EXPERIMENTAL STUDY ON THE SEISMIC PERFORMANCE AND INDEX FOR DIFFERENT PERFORMANCE LEVELS OF SRC COLUMNS

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ABSTRACT :

Six half scale steel reinforced concrete (SRC) columns were tested under cyclic loading. The effects of the axial compression ratio and stirrup ratio on the hysteretic characteristics of SRC columns were investigated. The results indicated that the displacement ductility index decreased with the increasing of the axial load and increased with the increasing of the stirrup ratio. When the axial compression ratio of specimens increased from 0.15 to 0.40, the displacement ductility index reduced with the proportion of 41.2%. When the stirrup ratio of the specimens increased from 0.78% to 1.86%, the displacement ductility index increased with the proportion of 17.8%. According to the damage characteristic and test data, a series of performance parameters and corresponding limit value that can be used to appraise the performance level of SRC columns under earthquake was proposed. It is suggested that the crack width and stress level of longitudinal bar, residual drift and ultimate drift index can be adopted as the key parameters to appraise the different seismic performance levels, i.e. functional, repairable and collapse avoidable, respectively. If the story drift angle be used as an appraisal parameter, it is recommended that the limit values for the four performance levels, i.e. fully operation, operation, repairable and collapse avoidable be 1/250, 1/150, 1/50 and 1/35, respectively. The conclusions of this paper can be used as references for the performance based seismic design and engineering practice.

KEYWORDS: steel reinforced concrete column, axial compression ratio, ductility index, hysteretic characteristics, seismic performance level

1 Introduction

The seismic behavior of SRC structures has been studied in Japan since the 1960s(Maeda, 1991, Wakabayashi, 1994, Otani,1996). Systematical studies on bearing capacity, seismic behavior and details of SRC specimens have been carried out. The effect of different parameters, such as shear span ratio, axial compression ratio and steel ratio et al, on strength and seismic behavior of SRC beams and columns under cyclic loading were researched. The studies of SRC structures in China have been carried out since 1980s. Jiang(1991) investigated the seismic behavior of lattice type SRC columns under cyclic loading. The calculation method of shear strength and ductility of SRC short columns was proposed. James(1994) tested 8 tow-third-scale SRC columns under cyclic loading to investigate the influence of stirrup ratio and concrete strength to the ductility of the specimens. The influence of the flange shear stubs to the flexural stiffness and strength of the specimens was also studied. Zhao(1996) studied the failure mode and deformation capacity of SRC columns based on the experimental study of 23 SRC columns and 3 RC columns under monotonic and cyclic loading. Li(2000) conducted an analytical work to investigate the relation of axial force and deformation capacity of SRC beam-columns. Jiang(2002) researched the main factors which affected the seismic behavior of steel reinforced high-strength concrete short columns based on the experimental study of 10 steel reinforced high-strength concrete columns and regular SRC columns under cyclic loading.

The work stated above studied the main influence parameters which affected the seismic behavior of SRC columns the most remarkably, but the deformation capacity and the index for different performance level of SRC structures were hardly mentioned. While the performance-based seismic design was widely accepted in engineering field, it is necessary to carry out an experimental study to investigate the deformation behavior of SRC structures under different performance levels.

2 Experimental Program

2.1 Description of Specimens

Six half-scale SRC column specimens were designed. The geometric characteristics and reinforcement details were shown in Fig. 1. All specimens have a span-to-depth ratio of 2.75. The main test parameters were the axial compression ratio n_k and the stirrup ratio ρ_v which were listed in Table 1. The steel ratio was 4.53% with welded steel plate. The mechanical properties of the rebar and steel were shown in Table 2.

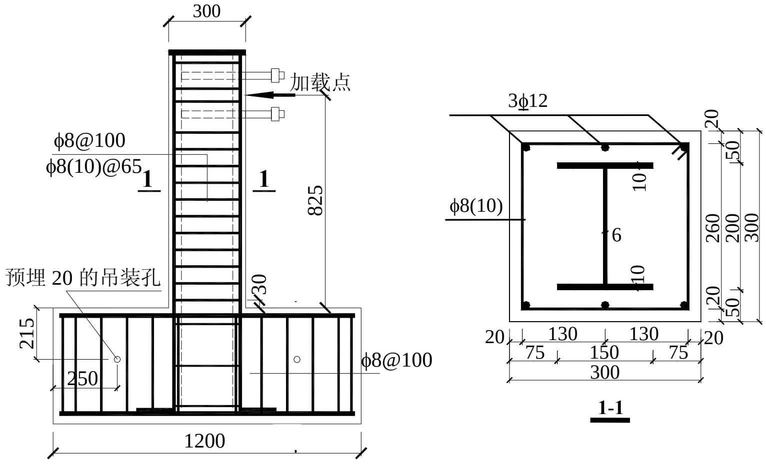


Fig.1 Details of Specimens

Table 1 Test parameter of specimens

No.	$f_{cu,k}$(MPa)	stirrup detail	ρ_v (%)	n_k
SRC1	25.9	ϕ8@65	1.19	0.15
SRC2	25.9	ϕ8@65	1.19	0.30
SRC3	25.9	ϕ8@65	1.19	0.40
SRC4	29.0	ϕ8@100	0.78	0.30
SRC5	29.0	ϕ10@65	1.86	0.30
SRC6	29.0	ϕ10@65	1.86	0.45

Table 2 Mechanical properties of steel

material	f_y/MP$_a$	f_b/MP$_a$	ε_y/με
ϕ12	353.79	2020	574.22
ϕ8	513.40	2570	523.35
ϕ10	466.11	2330	492.80
steel	309.59	1530	403.95

2.2 Test Setup and Instrumentation

2.2.1 Test Setup and Load Procedure

Axial load was applied to the column end by a vertical oil jack, and the horizontal load was applied by a servo-hydraulic actuator fixed on the reaction wall. The test setup is shown in Fig.2. The predetermined axial load was applied first and kept constant during the whole horizontal load history. The horizontal load was applied through a MTS servo-hydraulic structural loading system and the load history was controlled by displacement. Before the specimen yielded, only one loading cycle has been performed under each displacement level. After the specimen had yielded, three loading cycles were performed under each displacement level. The whole loading procedure finished when the bearing capacity of the specimen reduced to 80% of the maximum load (P_{max}) or the hysteretic curves appeared to be unstable distinctly.

2.2.2 Instrumentation

The horizontal and vertical loads were measured using two calibrated load cells. The horizontal displacement was measured using a LVDT with a travel stroke of 200mm which were fixed on an pre-embedded bolt on the left side of the column top. The strain gauges were used to measure the strains of longitudinal bars and stirrups. The detail layout of all the strain gauges was shown in Fig. 3.

Fig.2 Test setup

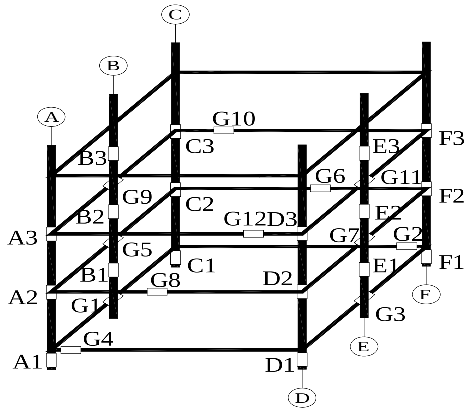
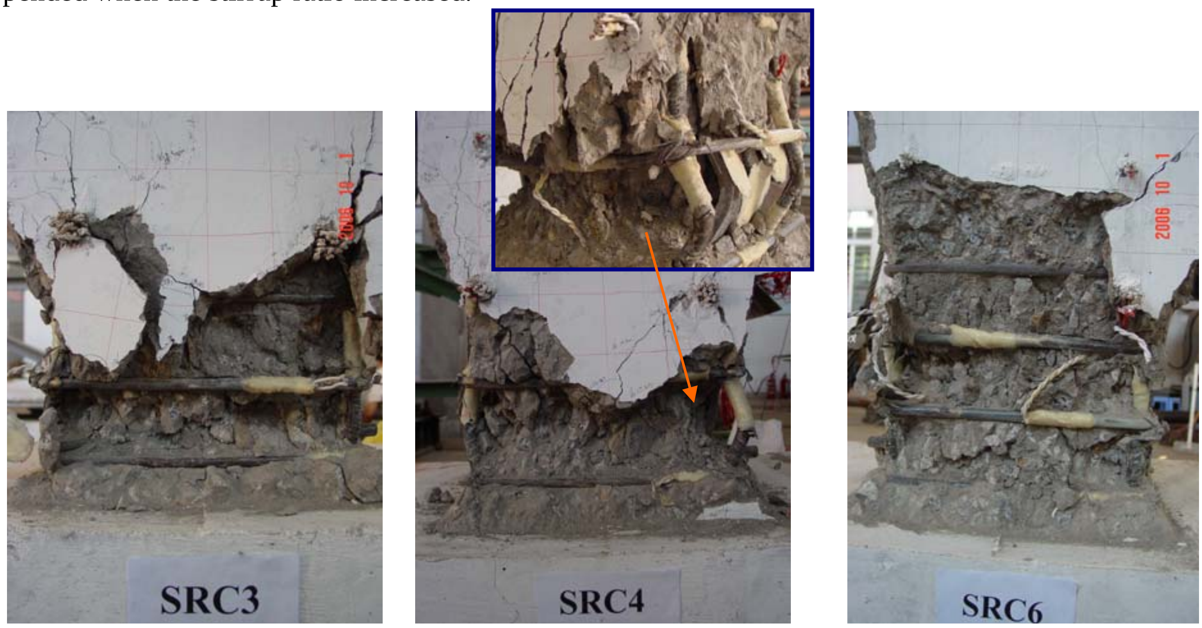


Fig.3 Layout of the strain gauges

3 Experimental Results and Discussion

3.1 Main Failure Characteristics of Specimens

All specimens had the following main failure phenomena: yielding of longitudinal reinforcement, yielding of steel flange, spalling of concrete cover, bulging of stirrups, buckling of longitudinal reinforcement and buckling of steel flange. The ultimate failure modes of specimens were shown in Fig. 4. It is indicated that the axial compression ratio and stirrup ratio have great effect on the ultimate failure mode of specimens. The appearance of flexural crack was suspended when the axial compression ratio increased, while the buckling of longitudinal reinforcement and steel was advanced. Based on the comparison of Fig. 4(b) and Fig. 4(c), it is indicated that the buckling of longitudinal reinforcement and steel due to high axial load was suspended when the stirrup ratio increased.



(a) SRC3 (b) SRC4 (c)SRC6

Fig.4. Ultimate Failure Modes (local)

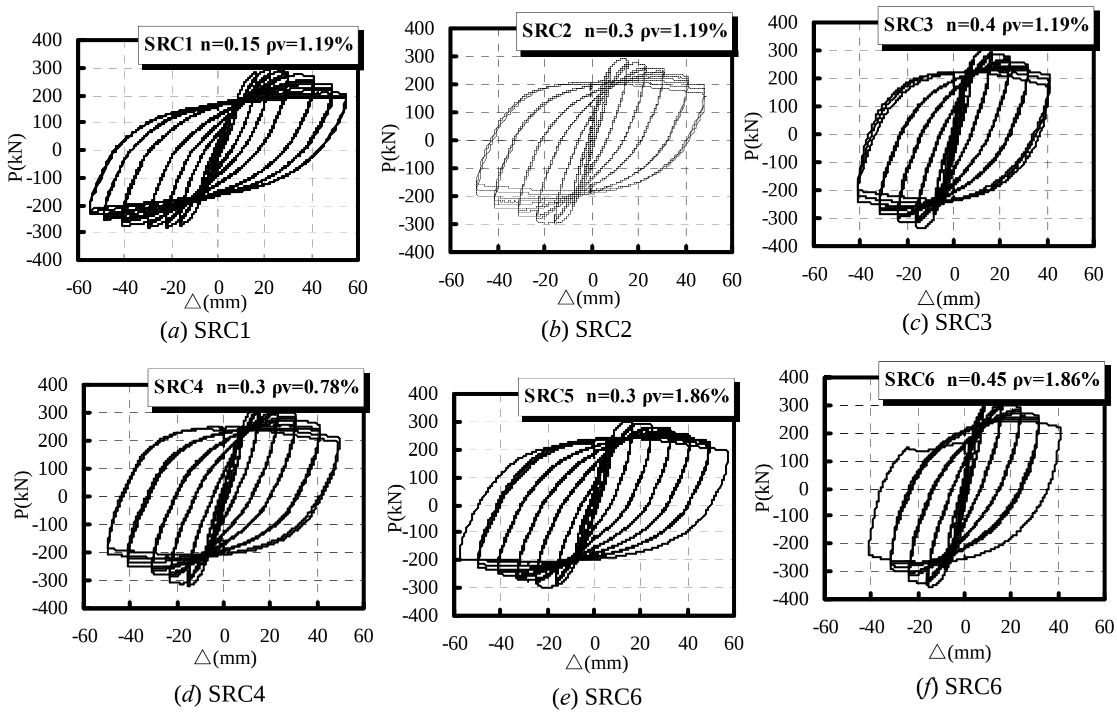
3.2 Characteristic of hysteretic curves

The *P-Δ* hysteretic curves of specimens under cyclic loading were shown in Fig. 5. The following hysteretic characteristics can be summarized.

(1) After the yielding of specimen, the loading and unloading stiffness of the specimens degraded when the displacement amplitude increased, and the degradation rate increased when the cyclic number increased.

(2) The axial compression ratio had a great effect on the hysteretic characteristics. The specimen with low axial compression ratio (SRC1) showed stable hysteretic behaviour and satisfactory energy dissipation capacity. On the contrary, the hysteretic curve of specimens with higher axial compression ratio (SRC6) showed poor hysteretic behaviour.

(3) The hysteretic behaviour became more stable during the cyclic loading when the stirrup ratio increased. The skeleton curve of these specimens after the point of maximum strength declined slowly, and their deformation capacity and the energy dissipation capacity had a great increase.



(*a*) SRC1 (*b*) SRC2 (*c*) SRC3

(*d*) SRC4 (*e*) SRC6 (*f*) SRC6

Fig.5 P-Δ hysteretic curves

3.3 Characteristics of Skeleton Curves

The skeleton curves of specimens were shown in Fig. 6. The test data of four key points on the skeleton curves were listed in Table 3. It is indicated that the maximum strength of specimens increased and the ultimate displacement decreased when the axial compression ratio increased based on the data in Table 3. The following conclusions can be summarized: (1) The strength of specimens increased when the axial compression ratio increased. When the axial compression ratio increased from 0.15 to 0.40, the maximum strength of specimens with the same stirrup ratio (SRC1, SRC2 and SRC3) increased from 298kN to 338kN. (2) The displacement ductility index decreased when the axial compression ratio increased. When the axial compression ratio increased from 0.15 to 0.40, the displacement

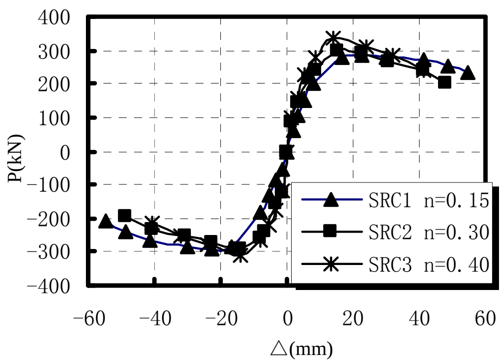


Fig.6 Typical skeleton curves

ductility index of specimens with the same stirrup ratio (SRC1, SRC2 and SRC3) decreased from 7.40 to 4.35. (3)The displacement ductility index increased when the stirrup ratio increased. When the stirrup ratio increased from 0.78% to 1.86%, the displacement ductility index of the specimens with the same axial compression ratio (SRC2, SRC4 and SRC5) increased from 5.22 to 6.15. (4)When the axial compression ratio of SRC6 reached 0.45, the strength deteriorated more quickly after ultimate strength even though the stirrup ratio of SRC6 was 1.86%. It is concluded that the effect of the stirrup ratio on the seismic behavior of SRC columns be limited when high axial compression load was applied.

Table 3 Characteristic points in skeleton curves

No.	n	P_c(kN)	Δ_c(mm)	P_y(kN)	Δ_y(mm)	P_m(kN)	P_u(kN)	Δ_u(mm)	$\mu=\Delta_u/\Delta_y$
SRC1	0.15	83	3.0	177	6.68	289	245	49.45	7.40
SRC2	0.30	161	3.3	252	6.63	304	251	36.34	5.48
SRC3	0.40	171	3.3	257	6.79	338	275	29.57	4.35
SRC4	0.30	115	2.9	247	6.3	319	275	32.91	5.22
SRC5	0.30	153	2.8	250	6.45	304	255	39.67	6.15
SRC6	0.45	193	4.0	278	6.34	348	296	24.29	3.83

P_c, P_y, P_u is the crack strength, yield strength and peak strength, respectively.

4 Index for Different Performance Levels

The allowable performance state of the four performance levels of SRC structures, i.e. fully operation, operation, repairable and collapse avoidable, are suggested as follows: (1) For the performance level of fully operation , the longitudinal reinforcement and steel of structures remain elastic and the strength are not exceeded 50 percent of the maximum strength. The width of cracks is about 0.05~0.2mm and the structure has no visible residual deformation; (2)As for the performance level of operation, the longitudinal reinforcement and steel of structures are allowed to yield but the steel web is not yield completely through the whole cross section. The strength under such level is about 50~90% of the maximum strength; (3) As for the performance level of repairable, the limit value of the residual story drift was recommended to be 1/100; (4) As for the performance level of collapse avoidable, the longitudinal reinforcement and steel might have buckled locally, but the current strength of the structure is not less than 70~90% of the maximum strength.

Three parameters, i.e. α, β and γ which represent the percentage of longitudinal reinforcement strain to the yield strain, the ratio of steel flange strain to the steel yield strain and the ratio of strength to the maximum strength, respectively, is adopted to evaluate the structure performance when the performance levels of the structure were fully operation and operation, respectively. According to the performance demands of different performance levels stated above, two story drift index, 1/250 and 1/150 are suggested as the limit value of fully operation and operation performance levels for the SRC columns, respectively, and the test results of α, β and γ are listed in Table 3 under the allowable drift index 1/250 and 1/150.

The residual story drift index of specimens Δ_r was 1/180~1/126, when the loading story drift index reached 1/50. But when the loading story drift index reached 1/35, the residential story drift index increased to be 1/79~1/57, which exceeded the allowable residential story drift index 1/100. Thus, for the performance level of repairable, the allowable story drift index is recommended to be 1/50. In order to obtain the reasonable allowable story drift index for performance level of collapse avoidable, two parameters, strength degraded ratio λ and stability ratio of the hysteretic curve η are introduced. Here, λ is the strength ratio of a given displacement to the maximum strength of specimens. η is the ratio of the strength of first cycle to that of the third cycle.

From Table 3, it is shown that when the story drift index reached 1/35, the strength degraded ratio λ is about 76.3~93.6%, which can meet the demanded of collapse avoidable performance. Thus, a drift limit of 1/35 is proposed for the collapse avoidable performance level.

Table 3 index for different performance level

Name of Specimens	Fully Operation			Operation			Repairable		Collapse Avoidable					
	1/250			1/150			1/50	1/35	1/35		1/25		1/20	
	α/%	β/%	γ/%	α/%	β/%	γ/%	Δ_r/%		λ/%	η/%	λ/%	η/%	λ/%	η/%
SRC1	22.6	16.0	28.7	50.5	31.9	43.6	1/147	1/79	93.8	94.4	88.6	94.9	83.3	92.5
SRC2	45.1	19.2	53.0	89.5	60.9	78.3	1/138	1/62	82.2	94.0	77.3	92.3	67.8	91.5
SRC3	20.3	20.8	50.6	60.2	48.7	66.0	1/126	1/56	76.3	93.6	66.3	92.6	48.5	82.6
SRC4	22.7	10.9	36.1	38.3	32.2	60.5	1/180	1/69	92.5	93.8	84.6	92.4	70.2	89.9
SRC5	22.2	15.3	50.3	69.6	53.9	71.4	1/137	1/58	87.5	95.1	83.9	95.1	74.0	95.9
SRC6	7.9	7.8	69.0	63.9	27.7	73.3	1/139	1/57	78.7	93.7	69.0	93.0	60.6	—

5 Conclusions

(1) Axial compression ratio and stirrup ratio have distinct effect on the hysteretic characteristics and ductility of SRC columns. Test results indicated that the ductility index decreased with the increasing of the axial load and increased with the increasing of the stirrup ratio.
The displacement ductility index decreased when the axial compression ratio increased. When the axial
(2) It is indicated that the effect of the stirrup ratio on the seismic behavior of specimens would be limited when the axial load of a SRC column is about equal or larger than 50 percent the axial bearing capacity.
(3) Different parameter should be used to appraise different performance levels. For fully operation and operation performance level, it is reasonable to use the strain of longitudinal bar and steel as the main appraisal parameter. For the performance level of repairable, the residual story drift would be a suitable appraisal parameter. For the performance level of collapse avoidable, the strength degraded ratio λ and stability ratio of the hysteretic curve η can be used as appraisal parameter.
(4) It is recommended that the limit drift index for the four performance levels, i.e. fully operation, operation, repairable and collapse avoidable, be 1/250, 1/150, 1/50 and 1/35, respectively.

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