DESIGN OF THE DONGGUAN SHUIDAO BRIDGE IN GUANGDONG , CHINA

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Abstract: *Dongguan Shuidao Bridge situated in the city expressway of Dongguan city, Guangdong Province, China, is half-through rigid-frame tied arch bridge. It consists of three spans, with a main span of 278m half-through CFST arch and the two side spans cantilever deck RC half arches. The ribs in main span and in the two side spans are fixed at the arch seats and tied by pre-stressed steel bars at the two ends of the side spans. This paper deals with the consideration to be paid to select the bridge type, its main structures, static and dynamic analyses preformed.*

1 INTRODUCTION

Concrete filled steel tubes (CFST) structures have advantages over either steel tubular structures or reinforced concrete structures. The in-filled concrete delays local buckling of the steel tube, and the steel tube reinforces the concrete to resist tension stresses and improve its compression strength and ductility. Moreover, in construction, the tube also acts as a formwork for the concrete. CFST arch bridge has developed rapidly in China since 1990[i]. In plain area, the CFST arch bridge usually is a through or half-through bridge. For a half-through bridge, when the foundation is not suitable to carry large thrust, a fly-bird structure is generally used to balance the large trust force from the dead load. It is composed by three spans with a main span in half-through arch and the two side spans in deck cantilever half arches. The ribs in main span and in the two side spans are fixed at the arch seats and tied by pre-stressed steel bars at the two ends of the side spans. It is called half-through rigid-frame tied arch bridge or self balanced arch bridge. Sometimes for simplicity, it is called fly-bird arch bridge as its appearance look like bird. The Dongguan Shuidao Bridge is one of such bridge under construction.

The Dongguan Shuidao Bridge in a key project in the fifth-ring road of Dongguan city, Guangdong province, China. The bridge runs over the Dongguan River with a 55-degree angle between its central line and the river way. No piers were permissible in the riverbed and a skew bridge is prevented due to difficulty in structural design and construction, thus the main span is about 280m. For such a span, the choice of the bridge type was either a cable-stayed bridge or an arch bridge. The side span of a cable-stayed bridge will be 0.3-0.5 times of the main span, but for a fly-bird CFST arch bridge it is generally only 0.2-0.25 Thus the total length of a bridge is shorter in fly-bird arch than that in cable-stayed one. And the deck depth in arch bridge is much smaller compared to cable-stayed bridge. Therefore an arch bridge was more economic than a cable-stayed bridge. Moreover, an arch is aesthetically pleasing and it will be a landmark of the new developing city. Therefore, at last a CFST arch bridge was selected as the structure.

Two separate bridges in the road section carry 4 lanes vehicle traffic, one direction for two lanes with the net wide of 15.5m and footway of 4.8m. The span arrangement is 50m+280m+50m. Elevation and plan view of the bridge is shown in Fig. 1.

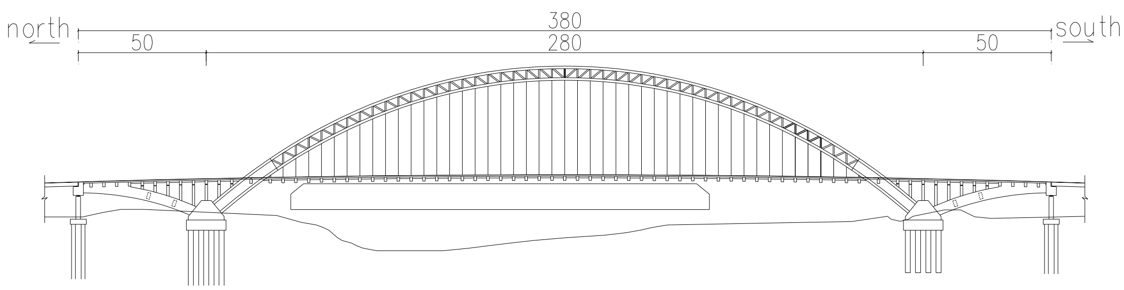


Fig. 1: Elevation and plan view (unit: m)

The design load of the bridge is vehicle-over 20, trailer-120 of China Highway Bridge Design Code[ii]. Earthquake reaction is considered based on the Chinese Seismic Standard with intensity of grade seven. At the bridge, it indicates a longitudinal decline of 4% from the centre of the span to the two sides with a vertical curve of 6500m radius. The bridge was erected by cantilever launching method by cable crane.

2 BRIDGE STRUCTURE

2.1 Main structure

There are two arch ribs in the main span. The arch axis is an inverted catenary curve with an axis coefficient of 1.5. The calculated span is 271.5m and the rise of the arch is 54.3m. Thus, rise-span ratio is 1/5.

The four chords in arch rib are steel tubes with 1000mm diameter and 16mm thickness (in the spring section the thickness increases to 18mm), filled with C50 concrete. Two of them in both upper and lower levels are welded together by two steel plates thick of 12mm to form horizontal laid dumbbell member. In the vertical direction, these two dumbbell members are joined by vertical and the diagonal web tubes 500mm diameter and 12mm thickness to form truss rib. The rib section is constant with width of 2.5m and height of 5.5m (Fig. 2). The arch rib about 2m in the spring portion is filled with concrete in the whole section to form a solid section in order to minimize the compressive stresses.

Two ribs with a center-to-center distance of 19.5m are connected to form a space frame by 12 K-shape steel tubular truss bracings, which consists both the struts and diagonals. The diameter of the tube of the strut and diagonal trusses are 670mm and the thickness of the wall is 12mm. The web tube diameter of the struts and the diagonals is 351mm and the thickness of the wall is 10mm. Two bracing groups are under the deck and the other fives are over the deck.

The two side spans are deck bridges of cantilever half arch. The arch ring is a rectangular rib of 4.0m height and 2.5m wide in general section and 3.19m wide in the section near the end cross beam. Between the two ribs of each side span, there are also reinforcement concrete lateral beams and end girders to connect them to form a space frame. The arch axis of the side span is also cantenary curve with a curve coefficient of 1.9. The rise-to-span is 1:9.819.

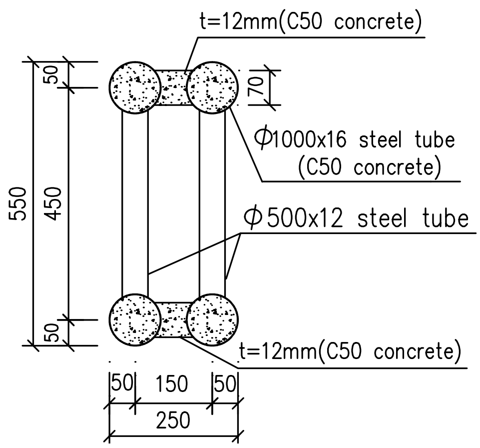


Fig. 2: CFST arch rib section (unit: cm)

The main CFST arch rib and the two side RC arch ribs are fixed at the pier and tied by steel strands at the two ends of the side spans to form a self-balance structure. Each tie bar uses 16 steel strands of $31\phi_j15.24$. The steel strength is 1860MPa and protected by Polyethylene. The tie bars are set along the longitudinal direction of the bridge, through the arch ribs. The two fronts of the tie bar are anchored in end cross beams with anchors.

2.2 Deck structures

The spandrel columns are reinforcement concrete columns. The hangers are high tensile steel wire strands. Hangers are generally in a single cable except the double hangers used in the first cross beam from the pier. Each cable contains 91φ7mm zinc-poured pre-stressed steel wires with the strength of R_Y^b=1670MPa. The strand anchorage is a cold cast steel socket. Adjustable chilled-casting pier nose anchors are used at the two fronts of the hanger.

The general cross PC beams suspended by cables or supported on the spandrel columns are 26.1m long with a box section of 0.8m wide and 1.622m to 1.722m high. The bracings connected the two main arch ribs at the deck level are steel box beams with 26.1m long, 1.2m wide and 1.5m high. The four cross beams at the end of the side spans are rectangular RC structures with 1.2m wide and 2.4m high.

The longitudinal laps between adjacent π -shaped pre-cast RC deck slabs and transverse laps between slabs and cross beams are cast concrete in-situ to form whole deck plate. The 10cm thick steel-fiber concrete will cast in-situ covering the deck and surfaced with 5cm thick SMA asphalt concrete.

2.3 Substructure

According to the soil investigation, the subsoils in the site from the surface to the deep are generally reclaimed earth, silt and fine-grained sand, coarse-grained sand, middle decayed rock, slightly decayed rock as well as fresh rock. The fresh rock was only found in some boreholes. The middle and slightly decayed rocks generally lay under the ground from 15.2 to 21.8 m and 18.6 to 29.0 m, respectively. The ultimate compression strength is 14.9 MPa and 24.5 MPa for the middle decayed and slightly decayed rocks, respectively.

There are 24 point bearing piles with 17.0 m to 22.9 m-long and 1.8m in diameter employed in each foundation of the two main piers (Z1 and Z2 pier). The arch seats and pile caps are in a whole block RC structure directly laid on the pile foundations. Two separate arch seats and pile caps for the two main arch ribs are connected by RC rectangular bracings.

The two side piers (Z0 and Z3) are composed of double circle RC columns with 1.8m in diameter. The diameter of the pile in Z0 and Z3 pier is 1.2m and 1.5m, respectively, due to the different geologic conditions.

3 STRUCTURAL ANALYSES

3.1 Finite element model

A three-dimensional finite element model has been developed to analyze the bridge. The arch rib was modeled taking account of all the CFST chord members, bracing plates and web tubes, each with its own geometric characteristics. The bracing members, cross and longitudinal girders as well as the spandrel columns are modeled by two-node beam elements having three translational and three rotational DOFs at each node. Hangers are simulated with truss elements. The concrete deck slab is also modeled by two-node beam elements. The pavement layers did not have their own geometrical and inertial properties, only masses. The arch ribs are assumed to be fixed at the abutments. As a result, the model has a total of 5836 elements of 52 types, 2866 nodes. Fig. 3 shows the full three-dimensional view of the finite element model.

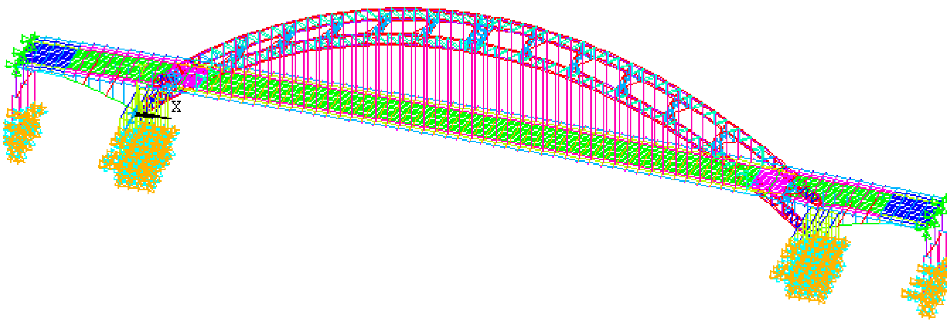


Fig. 3 Finite element model

3.2 Static analysis

Static analysis was performed in three phases:

- Analysis of the steel tubular arch in the main span only, carrying their own weight and the fresh concrete filled into steel tubes without strength and rigidities;
- Analysis of the fly-bird arch structure (the CFST arch rib in the main span and the two RC arch ribs in two side spans tied together by tied bars) carrying the dead loads of the deck system, including the cross-beams, deck slabs and pavement, columns and cable hangers, etc;
- Analysis of the completed bridge with dead loads and live loads.

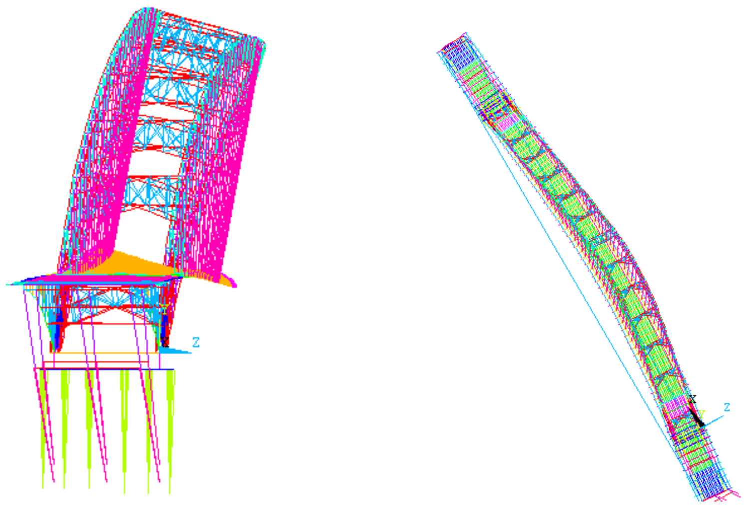
The second phase in fact is considerably complicated and can be divided into more detail phases. During the construction, the tied forces are stressed to the structure step by step according to the erection of the deck members.

When analyzing the completed bridge structure, three load combinations according to China Highway Bridge Design Code were considered. The live load conditions were considered in order to produce maximum and minimum (absolute maximum value) bending moments at spring section, crown section, L/8 section and L/4 section; to produce maximum thrust at the piers.

Comparing the maximum strength of each member to its maximum forces obtained from the static analysis shows that all the members were expected to be safe during its service life. The largest deflection of the bridge deck is 29.07cm under the service loads, smaller than the allowable deflection (L/800=35cm). Therefore, the stiffness of bridge can meet the requirement for design.

Analyzed by the eigenvalue method, the elastic buckling shape of the structure subjected to dead loads and dead loads plus live loads was out-of-plane instability, as shown in Fig. 4.

The safe factor of elastic buckling load compared to dead load is 5.706. The factor varies from 5.491 to 5.597 for dead load plus live load in different load conditions.



(a) Cross section view (b) Plan view

Fig. 4: Elastic buckled shape of the structure

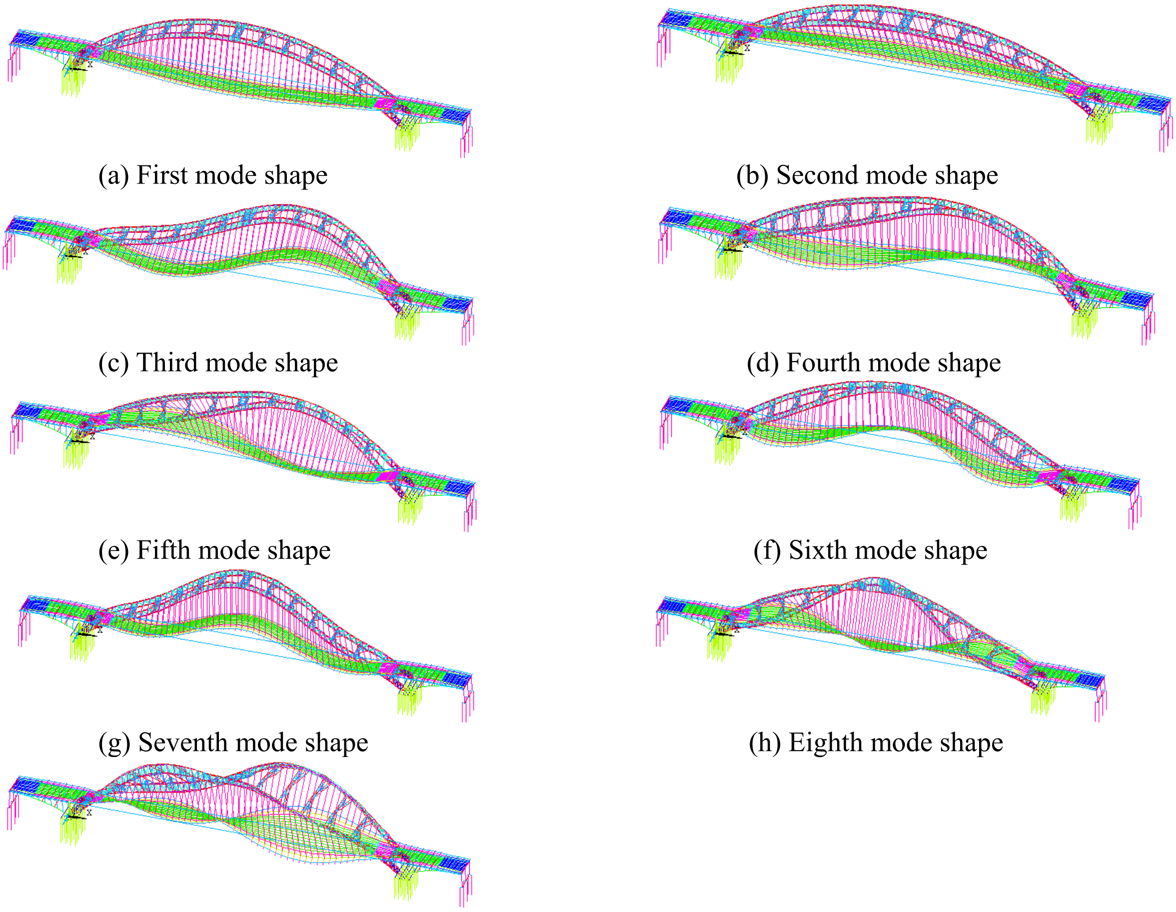
3.3 Seismic actions

Dynamic analysis was performed on the three-dimensional model using finite-element techniques in order to obtain the eigenvalues and eigenvectors of the structure. The model included masses and stiffness as in the real structure. Masses were distributed on beam elements. Results are given in Fig.5 and Table 1.

No	Mode	Frequency (Hz)
1	First bending of the bridge out of the vertical plane	0.272
2	Second bending of the bridge out of the vertical plane	0.344
3	Third asymmetric bending of the bridge in the vertical plane	0.536
4	Fourth asymmetric bending of the bridge out of the vertical plane	0.543
5	Fifth asymmetric bending of the bridge out of the vertical plane	0.608
6	Symmetric torsion of the bridge	0.886
7	Sixth symmetric bending of the bridge in the vertical plane	0.898
8	First torsion and bending of the bridge out of the vertical plane	1.002
9	Second torsion and bending of the bridge out of the vertical plane	1.047

Table1: First nine natural frequencies of the bridge

Seismic analysis is carried out using the response spectrum method. According to the geographical position of the bridge site, Dongguan Bridge belongs to the sixth seismic zone. Based on "Specifications for Anti-seismic Design of Highway Engineering (JTJ004-89)"[iii], the bridge should be designed as the seventh seismic zone and the bridge site is considered to be Type III. By the analysis, the acceleration spectrum is got shown as Table 2.



(a) First mode shape (b) Second mode shape

(c) Third mode shape (d) Fourth mode shape

(e) Fifth mode shape (f) Sixth mode shape

(g) Seventh mode shape (h) Eighth mode shape

(i) Ninth mode shape

Fig.5: First nine mode shapes

Frequency(1/s)	0.100	0.267	0.308	0.351	0.408
Acceleration(m/s^2)	0.1785	0.1786	0.2046	0.2318	0.2676
Frequency (1/s)	0.465	0.513	0.606	0.69	0.8
Acceleration (m/s^2)	0.303	0.3324	0.3896	0.4405	0.5072
Frequency (1/s)	0.952	1.176	1.538	2.222	2.5
Acceleration (m/s^2)	0.5986	0.7316	0.944	1.3387	1.3388
Frequency (1/s)	3.333	5.0	10	12.5	16.667
Acceleration (m/s^2)	1.3388	1.3388	1.3388	1.19	1.0412

Table 2: The seismic acceleration spectrum

The internal forces are calculated based on the acceleration spectrum above. When the bridge is subjected to an earthquake in the longitudinal and vertical direction, the axial force and longitudinal bending moment are much more important than shearing force, torque and lateral bending moment. When the bridge is subjected to an earthquake in the lateral direction, the axial force and lateral bending moment are predominant for the box girder by two arch ribs and twelve cross braces.

4 Conclusion

- This paper deals with Dongguan Shuidao Bridge, a truss CFST half-through tied-arch bridge. The key issue of this research is to deal with the nature of the site, the design criteria, the static and dynamic analysis performed.
- Finite-element method is adopted to analyse the static and dynamic characteristic of the bridge. For the static case, checking of computations about the strength of each member and the deflection of the bridge deck are done. It is verified that the strength and stiffness of bridge can meet the requirement for design. For the dynamic analysis, the first nine mode shapes and the corresponding frequencies are shown in this paper.

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