Stability analysis of double x-shape arch bridge during construction

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Abstract: The main bridge of Zhanhe River, which is located in Pingdingshan city, China, is a double X-shape reinforced concrete arch bridge. With the aid of the Midas/civil finite element software, the three-dimensional finite element model of the Zhanhe Bridge is established according to the actual construction stages and the design construction stages. The stability safety coefficients for different construction stages, such as arch-rib completion, tie bar beam tensioning and suspender tensioning are calculated. The calculation results indicate that the minimum stability coefficient for this arch bridge during construction is 7.28, which meets the requirement of arch bridge stability. The main results are useful for the design, construction and maintenance of the same bridges.

1. Introduction
The Double X-shape Arch Bridge is a new type of bridge structure, which has been developed on the basis of basket-type arch bridge. It consists of four arch ribs, including two vertical or outward-inclined main arch ribs which function as main load-bearing structure and another two inward-inclined arch ribs (referred to as stabilizing arch, inclined arch or outside arch). On each side, the stabilizing arch that inclines inwardly and its adjacent main arch constitute space for the footbridge. No horizontal connections between the two main arch ribs are provided and the space stability system is formed by mutual support between stabilizing and main arch ribs, ensuring structural stability. This bridge type is novel and beautiful in shape with broad and unblocked bridge floor and has technical features such as significant spatial effect and deformation compatibility between main and stabilizing arch ribs[1-2].

The stability of bridge structure is related to its safety. With continuous increase in bridge span and bridge pier (tower) height as well as application of thin box girder and high strength materials, overall and local stiffness of bridge structure reduces gradually, making bridge stability issue more prominent than before. In a certain sense, stability and stiffness of the bridge are equally important. Construction is a process to realize completion of the bridge and involves complicated system transformation, so the bridge structure must withstand all possible loads to remain stable; otherwise, accidents may arise. There have been many examples of bridge failures in the world caused by instability during construction. Construction stability is particularly important because the structure of double X-shape Arch Bridge is complicated, especially for the reason that the structural system is constantly changing and the load is continuously increasing.

By taking main bridge of Zhanhe Bridge (a double X-shape reinforced concrete arch bridge) as the research object, this paper establishes spatial finite element model for this arch bridge with the use of finite element software Midas/civil, in a bid to calculate spatial stability of this bridge during construction and compare the effects of two construction procedures on this bridge. The data obtained
from the said calculation and comparison will provide basis for construction supervision of this bridge.

2. Project description

The main bridge of Zhanhe Bridge is a double X-shape reinforced concrete arch bridge. Its main arch ribs incline outwardly by 1° and stabilizing arc ribs incline inwardly by 8.0075°. The main and stabilizing arch ribs constitute combined arch ribs and such combined arch ribs together with tie bar beam and cross beam form spatial structural system. The axial lines of main and stabilizing arches are quadratic parabola with a rise-span ratio of 1/4.444 and 1/2.711 for main and stabilizing arches respectively. The main and stabilizing arches adopt box profile. The box heights of main and stabilizing arches are all 2.7m and box widths for main and stabilizing arches are 1.5m and 1.2m respectively. The tie bar beam adopts prestressed concrete box profile with a box width of 1.5m and a box height of 2.7m. The middle cross beam adopts T-shaped prestressed concrete beam and the reinforced concrete slab is used as bridge floor. For the purpose of strengthening stability of bridge floor and improving forces acting on the bridge floor, two longitudinal beams are separately provided between two arch ribs and tie bar beam. Those two longitudinal beams are rigidly connected with bridge floor slab and each cross beam. The suspenders of main arch adopt cold-casted pier head anchor system which is made of high-strength galvanized steel wire, and the spacing between them is 4m. The spacing between two suspenders of the stabilizing arch is the same as that of main arch, and the suspenders of the stabilizing arch are arranged at the end of each cross beam, totaling 46 pairs of suspenders. The main arch is supported on the box-shape reinforced concrete pier through pot-type bearing, and 6 bored piles with a diameter of 120cm are arranged at each arch toe of stabilizing arch ribs. The front and side elevation layout are shown in figure 1.

![Figure 1. The front and side elevation of Zhanhe double X-shape arch bridge](image)

3. Establishment of finite element model

Finite element software Midas/ civil is used for modelling in order to analyze stability of this bridge during construction. Reference is made to finite element modelling for similar bridge type during modelling of this bridge[3-5], which means: (i) the spatial beam element simulates tie bar beam, cross beam, small longitudinal beam, arch rib and cross brace; (ii) the spatial truss element only withstanding tensile force stimulates the suspender; (iii) the spatial truss element only withstanding stress stimulates the bracket and (iv) the slab element stimulates the bridge floor. The calculation model for the whole bridge is planned to be divided into 1278 elements including 760 beam elements, 174 slab elements and 344 truss elements. Spatial finite element calculation model is shown in figure 2.

The boundary condition for main arch rib of this bridge is that main arch rib is hinged and supported on one end and is sliding on another end. The boundary condition for stabilizing arch is that both ends are consolidated. By considering construction processes, such as prestressed tension of tie bar beam, end cross beam, middle cross beam as well as tension of internal and external suspenders, this paper adopts activation and deactivation functions of finite element software Midas/ civil to activate and deactivate structural element, load and boundary condition during different construction stage so that the calculation model for construction stage under two tension construction procedures is
established. This calculation model is used for stability analysis during bridge construction.

4. Calculation and result analysis

In consideration of actual bridge construction sequence (alternative tensioning of internal and external suspenders) and initially designed construction sequence (first tension internal suspender and then external suspender), buckling analysis module of finite element software Midas/civil is used to establish calculation models for each construction stage under two different construction sequences to calculate stability during bridge construction. Due to text length limitation, this paper only presents the first two order stability coefficient and the first order instability characteristics of bridge structure under two construction sequences, as shown in table 1. Figures 3-6 show modal graph of the first order instability for partial construction stage.

Table 1. Stability coefficients and the 1st instability characteristics for each construction stage under two construction sequences

| serial number | alternatively tension internal and external suspenders | stability coefficient | first order | two order | stability coefficient | first order | two order | First order instability mode |
|---------------|------------------------------------------------------|-----------------------|-------------|-----------|-----------------------|-------------|-----------|----------------------------|
| 1             | pouring the inner and outer arch ribs               | 21.22                 | 21.22       |           | pouring the inner and outer arch ribs | 21.22       | 21.23     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 2             | tension internal suspender 9.20                     | 18.63                 | 18.63       |           | tension internal suspender 9.20       | 19.14       | 19.15     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 3             | tension external suspender 4.15                     | 18.67                 | 18.67       |           | tension internal suspender 12.17      | 16.37       | 16.38     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 4             | tension internal suspender 12.17                    | 15.47                 | 15.47       |           | tension internal suspender 4.25        | 15.23       | 15.23     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 5             | tension external suspender 7.12                     | 15.26                 | 15.26       |           | tension internal suspender 7.22        | 14.29       | 14.30     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 6             | tension external suspender 4.25                     | 14.16                 | 14.16       |           | tension internal suspender 10.19       | 13.68       | 13.69     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 7             | tension external suspender 2.17                     | 13.71                 | 13.71       |           | tension internal suspender 3.16         | 13.29       | 13.30     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 8             | tension external suspender 10.19                    | 12.92                 | 12.92       |           | tension internal suspender 13.16        | 12.60       | 12.61     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 9             | tension external suspender 5.14                     | 12.52                 | 12.52       |           | tension internal suspender 8.21         | 12.30       | 12.31     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 10            | tension external suspender 3.26                     | 12.52                 | 12.52       |           | tension internal suspender 11.18        | 11.81       | 11.82     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 11            | tension internal suspender 14.15                    | 12.15                 | 12.15       |           | tension internal suspender 2.27         | 11.59       | 11.60     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 12            | tension internal suspender 14.15                    | 11.35                 | 11.36       |           | tension internal suspender 14.15        | 11.40       | 11.41     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 13            | tension external suspender 8.11                     | 11.23                 | 11.24       |           | tension internal suspender 1.28         | 11.31       | 11.31     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
| 14            | tension internal                                  | 10.92                 | 10.93       |           | tension internal suspender              | 10.97       | 10.98     | Out-of-plane Antisymmetric Torsional Instability of Arch Ribs |
Note: the serial number for suspender of internal arch is 1 to 28 from left to right and that for suspender of external arch is 1 to 18 from left to right.

The following can be derived from analysis of calculation results:

(1) The first order stability coefficients for each bridge construction stage are all 7.28 to 21.23, which meet the requirement that the stability coefficient for general arch bridge shall be more than 4-5. Moreover, the instability form of the bridge is similar to that of general tied arch bridge without cross brace, which is instability caused by external surface torsion of the arch rib, suggesting that stiffness of external surface of arch rib is less than that of internal surface and playing a role in controlling stability of the bridge.

(2) With progress of bridge construction, the first-order stability coefficient for each construction stage tends to decrease in general, because the force acting on the whole structure changes after the suspender has been added during actual bridge construction. Tensioning of the suspender has dual effects. On the one hand, non-orienting force of the suspender acts to stabilize the arch rib; on the other hand, the suspender changes the force acting on the bridge structure to redistribute internal force of the structure component and the bridge floor weight originally borne by the bracket is to be borne by the arch ribs through the suspender. As the axial force of the arch rib increases, tensioning of the suspender results in decrease of stability of the bridge structure. As a result, the conclusion that the non-orienting force effect can enhance lateral stability of arch rib is correct only provided that status of internal force of arch rib is the same.

(3) It is shown from Table 1 that the stability coefficient for first tensioning internal suspender and then external suspender is slightly higher than that for simultaneous tensioning of internal and external suspenders, which is more beneficial for bridge stability during construction.
5. Conclusions

According to structural features of Zhanhe Double X-shape Arch Bridge, the finite element software Midas/ civil is used to establish spatial finite element calculation model under two construction sequences (simultaneous tensioning of internal and external suspenders as well as first tensioning of internal suspender and then external suspender) to analyze stability for main construction stage of this bridge. The calculation results indicate that: (i) the first-order instability mode for each bridge construction stage is instability caused by external surface torsion of the arch rib and the first-order stability coefficients for each bridge construction stage are all 7.28 to 21.23, which meet the requirement that the stability coefficient for general arch bridge shall be more than 4-5 and (ii) the stability coefficient for first tensioning internal suspender and then external suspender is slightly higher than that for simultaneous tensioning of internal and external suspenders, which is more beneficial for bridge stability during construction. The data obtained can provide basis for construction supervision of this bridge.

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