Analysis and Comparison on Dynamic Characteristics of CFST Arch Bridge

Jing Ji¹², Yubo Lin²*, Ming Xu¹, Meihui Zhong¹, and Liang qin Jiang²

¹Department of Architectural Engineering, Qiqihar Institute of Engineering, Qiqihar, Heilongjiang, 161005, China
²College of Civil and Architectural Engineering, Northeast Petroleum University, Daqing, Heilongjiang, 163318, China

*Corresponding author: jijing@nepu.edu.cn

Abstract. In order to obtain the natural frequency and vibration mode of concrete-filled steel tube (CFST) arch bridge with different parameters, the modal analysis of a double-span arch bridge with a total length of 257.4 meters and a full width of 31.8 meters is carried out. By controlling the three variables of concrete strength, steel tube thickness and the number of transverse braces in arch ribs, the regularity of the natural frequency and vibration mode of CFST arch bridge with different variables is discussed. The results show that with the increasing of the strength of concrete-filled steel tube in arch ribs, the fundamental frequency increases gradually. The vertical stiffness of the arch bridge is positively related to the thickness of the arch rib steel pipe. The fundamental frequency of the arch bridge can be improved by setting transverse brace, and the change of the number of transverse braces has a significant effect on the sixth-order natural frequency. It is limited for the arch bridge to improve the stiffness by changing the number of transverse braces. These can lay the foundation for the dynamic response analysis of the CFST arch bridge.

1. Introduction

Concrete-filled steel tube (CFST) structure is a new type of composite structures formed by filling concrete into steel tube, which is evolved and developed on the basis of rigid reinforced concrete and spiral reinforcement. According to the section form of steel tube, it can be divided into square steel tube, round steel tube and polygonal tube [1]. The radial constraint of steel tube makes the concrete in three-way compression state, which can significantly improve the compressive strength of core concrete. Steel tube can be used as construction template, which could facilitate concrete pouring, simplify construction technology[2] and shorten construction period because of its lightweight and less welding workload[3].

With rapid the development of high-performance materials, the research on steel tube material and high-performance concrete has become a hot issue[4-6]. High-performance concrete-filled steel tube structure can not only meet the requirements of high bearing capacity and good seismic behavior, but also reduce its cross-section size under the condition of constant bearing capacity, so that the traffic below the bridge is smoother and the use space inside the building is more flexible [7-9]. D. Yun et al. [10] discussed the influence of arch rib rise-span ratio and arch rib inclination angle on the dynamic characteristics of a long-span CFST arch bridge structure, and The results showed that by reducing the arch rib rise-span ratio or tilting the arch rib the out-of-plane vibration frequency of the structure can be improved. Q. X. Wu et al. [11] discussed the influence of main arch span, cross section and bridge
system structure on the vibration modal characteristics of the middle and lower CFST arch bridge deck, and based on Rayleigh [12-13] method, a practical formula for estimating the natural frequencies of the first-order antisymmetric and symmetric vibration modes in the middle and lower CFST arch bridge deck is proposed. R. M.Wu et al. [14] discussed the change of the dynamic characteristics of the bridge structure when the rise-span ratio, width-span ratio and the stiffness of the main arch rib of the thrustless CFST arch bridge were changed.

The finite element model of high-strength CFST arch bridge is established by ANSYS software. The modal analysis of this kind of arch bridge under different influencing factors is carried out, and the natural frequency and vibration mode of the structure under non-damping state are obtained.

2. Structural modal analysis theory
Modal analysis is a method to study structural dynamic characteristics. Modal is the inherent vibration characteristics of the structure, and each modal has specific natural frequency, damping ratio and vibration mode. The natural frequency and vibration mode of the structure can be obtained by modal analysis, and the motion control equation of the structure can be established by higher structural dynamics:

\[ [M] \ddot{\mathbf{U}} + [C] \dot{\mathbf{U}} + [K] \mathbf{U} = \mathbf{F}(t) \]  

(1)

Where, \([M]\) is the mass matrix, \([C]\) is the damping matrix, \([K]\) is the stiffness matrix, \([\mathbf{U}]\) is the displacement matrix, \(\{\mathbf{F}(t)\}\) is the force matrix.

The free vibration equilibrium equation of CFST arch bridge without damping is:

\[ [M] \mathbf{U} + [K] \mathbf{U} = \mathbf{0} \]  

(2)

Assuming that the displacement form of the structure is:

\[ \mathbf{U} = \{\bar{U}\} \sin(\omega t + \theta) \]  

(3)

Where, \(\{\bar{U}\}\) is a vector independent of time, and \(\omega\) is the circular frequency, and \(t\) is time, and \(\theta\) is the initial phase angle.

The free vibration equation can be expressed as:

\[ ([K] - \omega^2 [M]) \{\bar{U}\} = \mathbf{0} \]  

(4)

Structural vibration frequencies and corresponding vibration modes can be obtained by equation (4).

3. Finite element model

3.1. Project overview
The main bridge is divided into two spans, and the length of each span is 108.8 meters. The full width of the bridge is 31.8 meters, and the rise height is 25 meters, that is, the rise-span ratio is 0.23. Each span adopts the middle bearing concrete filled steel tube arch rib, and the arch axis is a quadratic parabola. The arch rib is composed of double steel tubes. The radius of the arch rib steel tube is 0.6 meters. The steel plate connection is used between the double steel tubes. The C60 concrete is filled inside steel tubes. The cross section of the arch rib is 3 meters high. The tie rod is composed of high strength steel wire. The suspender is composed of high strength steel wire with a diameter of 7 mm. The diameter of the pile foundation is 1.8 meters, and the net distance between the piles is 3.6 meters. Geometric model of CFST arch bridge is shown in Figure 1. The section type of Arch rib is shown in Figure 2.
3.2 Finite element modeling method

The finite element model of arch bridge is established by large general finite element software ANSYS. The steel pipe, concrete in steel pipe, longitudinal beam, transverse braces, cover beam, pier column, caps and pile foundation are modeled by BEAM44 element. BEAM44 is a uniaxial beam element which can withstand tension, compression, torsion and bending. Each node of the element has six degrees of freedom, that is, translation and rotation in three directions of X, Y and Z. The suspender and tie rod are modeled by LINK10 element. Each node of LINK10 element has three degrees of freedom, which has bilinear stiffness matrix characteristics. The pile and soil are connected by spring element, and each pile top is coupled with the lower node of the cap. The junction of cover beam and arch shaft is connected by coupling. In order to ensure the horizontal displacement of the arch bridge in the plane, the Y direction displacement and the X direction angle are not restricted. The material parameters of each component of CFST arch bridge are shown in Table 1. The finite element model of pile and soil of arch bridge is shown in Figure 3. The finite element model of transverse braces is shown in Figure 4.
4. Dynamic behavior of arch bridges

4.1. Concrete strength
Taking the concrete strength in arch rib as main parameters, the influence of concrete strength on natural frequency of CFST arch bridge is analyzed.

Table 1. Effect of concrete strength on natural frequency

| Frequency order | Concrete strength |
|-----------------|-------------------|
|                 | C60 | C70 | C80 |
| 1               | 0.105 | 0.115 | 0.116 |
| 2               | 0.380 | 0.391 | 0.392 |
| 3               | 0.426 | 0.427 | 0.427 |
| 4               | 0.437 | 0.446 | 0.447 |
| 5               | 0.556 | 0.557 | 0.559 |
| 6               | 0.866 | 0.877 | 0.868 |
| 7               | 0.873 | 0.875 | 0.876 |
| 8               | 0.876 | 0.886 | 0.887 |
| 9               | 0.896 | 0.901 | 0.906 |
| 10              | 1.026 | 1.033 | 1.040 |

It can be seen from Table 1 that with the increasing of concrete strength in the arch rib, the fundamental frequency increases gradually, but the increase is very small. The increasing of concrete strength is not obvious to the increasing of the stiffness of concrete filled steel tube arch bridge. The increasing of concrete strength in arch ribs has little effect on other natural frequencies. Overall, the increasing of concrete strength in arch ribs has little effect on natural frequencies.

4.2. Steel tube thickness
The influence of the thickness of steel tube on the natural frequency of CFST arch bridge is discussed by controlling the strength of concrete in arch rib for C60. The $n$-$f$ curve of arch bridge with different thickness of steel tube is shown in Figure 5.
Fig. 5 The $n$-$f$ curve of arch bridge with different thickness of steel tube

It can be seen from Figure 5 that the change of steel tube thickness has little effect on the first seven-order frequency, and the frequency increases gradually with the increasing of steel tube thickness after the seventh order. The natural frequencies of the ninth and tenth orders increase significantly, with the maximum increase of 3.6%. Since the CFST arch bridge is dominated by the in-plane vertical bending deformation under the 9th and 10th natural frequencies, increasing the thickness of the steel tube in the arch rib is conducive to improve the vertical stiffness of the arch bridge.

4.3. Transverse bracing

In order to clarify the influence of transverse braces on the dynamic characteristics of CFST arch bridges, the following four cases are considered: the first model is an open arch bridge without transverse braces, and the second model contains a cross brace every span, and the third model contains a cross brace and two K braces every span, as well as the fourth model remains all braces. The natural frequency and vibration mode characteristics of each order of the four models are obtained by ANSYS finite element software analysis. The $n$-$f$ curves of arch bridges with different number of braces are shown in Figure 6.

Fig. 6 The $n$-$f$ curves of arch bridge with different number of transverse braces

From Figure 6, it can be seen that the fundamental frequency of arch bridge increases with the setting of transverse braces, and the fundamental frequency of five transverse braces is 1.8 times larger.
than that of no transverse braces. Compared with a cross brace, the natural frequencies of 7th, 8th and 9th orders increase significantly without cross brace, and the out-of-plane deformation of arch bridge is mainly at the frequencies of 7th, 8th and 9th orders. Therefore, the setting of cross brace is conducive to improve the out-of-plane stiffness of arch bridge. The number of transverse braces has a great influence on the sixth order natural frequency, and has little influence on the other order natural frequency. It reflects that the change of the number of transverse braces has limited ability to improve the stiffness of arch bridges.

5. Conclusions

Based on the above modeling method, considering the influence of concrete strength in arch rib, the thickness of arch rib steel tube and the transverse brace on the dynamic characteristics of arch bridge, the modal analysis is carried out by ANSYS software, and the following conclusions are obtained.

(1) With the increasing of concrete filled steel tube strength in arch ribs, the fundamental frequency increases gradually, but the increase is small, therefore, the increasing of concrete strength in arch ribs has no obviously influence on the fundamental frequency.

(2) With the increasing of the steel tube thickness in the arch rib, the first seven natural frequencies of the arch bridge have little change, and the frequency increases significantly after the seventh order, with the maximum increase of 3.6%. Since the arch bridge is mainly vertical bending deformation in plane at the 9th and 10th orders, by increasing the thickness of steel pipe in arch rib the vertical stiffness of arch bridge can be improved.

(3) The setting of transverse brace increases the fundamental frequency of arch bridge, and the fundamental frequency with all transverse braces is 1.8 times that without transverse braces. Compared with a cross brace, the natural frequencies of 7th, 8th and 9th orders increase significantly without cross brace. The setting of cross brace is conducive to improve the out-of-plane stiffness of arch bridge. The number of transverse braces has great influence on the sixth order natural frequency, but has little influence on the other order natural frequency. It reflects that the influence of the number of transverse braces on the stiffness of arch bridge is limited, so the reasonable number of transverse braces should be selected in practical engineering.

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