Elastic-plastic time-history analysis of steel-tube stiff-frame arch bridge without inner filling concrete

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Abstract: Based on a case study of a typical arch bridge with hollow steel tube and stiffness frame located in the high intensity region of western China, this paper adopts the onlinear time-history method to analyze the structural response of the overall bridge elastic-plastic model under seismic action. Under the force of Wolong wave in Wenchuan Earthquake, the main load-bearing members of the structure have a good seismic performance. Only part of the columns on the main arch ring enter the plastic hinge state for energy dissipation, and the lower columns have a more obvious energy dissipation effect than the higher ones. The result indicates that the design idea of structure which is similar to that of strong column and weak beam in ductility design, has the characteristics of “strong arch and weak beam” and can therefore improve the ability of structure to resist collapse under earthquake action.

1. Introduction
The research object of this study is a reinforced concrete arch bridge (hereinafter referred to as N bridge), which is located in a secondary seismic zone in southwest China. This bridge uses hollow steel tubes as the rigid frame in the construction process and then installs templates to pours surrounding concrete after the hoisting work[1]. The study aims to study the actual ground motion effect of N bridge in the typical high earthquake intensity area and then provide reference for similar large-scale projects. Therefore, this paper conducts a detailed analysis on the damage state of the critical fiber section of the whole bridge and the time of the corresponding extreme point with the input of Wenchuan Wolong Wave earthquake on N bridge. Based on the time-history response results of each key section under the action of E2 rare intensity earthquake, the bending moment curvature of the section under dead load and the damage state of the section under seismic action are used to judge the seismic performance and energy dissipation of N bridge under the action of Wenchuan Wolong Wave earthquake.

2. Finite Element Model of Bridge
To study the seismic performance of the N bridge, the calculation model[2] should correctly reflect the
stiffness, mass distribution and damping characteristics of the upper and lower structures and supports of the bridge. Firstly, a three-dimensional spatial dynamic model of the N bridge with 533 nodes and 356 elements is established by using the finite element analysis software of spatial structure Midas/Civil. All the elements are simulated by using spatial beam elements. Meanwhile, the lead-core rubber bearing between pier cover beam and bridge panel is simulated by using the characteristic value of the lead-core rubber bearing isolation device in general connection, and the prestressed concrete T beam deck is simplified into single beam. The solid web sector of the cast-in-place vault is considered in accordance with the stiffness of the main arch ring, and the cast-in-place concrete slab, girder bridge deck and the connecting part are applied to the vault element through the joint load. In order to simplify the calculation, the influence of approach bridge and the interaction between pile and soil are not taken into consideration in the modeling. In addition, the bottom and arch foot of the side pier in the model are consolidated in this research. The specific model is shown in Figure 1.

To consider the nonlinearity of the material in the structure, the arch ring and pier column are given the properties of the fiber unit. In this sense, this study allocates 12 fiber elements to N bridge. In particular, the arch ring part is represented by the two side arch foot fiber A and the A#, arch ring 1/4 section fiber B and the arch ring 3/4 section fiber B#. The bottom of the side pier is represented by fiber 1# and fiber 8#, and the bottom of the arch column is represented by fiber 2#, fiber 3#, fiber 4#, fiber 5#, fiber 6#, fiber 7#. The distribution of the 12 fiber elements mentioned above is shown in Figure 2.

![Figure 1. 3D Model of Spatial Dynamics of N Bridge](image1)

![Figure 2. Location of the 12 Fiber Units](image2)

3. Elastic-plastic analysis of N bridge under Wenchuan earthquake

3.1. Analysis of energy dissipation and damage condition

The energy dissipation part of the structure and the damage condition of the section can be obtained by analyzing the hysteretic curve of moment-rotation and the status distribution diagram of the fiber section. In general, the narrower the hysteretic curve of the section is, the closer the section is to a fully elastic state[3,4]. The hysteretic curve of moment-rotation is generally an S-shaped curve when the control section does not enter the yield state. When the bending moment becomes zero, the rotation angle also approaches zero without any residual deformation. Conversely, when the control section enters the elastoplastic phase, the area enclosed by the bending moment hysteresis curve is positively related to the number of steel bars which enter yield state. Namely, the more steel bars come into yield state, the larger area enclosed by the bending moment hysteresis curve will be, resulting in a larger residual deformation. It indicates that the energy dissipation effect of the steel bar on the structure is more obvious when the section is in yield situation.

3.2. Input of seismic waves

With the characteristics of high peak, long duration and slow acceleration attenuation, the peak acceleration of Wolong wave of the Wenchuan earthquake can reach 0.957g. The analysis applies the Wolong wave of Wenchuan earthquake on the structure in an orthogonal combination of longitudinal (EW) + vertical (UD). The peak acceleration of ground motion in two directions is 0.957 g and 0.682 g respectively, and the duration is 180 secs with 0.02 secs interval. To satisfy the principle of [5] seismic
wave selection, the first 90 secs’ time-history curve of the original record, which includes the most violent part of the ground motion, is actually selected for analysis.

By loading the selected Wolong wave of Wenchuan, this paper makes a local analysis on the key section of the structure, and finds out the weak position of seismic resistance of the N bridge through the state of the fiber section. Through the time-history response, the response law of the structure under the seismic wave time-history is found out.

Table 1 below shows the responses of the fiber sections of the N Bridge to the longitudinal +vertical earthquake of Wolong wave of the Wenchuan earthquake.

| Location of section | A | B | 1# | 2# | 3# | 4# | 5# | 6# | 7# | 8# | B# | A# |
|---------------------|---|---|----|----|----|----|----|----|----|----|----|----|
| Yield state of steel bars | No | No | No | part | No | full | full | part | part | No | No | No |
| Time of extreme point of rotation angle /s | 27.6 | 27.7 | 31.6 | 32.1 | 32.1 | 33.3 | 33.0 | 32.1 | 32.1 | 31.6 | 27.6 | 28.0 |

For the energy dissipation and breakage of the fiber section where the steel bar yields, see Fig.3~7:

(a) Hysteretic curve (b) The state of the maximum rotation angle point of the fibre section

Figure 3. Energy consumption and breakage of column 2#

(a) Hysteretic curve (b) The state of the maximum rotation angle point of the fibre section

Figure 4. Energy consumption and breakage of column 4#

(a) Hysteretic curve (b) The state of the maximum rotation angle point of the fibre section

Figure 5. Energy consumption and breakage of column 5#
There are 5 main findings from the analysis of the charts above:

1) From the point of view of the occurrence time of the extreme rotation point of each fiber section, when ground motion is in different locations in the structure, the extreme rotation angles occur in different time. The result reflects the spatial variation characteristics of the ground motion.

2) Under the action of vertical and vertical seismic action, there is no yield phenomenon in both sides of the arch foot, 1/4 arch ring, 3/4 arch ring and steel bars at the bottom section of side piers on both sides. It indicates that these parts are basically in elastic state under the action of longitudinal and vertical earthquake, and the seismic capacity has a certain degree of surplus. The main load-bearing members of the N bridge have a good seismic performance.

3) From the analysis of the time node when the section of the arch ring reaches its extreme rotation point, it can be found that the arch foot A reaches its extreme rotation angle of the section at 27.80 s, and the arch foot A# reaches its extreme rotation point of the section at 28.04 s, 0.24 s later than the former; The cross section rotation angle of 1/4 arch ring B is maximum at 27.70 s, and that of 3/4 arch ring B# reaches its peak at 27.68 s, 0.02 s faster than the former. The results shows that there is a time difference in the structural response of ground motion to each part of the arch ring, and this difference is related to the distance between two sections, which means the shorter distance between two sections is, the smaller time difference of their structural response of ground motion will be.

4) According to the analysis of the yield situation of the bottom section of the columns on arch rings, it is found that the bottom section of each arch column do not come into yield state, except section 3#. The steel bars of other column sections have yield phenomenon and their yield positions differ. Among them, the longitudinal steel bars of section 4# and section 5# enter their yield state, and the corresponding extreme rotation angle are 0.0213 and 0.0252 respectively, both of which are less than the limited curvature of the section under constant load of 0.0719 and do not exceed the curvature of 0.036 when the ductility safety coefficient is 2. Therefore, the structure is in a state of repairable damage.

5) From the analysis of the hysteretic curve of the section where the steel bars yield, the researcher finds that the area enclosed by the hysteretic curve and the residual deformation of the bottom section 4# and section 5# are larger than those of other sections. It means that the structure is more prone to be damaged but the effect of energy dissipation becomes more obvious relatively.
4. Conclusion

By using the nonlinear time history analysis method, this research conducts the elasto-plastic analysis of the N bridge under over-designed earthquake and evaluates the seismic capacity of the N bridge. In the analysis of the damage state of the key parts of the fiber section of the N bridge and the time of the corresponding corner extremum under the input of the Wenchuan Wolong wave, it is found that the structural response of each key section has a time difference under the action of longitudinal and vertical orthogonal ground motions. The main load-bearing members of the N bridge do not come into the steel yield, indicating that this bridge has a good seismic performance. The steel bars are basically in an elastic state under the action of the Wenchuan earthquake wave. In addition, the columns on the main arch ring of the structure are prone to be damaged, especially the section 4# and section 5#, both of which have a larger area enclosed by the hysteretic curve, a larger residual deformation and a more obvious energy dissipation than other sections. When an earthquake occurs, energy can be dissipated through the arch column 2#, the arch column 4#, the arch column 5#, the arch column 6# and the arch column 7#, ensuring that the arch ring, side pier and other key parts undertake the normal force. The result indicates that the design of the structure which is similar to that of strong column and weak beam in ductility design, has the characteristics of “strong arch and weak beam”, and can improve the ability of structure to resist collapse under earthquake action.

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