Seismic Behaviors of an Upper Deck Type Steel Arch Bridge

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Abstract. The static and dynamic behavior of an upper deck type steel arch bridge was demonstrated. During the static analysis, both material and geometric nonlinear was considered based on finite element (FE) method. In-plane fault displacement case and out-of-plane fault displacement case were compared. During dynamic analysis, the model was modified and simplified firstly, and then the natural modals and the characteristics of the mode shape were analyzed. Both the in-plane seismic input case and out-of-plane seismic input case were analyzed. The different yielding process of members including main ribs, chord and columns were represented, and the possible damaged parts of the bridge were analyzed either.

Introduction

The behaviors of steel arch bridges, e.g. half-through ones, were studied during recent years [1,2]; and this paper concerns on upper deck type steel arch bridges. The span of background upper deck type bridge is 126m, rise is 15m, and the total length includes two approach span is 177.6m, shown in Fig.1. The main rib is consisted of two 1.85m diametrical steel tube, which thickness is varied from 12mm to 15mm. The diameters of columns over ribs include three types which diameters are 2.67m, 3.55m, and 4.06m. The diameter of side columns which connect decks over main ribs and approached decks is 5.59m. The static analysis is carried out based on nonlinear finite element method mainly use beam element, the complete model is shown in Fig.3. The material of the bridge is mainly SS41 which yield stress is 240Mpa, and the isotropic hardening is considered using bilinear von Mises plasticity.

Static Analysis

In static analysis, the loading was applied by set displacements at the feet of arch ribs and side columns as shown in Fig.5. The displacement of in-plane and out-of-plane is applied individually, and the amplitude is both 3m. The analysis takes into account the nonlinear caused by large deformation. Firstly, the static behavior under dead load was analyzed. The structure was under elastic range with maximum axial compression stress 83.2MPa at the pink of arch rib.

In-plane Direction Displacement. The longitudinal displacement was applied at one side of the ribs feet and side columns from 0 to 3m. However, the computation didn’t convergence when displacement reached 2.77m. The causes are partly because of large deformation that the vault downward displacement is -8.507m; and the whole vault segment appears plastic strains. The flexural moment under dead load is shown in Fig.3. At the arch vault maximum sag moment is 1121kNm, and the negative moment at one fourth span is maximum 781kNm.

The moment distribution of the main ribs various obviously with the fault displacement at rib feet increasing. When displacement attends 0.426m, whole bending moment diagram changes to the positive. When displacement reaches 0.995m, the main ribs began to yield, and steel tube at arch vault was partial plastic strain appeared, as shown in Fig.3.
In contrast, axial load at arch vault changed less in the elastic range; however, in plastic range, both axial force at arch vault and feet increased obviously. Most of the secondary members are in elastic range except several diagonal chords between main ribs at the arch vault, as shown in Fig.5, when fault displacement reaches 2.77m, the maximum von Mises plastic strain is 0.0094. The chords would be yield when displacement larger than 1.53m, later than main ribs’ yielding displacement (Fig.12).

As shown in Fig.9, displacement from 0 to 0.995m, the main structure performs in elastic range, except the transverse chord connect the ribs near the feet began to yield when fault displacement larger than 0.426m. Same as the flexural moment, under dead load, the compressed axle force of main ribs distributed uniformly which the variation range is from -429kN at foot to -368kN at vault. As the displacement increased, the axle force of two side of ribs changes asymmetric, and one side feet’s will appear tensile force when displacement larger than about 0.5m (Fig.10). And in the elastic range, when ribs’ feet segment began to yield, the force increased relatively slow. When displacement attends 1.728m, the axle force of two side feet was: -1470kN (compression) and 632kN (tension).
According to the analysis, in in-plane fault displacement case, the vault segments yield firstly and the main ribs damaged earlier than secondly members. While in out-off-plane fault displacement case, the structure appears plastic because foot segments yield, and the connection transversal chords between the ribs yield earlier than main ribs. The elastic performance range of in-plane and out-off-plane displacement cases was both about 1m.

Seismic behavior

In order to check whether the bridge is safe under seismic load, nonlinear dynamic behavior of the bridge is carried out based on time history response analysis. Both geometric and material nonlinear were considered, and the mass of asphalt layer’s mass was equivalent by increasing the density of concrete deck properly.

### Table 1 Natural frequency and periods

<table>
<thead>
<tr>
<th>MODE</th>
<th>Freq. (Hz)</th>
<th>Periods (sec)</th>
<th>Mode shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>0.696</td>
<td>1.44</td>
<td>in</td>
</tr>
<tr>
<td>Mode 2</td>
<td>0.848</td>
<td>1.18</td>
<td>Off, O</td>
</tr>
<tr>
<td>Mode 3</td>
<td>1.433</td>
<td>0.70</td>
<td>in</td>
</tr>
<tr>
<td>Mode 4</td>
<td>1.732</td>
<td>0.58</td>
<td>Off, O</td>
</tr>
<tr>
<td>Mode 5</td>
<td>2.474</td>
<td>0.40</td>
<td>In</td>
</tr>
<tr>
<td>Mode 6</td>
<td>2.806</td>
<td>0.36</td>
<td>In</td>
</tr>
<tr>
<td>Mode 7</td>
<td>3.068</td>
<td>0.33</td>
<td>Off, O</td>
</tr>
<tr>
<td>Mode 8</td>
<td>3.571</td>
<td>0.28</td>
<td>Off, T</td>
</tr>
<tr>
<td>Mode 9</td>
<td>3.782</td>
<td>0.26</td>
<td>Off, T</td>
</tr>
<tr>
<td>Mode 10</td>
<td>3.922</td>
<td>0.26</td>
<td>in</td>
</tr>
</tbody>
</table>

**Dynamic Model and Basic Characteristic.** During the analysis, the dynamic behavior is defined by the mass, stiffness, damping characteristics and time-varying foundation displacement. So the mass of the structure including the subordinate parts should be contained in the model. Because the material of the bridge deck is well reinforced concrete and connected with the upper truss using shear
connectors, the deck’s mechanic action is assumed to take into account. For asphalt layer, only the mass is considered by increasing the deck’s density, as shown in Fig.11. The amplification factor is about 1.4.

![Fig.12 1st, 2nd Mode shape (a, b)](image)

Fig.12 1st, 2nd Mode shape (a, b)

The modal analysis is carried out first by subspace iteration method. Table 1 shows the first 10 modal of the bridge, and the basement natural period is 1.44sec which mode shape is in plane asymmetric (Fig.12a). The 2nd mode is off plane and symmetric (Fig.12b), and its period is 1.18s. The distortion stiffness of the bridge is relatively large and its mode is appeared at the 8th mode which the period is 0.28sec. Based on the 1996’s Code [3] that for Type II input motion, ground type I records from the Kobe Maritime Meteorological Observatory during the Hyogo-ken Nanbu Earthquake of 1995 can be used. The regional class of Hyogo is A, and the modification factor $C_z$ is 1.0, Kumamoto’s Amakusa which the bridge located is at class A regional and the $C_z$ is 0.7. So using the Hyogo-ken wave for this bridge is conservative. The relatively large part of the signal which range from 4sec to 24sec was used (Fig.13). Reyleigh damping was applied in the following analysis based on the first two natural periods [4].

**Seismic Behavior Under Longitudinal Earthquake Wave.** The maximum longitudinal deformation of arch crown is 0.126m at 9.68sec (Fig.14). The column next to the arch crown (‘second column’) will yield firstly at 4.54sec (Fig.15). Then column next to the second column (‘third column’) will yield at 5.42sec, and the top longitudinal truss over arch crown yield at 5.44sec. Next the plastic deformation of main rib appeared at 5.46sec. The yielding process during first 5.46sec is shown in Fig.16. The yielding of the main ribs will continue progress, e.g. at 16.62s the main ribs between third and fourth columns appeared plastic deformation (Fig.17).
**Seismic Behavior Under Transversal Earthquake Wave.** The transversal deformation of arch crown is relatively large compared with longitudinal wave input shown above. The analysis became difficult to convergence after 4sec if geometric nonlinear was considered, so in the transversal earthquake wave input analysis only material nonlinear was included.

The maximum transversal deformation of the arch crown is 0.400m at 8.10sec (Fig.18). Plastic deformation was firstly appeared at top diagonal chord near the side column at 4.42s which is earlier than longitudinal seismic wave input case. At 5.16s the diagonal chords between the main ribs close to ribs’ feet began to yield (as shown in Fig.19). Then the plastic area developed from rib foot side to the arch vault side, at 16.62sec the plastic area is shown in Fig.19. Central part including main ribs and truss were still in elastic range.

The plastic of ribs was first appeared at the foot segment at 5.32sec, the plastic strain is relatively small compared with chords’.

![Fig.18 Longitudinal deformation at arch crown](image1)

![Fig.19 Yielding process during first 6sec](image2)

**Conclusions**

By static analysis: in in-plane fault displacement case, the vault segments yield firstly and the main ribs damaged earlier than secondly members. While in out-off-plane fault displacement case, the structure appears plastic because foot segments yield, and the connection transversal chords between the ribs yield earlier than main ribs.

During the modal analysis, the basement mode shape is in plane asymmetric, and the distortion stiffness of the bridge is relatively large. During the in-plane seismic input case, the column next to the arch crown yield firstly and the plastic deformation of main rib appeared at last. In contrast, during the out-off-plane seismic input case, plastic deformation was firstly appeared at top diagonal chord near the side column and then chords between main ribs and ribs’ feet segments.

In transversal earthquake wave input analysis only material nonlinear was included, so the analysis method still need improving. And the effective strengthening method of such bridge in order to improve its bearing capacity and ductility need further study.

**References**


