The investigation of seismic fragility for super-long column cable-stayed bridges

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Abstract: The number of super-long-span cable-stayed bridges over 800 meters is small, and the seismic damage data of such bridges are rare. The relevant research on seismic response and mechanism of seismic damage is still insufficient. Taking the Second Wuhu Yangtze River Bridge as the engineering background, the investigation of the fragility of super-long column cable-stayed bridge is carried out. The probabilistic seismic demand model (PSDM) is established using nonlinear time history analysis and taking account the uncertainty of the bridge model and the input earthquake. By comparing the fragility curves of the critical components and engineering demand parameters (EDPs), the failure rules and failure modes are explored, the vulnerability part and the failure mechanism of the component are investigated.

1. Introduction

Many scholars have done a lot of work on medium or small span bridge vulnerability curves, including the theory, method and conclusion, etc., and a lot of progress have been made. Cornell [1], Shinozuka M. [2], DesRoches [3], Mackie K.R. [4], Der kiureghian [5], Zhong, J. [6], Padgett [7] have made contributions on the quantitative component performance, probabilistic seismic demand model, the seismic wave selection, system vulnerability, etc. However, the research on the vulnerability of long-span cable-stayed bridges is still in the blank stage. Only some literatures have studied the model of the whole bridge, and many theories are in the starting stage. Due to the characteristics of long-span cable-stayed bridge, such as the period is long, the damping is small, coupling formations, high tower, etc, there are many methods of study of middle span of vulnerability curve does not necessarily apply to long-span cable-stayed bridge [8], such as the choice of ground motion intensity measure (IM), the influence of vertical ground motions, performance-based component ability, engineering demand parameter choice. Based on the above characteristics, accurate acquisition of seismic vulnerability curves requires detailed discussion. Therefore, this project selects the Second Wuhu Yangtze River Bridge as the engineering background and study the seismic vulnerability curve of component level, obtain the failure rules and order of each important component of super-long-span column tower cable-stayed bridge under different seismic levels. Then, the seismic vulnerability curves are compared and analyzed to reveal the main seismic failure modes of the super-long-span column tower cable-stayed bridge.

2. Probabilistic seismic demand model (PSDM)

Before the seismic vulnerability study, it is necessary to study the method for calculating the seismic
vulnerability curve of cable-stayed bridges. The theoretical framework is as follows [9]:

The vulnerability curve can be described as the conditional probability that the demand \((D)\) of the structure exceeds its capacity \((C)\) under the given intensity measure \((IM)\), and the calculation formula is expressed:

\[
Fragility = P[D \geq C | IM]
\]  

(1)

Cornell suggested that the average demand under the action of earthquake could be expressed as:

\[
\ln(EDP) = \ln a + b \ln(IM)
\]

(2)

where \(a\) and \(b\) are the regression coefficients. Assuming that given \(IM\), \(\ln(EDP)\) is normally distributed, and the standard deviation can be expressed as [10]:

\[
\beta_{EDPIM} = \sqrt{\frac{\sum_{i=1}^{n}[\ln(EDP_i) - (\ln a + b\ln IM)]^2}{n-2}}
\]

(3)

Therefore, the vulnerability equation can be expressed as:

\[
P[D \geq LS | IM] = 1 - \Phi\left(\frac{\ln(LS) - \ln(aIM^b)}{\beta_{EDPIM}}\right)
\]

(4)

3. Cable-stayed bridge model

The construction plan of the Second Wuhu Yangtze River Bridge is a small A-shaped cable-stayed bridge with two towers and five spans steel box girder, the main girder is a separated flat streamlined closed steel box girder. The span composition of the main bridge is: 100+308+806+308+100 m, and the main span is 806 m. The overall layout of the main bridge is shown in the Figure 1. The pylon adopts the single-column structure. The column adopts hollow octahedral section, and the upper column is an integral single box and single chamber. The middle and lower columns are of equal height cross-section and each tower is provided with an elevator hole. Viscous dampers have damping energy dissipation effect on the dynamic load caused by fluctuating wind and earthquakes. When the relative longitudinal displacement of the tower-beam caused by static wind is within the design stroke of the damper, the movement of the main beam is not restrained and beyond the stroke, the movement of the main beam is fixed. The main bridge constraint system is summarized in the Table 1. The main bridge design (Figure 3) of the Second Wuhu Yangtze River Bridge requires the longitudinal damping restraint system, which can effectively control the longitudinal displacement of the main girder and the structural stress under wind load and seismic load. The lateral constraint system needs to be designed on the premise of satisfying the longitudinal constraint system. If the consolidation system is adopted, the transverse displacement between the tower-beam can be effectively restrained, but in order to meet the relative longitudinal movement requirements of tower-beam, it is difficult to achieve complete lateral consolidation between the tower-beam. Therefore, the main bridge of the Second Wuhu Yangtze River 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.

Figure 1. Structure diagram of cable-stayed bridge
Figure 2. Structure diagram of the pylon

![Figure 2](image1.png)

Figure 3. Steel box girder cross section at tower (unit:mm)

![Figure 3](image2.png)

Table 1. Architecture constraint system overview

| Constraint direction | Transitional pier | North side pier | South side pier | Tower beam connection |
|----------------------|-------------------|-----------------|-----------------|---------------------|
| Longitudinal direction | Slide | Slide | Slide | Dynamic damping rated travel limit |
| Transverse direction | Constraint | Constraint | Constraint | Constraint |
| Vertical direction | Constraint | Constraint | Constraint | Free |

4. Oblique damper

In order to control the response of the girder in both the longitudinal and transverse directions, the oblique damper scheme is adopted, which is shown in Figure 4. In the damper parameter design, the impact of wind load on the structure needn’t be considered. According to the principle that the relative transverse displacement of the tower-beam under E1 earthquake doesn’t exceed the reserved clearance 200 mm and the relative longitudinal displacement of the tower-beam under E2 earthquake doesn’t exceed 500 mm, based on a large number of preliminary calculations, the viscous damper parameters are selected as shown in Table 2.

![Figure 4](image3.png)

Figure 4. Configuration diagram of the oblique damper

![Figure 5](image4.png)

Figure 5. The finite element model of the cable-stayed bridge
Table 2. Design parameters of oblique damper

| Types           | Name                          | Damping limit device |
|-----------------|-------------------------------|----------------------|
| Dynamic damping parameter | Force and velocity F=CV^a |
| Speed index α   |                               | 0.25                 |
| Damping coefficient C (kN/(m/s)) | 3000                 |
| Maximum reaction speed (m/s) | 0.475                 |
| Damping force (kN) | 2000                 |
| Rated maximum stroke (mm) | ±500                  |

The finite element analysis model of the cable stayed bridge is established using the OPENSEES software platform. In the finite element model, the beam element is used to simulate the beam, the pylon and the pier. The cable is simulated by beam element, and Ernst formula is used to consider the elastic modulus reduction caused by the sag effect caused by the cable's dead weight. The pile-soil interaction is simulated with a six-spring system. The nonlinear finite element model of the Second Wuhu Yangtze River Bridge is presented in the Figure 5.

5. Ground motions selection

In this paper, 100 ground motions [8] were selected, including 80 ground motions with a magnitude range from 5.8 to 6.9 and an epicenter distance ranging from 10 km to 60 km selected from PEER (Pacific Earthquake Engineering Research). The distributions of PGA, magnitude and epicenter distance are shown in Figure 6. And the rest 20 ground motions are selected from SAC database, which have a 2% exceedance probability and 10% exceedance probability in 50 years. The longitudinal and transverse response spectrums are shown in Figure 7.

Figure 6. The distribution of the ground motions

Figure 7. The acceleration spectrum of the ground motions

6. Engineering demand parameters

This paper selects 14 engineering demand parameters, namely the longitudinal and transverse bending moment yield curvature of four pylon sections (Figure 8) (μφ1x, μφ1y, μφ2x, μφ2y, μφ3x, μφ3y, μφ4x, μφ4y), auxiliary piers key cross sections and side piers (μφ5x, μφ5y, μφ6x, μφ6y), and bearing longitudinal displacement (δb), the relative displacement of girder-abutment (δa).
Figure 8. The critical section of the pylon

Figure 9. The PSDM curve of the component of the cable-stayed bridge

7. Fragility curves

100 pairs of ground motions are input into the nonlinear finite element model of the Second Wuhu Yangtze River Bridge to record the peak response of components under different seismic waves. The 100 PSDMs of 14 EDPs are shown in Figure 9 (only \( \mu_{\phi 1} \) for example). PGA is selected as the intensity measure of ground motions, and the regression parameters are put into the formula (4) to calculate the vulnerability of each engineering demand parameter. Figure 10 shows the vulnerability curves under four damage states, namely slight, moderate, extensive and collapse.

From the figure, we can compare the vulnerability of different components and get the following conclusions:

1. For the Second Wuhu Yangtze River Bridge column tower, the bridge section damage along the longitudinal direction is more severe than that along the transverse direction (\( \mu_{\phi 1 x} > \mu_{\phi 2 x} > \mu_{\phi 3 x} > \mu_{\phi 4 x} \)), namely the bridge tower along the transverse direction is more vulnerable under ground motions.

2. Auxiliary piers and side piers are easier to damage (\( \mu_{\phi 1 x} > \mu_{\phi 2 x} > \mu_{\phi 3 x} > \mu_{\phi 4 x} \) and \( \mu_{\phi 1 y} > \mu_{\phi 2 y} > \mu_{\phi 3 y} > \mu_{\phi 4 y} \)) than pylons, which is consistent with the requirement that auxiliary piers and side piers fail first before pylons. Because the pylon is more important, the damage probability is lower than that of piers.

3. The damage probability of the bearing and damper is between the auxiliary pier and pylon. Because the dampers protect the overall performance of cable-stayed bridges, it is not reasonable to destroy first.

4. In general, the damage probability meets \( \mu_{\phi 1 x} > \mu_{\phi 2 x} > \mu_{\phi 3 x} > \mu_{\phi 4 x} \) and \( \mu_{\phi 1 y} > \mu_{\phi 2 y} > \mu_{\phi 3 y} > \mu_{\phi 4 y} \).

8. Conclusion

Based on the Second Wuhu Yangtze River Bridge, this paper investigates the seismic vulnerability law of super-long-span column tower cable-stayed bridge in accordance with the structural characteristics and technical characteristics. Considering the uncertainty of ground motions and structural characteristics, the probabilistic demand seismic model of super-long-span column tower cable-stayed bridge is established by nonlinear dynamic time history analysis. However, due to the small number of
super-long-span cable-stayed bridges at home and abroad and the scarcity of seismic damage data, there are few studies on the seismic vulnerability of super-long-span cable-stayed bridges. Relevant studies don’t form a system and there is no existing seismic design code, which brings great difficulty to the seismic design of the kind of bridges.

Therefore, the innovation of this paper mainly includes: (1) this project combines the super-long-span cable-stayed bridge seismic design with the most advanced PBSD theory, (2) based on the seismic vulnerability analysis method, a comprehensive analysis of the effect of new technologies, such as the sub-limb tower, oblique damping system on seismic performance of super-long-span cable-stayed bridge. The results obtained in this paper can provide assistance to achieve the further research of super-long-span column tower cable-stayed bridge seismic damage mechanism.

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