Static and Dynamic Analysis of A through Tied Arch Bridge

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Abstract. Arch bridge is a widely used type of bridge. Its static characteristics and dynamic characteristics have attracted wide attention, so it is necessary to analyze its static and dynamic characteristics. In this paper, a finite element model of a through tied arch bridge was set up to analyze its static and dynamic characteristics under both dead weight and secondary dead load. By static analysis, the maximum deformation of the structure is located at the center of the span. The arch rib, as the main load-bearing component of the arch bridge, mainly bears axial pressure, and the maximum value occurs near the arch foot, while the tied beam bears axial tension. For arch rib and tied beams, they are also subjected to bending moment and shear force, and the maximum bending moment occur at the place of the middle point of the span and shear force near the arch foot. The first ten natural frequencies and modes of the structure were obtained by dynamic analysis, and the in-plane stiffness of the structure is larger than that of out-of-plane stiffness.

1. Introduction
Arch bridges have a long history in the history of bridge development. Their advantages such as large span capacity and beautiful bridge shape make them widely used in the world. However, due to the horizontal thrust of the arch rib, the requirement for the foundations are stringent, which limits the application of the arch bridges. While, the tied arch bridges can counteract the thrust of arch rib by imposing prestressed forces in the beams, which overcomes the deficiency of the ordinary arch bridges [1]. In addition, the main girder of through arch bridges have smaller height-span ratios, which are able to lower the deck elevation as much as possible, thereby shortening the length of the part of bridge approaches and reducing the cost. This makes the through tied arch bridges more extensive application prospects than the ordinary arch bridges. A through tied arch bridge in the northeast of China, this paper was established with its finite element model based on its drawings, The static and dynamic analysis were carried on. Deformations and internal forces were analyzed and the first ten modes were shown.

2. Engineering Survey
The through single arch rib tied arch bridge is located in the east of Ring Road across Zhuanghe River in Dalian, Liaoning Province of China. Its total length is 272.13m and the width is 35m. The design
The speed of the bridge is 50Km/h. It is on the urban main road. The main span is a prestressed concrete single box girder with five chambers. The arch rib is a steel box. The length of the connection section is 6.32m. The main span is 247.0807 m, the arch rise is 55.5m, and rise-span ratio is 1/4.5. There are 33 pairs of suspenders in the bridge. The distance between the suspender along the longitudinal direction and transversal one are 7m and 3m respectively. The elevation and sections of the bridge are shown in Fig. 1~ Fig.3.

3. Establishment of the Bridge Finite Element Model
The finite element analysis software ANSYS is used to establish the beam element model for the bridge [2]. According to the different structural properties of different members of the bridge, BEAM188 element is adopted to simulate the arch rib and beam of the bridge, while LINK10 element is used to simulate the suspender. As the MASS21 element is one nodal mass element, 67 MASS21 elements are distributed on the arch rib to simulate the mass of the diaphragm. For the constraints, the arch springers are fully restrained, and both ends of the deck are fully restrained. The finite element model has 279 units and 428 nodes, as shown in Fig. 4.

4. Static Analysis of the Bridge Finite Element Model
The static analysis function of ANSYS is used to obtain the deformation and internal force of the bridge under both dead weight and secondary dead load [3, 4]. The secondary dead load of the bridge mainly includes the loads generated by rails, fences, deck pavement and side pavement, etc.

The vertical deformation diagram of bridge structure is obtained by static analysis, as shown in Fig. 5. According to the calculation results of the model, the maximum displacement of the arch rib and the beam appears in the middle of the span, and the values are -0.2159m and -0.050687m respectively. The vertical displacement of the arch and beam is decreasing symmetrically from the middle of the span to springers. The positive and negative sign of displacement here indicates the direction of displacement. The positive sign indicates the positive direction along the Y axis, while the negative sign is the opposite.
The internal force of the bridge is analyzed by establishing the unit table [5, 6], and the internal force diagrams of the bridge are shown in Fig. 6. According to the calculation results of the internal force of the model, the arch rib are mainly compressed as the main load-bearing component of the bridge. The maximum pressures appears at the left and right arch springers, which are \(-0.1965 \times 10^9\) N, and decreases symmetrically from the arch springers to the middle of the span. In addition, the arch rib also bear bending moments, which are symmetrically distributed along the longitudinal direction, and the maximum bending moment is \(-0.1415 \times 10^8\) N·m at the middle of the span. This is consistent with the characteristics of the arch rib. The tied beams are mainly subjected to tension to counteract the horizontal thrust generated by the arch rib, and the tension is approximately uniformly distributed along the longitudinal direction of the beams. In addition, the beams also bear certain bending moments. The maximum shear forces on the girder and arch rib of the main span are located at the arch springers, and the shear force at the middle of the girder and arch span is zero. The shear forces in the arch rib are very small compared with the axial forces and bending moments.

![Axial force diagram](image1)
![Shear diagram](image2)
![Bending moment diagram](image3)

**Fig. 6** Internal force diagram of the finite element model

5. Dynamic Analysis of the Bridge Finite Element Model

The natural vibration characteristic of a bridge is an inherent characteristic, independent of the load it bears, and determined by its mass and stiffness. Since the natural vibration characteristics of the bridge depend on the quality and stiffness of the bridge, the stiffness of the bridge can be obtained by analyzing the natural vibration characteristics of the bridge, on the basis of which, the daily maintenance and safety assessment of the bridge can be targeted. The analysis of natural vibration characteristics of bridge structure is mainly to analyze its natural frequency and vibration mode [7, 8].

The subspace method was used in this paper. For an arch bridge, there are usually only the first few modes in control. Therefore, only the first 8 natural frequencies and their corresponding mode shapes are listed in this paper, as shown in Table 1. Due to the limitation on space, the first 3 order vibration modes of the bridge are shown in Fig. 7–Fig. 9.

The basic frequency of the arch bridge model is calculated to be 0.40728 Hz. Compared with the frequency range of the other arch bridge, this one is flexible [9]. The analysis of the vibration mode of the bridge shows that the first-order mode of the bridge model is external vibration of the arch rib, the second-order and third-order modes are in-plane vertical vibration, and the fourth-order mode is torsional vibration. The out-of-plane mode appears earlier than the in-plane mode, which indicates that the out-of-plane stiffness of the structure is smaller than the in-plane stiffness. And the torsional vibration mode of the structure appears later than that of the translational vibration mode, indicating that the torsional stiffness is greater than the translational stiffness. Therefore, in designing such bridges, attention should be paid to strengthening the lateral stability of the arch rib. In the in-plane mode, the vibration of the bridge rib and the deck surface tends to be synchronized, which indicates that the in-plane integrity of the arch rib and the bridge deck is good, and the boom plays a good role as the connection between the two members.
Table 1 The first ten order mode frequencies and shapes

| Order | Frequency | Modal shape                                                                 |
|-------|-----------|------------------------------------------------------------------------------|
| 1     | 0.40728   | Symmetrical lateral bending of arch rib                                     |
| 2     | 0.66556   | Antisymmetrical vertical bending of arch rib and bridge deck                |
| 3     | 0.86913   | Symmetrical vertical bending of arch rib and bridge deck                    |
| 4     | 1.0311    | Symmetrical lateral bending of arch rib and torsion of bridge deck system   |
| 5     | 1.1400    | Antisymmetric lateral bending of arch rib and torsion of bridge deck system |
| 6     | 1.2750    | Symmetrical lateral bending of arch rib and bridge deck                    |
| 7     | 1.3996    | Symmetrical vertical bending of arch rib and bridge deck                    |
| 8     | 2.0246    | Antisymmetrical lateral bending of arch rib and torsion of bridge deck system |

Fig. 7 First order vibration shape diagram

Fig. 8 Second order vibration shape diagram

Fig. 9 Third order vibration shape diagram
6. Conclusion
In this paper, a finite element model of a through tied arch bridge was established, and the static and dynamic analysis were carried out.

The maximum displacement and the location of the structure are obtained by static analysis. The axial force diagram, shear diagram and bending moment diagram of the bridge structure are obtained by establishing the element table analysis, and the section with the largest force is found.

The natural frequencies and modes of the structure are extracted by dynamic analysis. The natural frequencies of the structure can be used to avoid the structural damage caused by the resonance between the structure and its load.

Through the analysis of structural vibration mode, it can be seen that the structure is flexible, the in-plane stiffness is greater than the out-of-plane stiffness, the rotational stiffness is larger than the translational stiffness, and the structure has good integrity and symmetry.

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