Numerical Study on Biaxial Seismic Performance of Reinforced Concrete Box Piers Based on OpenSees

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Abstract. In order to study the seismic performance of reinforced concrete box piers under biaxial loading, the hysteretic model of reinforced concrete box piers was established by selecting appropriate material model, constitutive relation, structural element type, and the corresponding boundary conditions and loading method based on OpenSees. The numerical simulation of the ductility of reinforced concrete box piers with different axial compression ratio, stirrup ratio and slenderness ratio under biaxial horizontal loading was conducted. The results of biaxial quasi-static tests and that of numerical simulation were compared. The analysis showed that the hysteretic behaviour of reinforced concrete box piers under biaxial loading could be well simulated and the degradation of strength and stiffness of box piers in the process of bidirectional cyclic loading could be reflected by OpenSees on the basis of the appropriate material constitutive model and structural element type. Furthermore, the influence of reinforcement ratio and concrete strength on the ductility of reinforced concrete box pier was studied by OpenSees.

1. Introduction
With the rapid development of the large bridge engineering in the high seismic intensity area of Western China, the box pier has been widely used for its high stiffness mass ratio, strength mass ratio and good ductility. However, the research of the box pier mostly focuses on the pseudo static test under horizontal seismic action, and the seismic performance of the box pier under biaxial loading is still relatively weak [1] [2]. In fact, whether the movement of surface seismic wave or the seismic response of bridge structures are multidimensional while the earthquake occur, and the results of bridge damage show that the damage degree of bridge under biaxial loading was increased. It is mainly because of the mutual coupling of the load in different directions reduces the bearing capacity and deformation capacity of structure, and a pronounced gap exists as compared with the seismic performance of pier under horizontal uniaxial loading [3].

The push-over analysis, modal analysis and nonlinear dynamic analysis of structure can be realized with OpenSees. In addition, the bridge engineering, geotechnical engineering and other fields can be well simulated by OpenSees, which has attracted the attention of many scholars at home and abroad [4] [5]. Therefore, the numerical simulation of reinforced concrete box piers under bidirectional cyclic loading was conducted by selecting the appropriate material model, constitutive relation and structure unit type with OpenSees, and then the results of biaxial quasi-static tests and that of numerical
simulation were compared. Finally, the influence of reinforcement ratio and concrete strength on the ductility of reinforced concrete box pier was studied.

2. Establishment and verification of model

2.1. General situation about biaxial quasi-static test

In this paper, the numerical simulation of the specimens B3, B4 and B5 in the biaxial quasi-static test of reinforced concrete box piers was conducted based on OpenSees analysis program. The detailed design parameters of the piers can be found in reference [6].

2.2. Establishment of model

In this paper, concrete02 which considers the tension of concrete is used to simulate concrete material, and the simulation of reinforcement adopts Steel02 in the model of reinforced concrete box pier based on OpenSees. And the three parameters that control the transition from elastic stage to hardening phase of Steel02 are 18.5, 0.925 and 0.15 according to the suggestions given by OpenSees program.

The bottom of reinforced concrete box pier was set as fixed end, and the top was selected as free end in the case of establishing box pier model, because the specimen was fixed by the base and the top loading device could slide freely when the biaxial quasi-static test was carried out. At the same time, a constant axial load is applied at the top of the pier, and the axial load remains unchanged in the simulation. In the terms of biaxial horizontal loading, the simplification of loading method was taken into account, and the displacement control was adopted during the whole process of loading. According to the test results, the yield displacement of each specimen was between 4 and 16 mm, so 2mm was taken as the displacement increment. And after yielding, the increment of displacement was 3mm. Each load cycle was once. The displacement amplitude ratio of the strong and weak axis of the section was 1:1. Figure 1 shows the loading system of pier.

![Figure 1. Loading protocol of bridge piers](image1)

![Figure 2. Model of reinforced concrete box piers](image2)

According to mechanical properties and geometrical features of pier, the steel reinforcement and concrete of the cross section were divided into fiber of concrete protective layer, fiber of core concrete and reinforcement fiber; the encrypted area and non-encrypted area of stirrup in the bottom of pier were distinguished. The pier was modular in structure, and the element type selected nonlinear beam-column. Moreover, a number of integration points were set along the axial direction of pier. And then the hysteretic analysis model of reinforced concrete box pier was established, as shown in Figure 2.

2.3. Calculated values compared with test values

The comparison of the hysteresis curves obtained by numerical simulation with that obtained with the test measurements of B3 specimen is presented in Figure 3 to Figure 5.

Results of the comparison show that the hysteretic analysis model of reinforced concrete box pier has fine precision with the simulation of specimens. The hysteresis curves obtained by the numerical simulation are in good agreement with the experimental results of reinforced concrete box piers, and the rising segment, the strength degradation and the pinch effect of curves can be simulated well. Moreover, the difference of bearing capacity and deformation in different loading directions of box
pier under bidirectional cyclic loading is reflected, and the simulation error of y direction in cross section is larger. The error may result from the coupling effects of different loading directions have a greater influence on the bearing capacity and deformation of y direction in cross section, but overall, the agreement between the simulation and test demonstrates that simulation program for reinforced concrete box piers is reliable.

![Figure 3. Comparisons of the experimental and theoretical hysteretic curves of the bridge pier of B3](image)

![Figure 4. Comparisons of the experimental and theoretical hysteretic curves of the bridge pier of B4](image)

![Figure 5. Comparisons of the experimental and theoretical hysteretic curves of the bridge pier of B5](image)

By comparing skeleton curve of simulation and test of B3 specimen, it could be found that the calculating results have accordance well with those experimental observations and the calculated curve can reflect the yield segment and descent stage of specimen accurately, as shown in Figure 6. For the destruction phase of skeleton curve, there are some differences between the calculated values and the test values because the bond slip between steel and concrete is not considered in the numerical simulation.
Figure 6. Comparisons of the experimental and theoretical skeleton curves of the bridge pier of B3

Figure 7. Variation of displacement ductility coefficient with longitudinal reinforcement diameter

Figure 8. Variation of displacement ductility coefficient with concrete strength

3. Parameter analysis
Based on the established hysteretic analysis model of reinforced concrete box pier, the effect of reinforcement ratio and concrete strength on the ductility of box pier was conducted for the further analysis of the ductility of reinforced concrete box piers under biaxial horizontal loading.

The ductility of structure under cyclic loading refers to the inelastic deformation capacity of the structure which can still maintain a certain bearing capacity. Ductility index is an important index to evaluate the seismic performance of structures, and ductility coefficient is usually used to reflect the deformation capacity of the specimens. The displacement ductility factor is

$$\mu = \frac{\Delta_u}{\Delta_y}$$

Where $\Delta_y$ = yield displacement; $\Delta_u$ = ultimate displacement.

3.1. Diameter of longitudinal reinforcement
The diameter of longitudinal reinforcement is one of the most important factors which affect the ductility of reinforced concrete box pier. Figure 7 shows the variation of displacement ductility coefficient in different loading direction with longitudinal reinforcement diameter when axial
compression ratio is 0.05, 0.10 and 0.20, respectively. It can be seen that the displacement ductility coefficient in different loading direction with the increase of longitudinal reinforcement diameter decreases significantly, when the axial compression ratio is less than 0.20. This is because the damage of box pier is the failure of reinforcement when the axial compression ratio is relatively small. Although the yield displacement of box pier raises with the increase of diameter of longitudinal reinforcement, the change of the ultimate displacement of pier is smaller, this makes the ductility of box pier decreased; The displacement ductility coefficient in different loading direction does not change obviously with the increase of longitudinal reinforcement diameter when the axial compression ratio is greater than 0.2, and the specimen showed brittleness characteristic.

3.2. Concrete strength

The concrete strength has important influence on the ductility of reinforced concrete box piers. In this paper, the concrete strength of C30, C40, C50 and C60 were selected to study. Figure 8 shows the variation of displacement ductility coefficient in different loading direction with concrete strength when longitudinal reinforcement diameter is different. It can be found that the displacement ductility coefficient in different loading direction with the increase of concrete strength rises significantly when the strength of concrete is C30 to C60, which is due to the greater ultimate displacement with the increase of concrete strength, but the growth of displacement ductility coefficient is slower.

4. Conclusions

This paper conducted the numerical simulation of biaxial quasi-static test and parametric analysis of reinforced concrete box piers on the basis of the existing material model and structural element in OpenSees. The following conclusions can be obtained:

(1) Based on the appropriate material model, the constitutive relation and the fiber beam-column element, the established fiber element model of reinforced concrete box pier can simulate the hysteretic curve and skeleton curve of box pier under biaxial loading well, and it can reflect the degradation of strength and stiffness of the bridge pier specimen during biaxial loading.

(2) The calculated curves of numerical simulation of the piers are in good agreement with the test results on the whole, and the calculated values can reflect the bearing capacity and deformation characteristics of the pier specimens under bidirectional cyclic loading accurately.

(3) The displacement ductility coefficient in different loading direction decreases with the increase of longitudinal reinforcement diameter, and rises with the increase of concrete strength. But the growth of displacement ductility coefficient with the increase of concrete strength is slower.

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