Analysis of the Influence of Boundary Conditions on the Mechanical Characteristics of Arch Bridge with Composite Arch

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Abstract. Mid-through arch bridge with a composite arch rib of the main arch and vice-arch is novel and reliable in rigidity. It belongs to the high-order statically indeterminate structures, and the boundary form has a great influence on the internal force and deflection of the structure. In this paper, in order to study the influence of different boundary conditions on the static and dynamic characteristics of the structure, relying on a practical project, the static and dynamic characteristics of the bridge under different boundary conditions of the main arch foot are analyzed and compared by using finite element method, which provides scientific basis for the design of the arch bridge with composite arch. The results show that the boundary conditions of the main arch foot have obvious effects on the deflection and internal force of the arch under dead and moving loads, but have little effect on the dynamic characteristics and stability of the bridge.

1. Introduction

Arch bridges have many kinds of structural styles, and the influence of the overall layout of arch bridge on the mechanical properties of structure is not clear. Scholars have done a lot of research work on the construction of arch bridges, and relatively few research work has been carried out on structural systems of special-shape arch.

The research of bridge structure system has always been the focus of bridge researchers. For example, Yue Xu and Chengyue Shen\textsuperscript{[1]} studied the influence of tension force of hangers and tied-bars and the line-shape of the arch axis on the internal force distribution of through tied-arch bridge by using the finite element method. Zhenzhong Han, Jian Zhao\textsuperscript{[2]}, Hongxia Xiong, Zhihong Liu\textsuperscript{[3]}, Lixin Liu, Wenjie Zhao\textsuperscript{[4]}, Chunfeng Liu, Xiuyong Si\textsuperscript{[5]}, Rong He, Huai Chen\textsuperscript{[6]} and so on analyzed the influence of many different design parameters, such as the rise-to-span ratio, ratio of rigidity of tied beam, arch rib, arrangement of lateral bracing system for arch ribs, hanger arrangement and floor system, on the structural mechanical properties of bridges by using the finite element program. At the same time, some of the relatively good proposals for the said parameters are studied. Shengkui Di and Jia Wang\textsuperscript{[7]} studied the internal force response of arch bridges with different constrain types under
earthquake. In this paper, the influence of different boundary conditions of the main arch foot on the static and dynamic characteristics of the arch axis is studied by using the finite element method.

2. Finite element analysis

2.1. Project overview
The arch bridge adopts the composite arch rib of main and vice-arch, and the section is a composite steel box. The total length of the bridge is 274m, and one vice-pier is set for each side span. The hanger spacing is 10m+29×6m+10m, and the main beam is a steel-concrete composite beam. The main arch rib of the steel box arch has a calculated rise height of 55m, a calculated span of 220m, a rise span ratio of 1/4 and an arch axis coefficient of 1.543. The main arch rib adopts the form of variable cross-section. The height of cross-section of main arch changes from 5m to 3m, with a constant width of 1.5m. The arch bridge has a calculated vice-arch rib height of 44m, a calculated span of 253m, a rise span ratio of 1/5.75, and an arch axis coefficient of 1.543. The vice-arch rib adopts the form of a variable section too. The height of the section changes from 4m to 2m, with a constant width of 1.5m. The general layout of the arch bridge is shown in figure 1.

![Figure 1. The general arrangement of the main bridge (cm)](image)

2.2. Finite element model of the bridge
According to the structural form and mechanical characteristics of the bridge, the beam element and truss element are adopted to simulate the arch bridge in the finite element program Midas civil. The main girder and arch rib are simulated by the beam element, and the hanger is simulated by the truss element. The calculation model of the whole bridge structure is shown in figure 2. In this bridge, Q345qc steel and C50 concrete are used.

![Figure 2. Schematic diagram of the finite element model of the bridge](image)

2.3. Mechanical characteristics of the arch bridge.
With the calculation and analysis of the spatial finite element model and the project experience, it is well known that the section with the maximum stress or the maximum tensile stress is located at the
arch foot, L/8, L/4, 3L/8 and the arch vault. Therefore, these five sections are taken as the control section in the analysis and calculation. The boundary conditions of the main arch foot are analyzed in the following two cases: rigid connection and hinged connection. The internal force and deflection value of the main control section of the arch axis under the dead load and moving load in completion state are listed in Table 1 to Table 4 and Figure 4.

**Table 1. The axial force of main control section under dead load (kN)**

| Boundary condition of arch foot | Position | Control section | Arch foot | L/8   | L/4   | 3L/8   | Vault   |
|--------------------------------|----------|-----------------|-----------|-------|-------|--------|---------|
| Rigid connection               | Main arch| -16543.5        | -13004.1  | -11679.2 | -11099.5 | -14221.2 |
|                                | Vice-arch| -4428.2         | -3779.2   | -3597.2  | -3473.1  | -3403.6  |
| Hinged connection              | Main arch| -16562.0        | -13019.8  | -11695.1 | -11115.2 | -14259.9 |
|                                | Vice-arch| -4449.4         | -3802.2   | -3620.7  | -3473.1  | -3403.6  |
| Difference value               | Main arch| -0.11%          | -0.12%    | -0.14%   | -0.14%   | -0.27%   |
|                                | Vice-arch| -0.48%          | -0.61%    | -0.65%   | -0.68%   | -0.68%   |

2.3.1. *The influence of boundary conditions on internal forces*

It can be seen from Table 1 and Table 2 that, for the hingeless arch and the two hinged arch, the change trend of axial force of main arch and vice-arch under dead load is similar, and the axial force line is symmetrical. The axial force at the arch foot is the maximum, and the axial force from the arch foot to the mid-span decreases to the minimum value first, and then rises sharply to the extreme value. The influence of the main arch boundary form on the arch axial force is less than 1%, and the arch axial force is smaller when the boundary form is a rigid connection.

**Table 2. The bending moment of main control section under dead load (kN·m)**

| Boundary condition of arch foot | Position | Control section | Arch foot | L/8   | L/4   | 3L/8   | Vault   |
|--------------------------------|----------|-----------------|-----------|-------|-------|--------|---------|
| Rigid connection               | Main arch| -1575.3         | 86.6      | -724.4 | 2219.9 | -1791.3 |
|                                | Vice-arch| -353.8          | 722.2     | -953.4 | -510.4 | 2022.6  |
| Hinged connection              | Main arch| 0               | 186.9     | -715.8 | 2169.6 | -1841.1 |
|                                | Vice-arch| 0               | 794.8     | -992.7 | -565.0 | 2256.4  |
| Difference value               | Main arch| --              | -115.95%  | 1.18%  | 2.26%  | -2.78%  |
|                                | Vice-arch| --              | -10.06%   | -4.12% | -10.68%| -11.56% |

It can be seen from the Table 4 that under the dead load, the bending moment values of the main arch also show the trend of symmetry change. Both the hingeless arch and the two-hinged arch have the maximum negative bending moment at 3L/8, the bending moment value of the whole span fluctuates, and the absolute value of the negative bending moment is less than the positive bending moment. The boundary form of the main arch foot only has an obvious influence on the bending moment near the arch foot, but has a little influence on the bending moment of L/4 ~ arch axis, which is less than 3%. The boundary conditions have little influence on the tension of the hanger. The tension of the shortest hanger changes by 7.43%, and the change of the tension of the rest of the hangers can be ignored as shown in Figure 3.
As shown in Table 3 for the calculation results of internal force caused by moving load under two kinds of arch foot boundary conditions. The ratio of the maximum axial force caused by the moving load in each control section of the main arch to the axial force under the dead load is about 0.2, and that of the vice-arch is about 0.05. Under the action of moving load, the influence of boundary condition on the axial force of the main arch is very small, but the influence on the axial force of the vice-arch is very obvious. When the boundary condition of the arch foot is a rigid connection, the bending moment of the vice-arch increases by more than 30%, and the difference of the axial force at the arch vault is the largest, about 34.50%.

Table 3. The axial force of main control section under moving load (kN)

| Boundary condition of arch foot | Position | Control section |
|--------------------------------|----------|-----------------|
|                                |          | Arch foot | L/8 | L/4 | 3L/8 | Vault |
| Rigid connection               | Main arch| -3154.7    | -2654.3 | -2511.3 | -2330.7 | -2366.1 |
|                                | Vice-arch| -215.0     | -225.8  | -227.9  | -226.2  | -219.9  |
| Hinged connection              | Main arch| -3148.8    | -2620.6 | -2475.9 | -2299.3 | -2291.0 |
|                                | Vice-arch| -148.3     | -153.0  | -153.3  | -149.9  | -144.1  |
| Difference value               | Main arch| 0.19%      | 1.27%   | 1.41%   | 1.35%   | 3.17%   |
|                                | Vice-arch| 31.02%     | 32.24%  | 32.75%  | 33.73%  | 34.50%  |

Table 4. Bending moment of main control section under moving load (kN·m)

| Boundary condition of arch foot | Position | Control section |
|--------------------------------|----------|-----------------|
|                                |          | Arch foot | L/8 | L/4 | 3L/8 | Vault |
| Rigid connection               | Main arch| 14990.9    | 4539.2  | 4795.6  | 3831.0  | 3137.6 |
|                                | Vice-arch| 2078.3     | 160.2   | 632.8   | 908.0   | 1470.5 |
| Hinged connection              | Main arch| 0          | 6610.2  | 6655.3  | 4914.3  | 3827.2 |
|                                | Vice-arch| 0          | 929.9   | 1136.0  | 1090.6  | 1559.2 |
| Difference value               | Main arch| --         | -45.62% | -38.78% | -28.28% | -21.98% |
|                                | Vice-arch| --         | -480.59%| -79.50% | -20.11% | -6.03%  |

The positive moment caused by the moving load in the arch axis is greater than the absolute value of the negative moment. When the boundary condition of the arch foot is rigid connection, the positive bending moment of the main arch foot is 14990.9kN·m, the positive bending moment of the vault is 3137.6kN·m, the positive bending moment of the vice-arch foot is 2078.3kN·m, and the bending moment at L/8 is only 160.2kN·m, so the distribution of the bending moment along the arch axis is very uneven. When the arch foot is hinged, the bending moment of each section of the main arch is
relatively uniform, and the bending moment is larger in the range of L/8 ~ arch vault. The influence of main-arch foot boundary condition on the bending moment of the main arch and vice-arch decreases gradually from arch foot to arch vault. The maximum difference of the bending moment of the main arch is \(-45.62\%\). The bending moment of vice-arch changes greatly at the arch foot with different main-arch foot boundary condition, but the bending moment at arch vault changes only \(-6.03\%\).

2.3.2. The influence of boundary conditions on the deflection of arch rib

As shown in figure 4, under the action of moving load, the deflection change rule of the vice-arch and the main arch is the same. Under the action of moving load, the deflection at the arch foot is the minimum, and the deflection at L/4 reaches the maximum; from L/4 to the middle of the span, the deflection gradually reduces to the minimum. The boundary condition of the arch foot has an obvious influence on the deflection of the bridge. In general, the absolute value of the deflection of the two hinged arch is greater than the absolute value of the deflection of the hingeless arch. The maximum deflection difference between the main arch and the vice-arch at L/4 are 33mm and 43.5mm.

![Deflection graphs](image)

Figure 4. Deflection of main arch and vice-arch under moving load corresponding to the different boundary condition

2.3.3. The influence of boundary conditions on dynamic and stability characteristics

The analysis of dynamic characteristics of arch bridges is the basis of seismic response analysis and seismic design. The primary four steps natural frequencies and stability coefficient of two hinged arch and hingeless arch are shown in table 5 and table 6. The first two order mode-shape of the two kinds of arch bridges are the same but natural frequencies are different, and the first mode is anti-symmetric and the second-order model is positive symmetric. From table 5, it can be seen that the main arch boundary condition has no obvious effect on the natural frequency, the fundamental frequency of the hinged arch bridge is slightly smaller than that of the rigid connection, which indicates that the vertical stiffness of the bridge under the rigid connection is larger. It is also found that the transverse vibration mode shapes is not affected by the boundary conditions.

| Model | Rigid connection (Hz) | Hinged connection (Hz) |
|-------|-----------------------|------------------------|
| 1     | 0.37                  | 0.36                   |
| 2     | 0.72                  | 0.50                   |
| 3     | 0.77                  | 0.77                   |
| 4     | 0.83                  | 0.83                   |
Table 6. Stability coefficient corresponding to the different boundary condition

| Model | Rigid connection | Hinged connection |
|-------|------------------|-------------------|
| 1     | 31.4             | 30.8              |
| 2     | 41               | 40.7              |
| 3     | 76.2             | 74.9              |
| 4     | 76.3             | 75                |

It can be seen from table 6 that boundary conditions of the main arch have little influence on the stability of the structure, and the stability coefficient of the hinged arch is slightly greater than that of the two hinged arch, which means larger stiffness of hingeless arch. According to the past experience, the boundary condition of the arch foot will have a significant impact on the stability of the structure, but the theoretical calculation results of the bridge show that the impact is small. This is because the rigidity of the composite arch rib is greater than that of the common single-arch rib.

3. Conclusion and expectation
(1) Under the dead load, the boundary condition of the main arch foot has an obvious influence on the deflection of the arch axis, the bending moment near the main arch foot and the tension of the shortest hanger. And the boundary condition of the main arch foot has a great influence on the internal force of the vice-arch under the moving load.

(2) Because of the composite arch rib structure of the main arch and vice-arch, the rigidity of the bridge is large and the stability is high. Compared with the ordinary arch bridge, the boundary condition of the main arch foot has less influence on the stability of the arch bridge.

(3) In order to get more accurate calculation results, it is necessary to carry out more accurate simulation of the boundary conditions of arch foot, so that the theoretical calculation and the actual situation tend to be consistent.

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