Study on the longitudinal nonlinear seismic behavior of the arch bridge with steel tubular frame without inner filling

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Abstract: The dynamic analysis model of a typical cantilever hollow steel tubular skeleton arch bridge in the western high-intensity region is established to obtain the longitudinal nonlinear seismic performance of the bridge. By combining the N-F 2-D yield surface of each key fiber section of a bridge, the critical section state of a bridge under the action of E2 rare intensity earthquake is evaluated and described, and the overall seismic performance of the structure is evaluated. The research results show that: The results show that the damaged part of the structure under the longitudinal and vertical seismic action is mostly the bottom of the upper arch column, and the upper arch column closer to the arch is more likely to be damaged, which is the weak part of the structure.

1. Introduction
Since 1890, when the innovative technology (Milan method) of making the arch ring of cast-in-place concrete arch with shaped steel was born, the stiff-frame arch bridge has made great progress all over the world [1]. But at present, the seismic design and analysis of long-span Bridges and special Bridges are deficient in the existing seismic codes. Neither the European code nor the American AASHTO code explicitly stipulates that it is not applicable to arch Bridges, while China’s "Seismic Code for Highway Engineering" [2] and "Detailed Rules for Seismic Design of Highway Bridges" [3] only apply to arch Bridges with main span no more than 150m, and only provide design principles for special Bridges. Under this background, the seismic research of steel tubular stiffened skeleton arch bridge without inner filling concrete is lack of more systematic research results, which is a problem to be solved. In this paper, with Midas/Civil software, the nonlinear seismic performance of a steel tubular skeleton arch bridge with no inner filled concrete is studied under rare intensity earthquakes.

2. Establishment of finite element simulation model

2.1. Engineering situation
The length of the main arch bridge is 162.8m, the calculated span is 155m, the calculated sagittal height f = 39.3m, and the sagittal span ratio is 1/3.944, the arch axis coefficient of catenary arch frame m = 1.99. Single box and double chamber section formed by C50 concrete after closure. The arch ring section as a whole adopts the form of 8.8m×3m with the same width and height. The outer diameter and thickness of hollow steel tube arch rib of steel frame are 402mm and 32mm, and the material is Q345C.
The underside of the arch and the arch ring connecting the upper column are solid sections. The cross section of the upper arch ring is shown in figure 2, and the cross-section size of other parts of arch ring is shown in figure 3. The arch structure consists of 4×14.8m prestressed concrete post-tensioned T beams +3×14.8m cast-in-place concrete slab beams +4×14.8m prestressed concrete post-tensioned T beams. Small mileage of the foot of the arch set up a stepped box to expand the foundation. Large mileage of arch feet by 12 root Φ 2.2 m bored piles foundation. Four lead-core isolation rubber supports of type J4Q350×350×137*G1.0 are installed on the top of the main pier. The layout of bridge span is shown in figure 1.

2.2. The establishment of three-dimensional space model
It can be seen from the differential equation of structure vibration that the key point of modeling should be to truly and accurately reflect the mass, stiffness, damping and boundary conditions of the structure and components. Based on the finite element analysis software Midas/Civil of spatial structure, a three-dimensional spatial dynamic model of a bridge was established, with a total of 533 nodes and 356 units. All the elements are simulated by space beam element. The lead rubber bearing between pier cover beam and bridge face plate is simulated by using the characteristic value of the lead rubber bearing isolation device. Prestressed concrete T-beam bridge panels are simplified with single beams. The cast-in-place concrete slab beam bridge panel and its joints are loaded on the arch roof unit through joints. In order to simplify the calculation, the influence of the approach bridge and the interaction between pile and soil were not taken into account in the modeling. The bottom and arch foot of the side pier in the model were consolidated, and the specific model was shown in figure 4.
3. Nonlinear analysis of earthquakes with rare intensities

3.1. Definition of elastoplastic materials
The Mander model[4] is selected as the constitutive model of concrete materials, while the constitutive relation model of reinforcement adopts the double broken line model. A bilinear hysteretic model is used to simulate the nonlinearity of bearing boundary and bearing material[5]. Considering the nonlinearity of materials in the structure by assigning properties of fiber elements to arch rings and piers. As shown in figure 5, 12 fiber unit assigned to A bridge, the arch ring is represented by the arch foot fibers A and A# on both sides, the arch ring 1/4 section fibers B and the arch ring 3/4 section fibers B#, the bottom of the two side piers is represented by fiber 1 and fiber 8, the bottom of the arch upper column is represented by fiber 2, fiber 3, fiber 4, fiber 5, fiber 6, and fiber 7. For convenience, the following text is briefly indicated by symbols. The fiber model is used to segment the elements to simulate the response of the structure to ground motion.

3.2. Construction of yield surface
The elastoplasticity of a beam-column element can be represented by the Bresier recommended yield surface or can be simulated by a nonlinear beam-column fiber element [3]. As a typical flexural arch bridge, considering the coupling effect of axial force and bending moment on the section, the key section of the yield bridge is introduced for elastoplastic analysis. By using the Midas/Civil moment curvature calculation module to input different axial forces, the corresponding initial yield moment and equivalent yield moment of the specified section were obtained. The axial force moment curve (N-M correlation curve) was used, as shown in figure 6, to construct the two-dimensional yield surface of each key section of the structure.

3.3. Input of seismic waves
In this paper, artificial horizontal seismic waves are selected as shown in figure 7. through the adjustment coefficient, the vertical ground motion is 0.65 times of the horizontal direction, the time history response results of each key section were obtained by longitudinal + vertical input.

4. Time history analysis of key sections
By combining the N-M two-dimensional yield surface of each fiber section of a bridge, using this as the evaluation criterion, the key section state of a bridge under the action of rare intensity earthquake is described. The seismic performance of the structure under longitudinal and vertical seismic waves is
evaluated. The yield surface and timely response results of each key section are shown in figure 8, in which the axial force of the section is positive with compression.
4.1. Time history analysis of axial force bending moment of A and A#
According to the analysis in figure 8(a) and figure 8(b), it can be seen that under the longitudinal +
vertical seismic action, almost no external bending moment is generated on either side of the arch foot
or the external bending moment is very small. The in-plane bending moment response curve of arch foot
section A is basically located in the initial yield surface, occasionally exceeding, indicating the
possibility of local yield of arch foot A in the longitudinal direction. The in-plane bending moment
response curve of arch foot section A# is within the initial yield surface, indicating that arch foot A# is
in the basic elastic state in the longitudinal direction.

4.2. Time history analysis of bending moment axial force of B and B#
According to the analysis in figure 8(c) and figure 8(d), it can be seen that under the longitudinal +
vertical seismic action, almost none of the two sections produced external bending moments or produced
external bending moments that were very small, and the response curves of internal bending moments
were also within the initial yield surface, indicating that both sections were in basic elastic state in the
longitudinal direction.

4.3. Time history analysis of bending moment and axial force of 1# and 8#
According to the analysis in figure 8(e) and figure 8(f), it can be seen that under the longitudinal +
vertical seismic action, almost none of the two sections produced external bending moments or produced
external bending moments that were very small, and the response curves of internal bending moments
were also within the initial yield surface, indicating that both sections were in basic elastic state in the
longitudinal direction.

Figure 8. Time history curve of axial force bending moment of each key section under the action of
longitudinal + vertical rare earthquake
4.4. Time history analysis of bending moment and axial force of 2# and 7#
According to the analysis in figure 8(g) and figure 8(h), it can be seen that under the longitudinal +
vertical seismic action, the value of the external bending moment generated by the two sections is very
small and has certain similarity. A small part of the internal bending moment response curve is located
between the initial yield surface and the equivalent yield surface, indicating that the section produces
local yield in the longitudinal direction.

4.5. Time history analysis of bending moment and axial force of 3# and 6#
According to the analysis in figure 8(i) and figure 8(j), it can be seen that under the longitudinal +
vertical seismic action, the value of the external bending moment generated by the two sections is very
small and has certain similarity. A small part of the internal bending moment response curve is located
between the initial yield surface and the equivalent yield surface, indicates that the section produces
local yield in the longitudinal direction and the degree of yield is larger than section 2# and section 7#.

4.6. Time history analysis of bending moment and axial force of 4# and 5#
According to the analysis in figure 8(k) and figure 8(l), it can be seen that under the longitudinal +
vertical seismic action, the external bending moments generated by the two sections are not small, but
they are both within the initial yield surface, part of the in-plane bending moment response curve is
located on the equivalent yield surface, indicating that plastic hinge is generated in the longitudinal
direction of the section.

5. Conclusion
On the whole, the seismic performance of a bridge under the action of E2 rare intensity longitudinal +
vertical earthquake basically meets the design requirements that the structure can have limited damage,
but the normal traffic can be restored after the earthquake without repair or with simple repair. The
seismic performance of the main arch ring is good. Most of the damaged parts of the structure are at the
bottom of the upper arch column. Moreover, the closer the upper arch is to the top of the arch, the more
likely the upper arch column is to be damaged. In particular, section 4 and section 5 are earthquake-
resistant weak links. There is a certain similarity in the moment response of each fiber section of a bridge.

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