Spatial analysis of concrete filled steel tubular tied arch bridge

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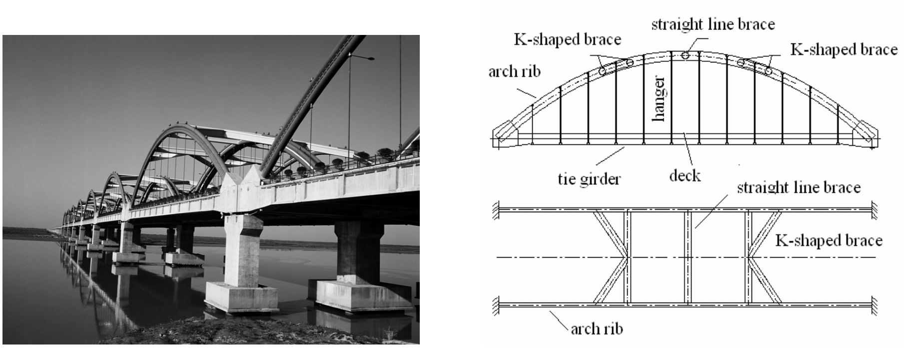
ABSTRACT: The Second Highway Bridge over Yellow River in Zhengzhou is a concrete filled steel tubular tied arch bridge. In this paper, both plane and spatial finite element models are developed to analyze lateral distribution coefficients of live load, behavior of cross beam, arch rib and tie girder, and spatial effect of the structure. The elastic buckling of the bridge is also investigated by the spatial finite element model. The analysis results show that it is reasonable to use the lever distribution method in design calculation for it can agree well with the result from the spatial FEM. The deck cross beam behave similar to simple beam while end cross beam is influenced by tie girder and should be analyzed by spatial FEM. Tie girders are subjected to considerable torsional moments. Diagonal bracing members of arch ribs and temporary falseworks for tie girders in construction can improve stability of tied arch bridge.

1 INTRODUCTION

Tied arch bridge or deck stiffened arch bridge is one of the five main bridge forms in the concrete filled steel tubular (CFST) arch bridges. In CFST tied arch bridge, the reactive horizontal forces acting on CFST arch ribs are supplied by PC or steel tied girders. Therefore, this type of bridge can be used in plane area with weak soil. More than 60 of such bridges with a main span not smaller than 50m have been built in China, in which the main bridge in the Zhengzhou Second Yellow River Highway Bridge, completed in 2004, is the largest scale one. The bridge is composed by two separated superstructures, each carries 4 lanes in a direction with a net width of 19.484 m. There are 8 main spans with each span of 100m as shown in Fig. 1 a (Chen 2004, 2007).

Its calculation span is 95.5m. The arch rib adopts cantenary curve with a rise to span ratio of 1/4.5. Each bridge comprises two 2.4 m high arch ribs of dumbbell cross-section and two tie PC box girders of 2.0m width and 2.75m high. The hanger is made of 91Φ7mm high tensile strength wires. There are two end cross beams and twelve deck cross beams in a span. The end cross beam is a PC box girder high 2.9m and wide 3.22m. The deck cross beams are I-shaped PC beams, on which are the precast RC π-shaped deck slabs. The configuration of superstructure is illustrated in Fig. 1b (Zhang 2004).

A CFST tied arch bridge is a static indeterminate spatial structure. It is common now to use a spatial finite element model (FEM) to analysis such a structure in design. However, if a plane FEM can be used or a simplified method can be used in design, especially in premier design work, it will be more convenient for engineers and more design time will be saved. In this paper, taking the Zhengzhou Second Yellow River Highway Bridge as an example, both spatial and plane FEMs are established. Analysis results from these two models are analyzed and the spatial behaviors of a tied CFST arch bridge is concluded as a reference for structural design of other CFST tied arch bridges.



(a) Photo (b) General Layout

Figure 1: The Zhengzhou Second Yellow River Highway Bridge

2 FINITE ELEMENT METHOD

The plane FEM is set up by a Chinese special program *Bridge Doctor*(Zhou 1999). In this FE model, tied arch bridge is simplified as a longitudinal structure composed of arch rib, tie girder and hangers, and both the cross beam and deck are not taken into account. In order to simplify structural analysis, deck loads (including the self-weight of the deck structure and the live load) were longitudinally distributed by lever method from deck slabs to deck cross beams and then transversely distributed by the same method from cross beams to the longitudinal structures. Thus, the concentrated loads in tie girders in the hanger points are adopted as the deck loads in plane FEM analysis. For the case study, the model (Fig. 2) includes 56 composite elements for CFST arch rib, 60 prestressed concrete elements for tied girder and 12 link elements for hangers.

The FE spatial model is set up by general purpose program *ANSYS*. In this model, all the main elements of bridge structure were treated as spatial beam elements, except deck plate as shell elements and hangers as cable elements. For the case study, the model (Fig. 3) includes 262 three dimensional elements (Beam4 element) for arch ribs and the bracings, tie girders and cross beams, 268 shell elements (Shell63) for deck plates and 24 cable elements (Link10) for hangers.

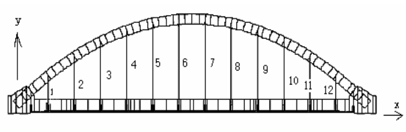


Figure 2 : Plane Finite Element Model

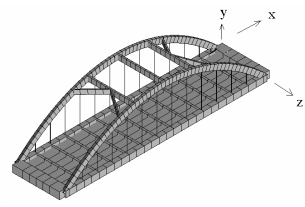


Figure 3 : Space Finite Element Model

CFST arch rib is made of steel-concrete composite material. Its rigidities are estimated by different methods in different design codes for CFST structures. In some codes, the compression and equivalent flexural rigidity are considered to be the algebraic sum of rigidity for each component as if each material acts separately. In other codes, reduced contribution of the concrete rigidity is considered by multiplying a factor smaller than 1.0 to it. Because tied arch bridge is static indeterminate structure, the larger the rigidity of the arch rib the larger the inner forces were obtained. Therefore, from the view of safety, the sum of compression and flexural rigidity of its steel tube and concrete core is adopted as the CFST compression and flexural rigidity, respectively (Chen 2007).

3 CALCULATION RESULTS

3.*1 Transverse Distribution of Live Load*

In plane model, the coefficient of transversely distributed live load on deck is calculated by lever method and assumed to be constant. However, the result by the spatial model shows that the transverse distribution of live load varies along the longitudinal direction. Fig. 4 gives a comparison of the transverse distribution coefficients by lever method in plane model and directly from the spatial FE model under trail loads or truck loads. However, it can be found out from Fig.4 that the difference in the two models are very small, the maximum difference is less than 5%. Moreover, the trail load is the design load and coefficients calculated by lever method are slightly larger and will result in a conservative design. Therefore, for CFST tied arch bridge, lever method can be used to calculate the transverse load distribution in order to obtain internal forces in FE plane model.

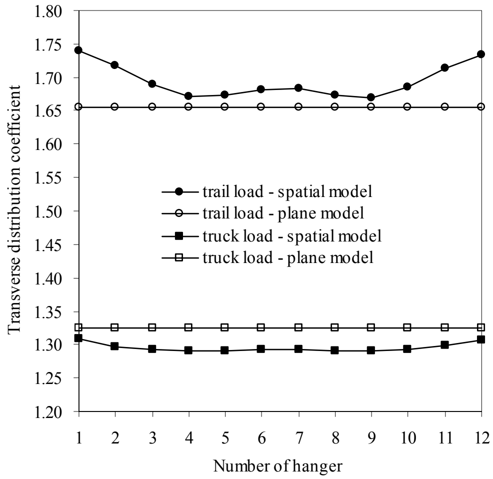
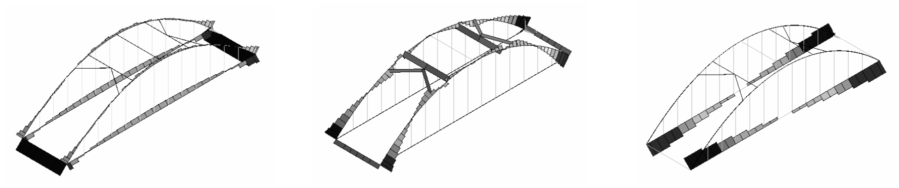


Figure 4: Transversely distribution coefficients of live load

3.2 Arch Rib and Tie Girder

In the plane model, loads can only be applied in the plane, and no bending moment out of plane and torsional moment in the structure can be obtained from the calculation. In order to investigate the forces out-of-plane on the arch rib and tie girder, a spatial FE model is employed in the calculation.

During construction of the bridge, precast deck cross beams were erected and connected to tie girder by wet joints after two tie girders, arch ribs and end cross beams had formed a spatial frame. At this time, the self-weight of the cross beam as concentrated forces acted on the inner edge of the tie girder and caused large torsional moment in it. Calculation shows that when the first cross beam weighing 463kN was erected, it would produce 250kN·m torsional moment, which was mainly reacted by 243kN·m bending moment (97.3% of 250kN·m) in the end cross beams and the rest 2.7% torsional moment was balanced by the torsional moments of the arch ribs and the tie girder as well as the out-of-plane bending moments of the arch ribs. From Fig. 5 it can be found the internal forces in the frame when the first deck cross beam was erected.



(a) bending moment in plane (b) bending moment out of plane (c) torsional moment

Figure 5: Internal force when erecting cross beam

In service time, the bending moments in deck cross beams and the deck slabs can react torsional moments by live loads, therefore the bending moments in end cross beams and torsional moments in tie girders will decrease greatly. When the distance of a concentrated load in deck to the central line of the tie girder in transverse direction increases from 1m to 2m, the torsional moment in the tie girder increases only about 35% but not double.

3.3 Cross Beam

The internal forces of the deck cross beams should be calculated by a spatial FEM but not a plane one. Although deck cross beam is fixed to tie girders, it is not a real fixed beam because the two ends of the deck cross beam will have rotation deformation, which is the torsional deformations of the tie girders in the joints. Under the deck dead load, deck cross beam's bending moment is between that of a simple beam and a fixed beam, as shown in Fig. 6. In the deck cross beam near the mid-span of tie girder, the negative bending moment at the support is very small, so it behaves like a simple beam. But in deck cross beams near arch spring, the negative bending moment is not negligible. However, these negative bending moments can be resisted by reinforced bars or the crook up prestressed bars, and no straight prestressed bar is needed.

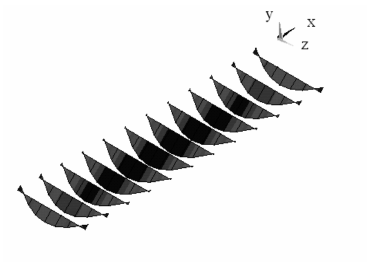


Figure 6 : Bending moment of deck cross beams under dead load

As mentioned in section 3.2, erecting the deck cross beam in construction would produce a dominated positive bending moment at the support section of the end cross beam. Fig. 7 gives the largest bending moment diagram of the end cross beam in the design calculation. It indicates that all of the bending moments in it are positive and the value is much larger than those in a simple beam.

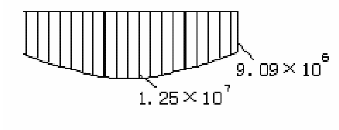
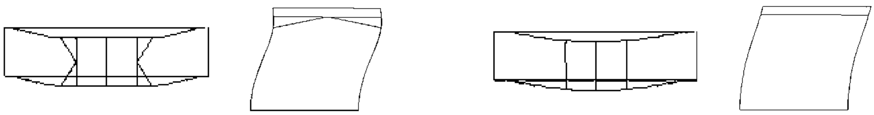


Figure 7 : Bending moment of end cross beam (unit: N·m)

3.4 Bifurcation Buckling Analysis

Generally, the first buckling mode of tied arch bridge is lateral buckling of arch rib. Therefore, the stability can not be analyzed by plane FEM and spatial FEM is used instead. Both the completed structure and the structure during construction are analyzed.

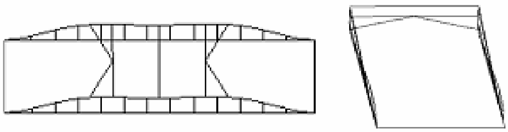
Fig. 8 shows the buckling modes of the structure with full bracing members and with only straight bracing members but no diagonal ones when casting concrete into steel tubular ribs. The two modes are some difference and the critical load will decrease by 37% when the diagonal bracing members are not installed.



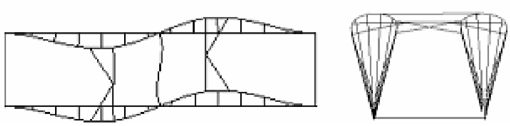
(a) With all braces (b) Without diagonal bracing members

Figure 8: Buckling mode during filling concrete into steel tubes of arch rib

The bridge site of Second Highway Bridge over Yellow River in Zhengzhou is a zone of shallow and broad reach, so the 99m long tie girder was divided into 6 segments and erected on falseworks. These falseworks could be removed after erection of tie girder. In this case, the buckling mode is a half sine curve out-of-plane when erecting deck cross beams, see fig. 9a. If the falseworks were still stand there, the buckling mode is a full sine curve and the critical load can increase about 30%, as shown in Fig. 9.



(a) Without falsework



(b) With falsework

Figure 9 : Buckling mode during installation of cross beam

Spatial FEM analyses show that the stability of the bridge can meet the design requirement both during the construction and in the service time. In the service time, the buckling mode is also a full sine curve out-of-plane as shown in Fig. 9b and the critical load is 5.21 times of the service load.

4 CONCLUSIONS

For CFST tied arch bridge, lever method can be used to calculate load distribution coefficient and the structure internal forces can be calculated by plane FEM.

The out-of-plane bending moments, the torsional moments of arch ribs and tie girders, the cross beam’s internal forces and the buckling of the structure should be calculated by a spatial FEM. Analysis results indicate that the torsional moments of the tie girders should be taken into account; deck cross beams behave more close to a simple beam than to a fixed beam and no straight prestressed bar is needed to react the negative bending moment. Bending moments in end cross beams are positive and the value is much larger than those in simple beam.

Diagonal bracing members of arch ribs and temporary falseworks for tie girders in construction can improve stability of tied arch bridge.

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