Research on Sensitivity of Seismic Performance of Precast Assembly Hollow Circular Bridge Piers to Design Parameters

Weiyu Dou

Anhui Transportation Investment Group Co., Ltd., Hefei 230088, China

Author’s e-mail: 2694927683@qq.com

Abstract: According to structural and seismic characteristics of new precast assembly hollow circular bridge piers, the nonlinear seismic fiber finite element model was developed. Failure modes and effects of different design parameters including axial compression ratio, longitudinal reinforcement ratio and stirrup spacing in the plastic hinge region on these piers were analysed by pushover analysis method. The results show that axial compression ratio and longitudinal reinforcement ratio have significant effects on horizontal load-carrying capacity, deformation capacity, hysteretic energy and ductility. The influence of stirrup spacing in the plastic hinge region on ductility is evident only.

1. Introduction

Because the prefabricated piers can realize standardized design, industrial production and assembly construction, it has very broad application prospects in modern bridge construction, especially the hollow piers with better economy. Therefore, some researches on the seismic performance of hollow piers have been carried out at home and abroad. Du Xiuli et al [1] passed the low-cycle reciprocating load test of a large proportion of concrete hollow piers, and it is considered that the seismic performance of concrete hollow piers is good and can be safely applied to engineering. Chen Mingqi [2] designed 12 rectangular hollow reinforced concrete bridge piers with different parameters and carried out pseudo-static test. The test shows that the axial compression ratio has obvious influence on the performance of hollow piers. Increasing the stirrup spacing improves ductility but reduces bearing capacity. Cui Haiqin et al [3] carried out quasi-static tests on rectangular hollow thin-walled piers. The results show that it is found that improving the hoop ratio and reducing the shear-to-span ratio can improve the ductility of the piers to some extent. Based on the analysis of PEER bridge pier test sample library design parameters on the seismic performance of reinforced concrete rectangular piers, Chen Xingzhen et al [5] found that the rectangular specimens with smaller axial pressure and higher hoop ratio have better seismic performance. Ge Jiping [6] and Wang Wenjun [7] used OpenSees to simulate the mechanical behavior and seismic performance of hollow piers under quasi-static forces. The results show that the proposed fiber model can accurately predict the seismic performance of pre-stressed hollow piers such as hysteresis and stiffness degradation. Bu Zhanyu et al [8] used OpenSees software to analyze the parameters of segmental concrete bridge piers, and the seismic performance of the piers was studied with the analysis parameters of axial compression ratio, pre-stressed reinforcement ratio and longitudinal reinforcement ratio. Shen Yanli et al [9] established 10 full-size reinforced concrete hollow
pier models with different parameters, and compared the effects of different aspect ratios, axial compression ratios, reinforcement ratios and hoop ratios on their seismic performance.

This paper relies on the new prefabricated circular hollow piers used in the Huainan-Hefei section of Jinan-Qimen Expressway to study the sensitivity of its seismic performance to different design parameters, in order to provide reference for the seismic design of such prefabricated piers.

2. New prefabricated circular hollow pier
In this paper, the new type of prefabricated circular hollow pier adopted by the Huaihe Bridge of Huaihe Bridge in Huainan to Hefei section of JiQi Expressway is taken as an engineering example. The typical piers are selected for seismic performance research in this example. The typical piers are selected for seismic performance research in this example. The pier height is 10m and the diameter is 1.2m, with a wall thickness of 0.25m and it is prefabricated with C70 concrete. The cast-in-situ section of the pier bottom with a length of not less than 0.5m is reserved between the precast section of the pier and the cap as the height adjustment section, and plays a positioning role in the installation of the prefabricated pier. The prefabricated pier is connected with the cap by the socket type, and the T-shaped pattern at the bottom of the pier is combined with the cup mouth of the second-stage pouring to form a whole. The size of the cap is 3.0×3.0×1.5m, and the C40 concrete is casted. The prefabricated pier elevation and the pier cross section are shown in Figure 1.

Figure 1. Elevations and cross sections of precast assembly hollow circular bridge pier

3. Seismic finite element model of prefabricated piers
In order to correctly analyse the seismic performance of the entire pier, the OpenSees (Open System for Earthquake Engineering Simulation) software platform was used to establish the seismic finite element model of the precast pier and structural dynamic analysis. Among them, concrete is Concrete04, a concrete constitutive model developed on the basis of Popovics concrete model; steel is a Steel02 model that can consider Bauschinger effect and isotropic strengthening effect. The pier body is simulated by displacement-based nonlinear beam-column elements, and the pier section is discretized by fiber units, including unconstrained concrete and confined concrete fiber units, and steel fiber units. However, this kind of prefabricated pier is connected with cast-in-place cup mouth and cap by socket method, and pier height adjustment section is set up. Therefore, different cross-section fiber unit divisions are set at different positions above the cup mouth, the cup mouth, and the bottom of the pier to accurately simulate the dynamic response of the pier, as shown in Figure 1 and Figure 2.

Because the upper mass of the pier is much larger than the weight of the pier, the seismic response is dominated by the first mode, so the prefabricated pier can be simplified as a single-degree-of-freedom cantilever column with concentrated mass at the top, and the horizontal force acts on the top of the cantilever column; the cap can be simplified as a mass simulation point and constrained by consolidation.
This paper analyzed three important design parameters of constant load axial compression ratio, longitudinal reinforcement ratio and encryption zone stirrup spacing, and discussed their effects on the seismic performance of new assembled prefabricated circular hollow piers such as hysteretic curve, bearing capacity and ductility. Among them, the ductility coefficient refers to the displacement ductility coefficient, which is determined by the ratio of the ultimate displacement to the yield displacement. As shown in Formula (2).

\[ \mu = \frac{\mu_u}{\mu_y} \]  

Yield displacement is defined as the first yield displacement of longitudinal steel bars. The ultimate displacement is defined as the displacement when the lateral force drops to 85% of the maximum lateral force.

4.1 Constant load axial compression ratio

The axially loaded ratios of 0.1, 0.2 and 0.3 are selected, and the corresponding axially loaded ratios are 2275 kN, 4550 kN and 6825 kN, respectively. The pier hysteresis curves and skeleton curves corresponding to different axially loaded ratios are shown in Figure 3 and Figure 4.

Analysis of Figure 3 and Figure 4 shows that as the load-to-load ratio increases from 0.1 to 0.3, the hysteresis curve becomes slightly full and the energy consumption increases by 8.19%. The increase of axial compression ratio also limits the lateral deformation ability of the pier. When the loading displacement is small, the lateral displacement of the pier can be reduced, which is beneficial to structural safety. Due to the second-order effect of gravity, when the pier is high, the pier damage may
be accelerated.

Tab 1. Bearing capacity (different axial pressure ratio)

| axial compression ratio | yield load (kN) | peak load (kN) | ultimate load (kN) |
|-------------------------|----------------|---------------|-------------------|
| 0.1                     | 274.286        | 310.085       | 263.437           |
| 0.2                     | 322.184        | 377.660       | 321.376           |
| 0.3                     | 367.157        | 435.534       | 370.700           |

Tab 2. Displacement and ductility (different axial pressure ratio)

| axial compression ratio | yield displacement (m) | ultimate displacement (m) | ductility |
|-------------------------|------------------------|---------------------------|-----------|
| 0.1                     | 0.077                  | 0.322                     | 4.167     |
| 0.2                     | 0.062                  | 0.241                     | 3.874     |
| 0.3                     | 0.056                  | 0.207                     | 3.674     |

Analysis of Tables 1 and 2 shows that the axial compression ratio increases from 0.1 to 0.3, and the yield loads, peak loads and ultimate loads of the precast pier are improved. The yield load increases by 25.29%, the peak load increases by 28.82%, and the ultimate load increases by 28.93%. It shows that the large axial force limits the yield and subsequent failure process of prefabricated hollow piers to a certain extent, and can improve the horizontal bearing capacity of piers, while the ultimate displacement decreases by 35.71% and ductility decreases by 11.83%.

4.2 Longitudinal reinforcement ratio

When the actual axial compression (3217 kN) and stirrup ratio are unchanged, the longitudinal reinforcement ratio is 1%, 1.34% and 1.78% respectively, and the pier hysteresis curve and skeleton curve are shown in Figure 5 and Figure 6.

Analysis of Figure 5 and Figure 6 shows that the ratio of longitudinal reinforcement greatly affects the shape of hysteretic curve. When the reinforcement ratio is small, the kneading phenomenon of hysteretic curve is obvious. With the increase of longitudinal reinforcement ratio, the hysteretic curve becomes fuller from kneading and the energy dissipation capacity increases. When the longitudinal reinforcement ratio increases to 1.78%, the hysteretic energy dissipation increases by 37.75%.

Tab 3. Bearing capacity (different longitudinal reinforcement rate)

| Longitudinal reinforcement ratio | Yield load (kN) | Peak load (kN) | ultimate load (kN) |
|---------------------------------|----------------|---------------|-------------------|
| 1.00%                           | 247.114        | 289.728       | 246.183           |
| 1.34%                           | 294.620        | 338.929       | 288.172           |
| 1.78%                           | 353.038        | 400.056       | 340.188           |

Tab 4. Displacement and ductility (different longitudinal reinforcement rate)
Longitudinal reinforcement ratio & Yield displacement (m) & ultimate displacement (m) & ductility \\
1.00% & 0.057 & 0.247 & 4.297 \\
1.34% & 0.070 & 0.276 & 3.971 \\
1.78% & 0.080 & 0.311 & 3.872 \\

Analysis of Tables 3 and 4 shows that under the same axial compression ratio, the yield load, peak load and ultimate load of the pier are improved with the increase of the longitudinal reinforcement ratio. The reinforcement ratio is increased to 1.08% to 1.78%, and the load increased by 30.02%, the peak load increased by 27.57%, and the ultimate load increased by 27.63%. Yield displacement and ultimate displacement increased, but ductility coefficient decreased by 9.89%.

4.3 Plastic hinge area stirrup spacing
With the axial loading (3217kN) and longitudinal reinforcement ratio unchanged, the stirrups are arranged in the range of the theoretical plastic hinge length \( L_p \) (\( L_p = 0.8m \)). The spacing of stirrups decreases from 0.15m to 0.10m, 0.075m and 0.05m. The volumetric stirrup ratio in the encrypted area is 0.389%, 0.622%, 0.777% and 1.243%, respectively. The corresponding pier hysteresis curve and skeleton curve are shown in Figure 7 and Figure 8.

Comparing the analysis of Figure 5 and Table 5, it can be seen that the hysteresis curve and the skeleton curve almost coincide, and the reduction of the spacing of the stirrups in the plastic hinge region has less influence on the horizontal bearing capacity and hysteretic energy dissipation capacity of the prefabricated pier. The reason may be that the concrete on the inner side of the hollow pier and the steel bar lose a certain lateral restraint effect, and the effect of increasing the hoop ratio is less than the lateral restraint effect lost by the inner hollow. At the same time, as the stirrup spacing decreases from 0.15m to 0.05m, the ultimate displacement increases and the ductility of the pier increases by 7.19%.

5. Conclusion
Aiming at the new assembled prefabricated circular hollow piers used in the Huainan-Hefei section of JiQi Expressway, a reasonable finite element model of non-linear fiber element is established, and the sensitivity of prefabricated piers to different design parameters is studied. The following conclusions
can be drawn:

1. The increase of the axial compression ratio can effectively improve the horizontal bearing capacity of the prefabricated pier, but the deformation capacity and ductility are significantly reduced.

2. The increase of longitudinal reinforcement ratio will increase the horizontal bearing capacity, yield displacement and ultimate displacement of prefabricated piers, but the ductility coefficient decreases. Moreover, the longitudinal reinforcement ratio significantly affects the shape of the hysteretic curve of the prefabricated pier. With the increase of the longitudinal reinforcement ratio, the hysteretic curve tends to be full and the energy dissipation capacity increases.

3. Reducing the spacing of stirrups in the plastic hinge area has little effect on the horizontal bearing capacity and hysteretic energy dissipation of piers, but it increases the ductility of prefabricated piers to a certain extent.

Acknowledgments
This research was supported by the technology project from Anhui Transportation Hold Group CO., LTD. (Research on Seismic Performance of The Steel-Concrete Plate Composite Beam Supported with Transverse Steel Beams). The support is gratefully acknowledged.

References
[1] DU Xiu-li, CHEN Ming-qi, HAN Qiang. Experimental evaluation of seismic performance of reinforced concrete hollow bridge columns [J]. Journal of Vibration and shock, 2011, 30(11):254-259.
[2] CHEN Ming-qi. Experimental evaluation of seismic performance of reinforced concrete hollow bridge columns[D]. Beijing University of Technonlogy , 2011.
[3] CUI Hai-qin, HE Shuan-hai, SONG Yi-fan. Experimental Study on Antiseismic Ductility of Hollow Rectangular Thin-walled Pier [J]. Journal of Highway and Transportation Research and Development , 2010, 27(6):58-63.
[4] LUO Zheng, LI Jian-zhong. Tests for a seismic performance of rectangular hollow thin-walled bridge columns under low-cycle reversed loading [J]. Journal of Vibration and shock, 2013, 32(8):183-188.
[5] CHEN Xing-ye, ZHAN Lv-jin, JIANG Dong-qing. Analysis of influence of design parameters of reinforced concrete rectangular piers on seismic performance [J]. Journal of China & Foreign Highway, 2016(2):116-120.
[6] GE Ji-ping, WANG Zhi-qiang, WEI Hong-yi. Seismic performance analysis of segmental bridge columns with match-cast dry joints using fiber beam-column element method [J]. Journal of Vibration and shock, 2010, 29(3):52-57.
[7] WANG Jun-wen, ZHANG Wei-guang, LI Jian-zhong. Quasi-Static Tests and Numerical Analysis of Prestressed Concrete Hollow Pier [J]. Journal of Bridge Construction, 2015(3):63-69.
[8] BU Zhan-yu, ZHAN Chen-wen, SHI Xin-lei atl. Research on Seismic Resistance of Precast Segmental Concrete Bridge Piers[J].Journal of Ningbo University(Natural Science &Engineering Edition) 2011, 24(2):83-88.
[9] SHEN Yan-li , GAO Su-yun . Numerical Analysis for Pseudo-static of Reinforced Concrete Rectangular Hollow Bridge Piers[C]. National Academic Conference on Structural Engineering. 2017.
[10] SHENG Guang-zu. Development of pushover analysis and its application to bridges[J].Journal of North China Earthquake Sciences, 2008, 26(4):25-30.