Experimental Study on Cumulative Damage Behavior of Steel-Reinforced Concrete Columns

Lianjie Jiang and Guoliang Bai

1School of Civil Engineering, Xi’an University of Architecture & Technology, Xi’an 710055, Shaanxi, China
2Department of Architectural Engineering, Suqian College, Suqian 223800, Jiangsu, China

Correspondence should be addressed to Lianjie Jiang; jianglianjie1983@126.com

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The cumulative damage behavior of SRC columns under far-field long-period ground motions was simulated and studied by quasi-static tests with the same displacement for 10 times. Quasi-static tests of 8 SRC columns were conducted under the horizontal cyclic loading with the same displacement for 10 times or 3 times, and then the effects of steel ratio, stirrup ratio, axial compression ratio, and number of cyclic loading on the cumulative damage of SRC columns under the far-field long-period ground motions were studied. The results showed that the number of cyclic loading had little effect on the peak load of the specimens, but had a significant effect on the deformation capacity, stiffness degradation, and energy dissipation capacity. Compared with the specimens after 3 cycles, the displacement ductility coefficient of specimens after 10 cycles was reduced by about 20%–26%, the ultimate hysteresis energy dissipation was reduced by 35%–48%, while the stiffness degradation rate was accelerated. After the peak load, the cumulative damage caused by multiple cyclic loading with the same displacement was more significant, which aggravated the reduction of bearing capacity and stiffness degradation. The smaller the steel ratio and stirrup ratio, the larger the axial compression ratio, and the greater the reduction of the bearing capacity and stiffness of specimens. However, accumulated damage caused by multiple cyclic loading with the same displacement had a slight impact on the energy dissipation capacity. Increasing the steel ratio and stirrup ratio can effectively improve the deformation capacity and energy dissipation capacity of the specimens and reduce the bearing capacity and stiffness degradation caused by cumulative damage.

1. Introduction

As a special kind of ground motion, the far-field long-period ground motion has the characteristics of long duration and rich low-frequency components; and in the latter vibration stage, obvious cyclic pulses which are similar to harmonic vibration can be observed [1–3]. The 2011 east Japan earthquake damage and E-Defense shaking table test results show that the high-rise structure with long natural vibration period has the following characteristics under the far-field long-period ground motions: large displacement response, multiple cycles, and long duration with large displacement; and the cyclic number in which the interlayer displacement angle exceeds the elastic-plastic displacement angle limit can reach more than 10 times, and the plastic deformation of multiple reciprocating cycles leads to serious cumulative damage of the high-rise structure [4–9].

Steel-reinforced concrete (SRC) columns are important load-bearing members in high-rise structures. Many experimental researches on seismic performance of SRC columns have been carried out at home and abroad. The low-cycle reversed loading tests of traditional SRC columns were carried out through changing the parameters of axial compression ratio, stirrup ratio, steel distribution form, steel ratio, and shear span ratio; the failure form, hysteresis curve, skeleton curve, bearing capacity, ductility, and energy dissipation capacity of SRC columns were studied [10–14]. The results show that SRC columns have better seismic performance than RC columns. Due to the wide application of high-strength and high-performance concrete, the low-cycle
2. Experimental Process

2.1. Specimen Design. Eight SRC columns with the same geometric dimension were designed in this experiment. The section size of SRC columns was 180 mm × 250 mm, the height was 1200 mm, reinforcing steel bars of 4C16 were arranged longitudinally, the reinforcement ratio was 1.79%; the section size of RC base beam was 400 mm × 700 mm, the length was 1350 mm, and the shear span ratio of specimens was designed as 4.4.

The main change parameters of the specimens included steel ratio, stirrup ratio, axial compression ratio, and number of cyclic loading. Q235 hot rolled I-beams of I12.6, I14, and I16 were used as section steel, with corresponding steel ratios of 4.0%, 4.8%, and 5.8%, respectively; C8@120, C8@100, and C8@80 were used as stirrups (C8@50 was used as column head stirrup), with corresponding stirrup ratios of 1.0%, 1.2%, and 1.5% respectively; the design axial compression ratio was 0.3 and 0.4; the number of cyclic loading was 10 times and 3 times when the displacement angle of column top was not less than 1.0%. Table 1 shows the design parameters of specimens, and Figure 1 shows the specific size and reinforcement.

The concrete design strength grade of the specimens was C40, and the commercial concrete was used. When pouring concrete of the specimens, six 150 mm × 150 mm × 150 mm cubic concrete blocks were made and cured under the same conditions with the specimens. The average cubic compressive strength of concrete blocks was measured to be 49.1 MPa. The properties of steel materials were tested by uniaxial tensile test, and the determined strength indexes are shown in Table 2.

2.2. Loading Devices and Loading System. The “Cantilever column type” quasi-static loading method was adopted. Figure 2 shows the test loading device. Steel beam and anchor screw were used to fix RC base beam on the ground to avoid the horizontal sliding during the loading process. The design axial compression ratio was used to determine the vertical load which was applied to the top of the columns by 1000 kN hydraulic jack and remained constant in the test. The horizontal load was applied by the MTS hydraulic actuator, and the distance between the loading center and the bottom section of the column was 1100 mm. A roller was arranged between the hydraulic jack and the loading steel frame beam to ensure that the hydraulic jack moved with the horizontal displacement of the column top; a one-way rotating hinge was placed between the column top and the hydraulic jack to ensure that the column top can rotate freely in the loading direction.

Displacement control was adopted in the horizontal loading process: the horizontal displacement was step-by-step loaded at displacement angle $\theta = 0.09\%$, 0.18\%, 0.23\%, 0.3\%, 0.36\%, 0.45\%, 0.6\%, and 0.9\%, and the displacement of each stage was cycled once; the horizontal displacement was step-by-step loaded at displacement angles $\theta = 1.0\%$, 1.5\%, 2.0\%, 2.5\%, 3.0\%, 3.5\%, and 4.0\%, and the displacement of each stage was cycled multiple times, including 10 cycles for specimens SRC1–SRC6 and 3 cycles for specimens SRC1-2, SRC4-2. When the applied load fell below 85% of the peak load, the test was terminated.

2.3. Measurement Content. In this test, the vertical load, horizontal load, horizontal displacement and strain of section steel flange, web, longitudinal reinforcement, and...
stirrup of the specimens were measured. The crack development and distribution of the specimens were observed under cyclic loading. The vertical load, horizontal load, and horizontal displacement of the column top were collected in real time by sensors. The horizontal displacement of the RC base beam was monitored by a displacement meter arranged on the side of the base beam. The tensile strain and compressive strain of the section steel flange, web, longitudinal reinforcement, and stirrup were measured by resistance strain gauge pasted in the steel and collected by the DH3816 static strain test system.

3. Results and Discussion

3.1. Damage Process and Failure Mode. Since the failure process and failure mode of each specimen are similar, SRC4 is specifically analyzed in the limited space. The failure process of SRC4 is divided into three stages: precracking, damage development, and failure. The test phenomena in each stage are as follows.

Precracking stage: before the cracking load of the specimen. When the displacement angle is not more than 0.23%, there is no visible change in the specimen; when the displacement angle is 0.3%, the first horizontal crack about

Table 1: Design parameters of specimens.

| Specimen | Section steel specification | Steel ratio (%) | Stirrup | Stirrup ratio (%) | Design axial compression ratio | Number of cyclic loading |
|----------|-----------------------------|----------------|---------|------------------|-------------------------------|-------------------------|
| SRC1     | I12.6                       | 4.0            | C8@100  | 1.2              | 0.3                           | 10                      |
| SRC2     | I14                         | 4.8            | C8@100  | 1.2              | 0.3                           | 10                      |
| SRC3     | I16                         | 5.8            | C8@100  | 1.2              | 0.3                           | 10                      |
| SRC4     | I14                         | 4.8            | C8@120  | 1.0              | 0.3                           | 10                      |
| SRC5     | I14                         | 4.8            | C8@80   | 1.5              | 0.3                           | 10                      |
| SRC6     | I14                         | 4.8            | C8@100  | 1.2              | 0.4                           | 10                      |
| SRC1-2   | I12.6                       | 4.0            | C8@100  | 1.2              | 0.3                           | 3                       |
| SRC4-2   | I14                         | 4.8            | C8@120  | 1.0              | 0.3                           | 3                       |

Figure 1: Specimen size and section reinforcement.

Table 2: Steel strength index.

| Steel type | Yield strength (MPa) | Ultimate strength (MPa) |
|------------|----------------------|-------------------------|
| I12.6 flange | 320.8               | 448.3                   |
| I12.6 web   | 338.9               | 452.2                   |
| I14 flange  | 387.5               | 523.3                   |
| I14 web     | 380.2               | 484.4                   |
| I16 flange  | 385.8               | 514.2                   |
| I16 web     | 366.7               | 480.7                   |
| C16         | 524.7               | 659.1                   |
| C8          | 453.8               | 614.7                   |
50 mm long appears on the tensile side of the column bottom, reaching the cracking load.

Damage development stage: from cracking load to peak load. With the increase of the displacement angle, the existing cracks of the specimen develop continuously. Several horizontal cracks are generated simultaneously and mainly concentrated in the bottom of the column within the range of 1 times the height of the column section. When the displacement angle is 1.0%, horizontal cracks of the specimen are basically complete, and the inclined cracks appear, extend, and intersect; the longitudinal bars and stirrups begin to yield. When the displacement angle is 1.5%, the vertical cracks appear at the corners of the specimen, the concrete cover begins to peel and peel off in a small amount, the development of existing horizontal cracks and inclined cracks is slow, and the damage of the specimen is not serious, as shown in Figure 3(a). When the displacement angle is 2.0%, the load of specimen reaches the peak load. With the increase of the number of cyclic loading, the horizontal cracks at the bottom of the column gradually develop and widen and the crack width reaches 0.8 mm, 1.0 mm, and 1.3 mm after the 1st, 6th, and 10th cycles respectively; the vertical cracks also extend upward and widen, the crack width reaches 0.5 mm, 1.0 mm, and 2.0 mm after the 1st, 4th, and 10th cycles, respectively, accompanied by the fall of the concrete cover, and the damage degree of the specimen gradually aggravates, as shown in Figure 3(b).

Failure stage: from the peak load to failure. When the displacement angle is 2.5%, the number of cyclic loadings has more influence on the damage process of the specimen. Horizontal cracks at the bottom of the column continue to widen with the increase of the number of cyclic loading, and most of the concrete cover between the two horizontal cracks at the bottom of the column fall off after the 3rd cycle. Vertical cracks also extend upward and widen obviously in multiple cycles, the maximum width after the 1st, 3rd, and 10th cycles reaches 2.0 mm, 3.0 mm, and 5.5 mm, respectively, and the damage and falling off area of the concrete cover increases greatly. Figures 3(c)–3(e) show the failure modes of the specimen after the 1st, 6th, and 10th cycles, respectively. During the 1st cycle with displacement angle of 3.0%, the concrete cover within the range of 1 time the column section height at the bottom of the column is crushed and falls off in large area, the longitudinal reinforcement and stirrup are exposed outwards, the longitudinal reinforcement is bent and bulged, and the section steel is partially bent. The damage of the specimen develops rapidly, and the bearing capacity decreases sharply, leading to the serious failure. The final failure mode of the specimen is shown in Figure 3(f).
The failure modes of other specimens are basically the same. The failure mainly occurs in the range of 250 mm–300 mm at the bottom of the column. During the failure, the concrete cover is severely crushed and peeled off, the longitudinal reinforcement and stirrup are exposed and buckled, and section steel is partially buckled, which belongs to the bending failure. Figures 3(g)–3(k) show the failure modes of other specimens.

It is found that multiple cyclic loading has certain influence on the cumulative damage and failure process of the specimens. Compared with the specimens after 3 cycles, the specimens after 10 cycles have an increasing crack width at the same displacement angle in the cyclic loading, and the corresponding displacement angle decreases with the same failure characteristics. For example, when the displacement angle is 2.0%, the maximum width of the horizontal crack of SRC4-2 is 0.5 mm, while that of SRC4 is 1.3 mm; when the concrete cover is seriously peeled off and the specimen is damaged, the corresponding displacement angles of SRC4-2 are about 3.0% and 3.5% respectively, while the corresponding displacement angles of SRC4 are about 2.5% and 3.0%, respectively.
3.2. Hysteresis Curves. The hysteresis curves of horizontal load $P$ and displacement angle $\theta$ of all specimens are shown in Figure 4. It can be concluded that

(1) The hysteresis curves of the specimens are full and fusiform, without obvious pinch phenomenon, indicating that the specimens have good energy dissipation capacity. Before the peak load, with the increase of the number of cyclic loading, the bearing capacity of the specimens decreases slightly, and the stiffness degradation is not obvious. After the peak load, with the increase of displacement amplitude and the number of cyclic loading, the damage accumulation of the specimens increases continuously and the bearing capacity and stiffness degradation are more significant.

(2) Through the comparison of specimens SRC1, SRC2, and SRC3, the steel ratio has obvious influence on the hysteresis performance of the specimens. With the increase of the steel ratio, the peak load of the specimens is greatly improved, the hysteresis curve is fuller, and the energy dissipation capacity is stronger; through the comparison of specimens SRC2, SRC4, and SRC5, after the peak load, the bearing capacity and stiffness of the specimen with larger stirrup ratio degrade slowly and the ultimate displacement angle increases greatly. This is because section steel and stirrup can effectively restrain the core concrete and improve the cooperative working ability of the core concrete and section steel, so as to improve the hysteresis performance of the specimens. At the same time, it is found that when the displacement angle is more than 2.5%, the bearing capacity and stiffness of SRC4 degenerate suddenly and significantly. The analysis shows that the stirrup spacing of SRC4 is larger, which weakens the effective constraints on the section steel frame and the core area concrete; and the concrete cover is severely crushed and peels off at the latter stage of loading, resulting in the significant degradation of bearing capacity and stiffness.

(3) As shown in hysteresis curves of specimens SRC2 and SRC6, when the axial pressure ratio is small, the hysteresis loop of the specimen is relatively full. When the load of the specimen reaches the peak load, the hysteresis curve is relatively stable, the ultimate displacement angle is large, and the energy dissipation capacity is strong. With the increase of the axial pressure ratio, the hysteresis curve of the specimen becomes thin, the bearing capacity and stiffness degrade sharply, the ultimate displacement angle and the number of cyclic loading reduce, and the deformation capacity and energy dissipation capacity decrease.

(4) The number of cyclic loading has a significant effect on the hysteresis properties of the specimens. The hysteresis loops of specimens SRC1-2 and SRC4-2 after 3 cycles are full. After the peak load, the hysteresis curves are stable, the reduction of bearing capacity and stiffness degeneration is slow, the ultimate displacement angle is large, and the energy dissipation capacity is strong. On the contrary, hysteresis curves of specimens SRC1 and SRC4 after 10 cycles decrease in fullness. After the peak load, bearing capacity and stiffness degrade rapidly and the ultimate displacement angle and energy dissipation capacity decrease. This phenomenon is mainly caused by the accumulated damage of the specimen under the action of multiple cyclic loading.

3.3. Deformation Capacity. According to the skeleton curve of the specimens, the yield displacement $\Delta_y$, yield displacement angle $\theta_y$, peak displacement $\Delta_{\text{max}}$, peak displacement angle $\theta_{\text{max}}$, ultimate displacement $\Delta_u$, and ultimate displacement angle $\theta_u$ of all specimens are determined, and the displacement ductility coefficients $u$ of specimens are calculated by $u = \Delta_u/\Delta_y$ [27]. The results are listed in Table 3. The values in the table are the average values of displacement, displacement angle, and displacement ductility coefficient under positive and reverse loading. The yield displacement $\Delta_y$ is determined by the equal energy method [28], and the limit displacement $\Delta_u$ is the displacement corresponding to the horizontal load falling to 85% of the peak load. In this paper, the ultimate displacement angle $\theta_u$ [29] and the displacement ductility coefficient $u$ are used to describe the deformation capacity of the specimens. From Table 3, it is concluded that

(1) The deformation capacity of the specimens decreases with the increase in the number of cyclic loading. For specimens SRC1-2 and SRC4-2 after 3 cycles, $\theta_u$ is, respectively, 2.95% and 3.53%, which is much more than 2.0%; $u$ is, respectively, 2.93 and 3.02, which are close to 3.0. This indicates that specimens SRC1-2 and SRC4-2 after 3 cycles have good deformation ability. With the increase of the number of cyclic loading, the damage of the specimens is accumulated. $\theta_u$ and $u$ of SRC1 after 10 cycles decrease by 12.5% and 26.6% than those of SRC1-2; $\theta_u$ and $u$ of SRC4 decrease by 43.3% and 20.5% than those of SRC4-2, respectively. Therefore, the cumulative damage greatly reduces the deformation ability of the specimen.

(2) The larger the steel ratio and stirrup ratio, the better the deformation ability of the specimen. For specimens SRC1, SRC2, and SRC3, with the increase of steel ratio, $\theta_u$ and $u$ increase. Comparing SRC1 with the minimum steel ratio, $\theta_u$ and $u$ of SRC3 with the maximum steel ratio increase by 17.4% and 18.6%, respectively. Compared with SRC2, SRC4, and SRC5, with the increase of stirrup ratio, $\theta_u$ and $u$ increase gradually. Compared with SRC4, $\theta_u$ and $u$ of SRC5 increase by 11.5% and 11.3%, respectively. This is because the effective restraint effect of section steel and stirrup on the concrete in the core area lead to three-dimensional compression state for the
Figure 4: Hysteresis curves of horizontal load and displacement angle ($P - \theta$) of specimens. (a) SRC1. (b) SRC2. (c) SRC3. (d) SRC4. (e) SRC5. (f) SRC6. (g) SRC1-2. (h) SRC4-2.
3.4. Bearing Capacity

3.4.1. Test Value of Bearing Capacity. Table 3 shows measured values of yield load $P_y$ and peak load $P_{\text{max}}$ of all specimens. The results show the following:

(1) The load of most specimens reaches the peak load when the displacement angle is about 2.0%, the peak load is about 1.15–1.21 times of the yield load, and the average value is 1.18 times.

(2) The number of cyclic loading has little effect on the peak load. Compared with those of SRC1-2 and SRC4-2 after 3 cycles, the peak load of SRC1-2 and SRC4-2 after 10 cycles decreases by 6.1% and increases by 7.6%, respectively, and changes slightly overall. Combined with the damage development, it is analyzed that the damage development of the specimens is relatively slow and the damage accumulation is not serious before the peak load, so the impact on the peak load is small.

(3) The peak load of SRC3 with the largest steel ratio is significantly greater than that of other specimens, which is about 1.32 times of SRC1 with the smallest steel ratio. This indicates that increasing the steel ratio can effectively improve the bearing capacity of the specimens.

(4) The peak load of SRC2, SRC4, and SRC5 with different stirrup ratio has little difference. The average value is 83.7 kN, and the maximum difference is 1.5%. This suggests that the influence of stirrup ratio on the peak load is small, and there is a limited effect of increasing stirrup ratio on improving the bearing capacity of the specimens.

(5) Although increasing the axial compression ratio can enhance the restraint effect on the specimen, the increase of the axial compression ratio does not significantly increase the peak load of the specimen.

3.4.2. Effect of Cumulative Damage on Bearing Capacity Decline. With the increase of the number of cyclic loading, the damage of the specimens accumulates and the bearing capacity of the specimens decreases. The ratio $P_i/P_1$, where $P_i$ is the maximum horizontal load at the $i$th cycle of the same displacement and $P_1$ is the maximum horizontal load at the 1st cycle, is used to investigate the reduction of bearing capacity of specimens caused by cumulative damage. The larger the ratio, the smaller the reduction of bearing capacity. Table 4 shows the calculation results of $P_3/P_1$ and $P_{10}/P_1$ of the specimens under different displacement angle cycles. From Table 4, following conclusions are made:

(1) In the same displacement angle cycle, $P_{10}/P_1 < P_3/P_1$, indicating that the bearing capacity of the specimens, decreases with the increase of the number of cycle loading.

(2) The reduction of bearing capacity is related to the amplitude of displacement angle. When the displacement angle is 1.0% and 1.5%, the specimens cannot yield or reach the peak load, $P_{10}/P_1$ is about 0.940–0.997 and slightly less than $P_3/P_1$, and the bearing capacity drops slightly. It shows that the cumulative damage of specimens caused by the multiple cyclic loading with the small displacement has little influence on the reduction of bearing capacity. When the displacement angle is 2.0%, the bearing capacity of the specimens reaches the peak load and the reduction range of bearing capacity begins to increase. The bearing capacity of the specimen SRC1 decreases by 12.3% in the 10th cycle, and the bearing capacity of the remaining specimens decreases by no more than 8.0%, indicating that the cumulative damage has a certain impact on the reduction of the bearing capacity of the specimen. When the displacement angle is 2.5% and 3.0%, the bearing capacity of the specimens decreases less than 7.0% in the 3rd cycle. However, with the increase of the number of cycle loading, the damage of specimens develops rapidly. In the 10th cycle, the bearing capacity of most specimens decreases more than

| Specimen | $P_y$ (kN) | $\Delta_y$ (mm) | $\theta_y$ (%) | $\Delta_{\text{max}}$ (mm) | $\theta_{\text{max}}$ (%) | $\Delta_u$ (mm) | $\theta_u$ (%) | $u$ |
|----------|----------|-------------|-------------|----------------|----------------|-------------|-------------|-----|
| SRC1     | 62.2     | 13.17       | 1.20        | 73.2           | 2.02           | 28.34       | 2.58        | 2.15|
| SRC2     | 71.2     | 12.66       | 1.15        | 83.3           | 2.02           | 31.88       | 2.90        | 2.52|
| SRC3     | 79.9     | 13.05       | 1.28        | 96.8           | 2.02           | 33.30       | 3.03        | 2.55|
| SRC4     | 72.1     | 11.88       | 1.08        | 82.8           | 2.02           | 28.55       | 2.60        | 2.40|
| SRC5     | 71.9     | 11.94       | 1.09        | 85.0           | 2.02           | 31.86       | 2.67        | 2.90|
| SRC6     | 70.0     | 12.31       | 1.12        | 84.0           | 2.02           | 25.00       | 2.27        | 2.03|
| SRC1-2   | 65.8     | 11.06       | 1.01        | 78.0           | 1.77           | 32.46       | 2.95        | 2.93|
| SRC4-2   | 65.7     | 12.86       | 1.17        | 76.9           | 2.02           | 38.85       | 3.53        | 3.02|

### Table 3: Bearing capacity and deformation capacity of specimens.
Table 4: $P_3/P_1$ and $P_{10}/P_1$ of specimens with different displacement angles.

| Specimen | Displacement angle (%) | $P_3/P_1$ | $P_{10}/P_1$ |
|----------|------------------------|-----------|-------------|
| SRC1     | 1.0                    | 0.984     | 0.984       |
|          | 1.5                    | 0.973     | 0.940       |
|          | 2.0                    | 0.940     | 0.877       |
|          | 2.5                    | 0.941     | 0.786       |
| SRC2     | 1.0                    | 0.964     | 0.950       |
|          | 1.5                    | 0.967     | 0.945       |
|          | 2.0                    | 0.965     | 0.924       |
|          | 2.5                    | 0.962     | 0.885       |
|          | 3.0                    | 0.944     | —           |
| SRC3     | 1.0                    | 0.967     | 0.964       |
|          | 1.5                    | 0.971     | 0.951       |
|          | 2.0                    | 0.981     | 0.973       |
|          | 2.5                    | 0.984     | 0.936       |
|          | 3.0                    | 0.973     | 0.703       |
| SRC4     | 1.0                    | 0.989     | 0.976       |
|          | 1.5                    | 0.985     | 0.963       |
|          | 2.0                    | 0.983     | 0.937       |
|          | 2.5                    | 0.974     | 0.739       |
| SRC5     | 1.0                    | 0.989     | 0.997       |
|          | 1.5                    | 0.990     | 0.991       |
|          | 2.0                    | 0.977     | 0.956       |
|          | 2.5                    | 0.968     | 0.907       |
|          | 3.0                    | —         | —           |
| SRC6     | 1.0                    | 0.993     | 0.993       |
|          | 1.5                    | 0.986     | 0.984       |
|          | 2.0                    | 0.973     | 0.952       |
|          | 2.5                    | 0.949     | 0.847       |
|          | 3.0                    | —         | —           |
| SRC1-2   | 1.0                    | 0.972     | —           |
|          | 1.5                    | 0.965     | —           |
|          | 2.0                    | 0.950     | —           |
|          | 2.5                    | 0.942     | —           |
|          | 3.0                    | 0.935     | —           |
| SRC4-2   | 1.0                    | 0.980     | —           |
|          | 1.5                    | 0.964     | —           |
|          | 2.0                    | 0.954     | —           |
|          | 2.5                    | 0.951     | —           |
|          | 3.0                    | 0.962     | —           |

Note: Specimen SRC3 is cycled for 8 times at the displacement angle of 3%, and in the table $0.703 = P_3/P_1$.

Therefore, increasing the steel ratio can reduce the reduction of the bearing capacity caused by the cumulative damage.

(4) For specimens SRC2, SRC4, and SRC5, after the peak load, with the increase of the stirrup ratio, $P_3/P_1$ and $P_{10}/P_1$ of the specimens increase and the reduction of bearing capacity decreases. For example, in the 10th cycle with displacement angles of 2.0% and 2.5%, the bearing capacity of SRC4 with minimum stirrup ratio decreases by 6.3% and 26.1%, while that of SRC5 with maximum stirrup ratio decreases by 4.4% and 9.3%, respectively. Therefore, increasing the stirrup ratio is beneficial to reduce the adverse effect of cumulative damage on the bearing capacity of specimens.

(5) For specimens SRC2 and SRC6, before the peak load, the bearing capacity of SRC6 with a large axial pressure ratio decreases slightly with the increase of the number of cyclic loadings, since the large axial pressure enhances the end restraint of the specimen; after the peak load, the bearing capacity of SRC6 decreases rapidly and the bearing capacity decreases 15.3% at the displacement angle of 2.5% in the 10th cycle, while the bearing capacity of SRC2 with the smaller axial compression ratio is reduced by 11.5%. It can be seen that, in the later stage of loading, the larger the axial compression ratio, the larger the reduction of the bearing capacity of the specimen. This is because the larger axial pressure results in the greater additional bending moment, which aggravates the degradation of the bearing capacity of the specimen.

3.5. Secant Stiffness

3.5.1. Average Secant Stiffness. Due to the elastic-plastic property and cumulative damage of the specimens, the stiffness decreases with the increase of displacement amplitude and the number of cyclic loadings. Secant stiffness $K_m$ is the ratio of the sum of the absolute values of the maximum positive and negative horizontal load and the sum of the absolute values of the maximum horizontal displacement at each cycle. Figure 5 shows the relation curves between the average secant stiffness $K_m$ and the displacement angle $\theta$ of the specimens. $K_m$ refers to the secant stiffness which is obtained by dividing the sum of secant stiffness of multiple displacement loading cycle by the number of loading cycles [26]. The meaning of “average hysteresis energy dissipation” below is similar to $K_m$. It can be seen that, with the increase of displacement angle, the average secant stiffness of the specimens decreases linearly, and the steeper the $K_m-\theta$ curves, the more significant the stiffness degradation of the specimens.

As shown in Figure 5(a), the stiffness degradation of SRC4-2 after 3 cycles is relatively gentle and that of SRC4 after 10 cycles is significantly fast; when the displacement angle is 3.0%, $K_m$ of SRC4 is about 50% lower than that of SRC4-2. It indicates that the cumulative damage caused by multiple cycles of displacement accelerates the rate of stiffness degradation. As shown in Figure 5(b), during the...
same displacement angle, with the increase of steel ratio, the stiffness of the specimen increases gradually and the stiffness degradation rate tends to slow down. As shown in Figure 5(c), the stiffness degradation of SRC4 with the minimum stirrup ratio is faster. With the increase of stirrup ratio, $K_m - \theta$ curve of the specimen gradually becomes flat and the stiffness degradation rate slows down. As shown in Figure 5(d), the greater the axial compression ratio, the greater the stiffness of the specimen. Before the peak load, the stiffness degradation rate of all specimens is basically the same; after the peak load, $K_m - \theta$ curve of the specimen SRC6 with the greater axial compression ratio is steeper and the stiffness degradation is faster. This is also related to the more significant P-Δ effect of large axial compression specimen.

3.5.2. Effect of Cumulative Damage on Secant Stiffness Degradation. As mentioned above, with the increase of the number of cyclic loading, the stiffness of the specimens also decreases. The relation curves between secant stiffness $K$ and cycle number $N$ of the specimens are shown in Figure 6, where $N = 1–10$ is the cycle number of 1.0% displacement angle, $N = 11–20$ is the cycle number of 1.5% displacement angle, $N = 21–30$ is the cycle number of 2.0% displacement angle.
angle, $N = 31–40$ is the cycle number of 2.5% displacement angle, and $N = 41–50$ is the cycle number of 3.0% displacement angle. With reference to $P_1/P_2$, the ratio $K_i/K_1$ is used to reflect the stiffness degradation of specimens caused by cumulative damage, in which $K_i$ is the secant stiffness in the $i$th cycle of the same displacement and $K_1$ is the secant stiffness in the 1st cycle.

According to Figure 6(a), when the displacement angle is 1.0% and 1.5%, with the increase of the number of cyclic loading, the stiffness of the specimens decreases slight, $K_{10}/K_1$ is more than 0.95 in the 10th cycle; when the displacement angle is 2.0% and 2.5%, the stiffness reduction range of the specimens increases with the increase of the number of cycles, $K_i$ decreases within 5.0% in the 3rd cycle; the reduction range of $K_{10}$ increases to 6.0%–20.0% in the 10th cycle, and the lower the steel ratio, the greater the reduction range of stiffness. When the displacement angle is 3.0%, the $K$–$N$ curve of specimen SRC3 develops unsteadily and the stiffness decreases sharply in the 5th cycle. The above analysis shows that the accumulated damage caused by multiple cycles of large displacement is more serious after the peak load, which aggravates the stiffness degradation of the specimens. Increasing the steel ratio can reduce the adverse effect of the accumulated damage on the stiffness degradation to a certain extent.

According to the analysis of Figures 6(b)–6(c), when the displacement angle is 1.0%, 1.5%, and 2.0%, with the increase of the number of cyclic loading, the stiffness reduction of the specimens with different stirrup ratios and axial compression ratios is not significant, indicating that the cumulative

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**Figure 6:** Secant stiffness-cycle loading number $K$–$N$ curves of specimens. Effect of (a) steel ratio on $K$, (b) stirrup ratio on $K$, and (c) axial compression ratio on $K$. 

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damage is not serious, and the impact on the stiffness degradation of the specimens is small; when the displacement angle is 2.5%, the smaller the stirrup ratio, the greater the axial compression ratio, and the greater the stiffness reduction. The maximum reduction can be up to 20.2%, and the stiffness degradation rate obviously accelerates.

3.6. Energy Dissipation Capacity

3.6.1. Average Hysteresis Energy. The hysteresis energy dissipation capacity can comprehensively reflect the influence of displacement amplitude and cyclic loading number on the damage accumulation of components. Figure 7 shows the relation curves between the average hysteresis energy $E_m$ and the displacement angle $\theta$ of the specimens, where the hysteresis energy of the specimens in each cycle is the area surrounded by the corresponding $P-\theta$ hysteresis curve. From Figure 7, it is concluded that:

1. With the increase of the displacement angle, the damage degree, the average hysteresis energy, and the energy dissipation capacity of the specimens increase.

2. When the displacement angle is 1.0% and 1.5%, the average hysteresis energy of specimens is almost the same. When the displacement angle exceeds 1.5%, the number of cyclic loading, steel ratio, stirrup ratio, and axial compression ratio all have great influence on the energy dissipation capacity of the specimens. Specific analysis shows that the average hysteresis energy of SRC1 after 10 cycles is about 8%–15% lower than that of SRC1-2 after 3 cycles, which indicates that the cumulative damage caused by...
multiple cycles with large displacement reduces the energy dissipation capacity of the specimens. The larger the steel ratio and stirrup ratio, the greater the average hysteresis energy and the stronger the energy dissipation capacity. Thus, increasing the steel ratio and stirrup ratio can effectively improve the energy dissipation capacity of the specimens. The average hysteresis energy of SRC6 with large axial compression ratio is significantly lower than that of SRC2 with small axial compression ratio. It indicates that the larger the axial compression ratio, the worse the energy dissipation capacity of the specimen.

3.6.2. Effect of Cumulative Damage on Hysteresis Energy Dissipation. Figure 8 shows the relation curves between the hysteresis energy $E$ and the number of cycle loading $N$, and the corresponding relation between $N$ and the displacement angle $\theta$ is the same as that described in Section 3.5.2. As shown in Figure 8, when the displacement angle is 1.0%, 1.5%, and 2.0%, with the increase of the number of cyclic loading, the hysteresis energy of the specimens is basically the same or slightly decreased and the decrease range is not more than 10%. It suggests that the cumulative damage caused by multiple cycles of displacement is slight and has little impact on the energy dissipation of the specimens. When the displacement angle is 2.5% and 3.0%, the hysteresis energy of the specimens remains the same or slightly increased with the increase of the number of cyclic loading, and the maximum increase range is 8.0%. Hence, the cumulative damage still has little influence on the energy dissipation capacity of the specimens. When the displacement angle is 3.5%, with the increase of the number of cycles, the damage degree of SRC3 increases gradually, the hysteresis energy increases rapidly, and the energy dissipation capacity increases continuously.

In general, the cumulative damage has little effect on the energy dissipation capacity of the specimens. When the specimen approaches failure, due to the increase of cumulative damage degree, the energy dissipation capacity still increases with the increase of the number of cycle loading to some extent although the horizontal load of the specimen decreases significantly.

3.6.3. Ultimate Hysteresis Energy and Ultimate Equivalent Viscous Damping Coefficient. When the specimen reaches the failure state, the corresponding hysteresis energy and
equivalent viscous damping coefficient are defined as the ultimate hysteresis energy $E_u$ and the ultimate equivalent viscous damping coefficient $h_{eu}$, respectively. $E_u$ and $h_{eu}$ can reflect the ultimate energy dissipation capacity of the specimen [28]. The larger $E_u$ and $h_{eu}$, the stronger the ultimate energy dissipation capacity of the specimen. The horizontal load falling to 85% of the peak load is taken as the failure criterion of the specimen. The displacement amplitude and hysteresis curve corresponding to the failure of the specimen [28]. The larger $E_u$ and $h_{eu}$ of the specimen are determined, and $E_u$ and $h_{eu}$ of each specimen are calculated. The calculation results are shown in Figures 9 and 10. It can be concluded that

1. When the failure state is reached, the ultimate equivalent viscous damping coefficient $h_{eu}$ of the specimens is 0.183–0.299, mostly above 0.2, which is greater than the ultimate equivalent viscous damping coefficient 0.1–0.2 of RC columns with bending failure [30]. It indicates that the SRC columns have better energy dissipation capacity than the RC columns.

2. With the increase of steel ratio and stirrup ratio, $E_u$ and $h_{eu}$ of the specimens increase gradually. $E_u$ and $h_{eu}$ of SRC3 with the maximum steel ratio are 1.9 times and 1.21 times than those of SRC1 with the minimum steel ratio, respectively; and $E_u$ and $h_{eu}$ of SRC5 with the maximum stirrup ratio are 1.14 times and 1.08 times than those of SRC4 with the minimum stirrup ratio, respectively. It can be concluded that increasing the steel ratio and stirrup ratio can improve the ultimate energy dissipation capacity of the specimens, and increasing the steel ratio is more effective.

3. $E_u$ and $h_{eu}$ of SRC2 with small axial compression ratio are larger than those of SRC6 with a large axial compression ratio. Therefore, the ultimate energy dissipation capacity of the specimens decreases with the increase of the axial compression ratio.

4. The number of cyclic loading has the greatest influence on the ultimate energy dissipation capacity of the specimen. $E_u$ and $h_{eu}$ of the specimens after 10 cycles are significantly lower than those of the specimens after 3 cycles. The former is only 0.52–0.65 times and 0.69–0.75 times of the latter, respectively. The cumulative damage greatly reduces the ultimate energy dissipation capacity of the specimens.

4. Conclusion

The cumulative damage behavior of SRC columns under far-field long-period ground motions was simulated and studied by quasi-static tests with the same displacement for 10 times. Through the quasi-static tests of 8 SRC columns under the cyclic loading with the same displacement for 10 or 3 times, the test phenomena and results are comprehensively analyzed. The conclusions are drawn as follows:

1. Bending failure is the main failure mode of the specimens. During the failure, the concrete cover is severely crushed and peeled off, the longitudinal reinforcement and stirrup are exposed and buckled, and the section steel is partially buckled. Compared with the specimens after 3 cycles, specimens after 10 cycles have a larger crack width at the same displacement angle cycle, smaller displacement angle at the same failure characteristics, and more significant failure degree.

2. For the specimens subjected to the cyclic loading of same displacement for 10 times, increasing the steel ratio can improve the peak load of the specimens, and increasing the stirrup ratio has less effect on increasing the peak load of the specimens. With the increase of steel ratio and stirrup ratio, the deformation capacity and energy dissipation capacity of the specimens enhance, and the rate of stiffness degradation slows down. With the increase of the axial compression ratio, the deformation capacity and energy dissipation capacity of the specimens decrease, and the stiffness degradation rate increases at the later stage of loading.

3. With the increase of the number of cyclic loading, the cumulative damage of 10 cycles before the peak load is slight, which has little impact on the bearing capacity, secant stiffness, and energy dissipation
capacity of the specimens; after the peak load, the cumulative damage caused by multiple cycles of displacement is serious, and the reduction range of bearing capacity and stiffness of the specimens in the 10th cycle is greater than that in the 3rd cycle; and the smaller the steel ratio and stirrup ratio, the larger the axial compression ratio and the larger the reduction range of the specimens. Besides, increasing the steel ratio and stirrup ratio can effectively reduce the reduction range of the bearing capacity and stiffness of the specimens caused by multiple cycles of the same displacement cumulative damage.

(4) The number of cyclic loading has a significant effect on the cumulative damage performance of the specimens. Compared with specimens after 3 cycles, the peak load of the specimens after 10 cycles changes slightly, while the fullness of the hysteresis curve decreases, the deformation capacity and the ultimate energy dissipation capacity decrease, and the stiffness degradation is more significant after the peak load.

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.

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