Research Article

Effect of Axial Compression Ratio on Seismic and Self-Centering Performance of Unbonded Prestressed Concrete Columns

Yun Shi ^{1,2}, Guanglin Yuan,¹ and Hao Zhu²

¹School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221008, Jiangsu, China

²School of Civil Engineering and Architecture, Suqian University, Suqian 223800, Jiangsu, China

Correspondence should be addressed to Yun Shi; sqshiyun@qq.com

Received 29 October 2021; Accepted 17 December 2021; Published 18 January 2022

Academic Editor: Wenjie Ge

Copyright © 2022 Yun Shi et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

To explore the influence of the applied axial compression ratio and preloaded axial compression ratio on the seismic performance of unbonded prestressed concrete columns, pseudo-static tests were carried out on four prestressed columns and one ordinary column in this study. The seismic performance indexes of test columns were studied and analyzed, including failure modes, hysteresis curves, skeleton curves, stiffness, ductility, and energy dissipation. The test results show that compared with concrete columns with ordinary reinforcement, the hysteresis curve of reinforced concrete columns with prestressed tendons has a pinch phenomenon to a certain extent, and the energy dissipation performance becomes worse. For the prestressed columns, the greater the applied axial compression ratio, the worse the fullness of hysteresis curves and the energy dissipation performance, the greater the residual displacement, the faster the strength attenuation, and the worse the self-centering performance. For the posttensioned unbonded prestressed concrete columns, the greater the preloaded axial compression ratio, the worse the energy dissipation performance of the test column, the slower the strength attenuation, and the better the self-centering performance.

1. Introduction

The previous analysis of earthquake disasters has shown that building structures after the earthquake can produce large residual deformation. Many building structures are not damaged but difficult to repair due to large residual displacement and have to be demolished and rebuilt, resulting in resource waste and property loss [1]. Therefore, the development and research of a building with small residual deformation after an earthquake are an important direction of building development in the future [2–10]. At present, the common methods to improve the self-resetting performance of specimens are adding unbonded prestressed reinforcement, adding viscous damper, setting unbonded high-strength reinforcement, and so on. Unbonded prestressed tendons are widely used because of their advantages of convenient construction and low cost. The existing research has shown that when unbonded prestressed tendons are added to the ordinary reinforced concrete columns for applying the prestress, the high-strength elastic recovery

characteristics of prestressed tendons can be used to effectively reduce the residual displacement of structures or members and obtain good self-centering performance.

Roke [11] conducted the time history analysis of three central braced frame structures with different positions of prestressed tendons and found that this structure has a good self-centering effect. Luo Haiyan [12] carried out comparative tests of three concrete columns with unbonded partially prestressed tendons and one concrete column with ordinary reinforcement. It was found that the prestress level has an important influence on the performance of the specimens. Yang Yiming et al. [13] performed pseudo-static tests of two RC frame column base joints equipped with unbonded prestressed tendons and energy dissipation damper. It was reported that the axial compression ratio has an important impact on the seismic performance and self-centering performance of RC frame column base joints. Through the above research, it can be found that the axial compression ratio is an important factor affecting the seismic and self-centering performance of reinforced

concrete frame columns. However, there is no research on the specific influence law of the applied axial compression ratio and preloaded axial compression ratio on their performance. In this study, four concrete columns with post-tensioned unbonded prestressed tendons and one ordinary reinforced concrete column were designed at a reduced scale of 1/2, and pseudo-static loading tests on these columns were performed to analyze their energy dissipation performance, strength attenuation, and self-centering performance.

2. Experimental Investigation

2.1. Description of Specimens. In this test, four concrete columns with posttensioned unbonded prestressed tendons (marked as PURC) and one ordinary reinforced concrete column (marked as PTRC) were designed and fabricated in the proportion of 1/2. The column height was 1200 mm, and the section size was 300 mm × 300 mm. Table 1 and Table 2 show the axial compression ratio of the test piece, and Figure 1 shows the size and reinforcement of the test piece. The C40 concrete was used, and the measured compressive strength of the cube was 44.5 MPa. The longitudinal main reinforcement was HRB400 grade, with a diameter of 20 mm, the measured yield strength of 536.2 MPa, elongation of 19%, and elastic modulus of 2.00×10^5 MPa. The stirrup was HPB300 grade, with the measured yield strength of 371.0 MPa and elastic modulus of 2.10×10^5 MPa. In this study, $\zeta = N_p / f_c A$ and $\eta = N / f_c A$, where ζ is the preloaded axial compression ratio, η is the applied axial compression ratio, N_p is the axial pressure exerted by prestressed tendons, N is the applied axial pressure, f_c is the design value of concrete compressive strength, and A is the column section area.

2.2. Prestressed Tendon Tensioning. To exert the prestress, four $\Phi^{S15.2}$ ($f_{ptk} = 1860 \text{ N} \cdot \text{mm}^{-2}$) 1×7 steel strands were uniformly arranged at the four corners of the column section during the production of the column specimens. To ensure the flatness of the upper and lower sides of specimens, one end of the prestressed tendons was pretensioned at the column top and embedded in the concrete. The steel strand was covered with a thin steel pipe and fixed at the design position through the perforated steel plate at the column top and the column bottom to avoid the shift of the steel strand during the pouring and vibrating of concrete. To obtain the smooth bottom of test columns for the subsequent test, a groove of 300 mm × 400 mm × 150 mm was reserved at the bottom of the column during the fabrication for tensioning and anchoring prestressed steel strand, and the single-hole tool anchor was used.

The size of the prestressed members used in this test was smaller than that in the actual project; moreover, the reduction in length can cause a large amount of prestress loss [14]. To solve this problem, a support foot device developed by the China University of Mining and Technology was used to supplement the tension by the insert gasket [15]. Figure 2 shows the specific operation process, and Table 3 shows the detailed tension control stress.

2.3. Loading Device and Loading System. The test was conducted in Jiangsu Key Laboratory Environmental Impact and Structural Safety in Engineering, China University of Mining and Technology. The electrohydraulic servo loading structure test machine was used for pseudo-static loading under low-cycle repeated loading [16]. Figure 3 shows the loading device. The vertical load was applied to the design value through two hydraulic jacks at the top of the column, and the horizontal load was applied by the actuator at the top of the column.

The load-displacement control mode was adopted in the loading process. The loading system was as follows: the yield displacement Δ of each test column was obtained by the load control with an increase of 10 kN. After the test column yielded, the loading was performed according to the controlled displacement of 1Δ , 2Δ , 3Δ , and so on. Before the test column yielded, load control and displacement control were cycled once; after the test column yielded, displacement control was loaded for three times at each level. When the load dropped below 85% of the maximum load value, the specimen was considered to be destroyed and the test was terminated.

3. Experimental Phenomenon and Failure Mode

Figure 4 shows the final failure modes of test columns. The loading failure process of test columns is described as follows:

- (1) Specimen PTRC-1. After formal loading, the test column showed significant elastic characteristics before yielding. When the horizontal force was applied to 56.8 kN, the first horizontal crack appeared on the right side of the column 130 mm from the base. When the controlled displacement was 18 mm, cracks on the front and rear sides extended obliquely and vertically, and multiple through cracks appeared on the left and right sides. The through cracks were clearly observed during the unloading. When the controlled displacement was 27 mm, a small area of damage was generated in the concrete of the column corner, and vertical cracks appeared in the middle of the left and right sides of the column body. The specimen reached the limit state, and the horizontal force had an extreme value (200.71 kN in the forward direction and 173.20 kN in the reverse direction). When the controlled displacement was 54 mm, the horizontal load dropped below 85% of the ultimate load value. After the test termination, the failure mode of the test column was mainly the flexural shear failure, showing good ductility characteristics.
- (2) Specimen PURC-1. After formal loading, when the load was added to 59.3 kN, the first horizontal crack appeared on the right side of the column 75 mm from the base. When the controlled displacement was 18 mm, vertical cracks were gradually produced in the bottom beam during the first cycle, and the horizontal cracks continued to extend and develop. When the controlled displacement was 27 mm, the

TABLE 1: Design parameters of specimens.

Specimen number	Section size mm × mm	Concrete strength grade	Longitudinal reinforcement	Reinforcement ratio ρ_l /%	Column stirrup	Prestressed tendons	Effective prestress	Shear span ratio λ
PTRC-1	300 × 300	C40	Φ 8 20	2.79	$\Phi 8@50/100$	-	-	3.5
PURC-1	300 × 300	C40	Φ 8 20	2.79	$\Phi 8@50/100$	4 $\Phi^s 15.2$	0.65 f_{ptk}	3.5
PURC-2	300 × 300	C40	Φ 8 20	2.79	$\Phi 8@50/100$	4 $\Phi^s 15.2$	0.65 f_{ptk}	3.5
PURC-3	300 × 300	C40	Φ 8 20	2.79	$\Phi 8@50/100$	4 $\Phi^s 15.2$	0.65 f_{ptk}	3.5
PURC-4	300 × 300	C40	Φ 8 20	2.79	$\Phi 8@50/100$	4 $\Phi^s 15.2$	0.45 f_{ptk}	3.5

TABLE 2: Axial compression ratios of specimens.

Specimen number	Axial compression ratio n	Preloaded axial compression ratio ζ	Applied axial compression ratio η	Applied axial compression kN
PTRC-1	0.15	—	0.15	238.05
PURC-1	0.55	0.40	0.15	238.05
PURC-2	0.45	0.40	0.05	79.35
PURC-3	0.65	0.40	0.25	396.75
PURC-4	0.40	0.25	0.15	238.05

FIGURE 1: Size and section reinforcement of test columns (mm).

specimen reached the limit state during the first cycle, and the horizontal force had an extreme value (201.06 kN in the forward direction and 195.19 kN in the reverse direction). When the controlled displacement was 54 mm, the horizontal load of the test column dropped below 85% of the ultimate load, and the test was terminated.

- (3) Specimen PURC-2. After formal loading, when the load was increased to 53.2 kN, the first horizontal crack was produced at the connection between the column body and the base. When the controlled displacement was ± 27 mm, the cracks on the column body were widened and the four cracks extended vertically. During the cycle under the controlled

displacement of 30 mm, new cracks were no longer generated and the load peak appeared (198.50 kN in the forward direction and 203.57 kN in the reverse direction). When the controlled displacement was 60 mm, the horizontal load of the test column dropped below 85% of the ultimate load, and the test was terminated.

- (4) Specimen PURC-3. After formal loading, when the load was added to 76.4 kN, multiple horizontal cracks were generated on the right side of the column 50 mm, 150 mm, 250 mm, and 375 mm away from the base. When the controlled displacement was ± 24 mm, the vertical crack perpendicular to the horizontal crack began to appear. When the controlled

FIGURE 2: Insert gasket for tension supplement. (a) Insert gasket for tension supplement and (b) brace angle and gasket (c) after tension supplement [15].

TABLE 3: Tensioning data of prestressed tendons.

Specimen No.	PTRC-1	PURC-1	PURC-2	PURC-3	PURC-4
Prestress loss/($N \cdot mm^{-2}$)	—	60.06	60.06	60.06	50.82
Tension control force/ kN	—	176.40	176.40	176.40	149.26

displacement was ± 32 mm, the specimen reached the limit state during the first cycle, and the extreme value of the horizontal force was obtained (211.16 kN in the forward direction and 209.83 kN in the reverse direction). After that, the bearing capacity decreased continuously with the failure of the specimen. When the controlled displacement was 48 mm, the horizontal load of the test column dropped below 85% of the ultimate load, and the test was ended.

- (5) Specimen PURC-4. After formal loading, when the load was 59.3 kN, the first horizontal crack appeared on the right cylindrical surface 160 mm away from the base. When the controlled displacement was 27 mm, the new cracks were not generated. During the first loading of 0 $\rightarrow$ 27 mm, the load peak appeared (192.14 kN in the forward direction and 192.46 kN in the reverse direction), the concrete at the column corner of the left foot began to crush, the cracks developed vertically, and a main vertical crack was formed in the middle of the left and right sides. When the controlled displacement was 54 mm, the

horizontal load of the test column dropped below 85% of the ultimate load, and the test was ended.

4. Experimental Results and Discussion

4.1. *Hysteresis Curves.* The hysteresis curves of different specimens are compared (Figure 5). It can be seen that:

- (1) At the initial stage of loading, the hysteresis curve of each specimen approximates a straight line, indicating that the specimen is in the elastic stage at this time. With the increase in load and displacement, the area of the hysteresis loop increases continuously, and the hysteresis curve no longer grows as a straight line. It indicates that the specimen enters the elastic-plastic stage. After unloading, the residual displacement increases, the plastic damage develops, and the energy dissipation performance is improved.
- (2) Hysteresis curves of PURC-1-PURC-4 and PTRC-1 are compared. It can be found that there is an obvious pinch phenomenon in hysteresis curves of

FIGURE 3: Test loading device.

FIGURE 4: Failure modes of specimens. (a) PTRC-1. (b) PURC-1. (c) PURC-2. (d) PURC-3. (e) PURC-4.

FIGURE 5: Hysteresis curves of specimens. (a) PTRC-1. (b) PURC-1. (c) PURC-2 and PURC-p3. (d) PURC-4.

specimens with posttensioned unbonded prestressed tendons, and the peak load of these specimens is increased by 5.97%, 7.53%, 12.59%, and 2.86%, respectively. It shows that the addition of post-tensioned unbonded prestressed tendons can reduce the energy dissipation performance of concrete columns, but cannot significantly improve their bearing capacity.

- (3) Hysteresis curves of PURC-2, PURC-1, and PURC-3 are compared. Under the same preloaded axial compression ratio of specimens, when the applied axial compression ratio increases from 0.05, 0.15, to 0.25, the fullness of hysteresis curve becomes worse, the limit displacement becomes smaller, and the load after yield decreases faster. It indicates that the energy dissipation performance of posttensioned unbonded prestressed concrete columns becomes worse with the increase in the applied axial compression ratio.
- (4) Hysteresis curves of PURC-1 and PURC-4 are compared. Under the same applied axial compression ratio of the specimen, when the preloaded axial compression ratio is 0.4 and 0.25, the fullness of the hysteresis curve of PURC-4 is relatively good, and the limit displacements of PURC-1 and PURC-4 are similar. It indicates that the greater the preloaded axial compression ratio, the lower the energy consumption capacity of the specimen.

4.2. Skeleton Curves. Figure 6 shows skeleton curves of test columns. The skeleton curves of test columns are compared.

- (1) By comparing skeleton curves of PTRC-1 and PURC-1, it is found that the rising section and falling section of the skeleton curve of PTRC-1 are steep, and the initial stiffness is large, while the falling section of the curve of PURC-1 is relatively gentle. This is because when the prestress is applied to the test column, the column is compacted, which is conducive to improve its stiffness. However, after the peak load, the concrete damage is accelerated and the bearing capacity is degraded rapidly due to the pressure of prestressed tendons.
- (2) By comparing the skeleton curves of PURC-1, PURC-2, and PURC-3, it can be seen that the rising and falling sections of the skeleton curve of PURC-3 are the steepest, with the largest initial stiffness and the smallest ultimate displacement; the rising section and the falling section of the skeleton curve of the PURC-2 are the most gentle, with the smallest initial stiffness and the largest limit displacement. It indicates that the greater the applied axial compression ratio, the smaller the ultimate displacement of the posttensioned unbonded prestressed concrete column and the more significant the ductility reduction.
- (3) By comparing the skeleton curves of PURC-1 and PURC-4, it can be seen that the rising section of the

FIGURE 6: Skeleton curves of specimens. (a) PTRC-1 and PURC-1. (b) PURC-1, PURC-2, and PURC-3. (c) PURC-1 and PURC-4.

skeleton curve of PURC-4 is relatively gentle, the limit displacement is large, and its ductility is good.

4.3. Stiffness Degradation. Under the condition of pseudo-static test, the stiffness degradation characteristics of structures or members are usually characterized by loop stiffness:

$$K_j = \frac{\sum_{i=1}^n V_j^i}{\sum_{i=1}^n \Delta_j^i}, \quad (1)$$

where K_j is the stiffness under the j th level load; V_j^i is the average value of forward and reverse loads under the j th

level load at the i th cycle; and Δ_j^i is the average value of forward and reverse displacement under the j th level load at the i th cycle. Figure 7 shows the skeleton curves of different specimens.

As shown in Figure 7, it is concluded that

- (1) The stiffness degradation curves of all specimens are smooth without sudden change, indicating that the damage of posttensioned unbonded prestressed concrete develops stably under seismic load.
- (2) Compared with ordinary reinforced concrete columns, the columns with posttensioned unbonded prestressed tendons present higher initial stiffness, but rapid stiffness loss after loading. It suggests that

FIGURE 7: Stiffness degradation curves of specimens.

the prestressing can accelerate the damage of specimens.

- (3) As shown in Figure 7(a), the effect of applied axial pressure ratio on stiffness degradation is significant. The greater the applied axial pressure ratio, the faster the stiffness degradation. As shown in Figure 7(b), the change in preloaded axial compression ratio before the specimen yielding has little effect on the stiffness degradation rate of the specimen; after the specimen yielding, the stiffness degradation of the specimen with a high preloaded axial compression ratio is accelerated. It shows that the greater the applied axial compression ratio, the faster the damage of the specimen and the faster the stiffness degradation. Besides, the preloaded axial compression ratio rarely affects the damage rate of the specimen before yielding, but accelerates the damage rate of the specimen after yielding and the stiffness degradation is accelerated.

4.4. Bearing Capacity

4.4.1. Test Value of Bearing Capacity. Tables 4 and 5 show the load, displacement, displacement angle, and displacement ductility coefficient of different characteristic points of the specimen. The yield displacement is obtained by the energy method [17], and the ultimate load and displacement are the corresponding load and displacement values when the load drops to 85% of the peak load. The experimental results show that

- (1) By comparing the PTRC-1 with PURC-1-1 and PURC-1-4, it can be found that the yield

displacement of concrete columns with unbonded prestressed tendons increases, while the addition of unbonded prestressed tendons rarely affects the peak load, peak displacement, ultimate load, and ultimate displacement. Compared with PTRC-1, the yield displacement of PURC-1 and PURC-4 increases by 36.31% and 26.18%, respectively. The three specimens enter the yield state at the displacement angle of $1/37$ – $1/36$ and fail at the displacement angle of $1/22$ – $1/21$. This is because for large eccentric compression members, the reinforcement in the tensile area first yields, and then, the concrete in the compression area is damaged by compression, but the existence of preload slows down the yield of reinforcement in the tensile area, resulting in the increase in yield load and displacement of the specimen; however, after the specimen yields, the prestressed tendons basically stop working. At this time, the specimen can be approximately equivalent to an ordinary reinforced concrete column. Therefore, the peak load, peak displacement, ultimate load, and ultimate displacement of PURC-1 and PURC-4 are not significantly different from those of PTRC-1.

- (2) The test values of PURC-1, PURC-2, and PURC-3 are also analyzed. Compared with PURC-2, the yield load of PURC-1 and PURC-3 increases by 19.39% and 22.20%, and their yield displacement decreases by 9.88% and 9.70%; the peak load of PURC-1 and PURC-3 increases by 2.64% and 11.63%, and their peak displacement decreases by 13.43% and 25.30%; the ultimate load of PURC-1 and PURC-3 increases by 3.71% and 10.19%, and their ultimate displacement decreases by 12.57% and 17.52%, respectively.

TABLE 4: Ductility coefficients of the specimens.

Specimen No.	Loading direction	Yield load P_y/kN	Yield displacement Δ_y/mm	Peak load P_b/kN	Peak displacement Δ_b/mm	Ultimate load P_u/kN	Ultimate displacement Δ_u/mm	Ductility coefficient $\mu = \Delta_u/\Delta_y$	Ductility coefficient average
PTRC-1	Forward direction	168.29	11.22	200.71	29.92	170.60	51.16	4.56	4.75
	Reverse direction	-160.80	-12.07	-173.20	-32.92	-147.22	-59.52	4.93	
PURC-1	Forward direction	178.26	15.73	201.06	25.00	170.90	53.84	3.22	3.29
	Reverse direction	-188.98	-16.02	-195.19	-30.24	-165.91	-56.94	3.35	
PURC-2	Forward direction	153.26	17.35	188.50	28.02	160.23	62.86	3.62	3.60
	Reverse direction	-154.33	-17.89	-193.57	-35.85	-164.53	-63.83	3.57	
PURC-3	Forward direction	189.97	15.22	211.16	22.82	179.47	53.53	2.94	2.92
	Reverse direction	-185.96	-16.59	-219.83	-24.90	-178.36	-50.97	2.90	
PURC-4	Forward direction	161.42	14.45	192.14	27.56	163.32	54.05	3.29	3.41
	Reverse direction	-163.77	-14.94	-192.46	-34.99	-163.59	-59.57	3.52	

TABLE 5: Average value of load and displacement angle of specimens.

Specimen number	Yield load P_y/kN	Average yield displacement Δ_y/mm	$\theta_y = \Delta_y/H$	Average peak load P_b/kN	Average peak displacement Δ_b/mm	$\theta_b = \Delta_b/H$	Average ultimate load P_u/kN	Average ultimate displacement Δ_u/mm	$\theta_u = \Delta_u/H$
PTRC-1	164.55	11.65	1/99	186.96	31.42	1/37	158.91	55.34	1/21
PURC-1	183.62	15.88	1/72	198.13	27.62	1/42	168.41	55.39	1/21
PURC-2	153.80	17.62	1/65	193.04	31.94	1/36	162.38	63.35	1/18
PURC-3	187.97	15.91	1/68	215.50	23.86	1/48	178.92	52.25	1/22
PURC-4	162.60	14.70	1/69	192.30	31.28	1/37	163.46	56.81	1/20

It shows that under the same preloaded axial compression ratio, the greater the applied axial compression ratio, the greater the yield load, peak load, and ultimate load, and the smaller the yield displacement, peak displacement, and ultimate displacement.

4.4.2. Bearing Capacity Attenuation. Under the control of displacement amplitude at the same level, the bearing capacity of the specimen after yielding decreases with the increase in loading times, which is called bearing capacity attenuation. The bearing capacity attenuation Φ_i can be expressed as follows:

$$\Phi_i = \frac{P_{j-i}}{P_{j-1}}, \quad (2)$$

where P_{j-i} is the peak load value of the i th cycle under the j th level displacement amplitude; P_{j-1} is the peak load value of the first cycle under the j th level displacement amplitude.

Figure 8 shows the strength attenuation of different specimens. It can be found that:

- (1) The strength attenuation of each specimen increases with the increase in loading displacement; during the same level displacement loading cycle, the attenuation degree of the third loading is less than that of the second loading.
- (2) The average attenuation rates of PURC-1, PTRC-1, PTRC-2, PTRC-3, and PTRC-4 before failure are 4.70%, 6.16%, 5.98%, 7.13%, and 7.46%; their maximum strength attenuation rates are 10.05%, 10.23%, 10.14%, 10.21%, and 11.93%, and the corresponding displacement angles are 1/23, 1/29, 1/26, 1/26, and 1/39, respectively. It can be found that the strength attenuation of prestressed reinforced concrete columns is faster than that of the ordinary columns. Comparing PURC-1 and PURC-4, it can be found that the average attenuation rate of PURC-4 is 21.10% higher than that of PURC-1, and the maximum attenuation rate of PURC-4 is 16.62% higher

FIGURE 8: Strength attenuation of each specimen. (a) PTRC-1. (b) PURC-1. (c) PURC-2. (d) PURC-3. (e) PURC-4.

than that of PURC-1. It indicates that for the specimen with a small preloaded axial compression ratio, the faster the strength attenuation, the smaller the maximum strength attenuation rate. This is because during the loading process, with the increase in displacement, the deformation of prestressed tendons increases, and the preloaded axial pressure gradually increases; for the specimens with a small preloaded axial compression ratio, the prestressed tendons quit work in the later stage. By comparing PURC-1, PURC-2, and PURC-3, it can be found that the greater the applied axial compression ratio, the greater the strength attenuation rate and maximum amplitude of the specimen.

4.5. Ductility and Energy Dissipation. Ductility refers to the deformation capacity of a certain section of a structure or component from the beginning of yield to the maximum bearing capacity. The calculation equation of ductility is as follows:

$$u = \frac{\Delta_u}{\Delta_y}, \quad (3)$$

where u is ductility coefficient; Δ_u is the ultimate displacement of the structure or member under load; and Δ_y is the yield displacement of the structure or member under load. The yield displacement is determined by the energy method. Based on the test data and calculation results, the ductility coefficient and displacement angle of each test

column are obtained, as shown in Tables 4 and 5, Table 4 shows the ductility coefficients of the specimens, and Table 5 shows the average value of load and displacement angle of specimens. The energy dissipation performance can be measured by the equivalent damping coefficient h_e , and the calculation results are shown in Figure 9.

As shown in Tables 4 and 5, the ductility of the column with unbonded prestressed tendons is worse than that of an ordinary reinforced concrete column. Through the data comparison of PURC-1, PURC-2, and PURC-3, it can be found that the greater the applied axial compression ratio, the smaller the displacement ductility coefficient of the test column; through the data comparison of PURC-1 and PURC-4, it can be found that the larger the preloaded axial compression ratio, the smaller the displacement ductility coefficient of the test column.

As shown in Figure 9, the energy dissipation coefficient of the column with unbonded prestressed tendons is less than that of ordinary reinforced concrete column. It indicates that the addition of prestressed tendons can lead to the deterioration of the energy dissipation performance of the member. Regardless of the axial compression ratio, the greater the loading displacement of each test column, the greater the equivalent damping coefficient; the larger the applied axial compression ratio and preloaded axial compression ratio of each test column, the smaller the equivalent damping coefficient. It shows that the increase in the applied axial compression ratio and the preloaded axial compression ratio leads to the deterioration of the energy dissipation capacity of the column.

FIGURE 9: Comparison of equivalent damping coefficients.

4.6. Self-Centering Performance. The self-centering performance of a structure or member refers to its recovery performance to the initial state after applying the load. To intuitively reflect the self-centering performance of test columns, the self-centering capability coefficient γ is used, and it can be calculated as follows:

$$\gamma = 1 - \frac{\Delta_r}{\Delta_m}, \quad (4)$$

where γ is the self-centering capability coefficient; Δ_r is the residual displacement of the structure or member after the load; and Δ_m is the maximum displacement of the structure or member under load. Figure 10 shows the changing curve of the self-centering capability coefficient of test columns.

As shown in Figure 10, it is concluded that

- (1) The concrete column with unbonded prestressed tendons has a large self-centering capability coefficient and strong self-centering performance, which can reduce the residual displacement of the test column. When the loading displacement is +54 mm, the residual displacement of PURC-1 is 34.10% less than that of PTRC-1, and the reduction capacity coefficient of PURC-1 is 1.3 times larger than that of PTRC-1.
- (2) When the displacement is small, the self-centering capability coefficient of the specimen is relatively stable with a small changing trend, and the self-centering capability curve is basically parallel to the x-axis. When the loading displacement increases, the self-centering capability coefficient of the test

column decreases gradually. The greater the loading displacement, the faster the reduction in the self-centering capability coefficient.

- (3) At the beginning of loading, the larger the applied axial pressure ratio of the test column, the larger the initial self-centering capability coefficient. However, with the increase in the loading displacement, the decline rate of the self-centering capability coefficient accelerates, the changing curve of the self-centering capability coefficient becomes steeper and steeper, and the self-centering capability coefficient of the column with a large applied axial pressure ratio is gradually smaller than that of the column with a small applied axial pressure ratio. It shows that the excessive applied axial compression ratio is not conducive to maintain the self-centering performance of prestressed concrete columns after damage. This is because the restoring force of the test column is provided by the prestressed tendons and the main reinforcement. The greater the applied axial pressure ratio, the more work the restoring force needs to overcome the axial pressure in the process of specimen recovery.
- (4) The larger the preloaded axial compression ratio, the smaller the residual displacement of the test column, and the larger the self-centering capability coefficient. This is because the greater the prestress, the greater the restoring force provided. Besides, the preloaded axial compression ratio has little effect on the reduction rate of the self-centering coefficient of the test column.

FIGURE 10: Self-centering capability coefficient of specimens. *Note.* (a) and (b) present the self-centering capability coefficients of specimens under the forward loading; (c) and (d) present the self-centering capability coefficients of specimens under the reverse loading.

5. Conclusion

In this test, the low-cycle repeated loading tests were conducted on one ordinary reinforced concrete column and four reinforced concrete columns with posttensioned unbonded prestressed tendons under different axial compression ratios. The conclusions are obtained as follows:

- (1) Adding posttensioned unbonded prestressed tendons to ordinary reinforced concrete columns can lead to poor energy dissipation performance, but it can effectively improve the self-centering

performance of the test columns and reduce the residual displacement of the columns.

- (2) Axial compression ratio is an important factor affecting the seismic performance of test columns. With the increase in the applied axial compression ratio, the bearing capacity and initial stiffness of the column increase, but the ductility and energy dissipation performance become worse, and the stiffness and bearing capacity decay faster. The increase in the preloaded axial compression ratio can deteriorate the ductility and energy dissipation

performance of columns, but rarely affects the bearing capacity of columns. Besides, the increase in the preloaded axial compression ratio can reduce the attenuation rate of bearing capacity.

- (3) The elastic displacement angle of each test column is between 1/21 and 1/18, which meets the design requirement that the displacement angle between elastic-plastic layers is not less than 1/50 under rare earthquake action. It indicates that the posttensioned unbonded prestressed concrete column has good collapse resistance.
- (4) The average strength attenuation rate of each test column under all levels of loading displacement amplitude is not more than 8%, and the maximum strength attenuation rate is not more than 12%. It indicates that the posttensioned unbonded prestressed concrete column has good seismic bearing capacity under earthquake.
- (5) The axial compression ratio has an important influence on the self-centering performance of post-tensioned unbonded prestressed concrete columns. The larger the applied axial pressure ratio, the better the initial self-centering performance of the column, but the faster the self-centering performance attenuation in the later stage of loading, the worse the self-centering performance. The greater the preloaded axial compression ratio, the better the self-centering performance of the column. Besides, the preloaded axial compression ratio has no significant effect on the attenuation rate of self-centering performance.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The work in this study was supported by the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (20KJB560012). The authors would like to acknowledge the support of the organizations for providing photographs and advice.

References

- [1] J. F. Jia, B. Wei, and J. P. Ou, "Test for seismic performance of prefabricated self-centering bridge piers with external replaceable energy dissipator," *Journal of Vibration and Shock*, vol. 40, no. 5, pp. 154–162, 2021.
- [2] E. Xiong, K. Zu, J. Wang, and Q. Zhang, "Seismic performance analysis of self-centering concentrically braced steel frame structures," *World Earthquake Engineering*, vol. 36, no. 3, pp. 69–79, 2020.
- [3] J. Erochko, C. Christopoulos, and R. Tremblay, "Design and testing of an enhanced-elongation telescoping self-centering energy-dissipative brace," *Journal of Structural Engineering*, vol. 141, no. 6, 2015.
- [4] C.-C. Chou, W.-J. Tsai, and P.-T. Chung, "Development and validation tests of a dual-core self-centering sandwiched buckling-restrained brace (SC-SBRB) for seismic resistance," *Engineering Structures*, vol. 121, pp. 30–41, 2016.
- [5] D. J. Miller, L. A. Fahnestock, and M. R. Eatherton, "Development and experimental validation of a nickel-titanium shape memory alloy self-centering buckling-restrained brace," *Engineering Structures*, vol. 40, pp. 288–298, 2012.
- [6] Z. Zhou, Q. Xie, X. C. Lei, X. He, and S. Meng, "Experimental investigation of the hysteresis performance of dual-tube self-centering buckling-restrained braces with composite tendons," *Journal of Composites for Construction*, vol. 19, no. 6, Article ID 4015011, 2015.
- [7] C. Fang, M. C. H. Yam, T.-M. Chan, W. Wang, X. Yang, and X. Lin, "A study of hybrid self-centering connections equipped with shape memory alloy washers and bolts," *Engineering Structures*, vol. 164, pp. 155–168, 2018.
- [8] H. Y. Luo, Q. Li, and Z. B. Wang, "Experimental study on restoring performance of unbonded partially prestressed concrete columns," *China Concrete and Cement Products*, vol. 7, pp. 44–48, 2013.
- [9] L. Lu, Y. L. Ye, and W. Q. Xia, "Study on the seismic performance of a 3D external prestressed self-centering reinforced concrete frame by shaking test," *China Civil Engineering Journal*, vol. 53, no. S2, pp. 68–73+108, 2020.
- [10] H. Qian, J. t. Xu, and J. t. Zhu, "Numerical simulation of mechanical behaviors of the innovative self-centering coupling beam damper," *World Earthquake Engineering*, vol. 36, no. 4, pp. 121–129, 2020.
- [11] D. Roke, R. Sause, J. M. Ricles, and N. Gonner, "Design concepts for damage-free seismic-resistant self-centering steel concentrically-braced frames," in *Proceedings of the 14th World Conference on Earthquake Engineering*, pp. 1–10, Beijing, China, October 2009.
- [12] H. Y. Luo, *Research on the Influence of the Degree of Prestress to Re-centering Behavior of Unbonded Partially Prestressed concrete Columns*, Yangzhou University, Yangzhou, China, 2008.
- [13] Y. M. Yang, P. Yang, and H. J. Gao, "Experimental study on the seismic behavior of self-centering RC frame column base joints under different axial compressive ratios," *Journal of Tianjin University*, vol. 53, no. 5, pp. 542–550, 2020.
- [14] F. M. Li, *Effect of Steel Strands Corrosion on Prestressed concrete Structures under Chloride Environment*, China University of Mining and Technology, Beijing, China, 2008.
- [15] China University of Mining and Technology, *A Tensioning Support Foot Device: 200720035651*, China University of Mining and Technology, Xuzhou, China, 2008.
- [16] China Academy of Building Research, *Specification For Seismic Test of Buildings: JGJ/T101-2015*, China Architecture & Building Press, Beijing, China, 2015.
- [17] J. Yan, Z. L. Li, and G. Zuo, "An experimental study on the seismic performance of welded closed stirrup concrete columns," *Journal of Vibration and Shock*, vol. 37, no. 24, pp. 148–157+171, 2018.