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Seismic performance of RC columns with full resistance spot welding stirrups

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Abstract. This paper aims to investigate the seismic performance of RC short columns and long columns with welding stirrups. Through the low-cyclic horizontal loading test of specimens, the seismic performance indexes such as failure modes, hysteretic curve, skeleton curve, ductility, energy dissipation capacity, stiffness degradation and strength degradation were emphatically analyzed. Furthermore, the effects of shear span ratio, stirrups ratio and axial compression ratio on the performance of specimens were studied. The results showed that the seismic performance of the RC short columns with welding stirrups were basically the same as that of the RC short columns with traditional stirrups, but the seismic performance of RC long columns with welding stirrups was better than that of RC long columns with traditional stirrups. The seismic performance of RC short columns and long columns with welding stirrups could be improved by increasing stirrup ratio and shear span ratio and reducing axial pressure ratio. Moreover, the welding stirrup have the advantages of steel saving, industrialization and standardization production, convenient construction, and reducing time, which indicated that the welding stirrups could be applied in practical engineering.

Keywords: welding stirrups; reinforced concrete; short column; long column; seismic performance

1. Introduction

The application of reinforced concrete structure in civil engineering is very wide, concrete, steel bars and formwork are the major building materials for cast-in-place reinforced concrete structures. With the continuous development of industrialization, concrete has been commercialized and concentrated production, the stereotype combination template and the slip form for the concrete formwork also appeared. However, the construction of steel bars is still basically the traditional method of artificial banding. In the traditional construction process of RC column, there are several steps to construct the stirrup configuration, such as artificial molding, assembly, binding and so on. It not only costs a lot of construction cost, but also difficult to guarantee the quality of processing and assembling. Therefore, it is the demand of social development to seek a more efficient, convenient and energy-saving steel bar configuration. In addition, the disaster survey conducted after the major earthquakes showed that the damage of the reinforced concrete frame column is very serious, and its damage is an important reason for the destruction or even collapse of the reinforced concrete structure, and its damage is closely related to the stirrup that takes an important role to bear the shear force in the column and constrain the concrete in the core area. Therefore, the research on the seismic performance of concrete columns under different stirrup constraints will be of great significance.

In this context, the welding stirrup technology develops rapidly, it is to overlap the reinforcement vertically and horizontally, equal strength welding is applied at intersection of reinforcement to obtain the mesh, which was used to replace the traditional composite stirrup (As shown in Fig.1 (a)) in RC column. All of intersection of reinforcement can adopt resistance spot welding, or the middle part can adopt resistance spot welding, and the surrounding part adopts flash butt welding. The welding stirrup used in this experiment is fully resistance spot welding, as shown in Fig.1 (b). Comparedh with traditional stirrup with bending hooks, welding stirrup have the following advantages: welding stirrup can reduce steel consumption because there is no bending hook and the repeated part of the traditional composite stirrup is removed. For projects with large amount of stirrups, the economic benefit is considerable. In addition, the hindrance of bending hooks is avoided, the internal space of steel bar skeleton is increased, which is beneficial to the pouring of concrete and the construction quality can be improved. Besides, the welding stirrup can be pre-fabricated in the factory, and the factory processing can be made into any complex stirrup form, while ensuring the processing quality and dimensional accuracy, saving construction time.

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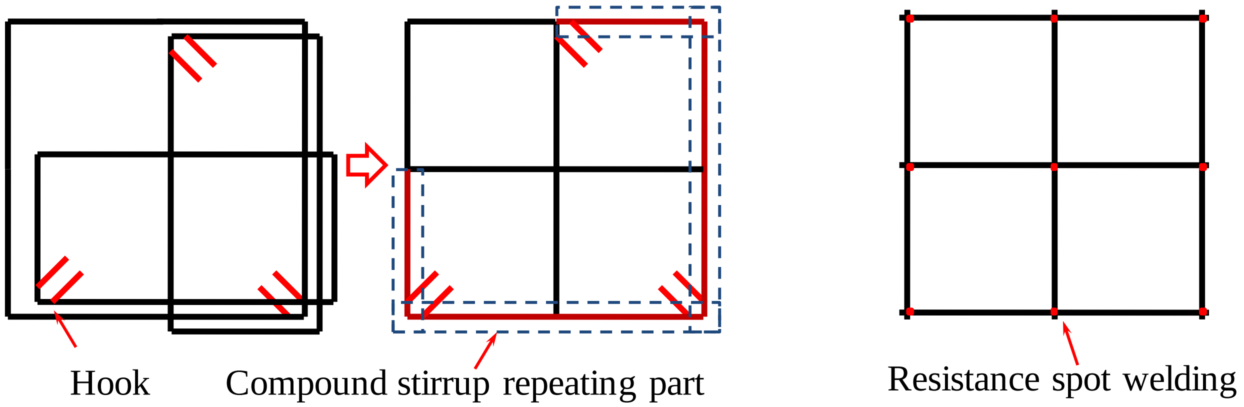


(a) Traditional stirrup (b) Full resistance spot welding stirrup

Fig. 1 Traditional stirrup and welded stirrup

In recent years, welding stirrup technology has been attracted more and more attention to many researchers because of its excellent comprehensive benefits, and has been applied more and more in practical engineering. Saatcioglu *et al*. (1992, 1999) studied the seismic performance of welded stirrup concrete columns. The results showed that the welded stirrup column has better ductility than the traditional stirrup column under the same condition. And showed that welded stirrup column has great engineering significance, especially in the seismic design of columns with high reinforcement ratio, the use of welded stirrup could greatly reduce the workload, and eliminate the situation of internal reinforcement congestion, conducive to the concrete pouring. Welded stirrup can be used as a reliable transverse reinforcement, but the strength must be higher than the strength of the stirrup itself, otherwise the overall strength and ductility of the stirrup will be affected. Baumann (2004, 2006, 2008) *et al*'s research showed that welding stirrup has not only in engineering applications to save materials, reduce the labor force, speed up the construction progress and other advantages, and still have sufficient strength and ductility in high-strength concrete specimens. Stirrup restraint welding tests showed that the high strength concrete specimen under seismic action were more resistant than traditional stirrup specimen. Li *et al*. (2012) conducted hysteresis test study on welding ring stirrup high-strength concrete columns. The results showed that the welding ring stirrup can exerted better restraint on high strength concrete, and the hysteretic curve of welding ring stirrup specimen was higher than that of ordinary RC specimen, and the energy dissipation capacity and ductility were improved. Li *et al*. (2016) carried out in-depth research on the seismic behavior and restoring force model of high-strength concrete columns with welding ring stirrup under high axial compression ratios, which showed that the bearing capacity of welding ring stirrup confined high strength concrete columns is much higher than that of ordinary stirrup columns. Yan *et al*. (2017) studied the seismic behavior of welding ring stirrup-constrained concrete based on two factors: axial compression ratio and stirrup ratio. The results show that the seismic performance is good and can meet the requirements of engineering practice.

At present, the application of stirrup flash butt welding technology has been very extensive, and in China there are already relevant technical regulations for construction quality guidance and constraints. However, the application of welding stirrup with full resistance spot welding in China's high-rise structures very rare, which is mainly lack of relevant design specifications, making the application in engineering relatively conservative and unable to give play to the advantages of this form of welding stirrup, and difficult to popularize them in engineering. In order to further popularize the application of welding stirrup, experimental research and theoretical analysis are needed to provide data support for standard design and engineering application (Yang *et al*. 2004, Luo *et al*. 2012).

In this paper, the seismic performance of RC long and short columns with welding stirrups and traditional stirrups are compared and tested. The seismic pseudo-static test of 17 RC columns was conducted and introduced, and the effects of axial compression ratio and stirrup ratio on the seismic performance of welding stirrup RC columns were analyzed. Through the comparative analysis of the failure phenomenon, hysteresis curve, skeleton curve, ductility coefficient, stiffness degradation and strength attenuation of welding stirrup RC columns under low cyclic repeated loading, the seismic behavior was discussed in detail, which can be utilized to provide reference for similar experiments and engineering applications.

2. Test program

2.1 Test specimens

In this experiment, seventeen specimens were designed, including six RC short columns with welding stirrups and three RC short columns with traditional stirrups as comparative specimens, and five RC long columns with welded grid stirrups and four RC long columns with traditional stirrups were also designed as comparative specimens. The short columns had a cross section of 350mm×350 mm, and the long columns had a cross section of 300mm×300mm. The details of all the specimens are shown in Table 1, Fig. 2 and Fig. 3, and the material properties of reinforcements are shown in Table 2.

Table 1 Design details of specimens

Specimen No.	Stirrup type	Height (mm)	Shear span ratio	Concrete strength (MPa)	Longitudinal reinforcement		Stirrup		Axial compression ratio
					Reinforcing bars	Reinforcement ratio	Reinforcing bars	Stirrup ratio	
BSC1	Banded	700	2.0	35.6	10C32	6.89	B8@150	0.49	0.36
WSC2	Welded	700	2.0	35.6	10C32	6.89	B8@150	0.49	0.36
BSC3	Banded	700	2.0	35.6	10C32	6.89	B8@150	0.49	0.28
WSC4	Welded	700	2.0	35.6	10C32	6.89	B8@150	0.49	0.28
BSC5	Banded	700	2.0	26.8	10C32	6.89	B8@100	0.74	0.48
WSC6	Welded	700	2.0	26.8	10C32	6.89	B8@100	0.74	0.48
WSC7	Welded	700	2.0	26.8	10C32	6.89	B8@150	0.49	0.48
WSC8	Welded	525	1.5	26.8	10C32	6.89	B8@100	0.74	0.48
BLC1	Banded	900	3.0	41.2	10B20	4.19	B8@80	2.4	0.45
WLC2	Welded	900	3.0	41.2	10B20	4.19	B8@80	2.4	0.45
BLC3	Banded	900	3.0	41.2	10B20	4.19	B8@100	1.9	0.45
WLC4	Welded	900	3.0	41.2	10B20	4.19	B8@100	1.9	0.45
BLC5	Banded	900	3.0	41.2	10B20	4.19	B8@80	2.4	0.39
WLC6	Welded	900	3.0	41.2	10B20	4.19	B8@80	2.4	0.39
BLW7	Banded	900	3.0	41.2	10B20	4.19	B8@100	1.9	0.39
WLC8	Welded	900	3.0	41.2	10B20	4.19	B8@100	1.9	0.39
WLC9	Welded	900	3.0	41.2	10B20	4.19	B8@80	2.4	0.33

Table 2 Material properties of reinforcements

Steel type	Steel grade	Diameter(mm)	Yield Strength / MPa	ultimate strength / MPa	modulus of elasticity / 10^5MPa
Welded stirrup	HRB335	8	602	690	2.10
Ordinary stirrup	HRB335	8	571	672	1.91
Longitudinal reinforcement	HRB335	16	425	512	1.91
	HRB335	20	578	680	1.91
	HRB400	32	540	943	1.90

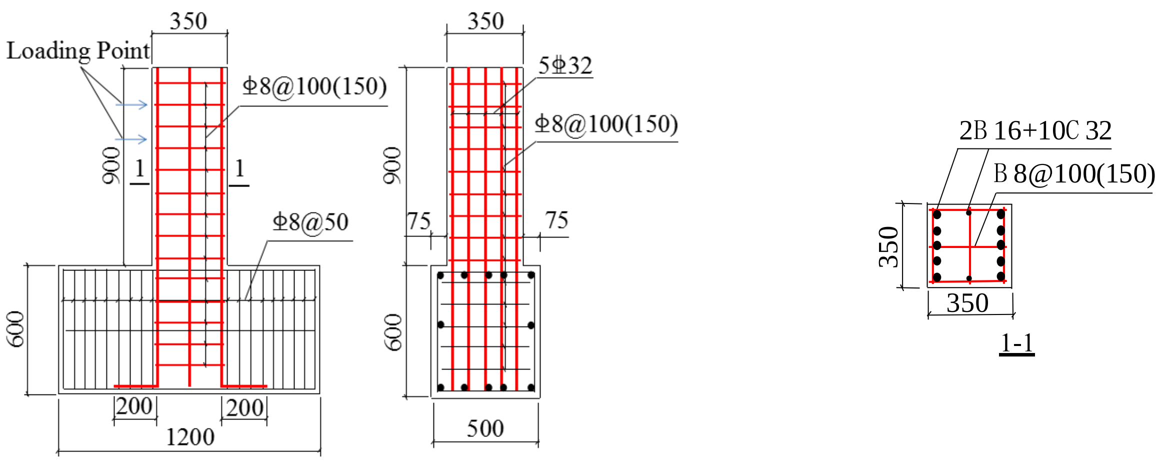


Fig. 2 Design details of short columns

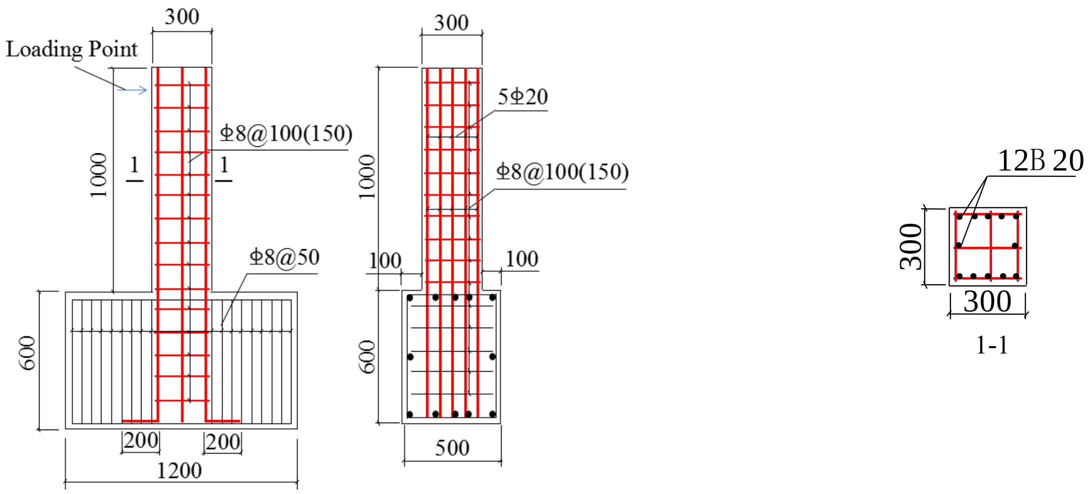


Fig. 3 Design details of long columns

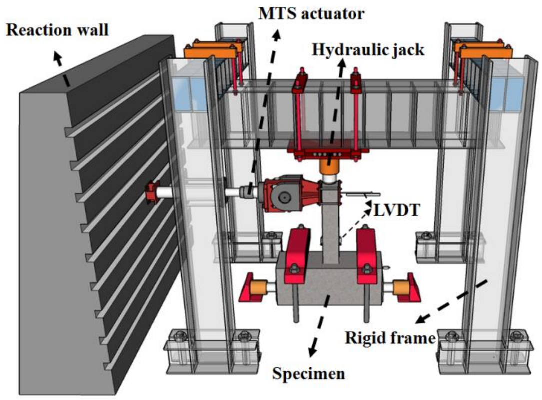


Fig. 4 Loading setup

2.2 Load set-up and protocol

All the specimens were conducted in Structural Engineering Key Laboratory of Xi'an University of Architecture and Technology. During the test, the constant vertical load was loaded on the top of column by hydraulic jack, and the load value was determined according to the axial pressure ratio. Besides, the horizontal loads were loaded by electro-hydraulic servo actuators, as shown in Fig.4. The loading protocol were illustrated in Fig.5. In the initial elastic phase, the MTS actuator reversely loaded one cycle for each loading step, and after yield, the displacement was reversely repeated three cycles for each loading step. It was not until the horizontal load decreased to less than 85% of the peak load that the experiments ended. During the test, several strain gauges were used to monitor the response of the reinforcement and stirrup, and the data of the strain gauges is automatically collected by the TDS-602 static strain gauge acquisition system.

3. Test results

3.1 Failure pattern

3.1.1 Failure pattern of short columns

In the initial stage of loading, many tiny transverse cracks appeared at the root of the column, and, these lateral

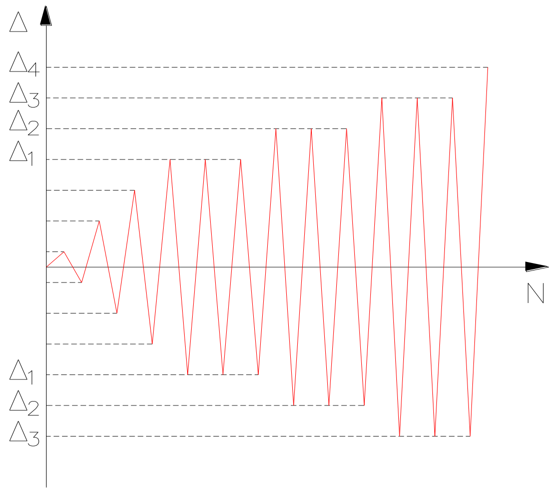
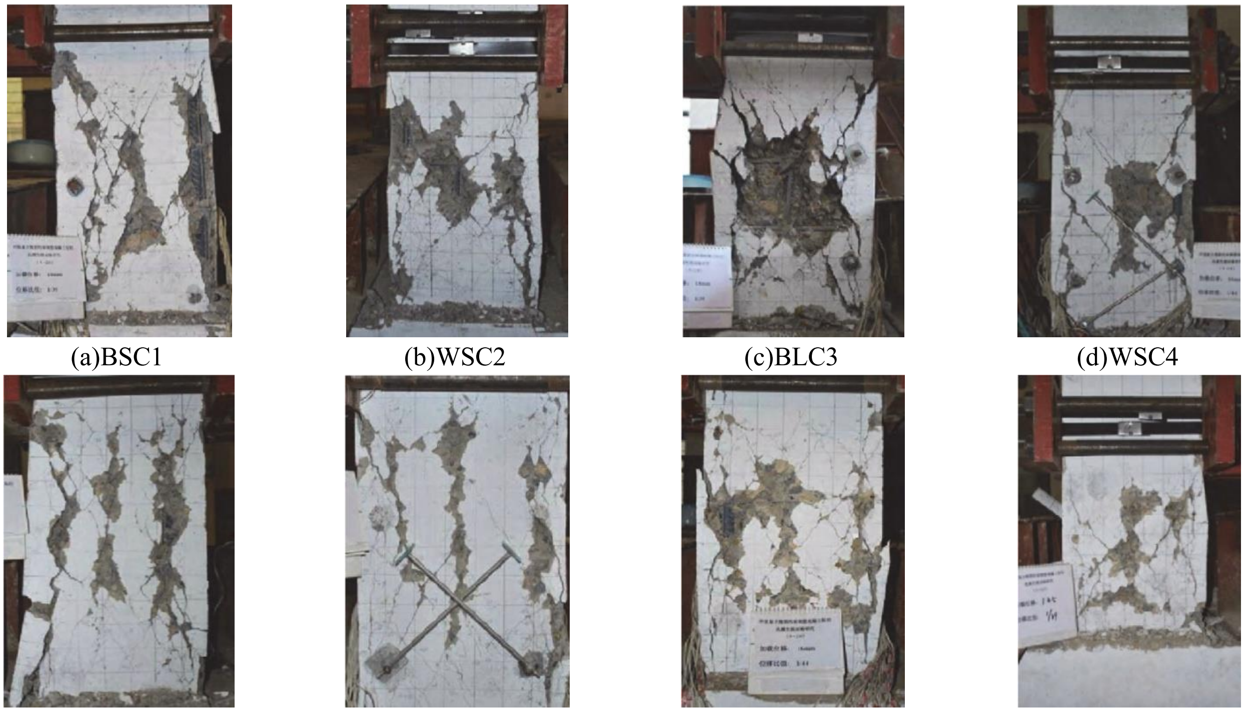


Fig. 5 Loading protocol of the test

cracks extended and developed obliquely. With the increase of load, obvious shear diagonal cracks in specimens BSC1, WSC2, BSC3 and WSC4 were observed, and the stirrups reached yield strength. Although slight-bond-split cracks were also generated between longitudinal reinforcement and concrete, it did not constitute to develop with the test going on. These four short columns failed in shear compression failure. For specimens BSC5, WSC6,and WSC7, the concrete strengths of them were lower than those of the first 4 short columns, and the axial compression ratios of them were higher than those of the first 4 short columns. When the horizontal load reaches about 75% of the maximum load, the bond-slip cracks between the longitudinal reinforcement and concrete occurred, subsequently, the vertical and oblique fine cracks occur appeared with the displacement increasing, and therefore the action between concrete and longitudinal reinforcement was not, combined thoroughly. As the load increases, the bearing capacity of the specimens began to decrease, and the specimen reached the ultimate state, these three short column specimens exhibited shear-bond failure mode. For specimen WSC8, which shear span was relatively small, the symmetrical main oblique cracks were observed and stretched to the bottom of the column



(a)BSC1 (b)WSC2 (c)BLC3 (d)WSC4

(e)BSC5 (f)WSC6 (g)WSC7 (h)WSC8

Fig. 6 Failure patterns of short columns

(a)BLC1 (b)WLC2 (c)BLC3 (d)WLC4 (e)BLC5

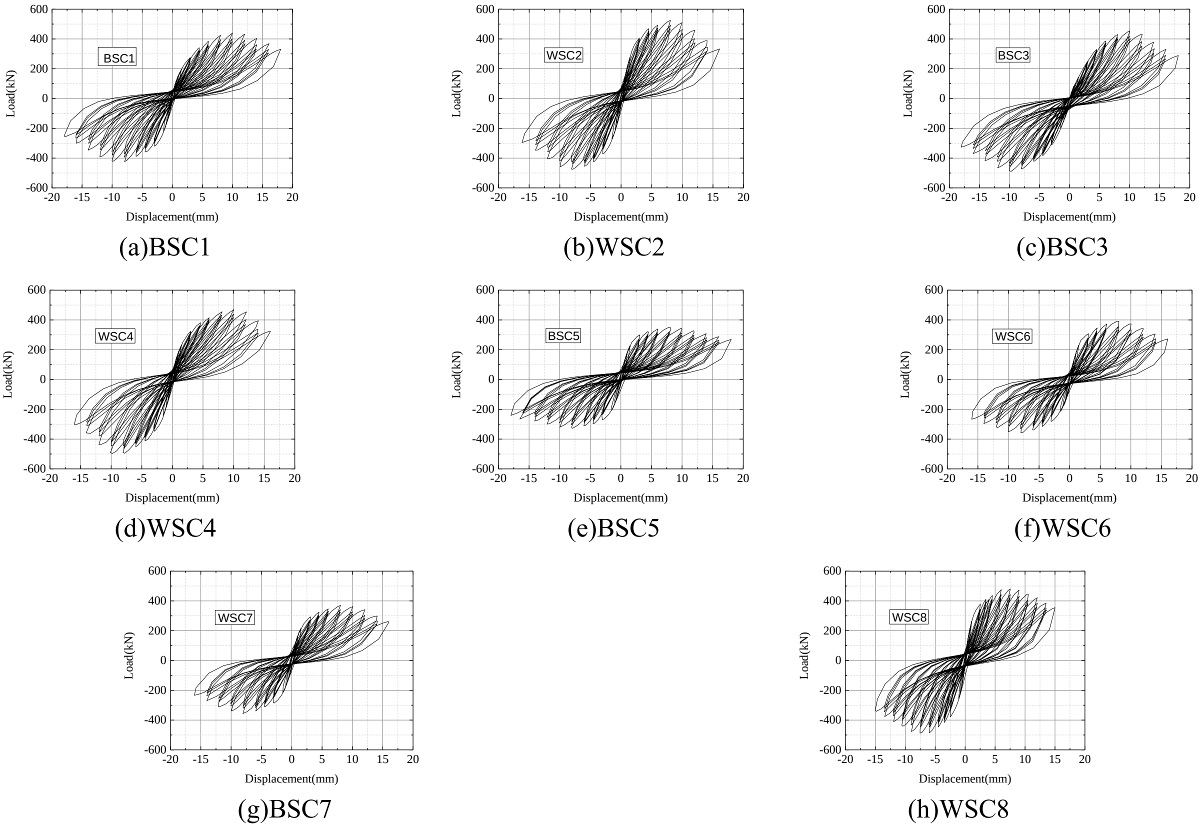
(f)WLC6 (g)BLC7 (h)WLC8 (i)WLC9

Fig. 7 Failure patterns of long columns

when the load reaches 85% of the maximum load. With the increase of load, the oblique cracks became more and more wide, and the concrete cover spalled off. Finally, the spalling of the concrete in the middle of the short column was serious, the longitudinal reinforces were exposed, and the stirrups still have not reached yield strength, which showed that the specimen WSC8 failed in shear compression failure. The failure pattern of each short column is shown in Fig.6.

3.1.2 Failure pattern of long columns

In this experiment, the crack development and the damage pattern of the long columns with welding stirrups and the long columns with traditional stirrups were basically the same, and all of them failed in bending failure mode. In the initial stage of loading, transverse cracks appear on the edges of the front and back surfaces of the column within about 500 mm height on the bottom of the

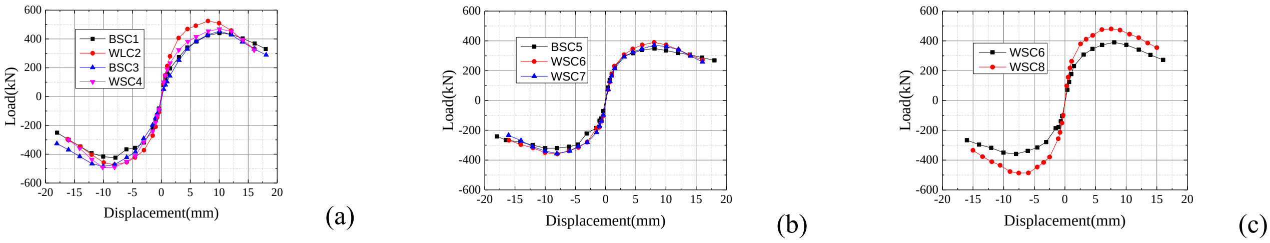


(a)BSC1 (b)WSC2 (c)BSC3

(d)WSC4 (e)BSC5 (f)WSC6

(g)BSC7 (h)WSC8

Fig. 8 Hysteretic curves of short columns



(a) (b) (c)

Fig. 9 The skeleton curves of short columns

column. With the increase of load, these cracks on the edge continue to develop and extend, and, new transverse cracks appeared on the edge of the column surface. Because of the compressive bending tendency of longitudinal reinforcements, the vertical cracks appeared and developed continuously. Finally, the specimen was damaged with the concrete at the corner of the end of the column peeling off. The failure pattern of each short column is shown in Fig.7.

3.2 Load-displacement curves

3.2.1 Hysteretic curves and skeleton curves of short columns

The hysteretic curve of each specimen is shown in Fig. 8. Because the failure modes of these specimens were shear compression failure or shear-bond failure, the "pinching" effect of each curve was obvious, and the hysteretic curve of each short column presented inverse "S" shaped, which showed that there were bond-slips in short columns. The hysteretic curves of short columns with welding stirrups were basically the same as those of short columns with traditional stirrups. Moreover, poor energy dissipation, and high speed of degradation of stiffness and strength were observed in Fig. 8.

The skeleton curves of short columns are shown in Fig. 9. The skeleton curve can reflect the yield displacement, yield load, ultimate displacement, ultimate load, and ductility of the structure or component, and these important indexes are generally employed to measure the seismic performance of RC short columns with welding stirrups. From Fig.9(a),(b),(c), it can be found, under the same conditions, that the maximum horizontal loads of short columns with welding stirrups were larger than those of short columns with traditional stirrups, the maximum horizontal loads of the short columns with welding stirrups decreased with the increase of the shear span ratio, and increases with the increase of stirrup ratio and axial pressure ratio. In addition, the yield strength of traditional stirrup in this experiment was 30 MPa lower than that of welding stirrup, but this difference was not significant for

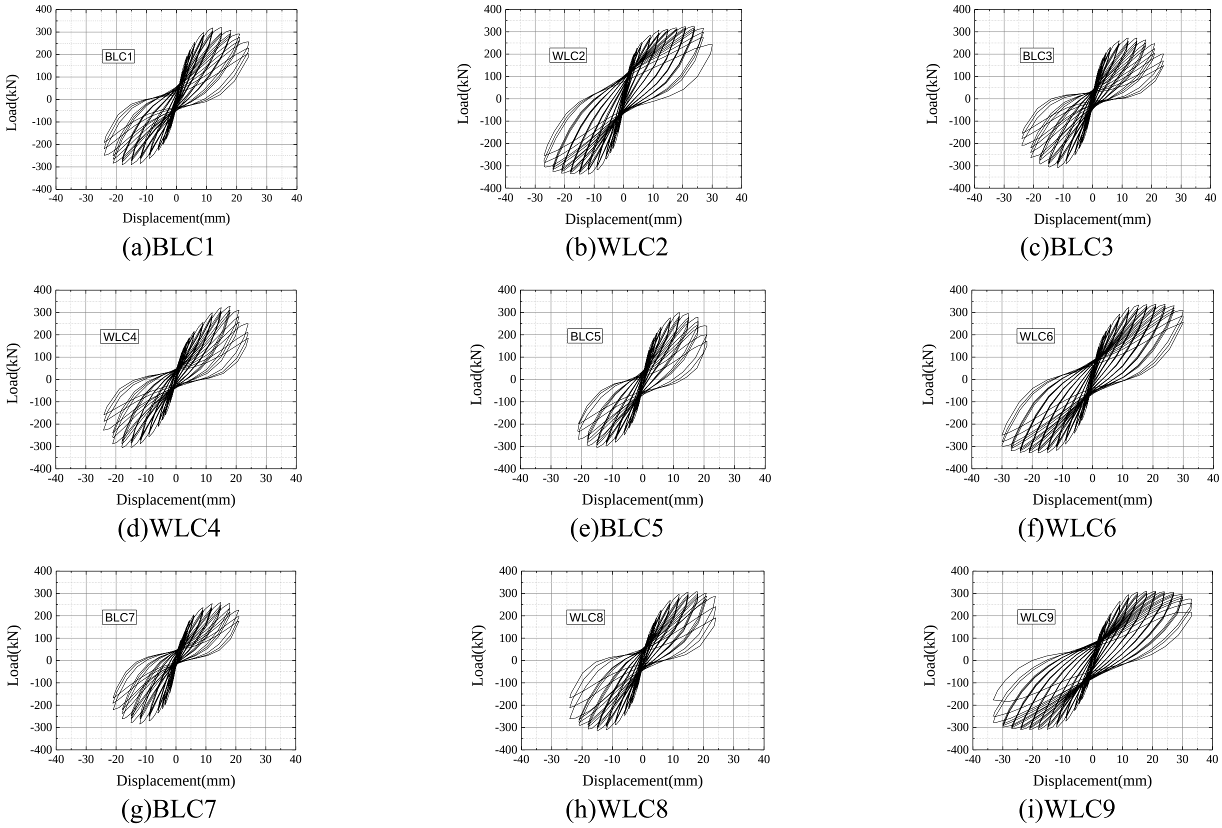


Fig. 10 Hysteretic curves of long columns

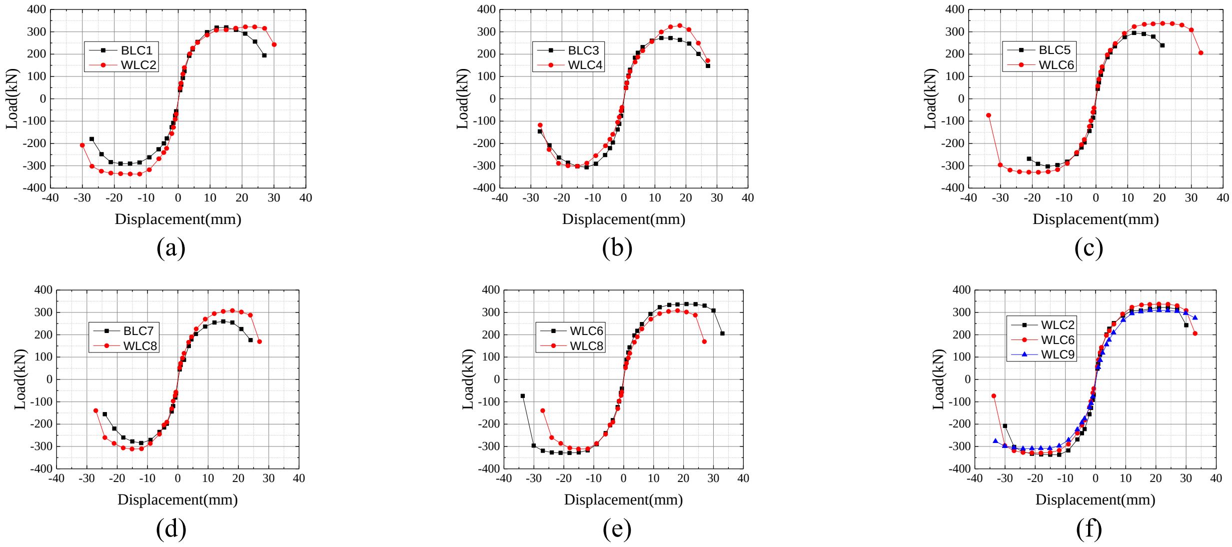


Fig. 11 Skeleton curves of specimens

overall seismic performance of the specimens and ignored in the following section.

3.2.2 Hysteretic curves and skeleton curves of long columns

The hysteretic curve of each long column is shown in Fig.10. It can be seen from the Fig.10, the hysteretic curves of long columns with welding stirrups were fuller than those of long columns with traditional stirrups, which indicated that the energy dissipation performance of the long columns with welding stirrups was better than that of long columns with traditional stirrups. By comparing the hysteretic curves of WLC2, WLC6 and WLC9, the hysteretic curves tended to be full with the change of the axial pressure ratio from large to small under the same reinforcement ratio. When the axial compression ratio was 0.33, the hysteretic curve of the specimen was close to a spindle shape, which showed that the energy dissipation of the long column with welding stirrups was enhanced with

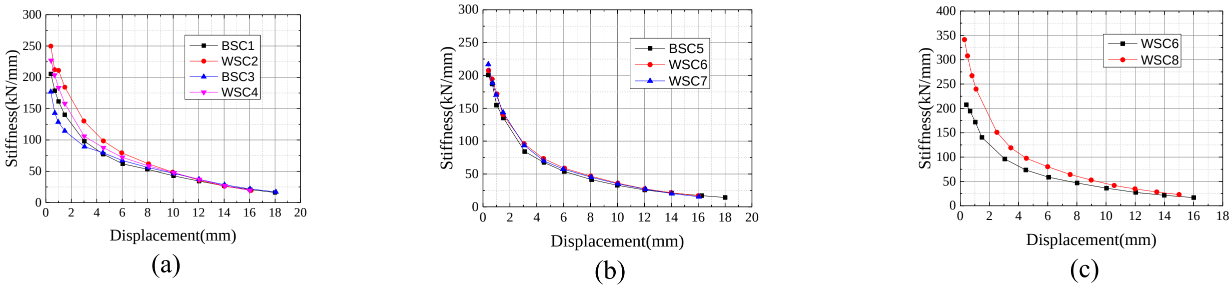


Fig. 12 Comparison of the stiffness degradation for short columns

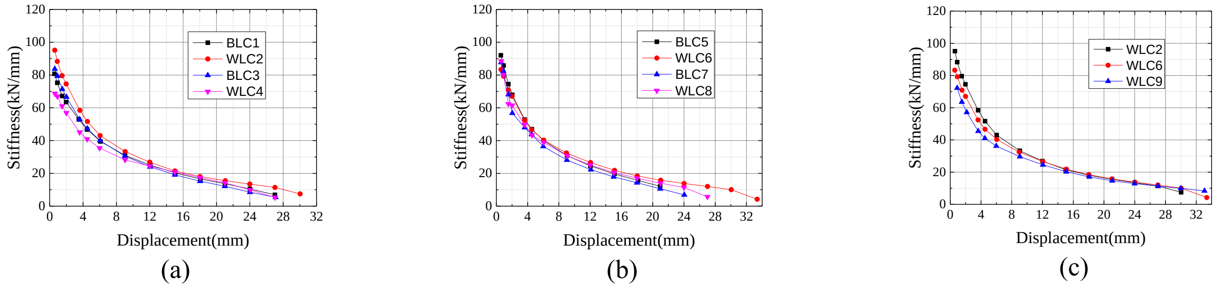


Fig. 13 Comparison of the stiffness degradation for long columns

the decreasing of axial compression ratio. The axial compression ratio of WLC2 and WLC4 were all 0.45, and WLC2 had a higher stirrup ratio than WLC4, so the hysteretic curves of WLC2 and WLC4 showed, the energy dissipation performance of the long column increased with the increasing of the stirrup ratio.

The skeleton curves of long columns are shown in Fig. 11. It can be seen from the (a), (b), (c), (d) that the skeleton curves of RC columns in the two stirrup forms were similar under the same axial compression ratio and stirrup ratio, and the peak load of long columns with welding stirrups was slightly greater than that of long columns with traditional stirrups. The axial compression ratio of the two specimens BLC5 and WLC6 was 0.39 and the stirrup ratio was 2.4%,WLC6 had a 12.2% increase in maximum horizontal load compared to BLC5.After the specimen reached the yield strength, the bearing capacity of the long columns with welding stirrups decreased slowly. From Fig. 11(e), it could be found that in the case of the same experimental axial compression ratio (n=0.39), the bearing capacity of WLC6 and WLC8 were 337.2kN and 308.1kN, respectively, it showed that the bearing capacity increased with the increase of the stirrup ratio. From the skeleton curves of WLC2, WLC6 and WLC9, in the case of the same stirrup ratio, the horizontal bearing capacity of the specimen is slightly reduced with the reduction of axial compression ratio.

3.3 Stiffness

For the seismic pseudo-static test, the degradation of stiffness was usually observed, which was one of the major cause of degradation of seismic performance of specimen. Here, the secant stiffness index Ki was used to reflect the stiffness degradation of each specimen, which was calculated by the following equation

$$\mathrm{K_i} = \frac{|-P_i| + |-P_i|}{|+\Delta_i| + |-\Delta_i|} \tag{1}$$

The relationships between the stiffness and the displacement are shown in Fig. 12. From Fig. 12(a), before the displacement reached 9mm, the stiffness degradation of short columns was rapid because of the bond-slip and diagonal cracks. Besides, the short columns with traditional stirrups had a faster stiffness degradation rate than the short columns with welding stirrups. When the displacement reached 9mm, stirrups had already yielded, the shear force was sustained by the concrete in the core section, which leading to the stiffness degradation rates of the four short columns were basically the same. Furthermore, the stiffness degradation rate was reduced with the increasing of the axial compression ratio. The reason may be that the axial force restricted the development of the diagonal cracks. The stiffness degradation curves of the short columns with welding stirrups and traditional stirrups under different stirrup ratio were presented in Fig. 12(b). From Fig. 12(a), it can be found that the increase of stirrups ratio did not effectively delay the stiffness degradation. Fig. 12(c) plotted the stiffness degradation curves of specimens under different shear span ratio conditions, the stiffness degradation rate of WSC8 was faster than that of WSC6, therefore, the smaller the shear span ratio, the faster the rate of stiffness degradation.

The regularity of the stiffness of the long column specimens and the displacement is shown in Fig.13. In the initial stage of loading, tensile cracks appeared and quickly extended, which leading to a rapid reduction in stiffness. With the increase of displacement, the shear force was mainly carried by the concrete in the core area, so the stiffness degradation of the specimen slowed down. From Fig. 13(a), it can be observed that for specimens with the

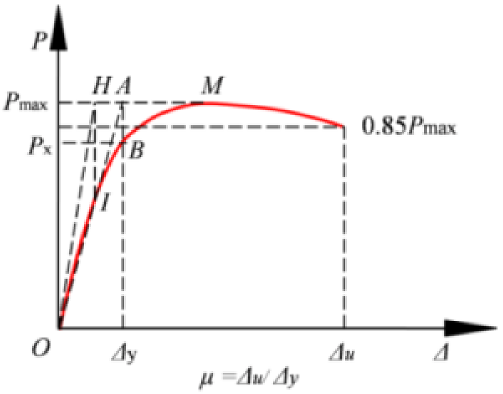


Fig. 14 Definition of the ductility

same stirrup ratio, as the axial compression ratio increased, the stiffness degradation rate increases. Besides, from Fig. 13(b)-(c), it can be found that under the same axial compression ratio, the speed of stiffness degradation slowed down with the increase of the stirrup ratio.

3.3 Ductility coefficient

Generally speaking, ductility coefficient is adopted to analyze the ductility resistance of structural component, each column, the definition of ductility coefficient is shown in Fig.14. The yield displacement, ultimate displacement, and ductility coefficient are listed in Table 3.

From the comparison of the ductility coefficients of BSC1 and WSC2, BSC3 and WSC4 listed in Table 3, it can be seen that the ductility of the short columns with welding stirrups was better than the short columns with traditional stirrups. However, there was a great difference in positive displacement ductility for specimen BSC5 and WSC6, this may be due to the error of the experimental data, and it may also be that in the case of a relatively high axial pressure, as the amplitude of the displacement increases, the hysteresis curve appears unstable, resulting in a faster degradation of the strength of the member. From the overall experimental data, short columns with welding stirrups exhibited better displacement ductility than that of short columns with traditional stirrup. Furthermore, with the change of the axial compression ratio and the stirrup ratio, the change rule of displacement ductility of short columns with welding stirrups is basically consistent with that of short columns with traditional stirrups. From the comparison of WSC6 and WSC7, the displacement ductility of the short column increased with the increase of the stirrup ratio. Compared WSC6 with WSC8, with the increase of the shear span ratio, the ductility was also increased. However, from the results of the specimens BSC1, BSC3 and WSC2, WSC4, the ductility of specimens tended to increase with the increase of axial compression ratio, this was inconsistent with previous related research results. The reason for the analysis may be as follows. Due to the high reinforcement ratio of the longitudinal reinforcement, the lateral restraint of the concrete in the core area is increased, so that it is closer to the three-way compression state, and the longitudinal reinforcement bears more Vertical load, while the concrete part bears less vertical load, then the vertical load of the concrete part increases with the increase of the axial pressure when the concrete part bears a small vertical load. The state of three-way compression will be more sufficient, and thus the ductility will increase.

From Table 3, it can be found that the ductility coefficient of the long columns with welding stirrup is slightly higher than that of the long columns with traditional stirrups, it showed that the seismic performance of the long columns with welding stirrups was better than that of the long columns with traditional stirrups in this experiment. Compare the ductility coefficient of WLC2, WLC6 and WLC9, it can be observed that the displacement ductility coefficient of the specimen increased slightly with the reduction of axial compression ratio; and from the comparison of ductility coefficients of WLC2, WLC4, WLC6 and WLC8, it could be concluded that the displacement ductility coefficient of the specimens increased with the increase of the stirrup ratio.

3.4 Energy dissipation capacity

When an earthquake occurs, the structure is in the seismic energy field, and continuous energy input and dissipation occur between the ground and the structure. When the structure enters an elastoplastic state, its seismic performance mainly depends on the dissipate energy performance. In the stage of increasing the load, the area enclosed by the load-displacement curve can reflect the energy absorbed by the structure (strain energy of the structure), and the area enclosed by the unloading curve and the loading curve is the dissipated energy. Therefore, the area of hysteresis loop in hysteresis curve is an important index to reflect the energy dissipation performance of structure. The energy Q dissipated in the corresponding cycle is obtained by calculating the area of each hysteresis loop in the hysteresis curve. The larger the Q value, the better the energy consumption capability. The energy dissipation of the short columns and long columns under each stage of cyclic displacement load are shown in Table 4 and Table 5, respectively. The number of cycles is represented by “n”, and the total energy dissipation is represented by “E”, unit kN·mm. Because the hysteresis curves for all the specimens almost are coincide with each other before the specimens reach the yield load, so this part of energy dissipation is neglected. Through comparative analysis, the following conclusions can be drawn:

(1) When specimens reached the yield load, peak load and ultimate load, the cumulative energy consumption of the test specimens WSC2 and WSC4 was greater than that of the test specimens BSC1 and BSC3.When WSC6 reached the yield load and peak load, the cumulative energy consumption was greater than that of the specimen BSC5, but the total energy consumption of the former was less than that of the latter. In general, the energy consumption of the welding stirrup short column is comparable to that of the short column with traditional stirrups or the former is slightly improved. By comparing the energy consumption of the specimens BSC1, BSC3, WSC2 and WSC4, the energy consumption increased with the axial pressure ratio increasing. Considering that the ratio of reinforcement was relatively high and the actual axial compression ratio of

Table 3 Results of ductility ratios

Specimen number	Positive							Negative						
	P_y/KN	Δ_y/mm	P_m/KN	Δ_m/mm	P_u/KN	Δ_u/mm	Ductility ratios	P_y/KN	Δ_y/mm	P_m/KN	Δ_m/mm	P_u/KN	Δ_u/mm	Ductility ratios
BSC1	322.6	4.08	440.6	10.00	374.5	15.69	3.85	332.8	3.43	424.4	7.93	360.7	13.34	3.89
WSC2	416.5	3.23	494.8	9.29	420.6	13.15	4.07	362.5	2.87	473.7	8.08	402.6	12.02	4.19
BSC3	374.7	5.73	453.8	10.05	385.7	13.74	2.40	382.0	4.42	489.2	9.72	415.8	14.05	3.18
WSC4	341.0	3.47	469.0	10.03	398.7	13.89	4.00	379.2	3.85	490.9	10.13	417.3	12.50	3.25
BSC5	271.7	2.48	351.6	7.89	298.9	14.09	5.68	258.1	2.75	328.1	7.91	278.9	14.75	5.36
WSC6	312.4	3.22	391.6	7.76	332.9	12.49	3.88	263.8	2.56	359.1	7.97	305.2	13.20	5.16
WSC7	294.7	3.16	370.4	8.05	314.8	13.33	4.22	262.8	2.45	356.3	8.06	302.9	12.37	5.05
WSC8	367.6	3.39	480.5	7.55	408.4	12.59	3.71	371.1	3.42	487.0	7.53	414.0	11.77	3.44
BLC1	255.6	6.16	319.8	15.06	271.8	22.14	3.59	181.4	6.36	209.4	18.05	177.9	27.12	4.26
WLC2	246.9	5.77	316.0	23.78	276.9	28.06	4.86	260.4	5.94	325.2	12.05	286.6	27.15	4.57
BLC3	216.6	6.93	272.0	12.07	231.2	22.07	3.19	245.2	5.72	307.7	11.61	261.6	21.11	3.69
WLC4	244.1	5.75	327.8	18.03	278.6	22.28	3.87	235.3	5.89	305.5	17.90	259.7	22.52	3.82
BLC5	229.5	5.68	300.6	11.89	255.5	19.32	3.40	234.2	5.38	304.0	14.96	258.4	22.14	4.11
WLC6	255.7	6.61	337.2	21.00	286.6	32.41	4.90	253.8	6.82	328.9	18.08	279.6	32.58	4.78
BLW7	204.8	5.93	259.6	14.99	220.7	21.25	3.58	221.6	5.00	284.7	12.08	242.0	19.13	3.82
WLC8	233.3	6.11	308.0	18.02	261.8	24.61	4.03	245.1	5.88	313.9	14.78	266.8	23.36	3.98
WLC9	235.6	6.45	309.9	17.65	263.4	32.55	5.05	235.4	6.72	310.0	24.03	263.5	33.74	5.02

Table 4 Energy dissipation of short concrete columns

Displacement	BSC1		WSC2		BSC3		WSC4		BSC5		WSC6		WSC7	
	n	*E*	*n*	*E*	*n*	*E*	*n*	*E*	*n*	*E*	*n*	*E*	*n*	*E*
$1\Delta_y$	3	1103	3	1544	3	958	3	1214	3	1479	3	1502	3	1432
$2\Delta_y$	3	1760	3	2301	3	1618	3	1828	3	1905	3	1921	3	1967
$3\Delta_y$	3	2400	3	3221	3	2410	3	2511	3	2649	3	2707	3	2664
$4\Delta_y$	3	3575	3	5027	3	3781	3	4007	3	3749	3	4314	3	3943
$5\Delta_y$	3	4622	3	6119	3	5005	3	5208	3	4516	3	4905	3	4694
$6\Delta_y$	3	5210	3	7184	3	6213	3	6256	3	5217	3	5648	3	5664
$7\Delta_y$	3	5860	1	2952	1	2677	1	2680	3	5890	1	2361	1	2375
$8\Delta_y$	1	2454							1	2415				
Total energy dissipation		26984		28348		22660		23705		27819		23352		22740

concrete was relatively low, the energy dissipation capacity increased slightly with the increase of axial compression ratio in the case of specimens with low axial compression ratio.

(2) By comparing the energy dissipation capacity of each long column specimens, the energy dissipation capacity of specimen WLC was obviously higher than that of specimen BLC, which indicated that the energy dissipation capacity of long column with welding stirrups was better, which were more conducive to resist earthquake action. From the energy consumption data of WLC2, WLC6, and WLC9, it can be concluded that the energy consumption capacity increased as the axial compression ratio decreased, and the energy consumption data of WLC2, WLC4, WLC5 and WLC8 indicated that the energy consumption of the long column with welding stirrups increased with the increase of the stirrup ratio.

4. Conclusions

Compared with the traditional stirrup, there is no doubt that the welding stirrup has the advantages of saving steel, facilitating concrete pouring and industrializing production in the production process. Through experimental research, it was concluded that the RC column with welding stirrups improved the seismic performance compared with the RC column with traditional stirrups. From the test results, some conclusions from the test were drawn as follows:

- The failure modes of RC short columns with welding stirrups are similar to those of RC short columns with traditional stirrups, shear compression and shear-bond failure were observed in the test. The hysteretic curve of each specimen showed a "pinching" effect. The ductility, energy dissipation capacity and the maximum bearing capacity of short column with welding stirrups were

Table 5 Energy dissipation of long concrete columns

Displacement	BLC1		WLC2		BLC3		WLC4		BLC5		WLC6		BLC7		WLC8		WLC9	
	n	E	n	E	n	E	n	E	n	E	*n*	*E*	*n*	*E*	*n*	*E*	*n*	*E*
1Δy	3	236	3	316	3	230	3	191	3	300	3	225	3	283	3	315	3	322
2Δy	3	651	3	873	3	681	3	616	3	716	3	674	3	694	3	741	3	757
3Δy	3	853	3	1026	3	854	3	805	3	921	3	813	3	885	3	841	3	904
4Δy	3	1377	3	1618	3	1401	3	1252	3	1425	3	1297	3	1338	3	1335	3	1353
5Δy	3	2891	3	3424	3	2707	3	2612	3	2825	3	2622	3	2726	3	2592	3	2704
6Δy	3	4731	3	5951	3	4517	3	4116	3	4551	3	4572	3	4056	3	4323	3	4109
7Δy	3	7394	3	8652	3	6449	3	6216	3	7484	3	7089	3	5403	3	6586	3	6597
8Δy	3	9635	3	12837	3	8293	3	8544	3	10398	3	10644	3	7280	3	9659	3	10200
9Δy	3	11889	3	16878	3	9378	3	10883	1	4586	3	14356	1	3129	3	11886	3	13762
10Δy	1	4704	3	20601	1	3602	1	4388			3	18111			3	13034	3	17522
11Δy			3	23231							3	21246			1	3767	3	21233
$12\Delta_y$			1	7778							3	22364					3	24575
$13\Delta_y$											1	7708					1	9342
Total energy dissipation		44363		103185		38110		39624		33205		111715		25795		55078		113379

basically the same as the short column with traditional stirrups, and even former short column were slightly higher.

- The failure modes of RC long columns with welding stirrups were similar to those of long columns with traditional stirrups, they all failed in bending failure mode. Under the same conditions, the hysteretic curve of the welded hoop concrete column is more full than the hysteresis curve of the traditional hoop concrete column, showing better hysteresis characteristics; the former peak load is slightly higher than the latter; After the yield load is reached, the falling section of the load-displacement curve of the welded stirrup concrete column is more gentle and the ductility is better.
- There was no obvious difference in seismic performance between the short columns with welding stirrups and with traditional stirrups, and the seismic performance of long columns with welding stirrups was higher than that of long columns with traditional stirrups. It shows that the stirrup resistance spot welding technology can be applied to the manufacturing process of composite stirrups and can be used in engineering practice.

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