Nonlinear seismic finite element modeling method for super long span column tower cable-stayed bridge

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Abstract: This project takes Wuhu Yangtze River Highway Second Bridge as an engineering example. In view of the structural and seismic characteristics of the new structure such as the super-long-span sub-limb column tower cable-stayed bridge and the oblique damping system, the partial precision modeling is applied to the seismic vulnerable components such as sub-limb column tower and pier on the basis of the seismic finite element model of the space bar system. In addition, the correct and reasonable finite element simulations of the important components and seismic construction measures such as cables and oblique dampers, are carried out by adopting the elements and constitutive relationships suitable for structural seismic analysis. Meanwhile, the material nonlinearity and geometric nonlinearity of super-long span bridges can be considered and nonlinear seismic finite element model of super-long-span column cable-stayed bridges is established.

1. Introduction

Most of the studies on bridges in the literature focus on the middle and small span girder bridges, and the study on the nonlinear finite element models of long-span cable-stayed bridges with a span of more than 800 meters is rare. Wuhu Yangtze River Highway Second Bridge Project is a two-tower and five-span steel box girder small A tower cable-stayed bridge, whose main girder is a separated flat streamlined closed steel box girder with an upper flange of orthotropic plate structure. The span composition of bridge is: 100+308+806+308+100 m, and the main span is 806 m, and the overall layout of the main bridge is shown in Figure 1.

Figure 1. Layout of bridge and tower

The main bridge is a full floating system, and a pair of vertical movable supports are set at the top of the side piers. In addition to the vertical supports, two sets of transverse wind-resistant supports are also set at the top of the transition piers, which are used to resist wind load and reduce the lateral deflection of steel box girder under the earthquake to protect expansion joints. The main tower is provided with a transverse wind bearing and a longitudinal damping device. Viscous dampers have damping energy dissipation effect on the dynamic load caused by fluctuating wind, brake and earthquake, but have no constraint on the slow displacement. Four viscous dampers are installed at the connection of tower and beam, a total of 8 dampers for the whole bridge. The cable tower adopts single column shape, including upper tower column (including upper and middle tower column connection section), middle tower
column (including middle and lower tower column connection section), lower tower column, tower block and lower beam, using C50 concrete.

2. OpenSEES simulation of nonlinear fiber elements of a main tower

Since the tower selected in this paper is a reinforced concrete structure, the elastoplastic fiber element proposed by Taucer et al. [1] and Lee J [2] is used for modeling in this paper. This element discretizes the reinforcement and concrete into fibers, which is shown in Figure 2. According to the characteristics of bridge concrete structure, three materials including unconfined concrete, confined concrete wrapped by stirrups and longitudinal reinforcement are considered in the modeling. The material model of fiber element used in this paper is described below.

In this paper, the modified hysteretic deformation calculation model of reinforcement was proposed by scholars such as Giuffré, Menegotto and Pinto. Both unconfined concrete and confined concrete adopt the Kent-Scott-Park model [3], as shown in Figure 4.

2.1. Steel model
A bilinear model of steel bars is modeled with a Steel01 material in OPENSEES. The statement is as follows:

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uniaxialMaterial Steel01 $matTag $Fy $E0 $b
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According to Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTGD62-2004) [4], the reinforcement of the main tower is HRB400, the standard strength value (Fy) is 400 \times 10^3 kPa, the initial stiffness (E0) is 2.0 \times 10^8 kN/m, and the hardening ratio is 0.005. Its hysteresis curve is shown in Figure 3.

2.2. Confined concrete and unconfined concrete models
Many scholars at home and abroad have studied the stress-strain relationship of ordinary confined concrete and proposed many different constitutive models of confined concrete, such as the Kent-Scott-Park model and the Mander model. Kent-Park model (Figure 4 (a)) was proposed by Kent and Park et al. on the basis of a large number of tests on rectangular stirrup pier columns, and has been widely used in practice. However, the model didn’t consider the effect of stirrups on the ultimate compressive stress of concrete, which was further modified by Scott et al. (1982) namely the Kent-Scott-Park model. Although more accurate constitutive models of concrete have been proposed, the Kent-Scott-Park model (Figure 4 (b)) achieves a good balance in terms of the accuracy and simplicity of calculation, which is adopted in OpenSees as Concrete 01 material model.
The Kent-Scott-Park model is composed of the 3-fold line, namely the rising section, the falling section and the horizontal section. Rising section is expressed as:

\[ f_c = K f_c' \left[ 2 \varepsilon_c \left( \frac{\varepsilon_c}{0.002} \right)^2 \right] \]  

(1)

falling section BC is expressed as:

\[ f_c = K f_c' \left[ 1 - Z (\varepsilon_c - 0.002K') \right] \]  

(2)

and horizontal section is expressed as:

\[ f_c = 0.2 K f_c' \]

\[ K = 1 + \frac{\rho f_{sh}}{f_c} \]

\[ Z = \frac{3 + 0.29 f_c'}{145 f_c' - 1000} + \frac{3}{4} \frac{b''}{s_h} - 0.002K \]

(3)

where \( f_c' \) is the longitudinal concrete compressive strength, \( f_c'' \) is the compressive strength of concrete for 28 days, \( b'' \) is the distance from the core concrete to the outside of the stirrup, \( s_h \) is the spacing of stirrups, \( f_{sh} \) is the yielding strength of stirrup. The ultimate compressive strain of confined concrete is defined as the compressive strain of concrete when transverse restraint stirrups begin to fracture, which can be derived from the condition that the total strain energy released when the transverse restraint steel bars reach the maximum compressive stress is equal to the energy absorbed by concrete due to the constraint of transverse reinforcement. Scott et al. (1982) suggested that the following formula could be used to conservatively estimate the ultimate compressive strain of concrete, generally between 0.012 and 0.05.

\[ \varepsilon_u = 0.004 + \frac{0.9 \rho f_{sh}}{300} \]  

(4)

This model is the concrete stress-strain model Concrete01 used in the OpenSEES:

\texttt{uniaxialMaterial Concrete01 $mat Tag $fpc $epsc0 $fpcu $epsU}

where \$fpc is the standard value of concrete strength for 28 days, \$epsc0 is the concrete strain corresponding to the maximum strength, \$fpcu is the concrete crushing strength, and \$epsU is the strain corresponding to the crushing strength. Various parameters in the OpenSEES command are shown in Table 1.

| Concrete position | fpc(MPa) | epsc0 | fpcu | epsU |
|-------------------|---------|-------|------|------|
| Cover             | 32.4    | 2.0x10^{-3} | 6.48 | 0.0035 |
| Core              | 40.4    | 2.3x10^{-3} | 7.30 | 0.012  |

2.3. Elastic girder

In literature [6], axial forces of cables, main girders, bending moments and vertical displacements of key sections of the superstructure of cable-stayed bridges under longitudinal-vertical and transverse-vertical seismic actions are analyzed. The results show that, compared with the response of the key
section of the structure under constant load, the seismic response of the main girder and the cable under seismic actions is not dominant. The stress level is relatively low to its material capacity, so it is not easily vulnerable in the earthquake, so in this paper assumes the main beam is assumed in an elastic state. The width of the standard box beam is 3.2 m, the width of the end beam is 3.05 m, and the width of the beam at the side piers is 4.0 m (the center distance of the web). And the length of the middle section of the beam is 10.2 m. High-strength bolt connection is set between the middle section of the beam and the end of the beam. The web of the beam corresponds to the position of the steel box girder diaphragm. There are 8 diaphragms inside the box beam, with the thickness of 10 mm and the spacing of 2.5 m. The steel box girder of the whole bridge is divided into 11 types of beam sections. Figure 5 gives the standard cross section and the section at cable tower.

2.4. Elastic prestressed cables considering sag effect

As abovementioned, it is assumed that the cable is in the elastic state during the earthquake process, which is simulated by truss unit, and the sag effect of the cable and the pressures of the cable are taken into account. In the last century, there were some theories and literatures to study how to simulate the cable. Gambhir and Batchelor [7] developed the two-point curve finite element with cubic function and applied it to the static and dynamic analysis of 3D prestressed cable surface. Ozdemir [8] developed another kind of curve finite element between two points with Lagrange function. Although these methods are accurate, the actual operation process is very complicated. The third method is equivalent stiffness method, which has been used by many scholars. This method is also called Ernst method [9], namely modified elastic modulus method to consider the sag effect of cables. The method uses parabola instead of catenary to simulate the cable, because the cable is a medium bending, high tensile line. The equivalent stiffness can be expressed as:

\[
E_{eq} = \frac{E_c}{1 + \left( \frac{\rho g L_x E_c}{12 \sigma} \right)^2}
\]  

where \( \sigma \) is the prestress of cables, \( \rho \) is the density of the unit area of the cable, the \( \rho \) value is \( 7.85 \times 10^3 \) kg/m³, \( g \) is the gravity acceleration, \( L_x \) is the projected distance of the cable, \( E_c \) is the elastic modulus of the prestressed cable, and the value is \( 1.95 \times 10^5 \) MPa.

2.5. Damper modeling

As stated in the above sections, the main bridge of Wuhu Yangtze River Highway Second Bridge innovatively adopts the oblique damping constraint system to constrain both the longitudinal and transverse displacement of the tower-beam and reduce the structural stress [10]. According to the relative transverse displacement of the transverse bridge of the tower-girder under the E1 earthquake doesn’t exceed the reserved clearance and the relative longitudinal displacement under the E2 earthquake doesn’t exceed 500 mm, based on a large number of preliminary calculations, the viscous damper parameters are listed in Table 2. According to the established dynamic calculation model, the first 10 order vibration mode periods, frequency and vibration mode characteristics of the main bridge are listed in Table 3.

| Types                      | Name                  | Damping limit device |
|----------------------------|-----------------------|----------------------|
| Dynamic damping parameter  | Force and velocity    | F=CV^α               |

Figure 5. Cross section of steel box girder

(a) Standard cross section of steel box girder
(b) Section of steel box girder at the tower
### Table 3. Basic dynamic characteristics of the calculation model

| Order number | Period (s) | Frequency (Hz) | Modal descriptions               |
|--------------|------------|----------------|----------------------------------|
| 1            | 14.91      | 0.067          | First-mode longitudinal wave     |
| 2            | 8.28       | 0.122          | First-mode lateral bending       |
| 3            | 7.64       | 0.127          | Second-mode lateral bending      |
| 4            | 5.20       | 0.170          | First-mode lateral bending       |
| 5            | 4.95       | 0.204          | First-mode vertical bending      |
| 6            | 4.01       | 0.254          | Second-mode vertical bending     |
| 7            | 2.76       | 0.364          | Third-mode vertical bending      |
| 8            | 2.97       | 0.38           | Second-mode lateral bending      |
| 9            | 2.12       | 0.427          | Fourth-mode vertical bending     |
| 10           | 1.87       | 0.464          | First-mode torsional            |

### 3. Summary

A locally refined finite element model with high nonlinearity is the basis for performance-based seismic evaluation. Most of the studies on bridges in the literature focus on the middle- and small-span girder bridges, and the study on the nonlinear finite element models of long-span cable-stayed bridges with a span of more than 800 meters is scarce. This project selects Wuhu Yangtze River Highway Second Bridge as the engineering example. Based on the characteristics of super span sub-limb column tower cable-stayed bridge and the seismic finite element model of space truss, the local refinement models are established for these vulnerable components and suitable elements and relationships are used to simulate the important components such as cables and oblique dampers. Meanwhile, considering the outstanding material nonlinearity and geometric nonlinearity of the super span bridge, the precision nonlinear seismic finite element model of the super span column tower cable-stayed bridge is established to provide support for performance-based seismic analysis and evaluation.

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