Determination of reasonable damage index for suspension bridge tower

Lei Liu¹, Tieyi Zhong†, Guangzhi Fu¹ and Junhua Xiao¹

¹ School of Civil Engineering, Beijing Jiaotong University, Beijing, 100044, China
†Tieyi Zhong’s e-mail: tyzhong2012@163.com

Abstract. The selection of damage index is not only the premise and basis for structural vulnerability analysis, but also plays an important role in the accuracy of structural damage assessment. Jinsha River long-span suspension bridge under construction is taken as the research object in this paper. Based on the OpenSees program, the selection of the damage index of the suspension bridge tower is studied. The influence of axial force change on the bending moment-curvature is analyzed by XTRACT software. The applicability of material strain as an indicator of bridge tower damage is studied by IDA analysis. The results show that the material strain is the most reasonable damage index for evaluating the damage of the bridge tower compared to the top displacement and the section curvature.

1. Introduction
Suspension bridges have great advantages over other long-span bridges in spans. Most of the bridges in the world with a span of more than 1000 meters are suspension bridges. Therefore, the suspension bridge is one of the most competitive long-span bridges. As the main load-bearing structure of the suspension bridge, the bridge tower is closely related to the safety, stability and durability of the suspension bridge. Therefore, it is particularly important to assess the damage of the bridge tower under earthquake action.

The selection of structural damage indicators is not only the premise and basis for structural vulnerability analysis, but also plays an important role in the accuracy of structural damage assessment. At present, more research has been done on the seismic vulnerability analysis of bridges of common structural form [1-8]. There are already reliable conclusions in the selection of damage indicators for bridges with the common structural form. However, for the special types of bridges such as cable-stayed bridges and suspension bridges, especially for the suspension damage of suspension bridges, there is still little research. In the selection of damage indicators, no unified and reliable conclusions have been reached[9]. Therefore, this paper takes the bridge tower of Jinsha river suspension bridge as the research object, and conducts an in-depth study on the determination of the reasonable damage index of the suspension bridge tower.

At present, the criteria for judging structural damage can be divided into three categories: strength index, deformation index and energy index[10-11]. For the strength index, when the structure yields, the internal force and the stress value do not change substantially, therefore, the strength index is difficult to measure the damage after the structural yield[12]. For the energy index, the energy theory can explain the mechanism of structural damage better, but the calculation process is more complicated, and further research is needed in practical applications[7][13]. Therefore, when assessing damage of a structure, deformation is usually used as a control indicator. The deformation index
mainly includes three levels: material, section and component, and the typical damage indicators of each level are strain, curvature and displacement. In this paper, a tower of suspension bridge is taken as the research object, and the reasonable damage index of the tower is studied. The most suitable deformation index is used as a criterion for evaluating dam damage, which provides an important reference for the selection of the damage index of the suspension bridge tower.

2. Engineering background and Finite element model

2.1. Engineering background
Jinsha river bridge under construction is studied in this paper. The three-span arrangement of the main cable is: 132m+660m+132m, and the three-span arrangement of stiffening beam is: 98m+660m+98m. The total length of the suspension bridge is 882.5m. Taking the higher tower of the bridge as the research object, the tower adopts a gantry frame structure, which consists of tower columns and beam. The structure diagram is shown in Figure 2-1. Tower column is reinforced concrete structure and beam is prestressed concrete structure. The grade of prestressed concrete is C50. The tower column adopts a hollow rectangular section. The cross-sectional size of the tower top is 9×6m. The cross-sectional size of the left tower column is 15.89×16.06m. The cross-sectional size of the right tower column is 15.79×15.85m. The slope point is set at 40m from the bottom of the tower. The wall thickness of the upper tower is 0.9m. The wall thickness of the lower tower is 1.1m above the slope point, and the wall thickness below the slope point is 1.1~1.5m.

The bridge tower is provided with two beams, and the beam also adopts a hollow rectangular section. The cross-sectional size of the middle of the upper beam is 8×7.5m and the wall thickness is 0.9m. The cross-sectional size of the middle of the lower beam is 8×9m and the wall thickness is 1.1m. 24 bunches steel strands are set in the upper beam, and 48 bunches steel strands are set in the lower beam. A bundle of steel strands is made up of 22 steel bars, the area of which is 15.2mm². The controlled stretching stress of steel strands under anchor is 0.7fpk=1302MPa, and the tensioning force of every bunch steel strand is 4010kN.

2.2. Finite element model
The OpenSees which is an open source finite element program to simulate the tower is used in this paper. Its element adopts Displacement Based Beam Column Element (which is a displacement-based fiber section beam-column element). Column is divided into 1 element every 3m, and beam is divided into 1 element every 2m. Five integral points are set in each element. It considers the middle section at the variable section as the section of the element. The entire tower has a total of 160 elements, of which 129 are divided into column and the beam is divided into 31 elements. The concrete of the
The bridge tower fiber section is simulated by Uniaxial Material Concrete02. The material of main reinforcement is Uniaxial Material Steel02. The structural damping ratio is 0.05, and the damping parameter is Rayleigh damping. By equating the vertical force at the top of the tower and the vertical and lateral forces at the beam as mass points. The mass points are applied to the top of the tower and the beam support respectively.

3. Comparison of reasonable damage indicators for bridge tower

3.1. Displacement

For the low piers, the displacement of the pier top is consistent with the response of the bottom strain and curvature, and the plastic hinges generally appear at the bottom of the pier or at the top of the pier. Therefore, the displacement of the pier top can be used as the damage index of the short pier. However, for the tower, the structure of the tower is more complicated. There are more stress points to be concerned, and the upper beams, the lower beams and the tower are potential plastic hinge positions. The damage state of some key sections cannot be accurately evaluated by the top displacement. Therefore, it is not appropriate to use the top displacement as the damage index of the tower.

3.2. Section curvature

When the section curvature is selected as the damage index, it is first to perform the moment-curvature analysis on each key section of the tower, and it can obtain the quantitative curvature index of each key section. However, the factors affecting the bending moment-curvature analysis results mainly include two aspects: firstly, material properties of reinforcement and concrete; secondly, the value of axial force. Because the material properties are determined to be constant, the factor that affects the results of the moment-curvature analysis is the axial force of the section. For the suspension bridge tower, the axial force of the tower and the beam is not constant under earthquake action. Therefore, the bending moment-curvature analysis of the section is used to investigate the influence of the axial force on the result. Using the No. 1 seismic wave given in the safety assessment report as the input ground motion of nonlinear dynamic time history analysis, IDA analysis of the tower. The seismic wave time history is shown in Figure 3-1. Figure 3-2 and Figure 3-3 show the axial time-history results of the bottom section of the tower column and the cross section of the lower beam at PGA=0.8g.

![Figure 3-1. Seismic wave time history curve of safety assessment](image1)

![Figure 3-2. Record of the seismic wave at tower bottom](image2)

![Figure 3-3. Record of the seismic wave at cross beam](image3)

It can be seen from Fig. 3-2 and Fig. 3-3 that for the bottom section of the tower column, the axial force under the dead load is -5.0E+08N, and the maximum axial force under the action of the earthquake is -6.5E+08N, and the minimum value is -3.8E+08N. For the cross-sectional beam, the axial force under the dead load is -2.6E+08N, and the maximum axial force of the bottom of the
The bending moment curvature analysis of the bottom section of the tower column and the end section of the beam under different axial forces are respectively carried out. The calculation results of beam end section are shown in Figure 3-4. The calculation results of tower bottom section are shown in Figure 3-5:

The above calculation results are organized as shown in Table 3-1. According to the axial force under the action of dead load, the calculation error of the minimum axial force and the maximum axial force is calculated respectively. The calculation error is shown in Table 3-2:

| Section position | Axial force (N) | Equivalent yield curvature (1/m) | Equivalent yield bending moment (N·m) | Limit curvature (1/m) | Ultimate bending moment (N·m) |
|------------------|----------------|---------------------------------|--------------------------------------|-----------------------|-------------------------------|
| Beam end section | 1.8E+08        | 0.4020E-3                       | 1.31E+09                             | 7.653E-3              | 1.46E+09                      |
|                  | 2.6E+08        | 0.3436E-3                       | 1.51E+09                             | 4.480E-3              | 1.56E+09                      |
|                  | 3.1E+08        | 0.2993E-3                       | 1.59E+09                             | 3.498E-3              | 1.61E+09                      |
| Tower bottom section | 3.8E+08        | 0.1958E-3                       | 7.83E+09                             | 5.003E-3              | 9.28E+09                      |
|                  | 5.0E+08        | 0.2020E-3                       | 8.54E+09                             | 4.458E-3              | 9.85E+09                      |
|                  | 6.5E+08        | 0.2044E-3                       | 9.40E+09                             | 3.476E-3              | 1.04E+10                      |

| Section position | Axial force (N) | Equivalent yield curvature calculation error | Equivalent yield bending moment calculation error | Limit curvature calculation error | Ultimate bending moment calculation error |
|------------------|-----------------|-----------------------------------------------|------------------------------------------------|-------------------------------|------------------------------------------|
| Beam end section | 1.8E+08         | -14.53%                                       | 15.27%                                        | -41.46%                        | 6.85%                                     |
|                  | 3.1E+08         | 14.80%                                        | -5.03%                                        | 28.07%                         | -3.11%                                    |
According to Table 3-2, for the beam end section, if the axial force under the dead load is used as the axial force of the bending moment curvature analysis, the maximum error of the equivalent yield curvature is about 15%, and the maximum calculation errors of the ultimate curvature are -41.46% and 28.07% respectively. For the bottom section of the tower, if the axial force under the dead load is used as the axial force of the bending moment curvature analysis, the equivalent yield curvature error is small and can be controlled within 5%. However, the maximum calculation error of the limit curvature is -11.15% and 27.88% respectively. If the section curvature is used as the damage index of the suspension bridge tower, the equivalent yield curvature calculated by the dead load and the axial force under earthquake action may cause a large error. Therefore, the section curvature is not accurate as the damage index of the suspension bridge tower.

3.3. Material strain

Draw the IDA curves of the lower beam end and the left column bottom, as shown in Figures 3-6~3-7.

The Reinforcement in this model adopts HRB400, which the yield of strain is 0.002. From the above two figures, the PGA when the section is yielded can be clearly observed. Reinforcement strain (concrete strain) is not affected by axial force changes under earthquake. Therefore, it considers material strain as the optimal choice for dam tower damage index in this paper.

At present, most scholars choose the damage index of the long-span rigid frame bridge. The damage index of the bridge pier is often the section curvature rather than the material strain. If we want to obtain the strain of reinforcement and concrete fibers, it is necessary to establish a model that is fine to each fiber. But the calculation amount is large. For the suspension bridge tower, the curvature of the section is not accurate as the damage index of the tower. Therefore, in order to more accurately evaluate the damage of the tower, the material strain can be selected as the damage index.

4. Conclusions

Based on OpenSees finite element program, the reasonable damage index of suspension bridges is studied in this paper. Through the nonlinear time history analysis of the tower model, the conclusions are as follows:

(1) The structure of tower is relatively complicated, and there are more points which are applied force of attention. But the top displacement does not reflect the yield position of the tower, it cannot be used as an indicator of damage.

(2) For the tower, the axial force changes are greatly affected by the earthquake. Therefore, it is not accurate to choose the section curvature as the damage index of the tower.

(3) The material strain is not affected by the axial force change of the tower under the action of earthquake, and can more accurately reflect the structural damage state. It considers materials as the
best choice for bridge tower damage indicators in this paper.

**Acknowledgments**

This study is sponsored by the Science & Technology Research Development Project of China Railway (Grant No.2015G002-B, Grant No.2010G004-I).

**References**

[1] Nielson B G, Desroches R. Analytical Seismic Fragility Curves for Typical Bridges in the Central and Southeastern United States[J]. Earthquake Spectra, 2012, 23(3):615-633.

[2] Pan Y, Agrawal A K, Ghosn M. Seismic Fragility of Continuous Steel Highway Bridges in New York State[J]. Journal of Bridge Engineering, 2007, 12(6):689-699.

[3] Alam M S, Bhuiyan M A R, Billah A H M M. Seismic fragility assessment of SMA-bar restrained multi-span continuous highway bridge isolated by different laminated rubber bearings in medium to strong seismic risk zones[J]. Bulletin of Earthquake Engineering, 2012, 10(6):1885-1909.

[4] Dezfuli F H, Alam M S. Effect of different steel-reinforced elastomeric isolators on the seismic fragility of a highway bridge[J]. Structural Control & Health Monitoring, 2016, 24(2):-.

[5] Wan Huaping, Zhong Jian, Ren Weixin. Global Sensitivity Analysis of Structural Dynamic Characteristics Considering the Uncertainty of Alternative Models[J]. Applied Mathematics and Mechanics, 2018, 39(1):1-10.

[6] Bai Yue. Research on seismic vulnerability of high pier and long span concrete continuous rigid frame bridge based on OpenSees[D]. Southwest Jiaotong University, 2016.

[7] Jin Jiamin. Research on seismic damage performance of long-span deep water rigid frame bridge based on IDA method[D]. Beijing Jiaotong University, 2016.

[8] High energy. Analysis of seismic vulnerability of long-span continuous beam bridges [D]. Southwest Jiaotong University, 2017.

[9] Yu Chong. Performance-based seismic vulnerability analysis of Aizhai Bridge [D]. Hunan University, 2013.

[10] Shi Qingxuan. Performance-based seismic research and damage assessment of reinforced concrete structures [D]. Xi'an University of Architecture and Technology, 2002.

[11] Wang Chongchong. Seismic vulnerability and risk analysis of long-span railway-dual cable-stayed bridge [D]. Southwest Jiaotong University, 2017.

[12] Xiao Mingyang. Seismic vulnerability analysis of high pier concrete continuous rigid frame bridge [D]. Southwest Jiaotong University, 2013.

[13] Li Lifeng, Huang Jiamei, Wu Wengpeng, et al. Seismic performance evaluation of high pier and long span bridge based on IDA[J]. Earthquake Engineering and Engineering Vibration, 2012, 32(1): 68-77.