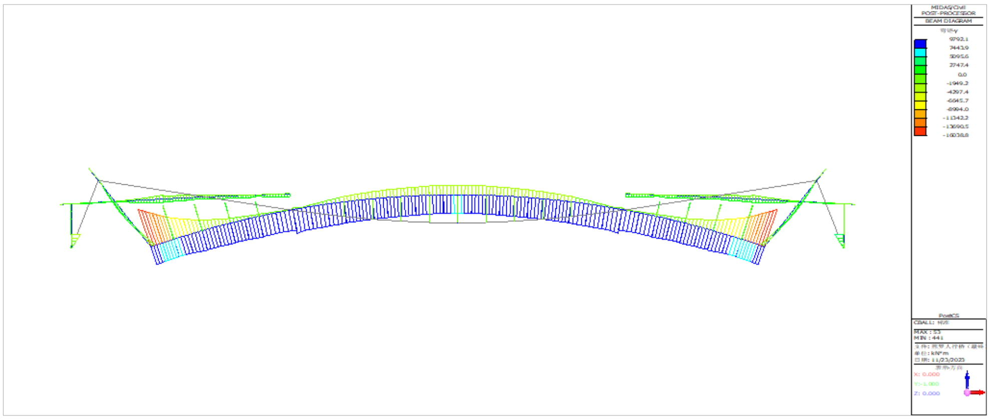
Under standard load combinations, the forces in various parts of the structural system are as follows:



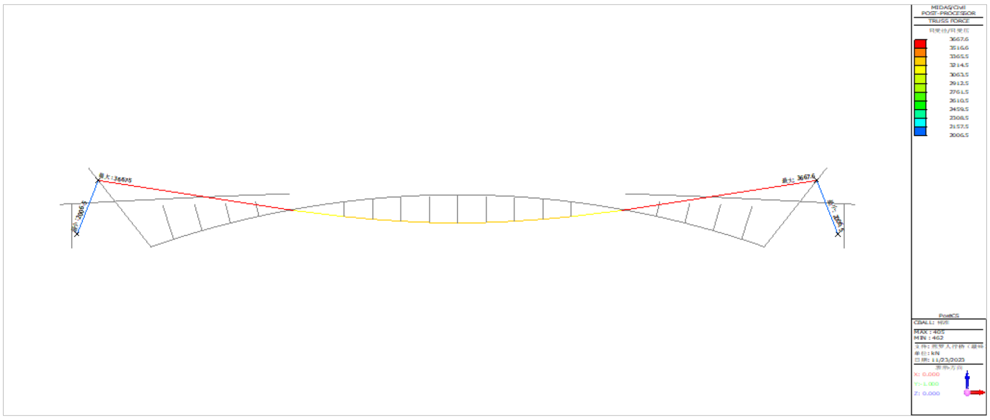
(a) Axial force (kN)



(b) Shearing force (kN)



(c) Bending moment (kN·m)



(d) Cable force (kN)

Figure 7 Forces in various parts of the structural system under standard load combinations

Under standard load combinations, the summarized forces in various parts of the structural system are presented in the table below.

Table 2 Internal Forces in the Structural System under Standard Load Combinations

Various part of structural system	internal force of section			Cable force (kN)	Foundation reaction		
	Axial force (kN)	Shear force (kN)	Bending moment (kN·m)		Axial force (kN)	Shear force (kN)	Bending moment (kN·m)
Main arch	14866.0	1712.8	16038.8	/	/	/	/
Main girder	405.5	692.9	1592.7	/	/	/	/
Bridge tower	5262.9	490.8	1761.8	/	/	/	/
Main cable	/	/	/	3667.5	/	/	/
Back cable	/	/	/	2006.5	/	/	/
Vertical brace	105.8	47.9	119.4	/	/	/	/
Steel pipe column	352.6	118.4	174.7	/	/	/	/
foundation	/	/	/	/	27918.4	9430.0	29102.3

3.2.3 Internal Forces in the Structural System Under Basic Load Combinations

Under basic load combinations, the forces in various parts of the structural system are as follows:

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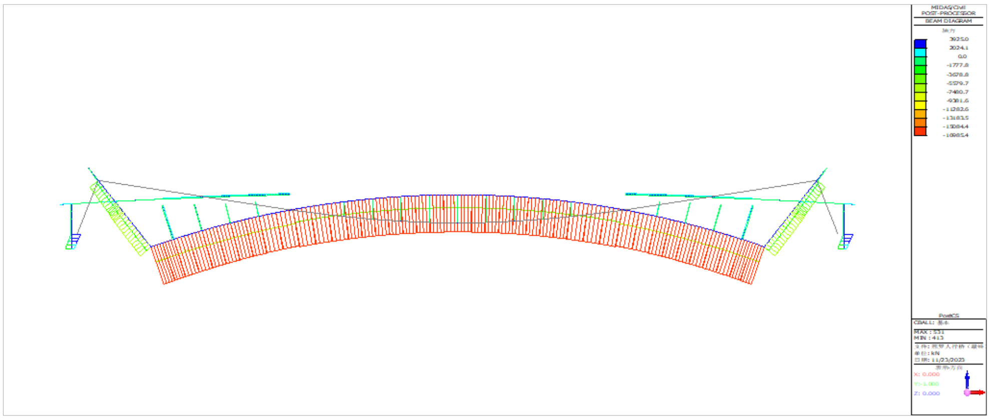
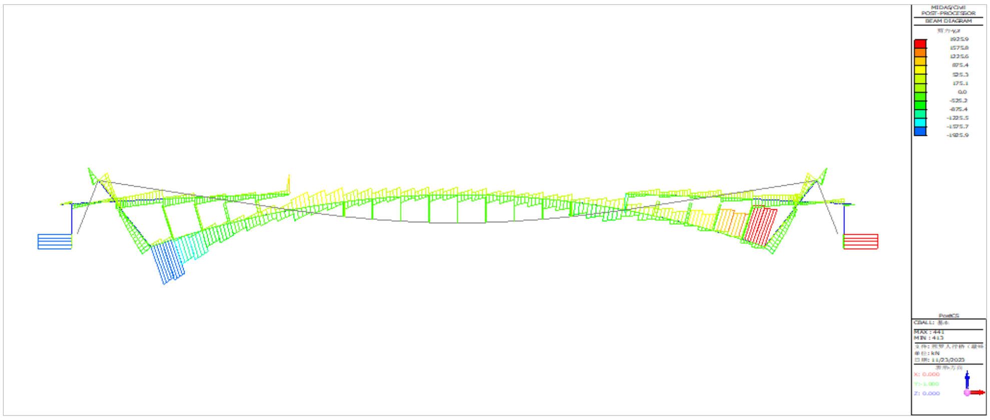
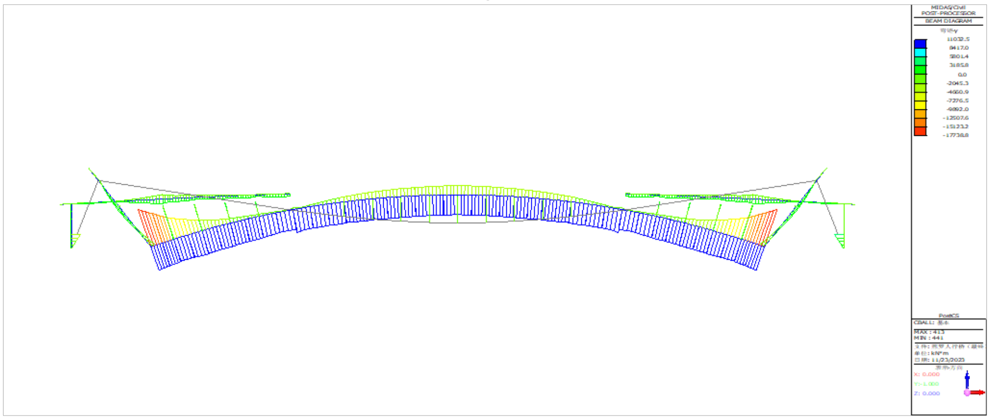


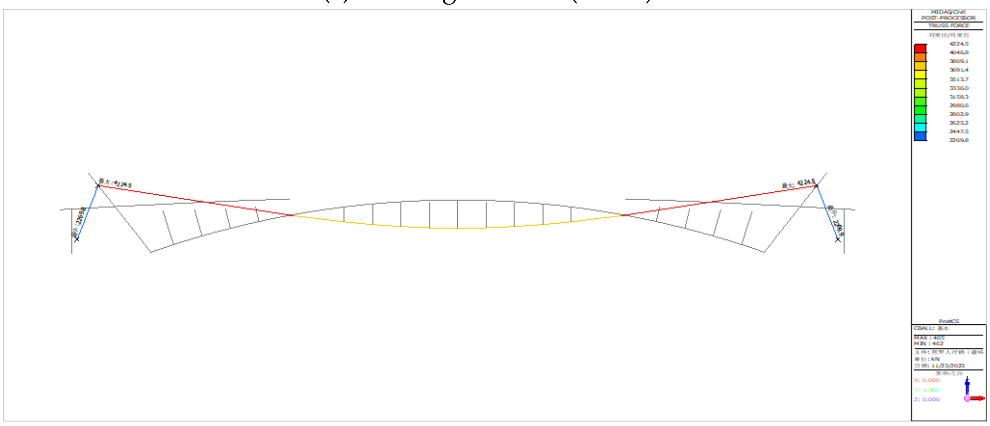
(a) Axial force (kN)



(b) Shearing force (kN)



(c) Bending moment (kN·m)



(d) Cable force (kN)

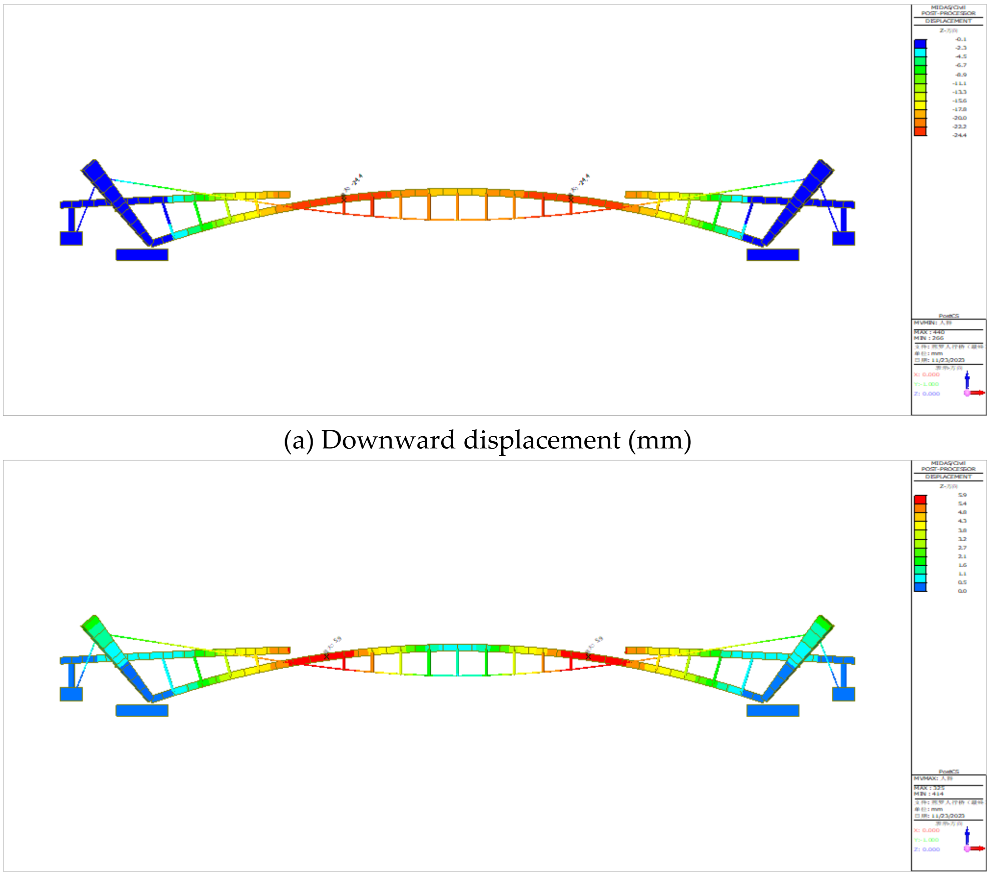
Figure 8 Forces in various parts of the structural system under basic load combinations

Under basic load combinations, the summarized forces in various parts of the structural system are presented in the table below.

Table 3 Internal Forces in the Structural System under Basic Load Combinations

Various part of structural system	**Internal force of section**			**Cable force (kN)**	**Foundation reaction**		
	Axial force (kN)	**Shear force (kN)**	**Bending moment (kN·m)**		**Axial force (kN)**	**Shear force (kN)**	**Bending moment (kN·m)**
Main arch	16985.4	1925.9	17738.8	/	/	/	/
Main girder	432.3	897.0	2052.1	/	/	/	/
Bridge tower	6113.9	581.1	2038.7	/	/	/	/
Main cable	/	/	/	4224.5	/	/	/
Back cable	/	/	/	2279.6	/	/	/
Vertical brace	125.5	51.5	128.4	/	/	/	/
Steel pipe column	455.3	140.2	194.1	/	/	/	/
foundation	/	/	/	/	32964.3	11880.0	33863.4

3.2.4 Structural Deflection Under Crowd Load Effects



(a) Downward displacement (mm)

(b) Upward displacement (mm)

Figure 9 Maximum Vertical Displacement under Crowd Load Effects

Under the influence of crowd loads, the structure experiences a maximum downward displacement of 24.4mm and a maximum upward displacement of 5.9mm. The ratio of the maximum displacement to the span is 1/3564, indicating that the structural system stiffness meets the requirements.

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3.2.5 Comparison with Conventional Deck-Type Arch Bridges

To further reveal the force characteristics of the " Downward Through-pass Cable-stayed-Arch Composite Structural System," a comparison is made with a conventional deck-type arch bridge of the same scale and the same rise span ratio. The focus is on comparing the internal forces in the main arch, horizontal forces on the foundation, and deflection under crowd loads. Refer to Table 4 for the detailed comparison.

Table 4 Mechanical performance comparison between two bridge types

Structural system		Type ①	Type ②	Optimization rate (%)
Internal force of basic composite main arch	Axial force (kN)	18810	16985	9.7
	Shear force (kN)	2604	1926	26.0
	Bending moment (kN·m)	22574	17739	21.4
Horizontal force of arch foundation（kN）	Completed bridge stage	10880	3550	67.4
	Standard load combinations	15220	9430	38.0
	Basic load combinations	17620	11880	32.6
Maximum displacement under crowd load（mm）		40	24	40.0

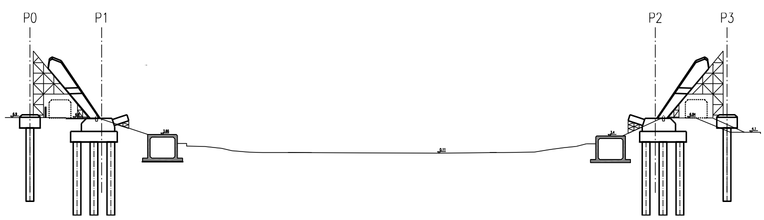
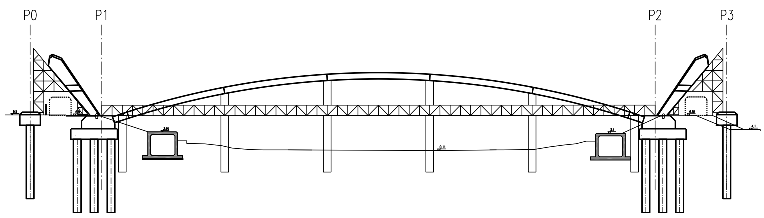
Note: Type ① is conventional deck-type arch bridge; Type ② is downward through-pass cable-stay-arch composite bridge; and optimization rate equal to (① - ②)/ ①.

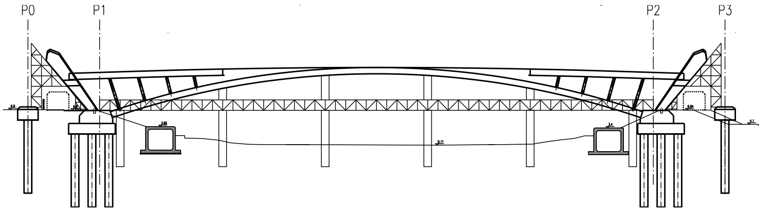
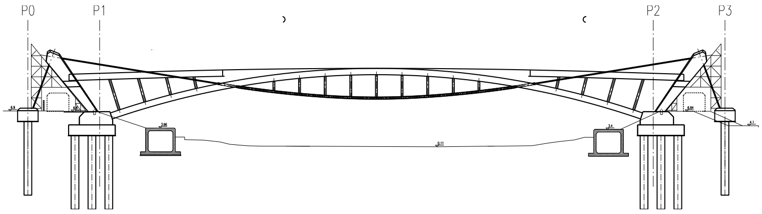
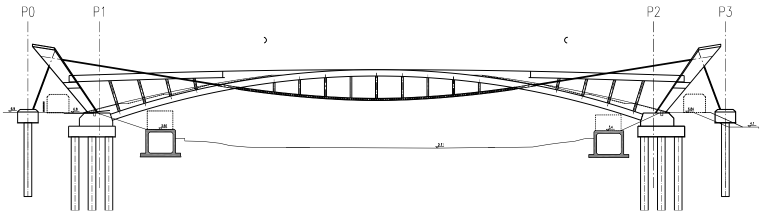
Compared to conventional deck-type arch bridges, the "Downward Through-pass Cable-stayed-Arch Composite Structural System Bridge" exhibits significant improvements in its mechanical performance. Specifically, under basic load combinations, the bending moment in the main arch is reduced by approximately 21%. In the completed bridge state, the horizontal force at the arch abutments decreases by around 67%, under standard load combinations by about 38%, and under basic load combinations by approximately 32%. Additionally, the structural stiffness increases by approximately 40%. The "Downward Through-pass Cable-stayed-Arch Composite Structural System Bridge" demonstrates excellent mechanical performance.

4 Construction Scheme

The bridge construction scheme adopts the method of underwater minimal support construction, and the specific construction steps are as follows:

Table 5 Schematic Representation of Construction Steps

Step No.	Schematic diagram of construction
Step 1: (1) Level the site and clear the working area for pile foundation construction. (2) Excavate the foundation pit and pour concrete for the arch abutment, arch seat, and back cable anchorage foundation. (3) Erect support structures and pour concrete for the bridge tower.	
Step 2: (1) Erect temporary construction bridges. (2) Lift and assemble the main arch segments and mid-span closure segments, performing on-site welding.	

Step No.	**Schematic diagram of construction**
Step 3: (1) Erect the columns on the arch, install the main beams. (2) Remove the steel construction bridge, remove temporary supports for the arch ribs.	
Step 4: (1) Erect the main cables and back cables. (2) Tension the main cables and back cables. (3) Remove the bridge tower supports.	
Step 5: (1) Pour the top closure segment of the tower. (2) Proceed with auxiliary construction work. (3) Complete the bridge.	

The completion photos of Yanluo Pedestrian Bridge are as follows:

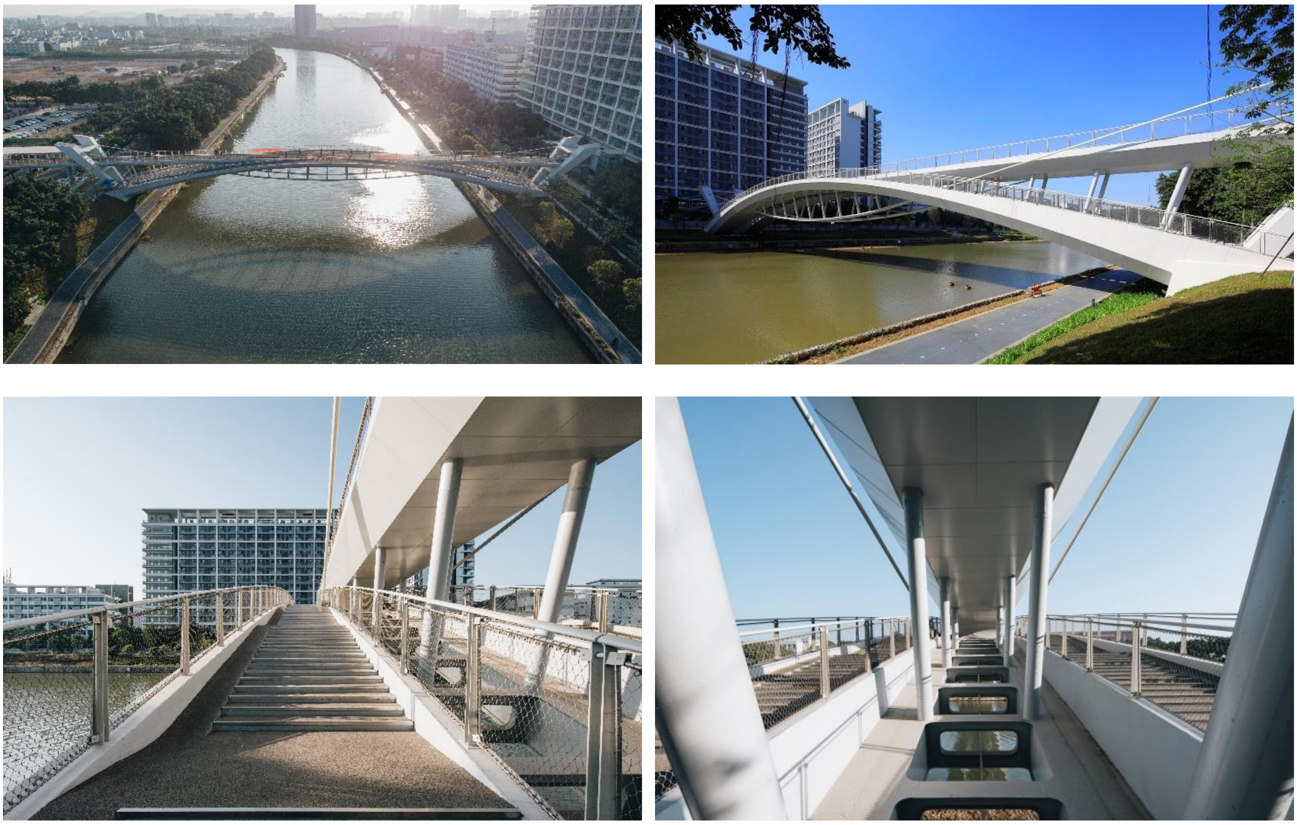


Figure 10 Photos of Yanluo Pedestrian Bridge

Conflict of Interest: All authors disclosed no relevant relationships.

Date Availability Statement: The data that support the findings of this study are available from the corresponding author, Jiang, upon reasonable request.

References

1. Jiao, Y. Research on the Design of Contemporary Urban River-crossing Footbridge from the A Rchitectural View. Master, Huazhong University of Science and Technology, Wuhan, 2022.
2. Zheng, B.; Li, X.; Chen, Y. Liyang Jingzhan丨Shahe Bridge. *Prestress Technology* **2023**, *1*, 72-77, doi:10.59238/j.pt.2023.02.007.
3. Yu, J. The Bridge Type Quadrant Diagram and New Basic Bridge Type: Umbrella Truss Bridge. *Prestress Technology* **2023**, *1*, 15-29, doi:10.59238/j.pt.2023.03.002.
4. Ministry of Transport of the People's Republic of China JTG 3362—2018 Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts. China Communications Press: Beijing, 2018.

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