

DESIGN OF THE LING-TIE BRIDGE

by

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INTRODUCTION

The Ling-Tie Bridge is currently under design to carry six lanes of mixed traffic across the Yong River in Nanning City, Capital of Guangxi Autonomous Region, China. A primary objective of the bridge design was to provide a unique bridge to satisfy the City's desire for a landmark, but with a rational and efficient form that meets performance and constructibility requirements.

The bridge consists of a horizontally curved steel box girder with a 300-meter span, supported by two independent inclined steel arch ribs. The approaches are curved post-tensioned concrete box girders on reinforced concrete piers. The 300 m span provides adequate navigation clearance, the curved horizontal alignment matches the layout of existing city streets, and the inclined arch ribs support the curved deck as true arches, without significant in- or out-of plane bending.

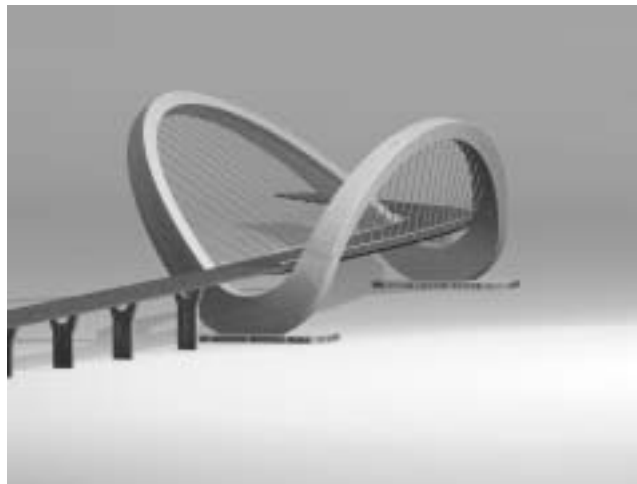


Fig. 1. Ling-Tie Bridge – Artist's Rendering

The curved through-arch bridge form was selected from among eight different structural concepts developed for the bridge. It provides a unique architectural statement, a rational solution to a relatively long span on a curved alignment, and a landmark structure for the City and its region.

STRUCTURAL SYSTEM

The principal architectural and structural feature of the bridge is its curved 300-meter main span. It is supported by two independent steel arch ribs, each on a separate inclined plane, with no bracing between the arches. The two arch ribs converge beneath the deck girder, and are separated widely at their crowns, to both control the flow of forces and visually cradle the deck.

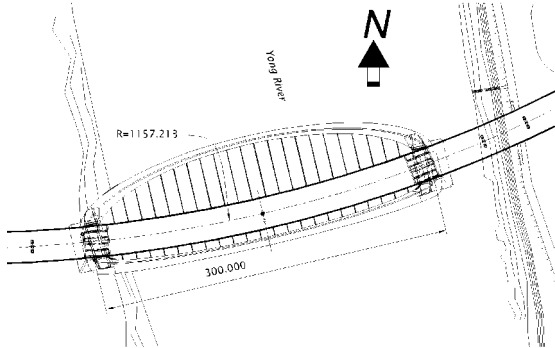


Fig. 2. Bridge Plan

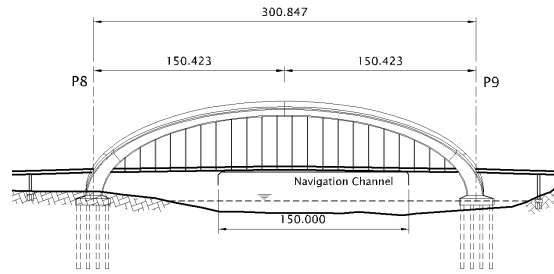


Fig. 3. Bridge Elevation

The arch ribs end at two concrete tabular-piers, whose compound curve geometry delivers loads to the foundations and provides visual continuity. The piers are designed to connect the arch ribs, roadway girders, foundations, and approach viaducts, to anchor the post tensioned arch tie that is within the deck girder, and to serve as the structural and architectural transition among them.

The arch ribs and the roadway girder are designed as closed orthotropic steel boxes, to achieve strength, stiffness, stability, and uniformity of fabrication. The ribs support the weight of the roadway girder via a system of inclined suspender ropes. The lateral components of the suspender forces also support the arch ribs and direct the arch pressure line into the plane of the arch; the arch ribs would not be stable without the weight of the girder. The curved girder becomes a third (horizontal) arch under the unbalanced lateral loading of the suspenders.

The viaducts at each end of the arch span are continuous post-tensioned concrete multi-cell box girders. The arch span and the viaducts form a continuous structure from abutment to abutment.

ARCH GEOMETRY

The arch shapes were developed so that they perform as true “funicular” forms, with dead load pressure lines oriented close to the centerlines of the ribs. This geometry helps to assure that main load resistance is provided by compression in the ribs, and that bending and torsional loads on the ribs are relatively small. Technical criteria for shape development included

1. Roadway girder dead loads must be carried by the suspenders to the arch ribs, so that the girder is subjected to minimum bending moments.
2. The arch ribs must be subject to minimum bending and torsion moments under the combined effects of dead loads, arch thrusts, and the restraint of the arch bases and roadway girder.
3. The vertical and thrust loads on the arch foundations must be nearly centered on the foundations, so that the foundations are under minimum dead load overturning and torque.
4. A balance must be reached between the height of the arch ribs, the magnitude of thrust to be resisted by the arch tie, the rigidity of the structural system, and the quantities of structural steel required for the arch ribs and tie.

5. An aesthetically pleasing formation must result from the combined shapes of the arch ribs and the shapes formed by the suspenders.
6. Constructibility must be achieved by maintaining simple curvature of each steel arch rib. Compound curvature is used only in the concrete arch bases.

Geometrical forms to meet these criteria were developed using theoretical shape-optimization tools, and then adjusted pragmatically to better address aesthetic, clearance, and constructibility issues. It was found that slight variations from the theoretical optimum shape do not cause appreciable difference in material requirements or computed performance.

The shape-optimization studies used the principal of virtual displacements to derive shapes for the arch ribs that result in pure compression in the ribs under dead load and idealized support conditions. These studies concluded that the optimum rib shapes have the following features:

1. Each rib lies in an inclined plane; a non-planar curve is not optimal. The incline angles of these planes depend on the relative weights of the deck girder and ribs.
2. The rib on the outside of the curve lies in a plane about 5 degrees off vertical, so that in plan it follows the curvature of the roadway girder with small suspender slope.
3. The rib on the inside of the curve lies in a plane about 30 degrees off vertical. The overturning due to the slope of this rib is offset by the horizontal pull of the suspenders.
4. The rib on the inside of the curve is taller than the rib on the outside of the curve, to reduce the eccentricity of the dead load weight and thrust on the foundations.
5. The optimum shape of each rib in plan and elevation above deck level is essentially parabolic.

With this bridge geometry, the deck girder is subjected to net lateral loading due to the unbalanced horizontal component of the inclined suspender forces. The curved girder resists these lateral loads as a third arch. The girder radius is large, however, so to provide a more efficient system without large lateral bending in the girder, the arch tie is diverted to the inside of the curve within the girder.

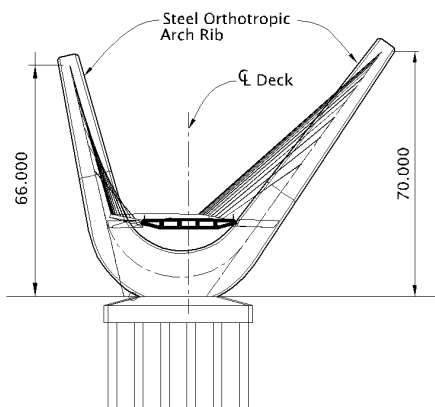


Fig. 4. Bridge cross section

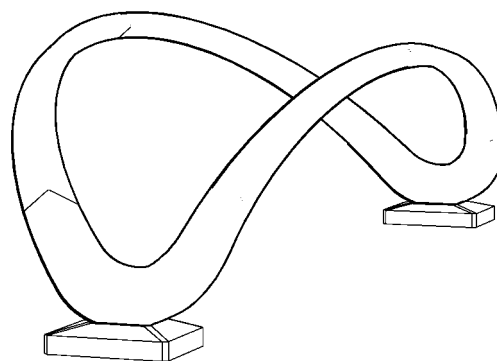


Fig. 5. Arch rib form

ARCH RIB DESIGN

The arch ribs are single-closed-cell steel box girders, with quadrilateral (roughly square) cross sections varying from about five meters square at their crowns to about seven meters square at their bases. The corners are

chamfered for aesthetic effect and to reduce wind loads. Fabricated steel components of the arch ribs are specified as Grade 345 MPa steel.

The faces of the ribs are steel plates, stiffened with longitudinal trapezoidal ribs, transverse frames, and diaphragms at the suspender locations. The skin plates and stiffeners are designed for strength in compression, bending, shear, and torsion including local buckling and interaction effects. The system was checked for global and regional structural stability using linearized buckling analysis and nonlinear analysis to impending instability.

The ribs have no hinges, and are connected monolithically to the arch bases. The base joints utilize steel plates bearing on concrete, high-strength anchor bolts, steel embedded in concrete, and shear connectors to develop the strength of the steel rib into the concrete base.

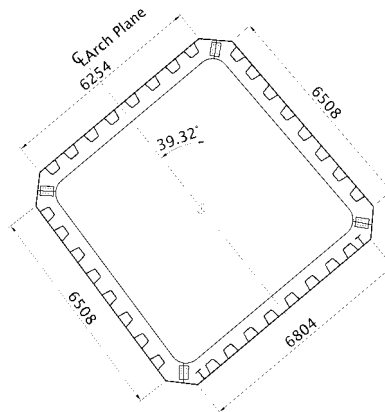


Fig. 6. Arch rib typical section

GIRDER DESIGN

The girder is a curved single-closed-cell steel box with an orthotropic steel deck. It is continuous and jointless over the length of the arch span, with monolithic connections to the concrete arch tables at each end. Fabricated steel components are specified as Grade 345 MPa steel.

The box girder cross section is 27 meters wide and about 2.7 meters deep. Its overall shape and dimensions were developed to provide adequate width for the traveled lanes, strength and rigidity, minimal wind drag, aerodynamic stability, and adequate storm water drainage.

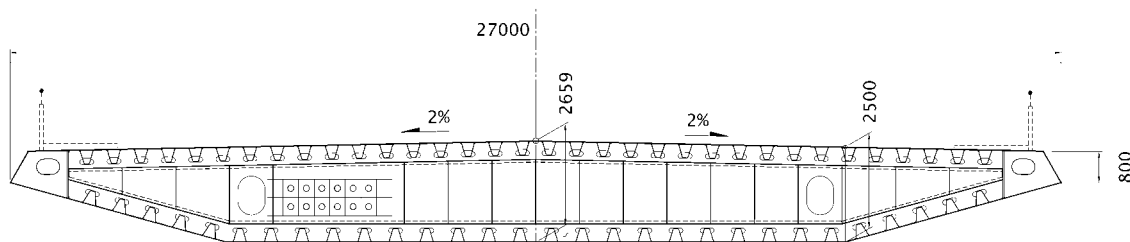


Fig. 7. Girder typical section

The girder is supported at its edges by suspenders at 12-meter intervals. The suspenders are inclined transversely and are parallel in plan. The framing of the girder consists of longitudinal edge-bulkheads, transverse bulkheads, bottom plate, inclined side plates, and orthotropic deck.

Longitudinal edge-bulkheads form compact box-beams at each side of the girder. They distribute loads to the

suspender ropes, provide strength in vertical shear and transverse bending, and stiffen the nose of the girder to improve the shear performance of the edge and side plates. Transverse bulkheads support the orthotropic deck and stiffen the box girder. Their 4-meter spacing allows an economical orthotropic deck, and efficient stiffening of the side and bottom plates. The arch tie bears laterally on each bulkhead, to offset the transverse load from the sloping suspenders.

The orthotropic deck spans 4 meters between bulkheads. Straight ribs follow the girder curvature with angle breaks at 12-meter intervals. 300 mm deep closed trapezoidal ribs provide rigidity and low stress ranges. A 16 mm deck plate reduces deflections between ribs and strains in the surface overlay. A simple bulkhead cutout is allowed by the relatively small deflections and stress ranges. Field splices will be bolted in the ribs and groove welded in the deck plate.

The bottom plate and inclined side plates are stiffened longitudinally with closed trapezoidal ribs and transversely by the transverse bulkheads. These plates and stiffeners are similar to those in the orthotropic deck, but simplified somewhat due to lower fatigue demands.

The girder is connected to the concrete arch tables with moment- and force- resisting connections. The connections utilize steel plates bearing on concrete, high-strength anchor bolts, steel embedded in concrete, and shear connectors. These details are capable of developing the strength of the steel box girder into the concrete arch table.

ARCH BASE DESIGN

The arch bases serve as piers to support the steel arch ribs, the steel roadway girder, and the concrete viaducts. They are reinforced and post tensioned concrete slab, beam, and shell structures. The complex curves of the arch base edges are joined by faces formed from surfaces of single curvature. Therefore, they can be formed readily using conventional formwork. They are post-tensioned vertically and transversely to facilitate the transfer of arch rib thrust forces through the curved forms of the arch bases to the foundations.

The arch table is an integral part of the arch base that serves as a transition between the steel box girder of the main span and the post-tensioned concrete box girder of the approach viaducts. It also transfers arch thrust from the ribs into the tie that is inside the steel roadway girder. It is a multi-cell concrete box girder with transverse diaphragms spanning to the arch ribs sections of the arch base. The arch tables are post-tensioned longitudinally to provide connections with the main span and viaduct girders, and transversely to provide connections with the arch ribs.

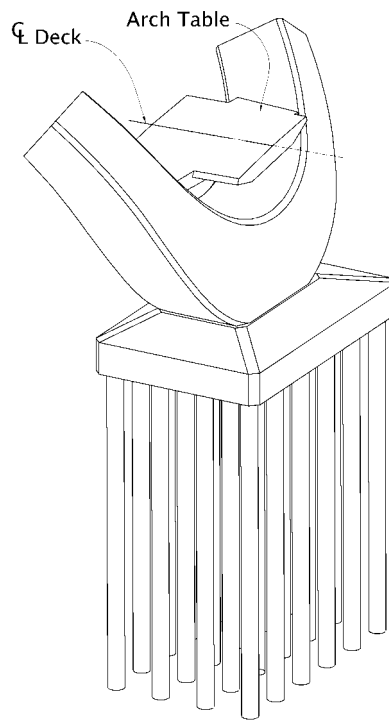


Fig. 8. Arch base, arch table, and foundation

FOUNDATIONS

Each arch base will be supported by a reinforced concrete pile cap and cast-in-steel shell concrete piles. The top surfaces of the rectangular pile caps are sloped away from the arch bases for aesthetics and drainage. They are reinforced to carry vertical and lateral loads to the piles, and to develop the moment capacity of each pile. The steel pile shells will be driven to a bearing layer, emptied of soil, reinforced with a steel cage, and concreted.

VIADUCTS

The viaducts are continuous post-tensioned multi-cell concrete box girder systems supported on reinforced concrete piers and pile foundations. The viaducts were designed to be economical to build and maintain, and to be aesthetically compatible with the main span arch. Viaduct span lengths range from 30 meters to 50 meters.

The viaduct superstructure is a multi-cell post-tensioned concrete box girder with an outside form matching the arch span girder. The five box cells are each nominally 5.1 meters wide; the four interior webs are the main load-carrying elements and contain longitudinal post-tensioning. The two partial-depth webs at the edges of the girder carry little load and are not post-tensioned.

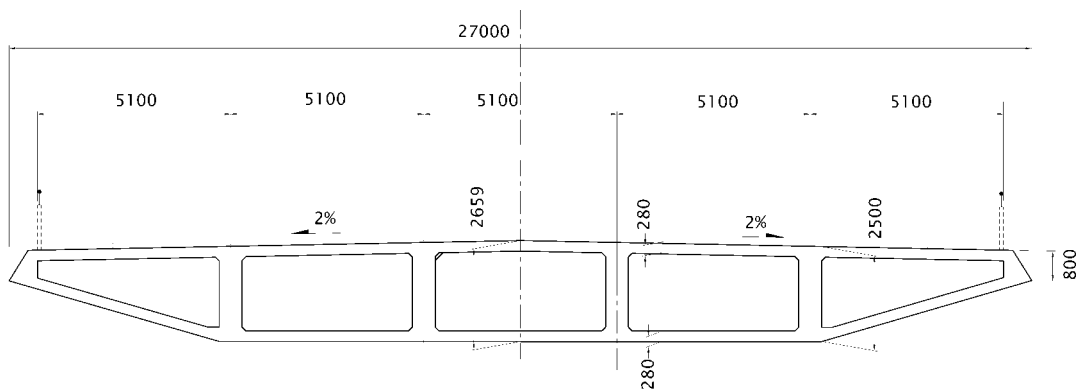


Fig. 9. Viaduct girder typical section

Expansion joints in the bridge deck are located at the viaduct abutments only. The viaduct girders are post-tensioned to the arch table to provide a force- and moment- resisting connection with no expansion joint. Thus the girder is continuous over the full length of the bridge.

Y-shaped reinforced concrete piers on pile foundations support the viaduct girders. Each pier consists of a vertical rectangular shaft, supporting a pair of narrower inclined shafts. The 6 meter tall inclined shafts support the box girder at a transverse diaphragm, within the outer rectangular cells. This pier geometry allows multiple re-use of concrete forms.

The taller piers near the arch span are built monolithically with the viaduct girder, to reduce -maintenance. The shorter piers near the abutments are built with sliding bearings, to allow temperature expansion and contraction with overloading the piers and their foundations.

CONSTRUCTION

The construction method envisioned for this bridge utilizes temporary falsework towers and high lines to erect the arch ribs and girder from prefabricated steel segments.

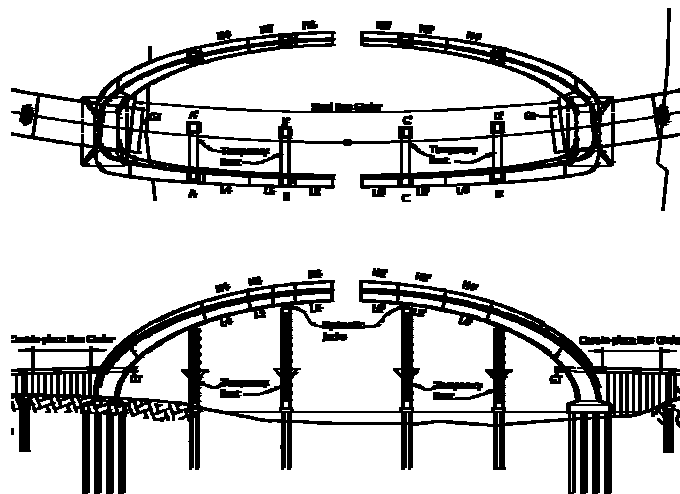


Fig. 10. Construction falsework

After completion of the foundations and pier tables using standard methods, temporary falsework bents and high lines anchored on the shores will be built. Arch rib segments and girder segments will be erected onto the temporary bents using the high lines and other hoisting equipment. After all segments are erected, the suspender ropes and arch ties will be installed and tensioned.

This construction method, identified as feasible based upon proven Chinese construction practices, is currently under development for use by the construction contractor.

CONCLUSIONS

The unique design of the Ling-Tie Bridge considers aesthetics, performance, constructibility, and economy. The form provides a funicular through arch to support a curved span. The arch ribs and deck girder balance each other's weight to provide a structure that is yet both rational and efficient. The concrete arch bases accommodate the complex curvatures of the arch intersections using principles of shell structures and post tensioning. The curved concrete viaducts provide both aesthetic and structural continuity. The bridge will be built using only techniques which have been proven elsewhere.

The design is supported by extensive analytical and model studies addressing overall load resistance, buckling stability, strength of stiffened panels, construction sequence, dynamic seismic performance, and dynamic wind performance including self-excited phenomena.