Research on Natural Vibration Characteristics and Seismic Performance of Single-ribbed Steel Arch Bridge

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Abstract: The single-ribbed steel arch is beautiful but with weakness of its lateral stability and lateral stiffness. Taking the single-rib steel arch bridge as the research background, finite element program of Midas is used to establish calculation models on the variation of vector span ratio, pier height and stiffness of the main arch for exhaustive analyzing the natural vibration characteristics and seismic response spectrum of the structure, and the corresponding laws are summarized in this paper. Research indicates that the change of pier height has a greater impact on the period and mode shape, and the change of the vector span ratio and the stiffness of the main arch have small effect on those of structure. The internal force of the arch leg is larger under the action of earthquake, which is jointly controlled by the longitudinal earthquake and the transverse earthquake, and the internal force of the arch is controlled by the lateral earthquake, and the internal force of the vault section is controlled by the transverse earthquake, and the internal force of the main beam cross-section is controlled by the transverse earthquake, providing reference for the design of single-ribbed steel arch bridge.

1. Introduction

Steel arch bridge [1-3] has the advantages of large spanning capacity, high strength, light weight and fast construction speed. In recent years, it has sprung up in the construction of bridges in China. Double-ribbed steel arch bridges are widely used due to their lateral stability, good seismic performance [4-5], and large spanning ability, and summarize more research results [6-9]. The single-ribbed steel arch is less used due to weak lateral stiffness and poor seismic performance, but the single-ribbed steel arch bridge has a simple shape and a novel and beautiful line shape, and has good competitiveness in urban landscape bridges [10]. Single-ribbed steel arch bridges have been completed in China, and the corresponding research results are still few. At present, the research on the stress, stability and seismic performance of single-ribbed steel arch bridges is not enough, especially in the recent occurrence of a single-ribbed steel arch bridge collapsed. Therefore, it is necessary to conduct in-depth research on the mechanical characteristics and seismic performance of single-ribbed steel arch bridges.

The stress-free status method is applied to the whole bridge to analyze rational cable force, tension sequence and tension time of suspenders in this paper[11]. The stability of rigid-frame single-ribbed arch bridges is studied in article[12]. The stability and dynamic performance of single-rib arch stiffened V-supported rigid-framed bridges are studied in article[13], and force characteristics of the combined structure is summarized. Based on the space finite element model of concrete-filled steel tubular single-rib arch bridge, the calculation methods of the out-of-plane buckling critical load are
discussed and compared, and the arch axis type, the loading point number, the span ratio, the steel content, and the concrete inside the pipe are discussed. The influence of parameters such as arch rib stiffness on the out-of-plane buckling is analyzed and the corresponding laws are summarized in this article[14].

In this paper, a single-ribbed medium-supported steel arch bridge is taken as the research background, shown in figure 2. From the structural dynamic characteristics and seismic performance, the natural vibration characteristics and vibration modes of single-rib arch bridges are studied. The seismic response of structures is analyzed, and the dynamic characteristics of single-rib arches are analyzed in detail. The seismic performance of the E1 seismic response spectrum provides a reference for the seismic design of single-ribbed steel arch bridges.

2. Model establishment
A steel arch bridge with a span of 40 + 40 + 150 + 40 + 40m steel box rigid frame-single rib tie bar arch bridge is shown in Figure 1, and the bridge deck width is 11.2m and the vector span ratio is 1/4. The structure consists of two rigid frames, a tied arch, concrete beams, side pier and side pier, and the upper structure is made of C60 concrete, and the lower structure is made of C50 concrete, and the steel beam is made of low relaxation high strength steel strands.

A single-ribbed steel arch bridge model was established by Midas civil, in which the pier, main beam and main arch were simulated as beam elements, and the boom and tie rod were simulated into truss elements. The whole bridge is divided into 243 units and 244 nodes, and the connection between the main beam and the pier is connected by rigid nodes, and the connection between the main beam and the main arch is rigid. The finite element model is shown in Figure 2.

3. Structural dynamic characteristics analysis
The commonly used mode combination method of the structure is CQC method or SRSS method. According to the self-vibration characteristics of the bridge, the CQC method in this paper is used for vibration mode combination. The seismic design code for bridges stipulates that when multi-vibration type response spectrum analysis is carried out, the number of modes to be considered should be more than 90% of the total mass in the calculation direction. The structural dynamic characteristics mainly show the low-order natural frequency and mode shape.

In general, the vibration characteristics of the first few modes of the arch bridge are relatively simple, while the high-order modes are more complicated, which is related to the structural form and the support connection condition. It can be seen from Table 1 that the first 8 modes of the bridge have less mode-type coupling and the mode shape is simpler. The low-order modes of the structure are mainly side-bending, the fundamental frequency is 0.51 Hz, the second order is the longitudinal mode, and the third to the seventh is the side-bend mode, and the eighth-order is the complete vertical vibration, which means that the lower-order modes of arch bridges are mainly transverse mode, and the stiffness outside the plane of the main arch is much smaller than the stiffness in the plane. Therefore, the lateral seismic problem of such arches is very important.
Table 1 Structure natural frequency

| Modal | Frequency | Mode description | Mode diagram | Modal | Frequency | Mode description | Mode diagram |
|-------|-----------|------------------|--------------|-------|-----------|------------------|--------------|
| 1     | 0.51      | Lateral first    |              | 5     | 0.84      | Lateral fourth order |              |
| 2     | 0.59      | Vertical first   |              | 6     | 1.02      | Lateral fifth order  |              |
| 3     | 0.66      | Lateral second   |              | 7     | 1.47      | Lateral sixth order  |              |
| 4     | 0.71      | Lateral third    |              | 8     | 1.5       | Vertical first order |              |

It can be seen from figure 3 that the natural frequency of the arch bridge gradually decreases as the span ratio increases. When the span ratio changes from small to large, the fundamental frequency changes from 0.55Hz to 0.42Hz, which is reduced about 20%. The second-order and third-order frequency variation laws are basically consistent with the fundamental frequency variation law, indicating that the lateral stiffness of the arch rib decreases with the increase of the span ratio, but the vibration mode does not change. The fundamental frequency of the arch bridge decreases from 0.55Hz to 0.45Hz as the height of the pier increases, indicating that the lateral stiffness of the arch ribs gradually decreases with the increase of the pier height. However, the low-order mode does not change with the increase of the pier height. Therefore, it can be seen that the increase of the pier height has a great influence on the natural vibration period of the bridge. The main arch stiffness variation on the fundamental frequency is small, which has little effect on the fundamental frequency of the structure and can be ignored.

4. Response spectrum analysis

In this paper, in accordance with the Code for Seismic Design of Urban Bridges, the mode decomposition response spectrum method (CQC) is used to analyze the elasticity of the structure under E1 earthquakes in x and y directions. The design response spectrum curve used for calculation is determined according to the Highway Seismic Design Detailed Rules for seismic response analysis.

The seismic fortification category is Class A, and the peak acceleration of basic ground motion is designed to be 0.10g. The seismic importance coefficient Ci of the bridge is 1.0, and the site category is type II site, and the design site excellent period Tg is 0.35s, and design site predominant period Cs is 1.0, and the damping adjustment coefficient is 1.0, and the bridge's damping ratio is 0.05. In addition, 6 degrees (0.05g) and 8 degrees (0.20g) earthquake protection effects need to be considered.

4.1. Influence of seismic intensity

It can be seen the following conclusions from figures 4–6:
(1) When the seismic intensity is increased, the internal force value and the displacement value of the structure under longitudinal and lateral seismic excitation are increased by 2 and 4 times respectively;

(2) For the same intensity, the longitudinal displacement values of the arch and the dome are basically the same, but the difference between the lateral displacement of the dome and the arch is large. When the intensity is 8 degrees, the maximum value of the dome is about 7 times those of arch foot, indicating that the single-rib arch top section is the weakest position of the structure, and the in-plane stiffness of the structure is much smaller than the out-of-plane stiffness of the structure, and the internal force of the dome is controlled by lateral earthquakes;

(3) Under the longitudinal seismic excitation, the axial force and vertical bending moment of the arch are affected. From the vibration mode analysis, the in-plane stiffness of the single-rib arch is much larger than the out-of-plane stiffness.

4.2. Analysis of other influencing factors
The linear elastic analysis of the arch bridge under the E1 seismic response spectrum, the different span-to-span ratio, pier height, and main arch stiffness under the action of earthquake, the key internal forces of the structure are shown in Table 2 ~ Table 4.

The data shows that the internal force value of the arch section is larger than that of the longitudinal seismic calculation, and the internal force value increases with the increase of the span ratio, but the variation range does not exceed 10%, and the internal force values of other sections are changed. In the transverse earthquake, the internal force value of the arch section is irregular with the increase of the span ratio. The effect of the span ratio change on the longitudinal displacement of the section is negligible, while the effect of the span ratio on the lateral displacement of the structure is irregular.

It can be seen from Table 3 that the variation of the pier height has a significant effect on the internal force of the bridge. Under the action of longitudinal earthquake, the internal force value of the section decreases with the increase of the pier height. The internal force values of the cross-section of the transverse earthquake decrease with the increase of the pier height, but the reduction magnitude of each section is inconsistent.

It can be seen from Table 4 that the change of the arch rib stiffness has a great influence on the internal force value of the vault. However, the variation of the internal force value of the cross section of the arch foot and the mid-section of the main beam is less than 10%, so the stiffness of the arch rib has a greater influence on the internal force of the arch, and the internal force of the arch and the main beam is relatively smaller.

In addition, it can be seen from Figure 7 that the change of the stiffness of the arch rib has a great influence on the displacement of the arch, this is mainly due to the fact that the stiffness variation of the arch rib has little effect on the structural stiffness distribution of the overall structure. Therefore, the displacement of the cross section of the arch and the main beam is almost unchanged, and the calculation result is consistent with the actual situation.

The internal force of the dome is controlled by lateral earthquakes. The internal force of the arch is controlled by longitudinal and lateral earthquakes. The internal force of main beam is controlled by lateral earthquakes.
Table 2 The critical section internal force with increase of the span ratio under earthquake

| Vector span ratio | Longitudinal earthquake | Lateral earthquake | Longitudinal earthquake | Lateral earthquake |
|-------------------|-------------------------|--------------------|-------------------------|--------------------|
|                   | Axial force (kN)        | Vertical shear (kN) | Vertical bend (kN.m)    | Cross shear (kN)   |
| 1/5.0             | 23.4                    | 3.4                | 9.6                     | 1.5                |
|                   | 106.8                   | 23.6               | 321.4                   | 288.2              |
| 1/4.5             | 36                      | 4.3                | 11.9                    | 3.4                |
|                   | 381.5                   | 36.2               | 320.1                   | 305.7              |
| 1/4.0             | 25.5                    | 6.5                | 17.9                    | 7.6                |
|                   | 1623.4                  | 50.8               | 3110.9                  | 332.6              |
| 1/3.0             | 18.1                    | 7.6                | 14.7                    | 2.1                |
|                   | 387.67                  | 35.8               | 3182.5                  | 361.1              |

Table 3 The critical section internal force with increase of the pier height under earthquake

| Pier height | Longitudinal earthquake | Lateral earthquake | Longitudinal earthquake | Lateral earthquake |
|-------------|-------------------------|--------------------|-------------------------|--------------------|
|             | Axial force (kN)        | Vertical shear (kN) | Vertical bend (kN.m)    | Cross shear (kN)   |
| 1 times     | 25.5                    | 6.5                | 17.9                    | 7.6                |
|             | 1623.4                  | 50.8               | 3110.9                  | 332.6              |
| 1.25 times  | 16.8                    | 4                  | 10.4                    | 5.8                |
|             | 1119.1                  | 39.5               | 2849.4                  | 276.5              |
| 1.5 times   | 13.6                    | 3.7                | 7.1                     | 3.1                |
|             | 759.6                   | 28.1               | 2465.2                  | 235.6              |
| 1.75 times  | 11.5                    | 3.2                | 4.9                     | 2.8                |
|             | 558.4                   | 25.7               | 2190.6                  | 211.3              |
| 2 times     | 13.3                    | 3.1                | 3.8                     | 2.2                |
|             | 507.6                   | 21.1               | 2021.1                  | 196.5              |

Table 4 The critical section internal force with increase of the main arch stiffness under earthquake

| Arch rib Stiffness | Longitudinal earthquake | Lateral earthquake | Longitudinal earthquake | Lateral earthquake |
|--------------------|-------------------------|--------------------|-------------------------|--------------------|
|                    | Axial force (kN)        | Vertical shear (kN) | Vertical bend (kN.m)    | Cross shear (kN)   |
| 1 times            | 25.5                    | 6.5                | 17.9                    | 7.6                |
|                    | 1623.4                  | 50.8               | 3110.9                  | 332.6              |
| 1.25 times         | 25.7                    | 7.6                | 19.9                    | 7.4                |
|                    | 1387.5                  | 48.9               | 3181.7                  | 328.5              |
| 1.5 times          | 25.8                    | 8.6                | 21.7                    | 7.2                |
|                    | 1280.4                  | 46.9               | 3261.1                  | 328                |
| 1.75 times         | 26.1                    | 9.6                | 23.2                    | 7.1                |
|                    | 1243.6                  | 45.6               | 3133                    | 326.8              |
| 2 times            | 26.3                    | 10.5               | 24.6                    | 7                 |
|                    | 1226.3                  | 43.9               | 3139.7                  | 324.6              |

Figure 7 Lateral displacement

(a) vector span ratio change
(b) pier height change
(c) Main arch stiffness change
5. Conclusion
Through the comprehensive analysis of the natural vibration characteristics of the single-ribbed steel arch bridge and the E1 seismic response spectrum, the following conclusions can be drawn from its dynamic characteristics and seismic performance.

The low-order vibration mode of single-ribbed steel arch bridge is basically transverse vibration mode, the vibration mode is single, the coupling is less, the lateral deformation is larger, and the lateral stiffness of the structure is weak.

The low-order mode of a single-rib steel arch bridge is basically a transverse mode with single and less coupling mode, and with greater lateral deformation and weaker lateral stiffness of the structure;

The variation of the span ratio has a relatively large influence on the natural vibration frequency of the structure, and there is no obvious regularity in the periodic variation. The natural vibration frequency tends to decrease with the increase of the pier height, the natural vibration period and vibration mode of the bridge when the main beam stiffness changes. Feature impact is almost negligible.

The E1 seismic line elasticity analysis of the single rib steel arch bridge shows that the change of the vector span ratio has a slightly significant effect on the internal force of the structure, but there is no obvious law on the internal force and displacement, and the effect of the change in pier height on the internal force and displacement of the section is not particularly obvious, and the change in the stiffness of the main arch has a small effect on the internal force of the bridge structure under longitudinal earthquakes;

The internal force of the dome section is controlled by lateral earthquake, and the internal force of the arch foot section is jointly controlled by longitudinal and lateral earthquakes. In the single-rib arch seismic design, the arch foot is the section is the main control section.

For seismic design of single-ribbed steel arch bridges, it is necessary to ensure that the value of the span-to-span ratio of the structure is reasonable. At the same time, the bending stiffness and torsional stiffness of the arch rib section should be increased, and the lateral deformation of the arch rib should be reduced the roll rib which causes adverse effects on structural forces.

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References
[1] Xu Y., Hu S.D, Wang Z.Q., Wang J.J. (2004). Analysis of Lateral Nonlinear Seismic Response of Long Span Steel Arch Bridges. Journal Of Tongji University(Natural Science).pp.878-883
[2] Cheng J., Jiang J.J., Xiao R.C., et al. (2003). Ultimate load carrying capacity of the Lu Pu steel arch bridge under static wind loads[ J]. Computer and Structures. pp. 61-73.
[3] Nazmy A S. (1997) Stability and load-carrying capacity of three-dimensional long-span steel arch bridges. Computer and Structures. pp.857-868.
[4] Xu Q., Xu T., Li J.. (2013). Seismic Response Analysis of Steel Through Arch Bridge Considering Effects of Nonlinearity. Science & Technology Review. pp. 59-63.
[5] Du S.Y., Chen H., Wang B.J..(2007). Journal of Zhengzhou University:Engineering Science. pp.158-162.
[6] Song B., Liu Q., Li F.F., Zhou H.Y.. (2009). Influence of soil-pile interaction on the seismic response analysis of a large-span steel arch bridge. Journal of University of Science and Technology Beijing. pp.1077-1105.
[7] Wei X., Fan L. C., Wang J J.(2002). Shake table test on soil-pile-structure interaction. China Civil Eng J, pp. 91.
[8] Song B., Yi H.B., Zhou H.Y., Seismic Response analysis for long-span Arch Bridges under Consideration of Traveling Wave Effect. Journal of Beijing University of Technology.
pp.375-380.

[9] Zhang Y.L., Xu J.L. Sun J.F. (2013). Analysis of Seismic Response of Cangde Bridge on Beijing-shanghai High Speed Railway. world bridges. pp.43-47.

[10] Yan Q.S., Han D.J. (1999). Nonlinear stability of the JieFang concrete-filled steel tube tie-bar arch bridge. Journal of South China University of Technology. pp.98-103.

[11] Liang H.L. (2013). Analysis of suspenders Tension Process for long-span single-rib Arch Bridge. Transportation Science & Technology. pp. 5-8.

[12] Tan H.X., Chen Z.Q., Feng Z.Q. (2008). Stability of combinative bridge with rigid frame and single-ribbed arch. Journal Of Vibration And Shock .pp.122-125

[13] Song F. C., Su H. R. (2010). Research on the Stability and Dynamic Characteristics of V-Bracing Rigid Frame Continuous Beam Bridge with Single Stiffener Arch. Journal Of Shenyang Jianzhu University Natural Science. pp. 849-854.

[14] Liu M.Y., Gong K., Sun X.D., Yuan W.G. (2009). Dynamic Characteristics Analysis of Single Rib Braces CFST Arch Bridge. Journal of Wuhan University of Technology (Transportation Science & Engineering). pp.1104-1107.