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Design Strategies for Leaning-Type Arch Bridges

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Abstract: This paper presents a study on the design strategy of leaning-type arch bridges. The main characteristics of leaning-type arch bridges are first introduced; Kunshan Yufeng Bridge is taken as an example to discuss different aspects of a design strategy, which includes self-system optimization, selection of beam length and bridge deck position, and other aspects. This paper can be used as a reference to further improve and develop bridge design.

Keywords: Leaning beam-arch composite system; Cantilever length; Space calculation

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1. Introduction

Compared to other types of bridge structures, leaning-type arch bridges are more novel and unique. This type of bridges is remarkably strong with beautiful curves, which makes them stand out from other types of bridges. For example, the world's first reclining beam-arch composite system bridge, the Bac de Roda Bridge in Spain, Jiangyin Xingchun Bridge in Jiangsu Province, and Zhejiang's Yiwu Danxi Bridge all use leaning-type arch bridge.

2. Overview of leaning-type arch bridges

In the beam-arch composite bridges, the two basic structures of the arch bridge and the beam are combined to bear the load together after the bridge is put into use, so as to utilize the compression of the arch and the bending of the beam, which can not only improve the performance of the bridge, but also save construction materials. Usually, bridges with beam-arch composite system mainly include arch ribs, columns or suspenders, roadway slabs (beams), tie rods, and bridge deck. This combination belongs to a typical ternary structure in terms of mechanical characteristics, including force transmission components, live load distribution components, and main load-bearing components [1]. The live load is distributed among the beam and the longitudinal girder under the bridge deck; the main force transmission component is the suspender or suspender + column, the arch rib, and the tie beam are the main load-bearing components [2]. Under different classification standards, based on the different combinations of arch beams and driveway beams, beam-arch composite bridges can be divided into two types: with thrust and without thrust. Beam-arch composite bridges without thrust are externally statically indeterminate and internally super-statically indeterminate. They have both the large spanning capacity of arch bridges and the strong adaptability to foundations of simply supported beam bridges [3], thus, they are widely used. Based on the different supporting forms of the structure, the beam-arch composite bridges can be divided into simply supported beam-arch composite bridges, continuous beam-arch composite bridges and single-cantilever beam-arch composite bridges. Among them, the simply supported beam-arch composite bridge is mainly suitable for the down-through type, which belongs to the external non-thrust and internal high-order super-statically indeterminate structure. The core of the single cantilever beam-arch composite bridge design is to hollow out the solid web beam, and replace the beam web with columns, so that its shear force is mainly shared by the vertical force component of the arch rib and the shear force of the stiffened beam. Continuous beam-arch composite bridges can be adjusted into middle-supported, upper-supported or lower-supported types, and also allow the combination of double-rib arches, multi-rib arches, and stiffened beams [3].

3. Analysis of bridge characteristics of leaning-type arch bridge

Among the beam-arch composite system bridges, the leaning-type arch bridge is composed of two vertical main arches and two leaning arches in the form of two-by-two combination to form a space stress system, and the parallel arch ribs in the middle are used as bridges. The load is mainly bore by the anti-overturning and anti-torsion capabilities by inclined arch ribs, including the load from the non-motor vehicle lane of the bridge. The oblique arch and main arch of leaning-type arch bridge will form a spatially stable system with strong lateral stiffness in the form of lateral connection [5].

4. Research on bridge design strategy of leaning-type arch bridge

This paper studies the design strategy of leaning-type arch bridges by using Yufeng Bridge in Kunshan City as an example.

4.1. Project overview

Yufeng Bridge in Kunshan City is a leaning-type arch bridge, with a bridge span of 110 m, a 21 m wide motorway between the two main arches of the transverse bridge, and a width of 3.5 m between the main inclined arches non-motor vehicle belt and 3 m wide sidewalks; with an arc-shaped viewing platform. In terms of width, the width of the main pier of Yufeng Bridge is 48 m, and the width gradually expands to 60.9 m in the middle of the span. Two pedestrian stairs are set on the main pier on both sides, and the width of the sidewalk and sightseeing platform gradually increases from 2.8 m at the main pier to 10 m in the widest area in the center. **Figure 1** illustrates Kunshan Yufeng Bridge:

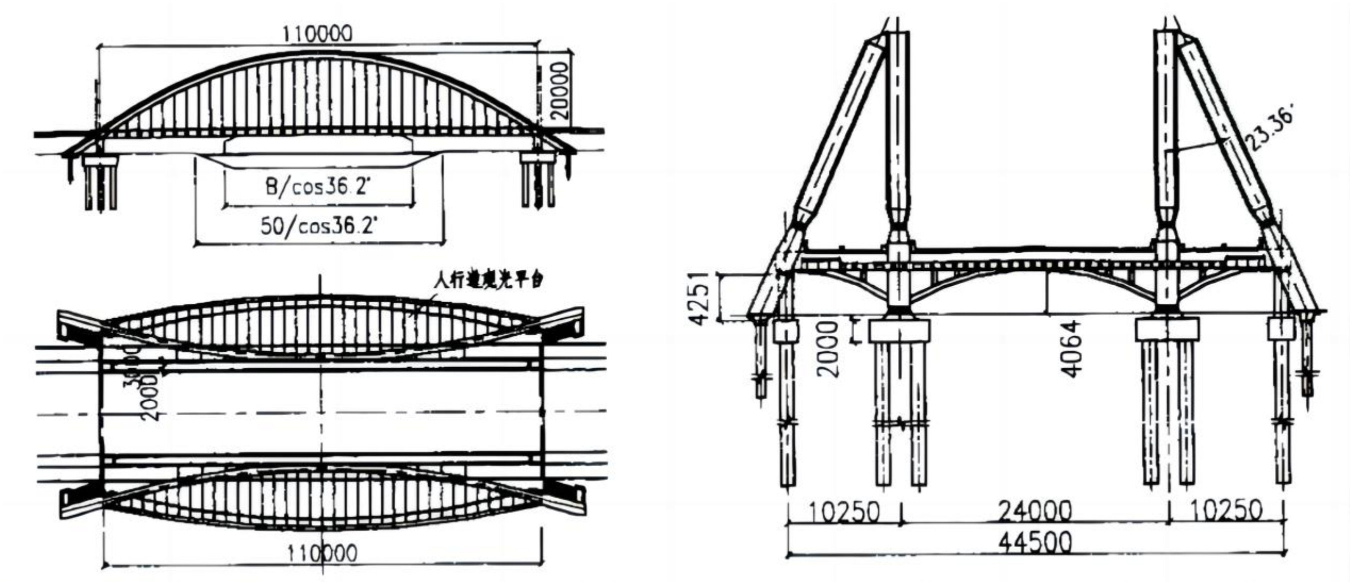

Figure 1. Plan and elevation of Kunshan Yufeng Bridge. Translation: 人行道观光平台, viewing platform

The main arch and the oblique arch of Kunshan Yufeng Bridge have an equilateral triangular cross-section, and the arch axis adopts the form of a quadratic parabola. The inclination angle of the oblique arch is 23.36°. There are 13 horizontal braces between the main arch and the oblique arch. In terms of the vertical spacing of the slings, both the main arch and the inclined arch are 3 m, the waterway is at Level 5, and the clear navigation height is > 5m. **Table 1** shows the main components and their construction materials of Kunshan Yufeng Bridge.

Table 1. Main component forms and construction materials of Kunshan Yufeng Bridge

Component	Material	Section form	Other description
Main rib	C40 micro-expansion concrete, Q345C steel	Equilateral triangle concrete filled steel tube	Quadratic parabolic arch axis, 1/5.5 rise-span ratio, 23.36° main inclined arch inclination angle
Diagonal arch rib	C345C steel	Equilateral triangle steel pipe	Quadratic parabolic arch axis shape, 1/5.4 rise-span ratio, with stainless steel wire rope as suspender
Main beam	C345C steel	Box type 2 m × 2.5 m	Beam structure composed of concrete bridge deck and steel girders

4.2. System optimization

The Kunshan area has soft ground, and if a leaning-type arch bridge with thrust is adopted, in addition to the high cost, the uneven deformation of the foundation will also cause additional internal forces in the bridge structure, especially for bridges with large span. If load-reducing non-thrust leaning-type arch bridge is built on soft soil, factors like the coordinated deformation between the main arch and the oblique arch, and maintenance of the original landscape of the oblique arch needs to be considered [6].

To solve these problems, three system optimization design options can be adopted: the first option is to strengthen the foundation (Option 1), the second option is to stretch the horizontal cables underground (Option 2), and the third option is to stretch the horizontal cables under the bridge deck (Option 3). In contrast to the three options, the leaning arch foot of Option 1 can extend to the ground and connect to the sidewalk of the lower bridge, which has better aesthetics; but the disadvantage is that a huge foundation capable of resisting horizontal force is needed. However, it is costly regardless of whether pile foundation or sedimentation is adopted, and the stability of horizontal displacement cannot be guaranteed in long-term. Option 2 has the same advantages as Option 1, but the horizontal stay cables need a deeper buried depth, and the span of the leaning arch needs to be increased, which not only increases the cost, but the horizontal cables also cannot be inspected or replaced after the completion of construction, which will lead to safety hazards to the subsequent commissioning of the bridge. Option 3 is relatively reasonable, safe, and economical, and there will be no hidden dangers under long-term loads. After reasonable modification of the parts leaning against the arch feet, the overall aesthetics of the bridge can be preserved.

Combined with the actual construction environment of Yufeng Bridge in Kunshan, while adopting Option 3, that is, while tensioning the horizontal cables under the bridge deck, a decorative extension strategy was adopted at the junction of the arch and beam, which not only ensured the continuity of the structural appearance, but also ensured the adjustment of the horizontal cables. Moreover, the horizontal displacement of the end beam and the rubber part of the arch foot could also be kept consistent, so that the force of the bridge could be more reasonable distributed. Both the main arch and leaning arch of Yufeng Bridge adopted the form of horizontal force self-balancing arch beam combination, with the longitudinal main arch rib as the main load-bearing structure; the two non-thrust systems are connected horizontally to form a structure with high lateral stiffness, which can ensure the stability and rationality of the structure [7]. In addition, the lateral force is dominated by the two end beams and the internal beams, and the end beams can effectively balance the lateral horizontal force transmitted by the inclined arch.

4.3. Selection of beam length and bridge deck position

In terms of the length of the cantilever beam, after fixing the inclination angle of the leaning arch, it is necessary to reasonably adjust the length of the cantilever beam to ensure that the bridge deck of the cantilever part is combined with the inclined arch rib to form a self-balancing system. **Figure 2** is a schematic diagram of the inclined arch self-balancing system of Yufeng Bridge.

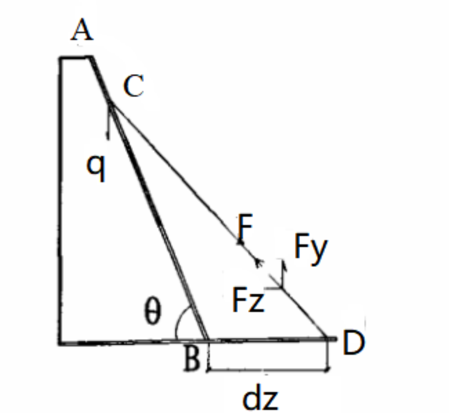

Figure 2. Schematic diagram of self-balancing system of oblique arch of Yufeng Bridge

As shown in **Figure 2**, *CD* represents any suspender of the inclined arch, *AB* is the inclined arch, *BD* is the cantilever beam, *dz* represents the length of the cantilever beam at the suspender, and *q* represents the self-weight of the inclined arch shared by the suspender, and *F* represents the suspender force.

$$M - F_y dz - qL_{BC} tg\theta$$

In the equation above, *M* represents the out-of-plane bending moment of the inclined arch at point *C*, which is based on the partial tension of the inclined arch sling to balance the out-of-plane component force caused by the inclined arch's self-gravity. Reducing the value of *M* as much as possible in the design stage can effectively reduce the external bending force on the main arch and inclined arch, so as to promote the improvement of the overall structural stress. At the same time, the comfort and safety of pedestrians must also be ensured in the design stage. In terms of the position of the bridge deck, in Kunshan Yufeng Bridge, the layout of the concrete bridge deck and the position of the center of the column beams have effectively reduced the impact of the bending of the columns and beams on the bridge deck [8].

4.4. Plane and space computing

For the plane calculation of bridges with leaning-type arch bridges, the main consideration is how to simplify the complex space system into a plane model. Since the cantilevered beam and main beams of Yufeng Bridge are weakly connected, it is necessary to calculate the main arch and oblique arch separately for plane static analysis. For the main arch, a main arch rib, a rigid beam, and a main arch suspender are used for calculation, and the stiffness of the main beam is corrected by the calculation results of the space model, and the two systems of the bridge deck are fully considered. The dead load includes a single arch rib + one-sided non-motorized vehicle lane, 1/2 range of pedestrian crossings, and the load shared by the half-width roadway slab. The hinge constraint is used as the constraint of the arch foot and tie beam [9]. The bridge deck and suspenders are hinged, and the entire system is externally restrained by simple support. The bridge deck system, arch upper cross braces, and stiffeners of steel members are applied to the structure as a uniform force.

The calculations of inclined arch is done within its own plane, and the calculation model includes a single inclined arch rib, two small longitudinal beams under the inclined arch, and inclined arch suspenders. The flexible tie rod between the two arch feet is not included in the cantilever beam grid's effect on the longitudinal stiffness of the structure. The total load includes the dead load is the load of one-sided non-motorized vehicle lane and 1/2 sidewalk slab range + the load of a single inclined arch rib, and the rigid constraint is used as the constraint condition of the arch foot and tie beam.

The bridge components are simulated by the beam unit and the plate unit in the calculation stage, and the spatial and plane models are used for comparative analysis: the values obtained from the space model is slightly larger than the those from the plane model. The longest beam on the sidewalk is close to 20m, which will cause the entire arch-rib cross bridge to bear a large force. Considering the space calculation, the stress of the arch rib is based on the superposition of the three directions in space, so the stress needs to be greater than the result of the plane calculation. Based on this requirement, the size of the arch rib needs to be adjusted based on the plane calculation results and the space effect of the arch bridge ensure the safety of the space [10].

5. Conclusion

The design of leaning-type arch bridges is highly specialized and complex. In addition to the key design strategies proposed in this paper, other parameters that affect the stability of the bridge includes different structural systems, inclined arch angles, and support stiffness, number of supports, and many more. Therefore, to carry out the bridge design of the reclining beam-arch composite system, it is necessary plan everything in detail with the full picture in mind and to fully analyze the various influencing factors of bridge design in combination with previous examples, so as to improve the quality of the design.

Disclosure statement

The author declares no conflict of interest.

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