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Axial Load and Bending Moment Behaviour of Square High Strength Concrete (HSC) Columns Reinforced with Steel Equal Angle (SEA) Sections

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Abstract

This paper presents the behaviour of square high-strength concrete (HSC) specimens reinforced longitudinally with steel equal angle (SEA) sections under different loading conditions. For the same cross-sectional area, a SEA section has a higher second moment of area than a steel bar, which results in a greater bending stiffness of the concrete member reinforced with SEA sections. Also, the area of confined concrete is greater in concrete members reinforced with SEA sections compared to members reinforced with steel bars, which results in higher strength and ductility. A total of 8 specimens of 210 mm square cross-section and 800 mm height were constructed and tested. The specimens were divided into two groups with four specimens in each group. Group R-S50 specimens serve as the reference group and were reinforced longitudinally with four N12 (12 mm diameter) deformed steel bars. Group A30-S50 specimens were reinforced longitudinally with four A30 (29.1 mm x 29.1 mm x 2.25 mm) SEA sections. All specimens were reinforced laterally with R10 (10 mm diameter) plain steel bars and spaced at 50 mm centres. The main variables considered in the study included the type of longitudinal reinforcement and the magnitude of load eccentricity. It was obtained from the experimental results that specimens reinforced longitudinally with SEA sections showed greater ductility compared to specimens reinforced longitudinally with steel bars under different loading conditions.

Keywords: High strength concrete, Columns, Ductility, Steel equal angle sections, Eccentric axial load.

1. INTRODUCTION

The use of high strength concrete (HSC) in the construction of concrete structures has been increased over the last few decades. The main problem associated with the use of HSC in the construction of columns is the lower ductility of the HSC column than the ductility of the Normal Strength Concrete (NSC) column for the same amount of confinement reinforcement (Ho et al. 2010). This is because the ductility of concrete decreases with the increase in the compressive strength.

Columns are structural members subjected to a combined axial compression and bending moment, rather than pure axial compression as flexural effects may be created by construction errors and lateral forces (Hadi et al. 2016). A number of researchers have studied the behaviour of the HSC columns under axial compression. However, a few research studies were carried out on the behaviour of the high strength concrete (HSC) columns under eccentric axial loads. The most important factor is the value of initial eccentricity of the axial load that affects the performance of the columns. The effectiveness of lateral confinement on the ductility decreases when the initial eccentricity is less than 30% of the lateral dimension of the cross-section of the RC column (Lloyd and Rangan 1995). Furthermore, as the initial eccentricity of axial load decreases, the spalling of the concrete cover increases (Lee and Son 2000). Also, the value of initial eccentricity affects the strength of columns. In this study, a new method is proposed to reinforce HSC columns with steel equal angle (SEA) sections as longitudinal reinforcement. For a given cross-sectional area, the use of longitudinal SEA sections as main reinforcement results in improving the effectively confined core of the columns and also the minimum second moment of area of SEA section is greater than steel bar, thus leading to the increase of the ductility and the delay buckling of longitudinal reinforcement. Parameters investigated included the type of longitudinal reinforcement and the magnitude of load eccentricity of SEA specimens.

2. EXPERIMENTAL PROGRAM

2.1 Test Specimens

A total of 8 specimens of 210 mm square cross-section and 800 mm height were constructed and tested under different loading conditions. The specimens were divided into two groups with four specimens in each group, as shown in Table 1. Group R-S50 specimens were reinforced longitudinally with four N12 deformed steel bars of 12 mm diameter. Group A30-S50 specimens were reinforced longitudinally with four A30 steel equal angle (SEA) sections. For lateral reinforcement, R10 plain steel bars (10 mm diameter) were used to fabricate lateral square ties for all specimens with spacings of 50 mm centre-to-centre.

From each group, the first specimen was tested under monotonic increased concentric axial load and labelled as C. The second specimen was tested under 25 mm eccentric axial load and labelled as E25. The third specimen was tested under 50 mm eccentric axial load and labelled as E50. The fourth specimen was tested under four-point bending and labelled as F. All specimens were reinforced laterally with constant tie spacing of 50 mm and labelled as S50.

Table 1. Test matrix.

Group	Specimen	Longitudinal Reinforcement			Lateral Reinforcement		Eccentricity
		Type	ρ^a %	fy^b (MPa)	Diameter (mm)	Spacing (mm)	
R-S50	R-S50-C	N12 steel bars	1.03	556	10	50	0
	R-S50-E25		1.03	556	10	50	25 mm
	R-S50-E50		1.03	556	10	50	50 mm
	R-S50-F		1.03	556	10	50	Flexural
A30-S50	A30-S50-C	A30 SEA sections	1.11	374	10	50	0
	A30-S50-E25		1.11	374	10	50	25 mm
	A30-S50-E50		1.11	374	10	50	50 mm
	A30-S50-F		1.11	374	10	50	Flexural

[a] ρ is the volumetric ratio of longitudinal reinforcement.
[b] fy is yield tensile strength of the longitudinal reinforcement.

2.2 Material Properties

All column specimens were cast vertically from the same batch of ready mix high strength concrete (HSC) with an average 28 day compressive strength of 68.5 MPa. Two different types of longitudinal reinforcement were used to reinforce the reinforced concrete (RC) column specimens. Three pieces of each steel bar diameter (N12 and R10) were tested to determine the mechanical properties of the reinforcing steel bars according to AS 1391 (2007), and the results were 556 MPa and 323 MPa, respectively. Also, three coupon pieces of A30 SEA sections were tested to determine the tensile strength of the reinforcing SEA section according to Australian Standard AS 1391 (2007), and the result was 374 MPa.

2.3 Preparing of Specimens

The formwork used for constructing the column specimens was fabricated from 17 mm thick plywood. The longitudinal N12 steel bars and A30 SEA sections were cut to 760 mm to have 20 mm clear cover at the top and bottom of the steel cage. The square ties were fabricated from mild R10 bars in the lab with 21 mm clear side covers to the face of the formwork. These ties were made with 90-degree hooks around one of the longitudinal reinforcement and extended to a minimum overlap of 80 mm at both free ends. Afterwards, each tie was welded at three points on the hook corner to ensure that the ties would provide adequate confinement. Then, the steel cages were prepared by assembling longitudinal and lateral reinforcement. Wooden timbers were used vertically and transversely to fix the formwork before pouring the concrete and then the steel cages were inserted into the wooden formwork. The concrete was poured into the formwork and vibrated using an internal vibrator to compact and to expel the air bubbles. After 24 hours, the specimens were cured by covering with wet hessian and kept in the lab at an ambient temperature for four weeks before testing.

2.4 Test set up and instrumentation

A total of 8 specimens were cast and tested at the laboratories of the School of Civil, Mining, and Environmental Engineering at the University of Wollongong, Australia. The Denison 5000 kN compression testing machine was used to test the specimens. After removing the formwork, the top and bottom of each specimen were wrapped by two layers of CFRC sheet with a width of 100 mm to prevent premature failure during testing. The eccentric axial load was applied to the specimen by an eccentric loading head system manufactured at the University of Wollongong, Australia . The axial deformation of the specimens was measured by using two Linear Variable Differential Transducers (LVDTs) placed vertically in the testing machine in the diagonal opposite direction (Figure 1). For eccentric load tests, as well as to the two LVDTs a laser triangulation was used to capture the lateral deformation of the tested specimens. For flexural loading, the load was applied to the beam specimen using two rigs; one under the specimen and the other above the specimen (Figure 1 (b)). A laser triangulation was attached in the mid-span on the tension side of the beam specimen to monitor the mid-span deflection. All specimens were tested under displacement control with a loading of 0.3 mm/min. Figure 1 shows a typical testing setup for the tested specimens.

(a) (b)

Figure 1. Test setup: (a) Axial compression and (b) Four-point bending

3. EXPERIMENTAL RESULTS AND DISCUSSION

Table 1 summarises test results of the tested column specimens under different eccentric axial loads. To evaluate the performance of the column and beam specimens, ductility capacity is conducted for all specimens. The ductility capacity in this study was calculated as the ratio of the deformation at 80% of the applied axial load in the descending branch of the load-deformation curves to the deformation at yield axial load. The yield load was taken as the load at the end of the limit of the elastic behaviour

(Pessiki and Pieroni 1997). The failure of Specimens R-S50-C and A30-S50-C was characterised by sudden loss of the concrete cover, followed by the dilation in the lateral direction and outward buckling of the longitudinal reinforcement (Figure 2). The failure of Specimens R-S50-E25, R-S50-E50, A30-S50-E25 and A30-S50-E50 was characterised by the forming of lateral cracks in the tension zone, and then spalling of the concrete cover and outward buckling of the longitudinal reinforcement in the compression zone (Figure 2). The failure of specimens R-S50-F and A30-S50-F was due to the rupture of longitudinal reinforcement (Figure 2)

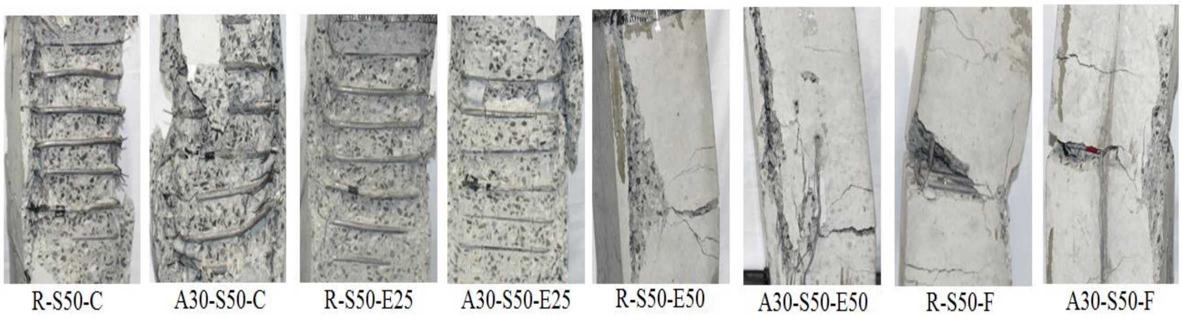

Figure 2 Failure modes of the tested specimens

The load versus deformation curves of the tested specimens under different loading conditions are presented in Figure 3. The axial load versus axial deformation of the column specimens tested under axial compression (Figure 3 (a)). Specimen R-S50-C achieved only 6.6% higher maximum axial load compared to Specimen A30-S50-C because the yield tensile strength of the steel bars was 49% higher than the yield tensile strength of A30 SEA sections. However, the ductility of Specimen A30-S50-C was increased by 21.4% compared with Specimen R-S50-C. This indicates that the use of SEA sections as longitudinal reinforcement into HSC columns results in a significant increase in the effective confined concrete core, thus leading to increase the ductility of the columns. The axial load versus axial and lateral deformations of the specimens that were tested under 25 mm and 50 mm eccentric axial loads are shown in Figure 3 (b) and (c), respectively. The maximum axial load of Specimen R-S50-E25 showed only 8.8% higher than that of Specimen A30-S50-E25. However, Specimen A30-S50-E25 exhibited 16.7% increase in the ductility compared to Specimen R-S50-E25. For the column specimens that were tested under 50 mm eccentricities, Specimen R-S50-E50 was only 6.3% higher maximum axial load compared to Specimen A30-S50-E50. Specimens R-S50-E50 and A30-S50-E50 had about similar ductilities.

Table 2 shows test results of the tested beam specimens under four-point bending. The load versus midspan deflection curves for the specimens testing under four-point bending are shown in Figure 3 (d). It can be noted that the maximum load and ductility of Specimen R-S50-F was 6.6% and 45.2% lower than the maximum load and ductility of Specimen A30-S50-F, respectively. This was because the bending stiffness of SEA sections was much higher than the bending stiffness of steel bar with a similar cross sectional area.

Table 1 Summarise test results of specimens testing under different eccentricity

Specimen	Maximum Axial Load (kN) P_{max}	Deformation at P_{max} (mm)		Ductility
		Axial	Lateral	
R-S50-C	2716	2.8	-	1.4
R-S50-E25	1967	2.7	1.2	1.7
R-S50-E50	1340	2.7	1.9	1.2
A30-S50-C	2548	2.6	-	1.4
A30-S50-E25	1808	2.9	2.2	1.1
A30-S50-E50	1260	2.5	1.1	1.1

Table 2 Summarise test results of specimens testing under four-point bending

Specimen	Maximum load P_{max} (kN)	Midspan deflection at P_{max} (mm)	Ductility
R-S50-F	244	9.5	3.1
A30-S50-F	260	9.5	4.5

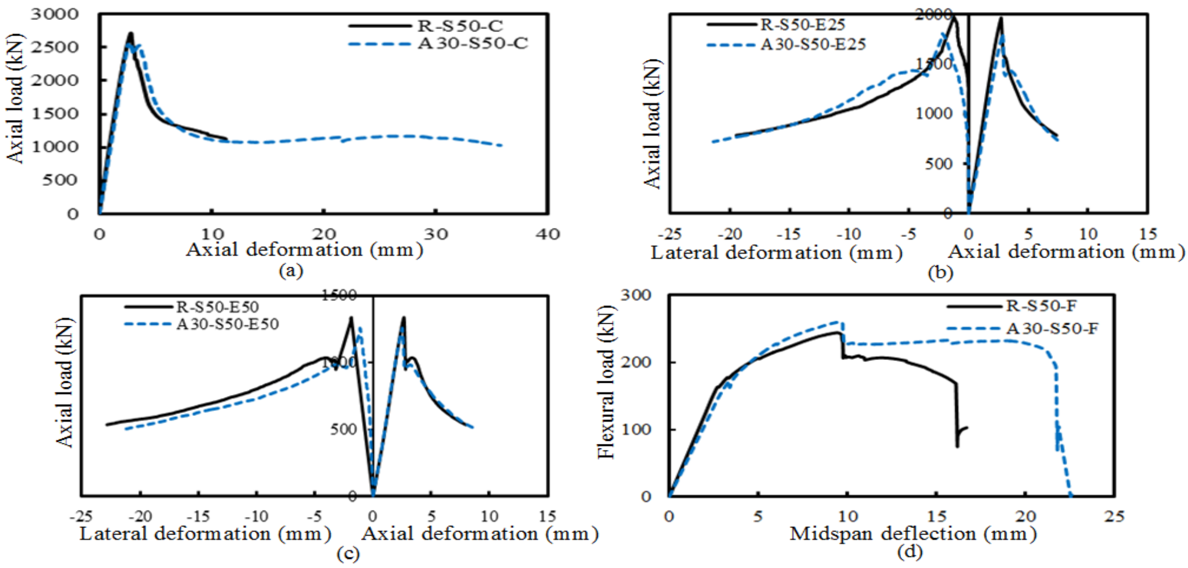

Figure 3 Test results of specimens under (a) concentric axial load (b) 25 mm eccentric axial load (c) 50 mm eccentric axial load and (d) four-point bending

4. AXIAL LOAD-BENDING MOMENT (*P-M*) INTERACTIONS

The experimental axial load-bending moment (*P-M*) interactions were constructed using pure concentric axial load, combined axial load and bending moment and pure bending moment. The bending moment capacity of the specimens under eccentric axial load was calculated using Equation 1:

$$M=P(e+\Delta) \tag{1}$$

where P is the maximum axial load, e is the axial load eccentricity, and Δ is the lateral deformation at the maximum axial load. The pure bending moment capacity at the mid-height of the specimens tested under four-point bending was calculated using Equation 2:

$$M=FL/6 \tag{2}$$

where F is the maximum load under four-point loading and L is the clear span of the tested specimen. The experimental axial load-bending moment (*P-M*) interactions of Groups R-S50 and A30-S50 specimens are shown in Figure 3. It can be seen that SEA reinforced A30-S50 specimens showed slightly lower maximum axial load than the steel bar reinforced R-S50 specimens. This is because steel bars had 49% higher yield tensile strength than A30 SEA sections. However, it can be observed that specimen reinforced with SEA sections exhibited higher bending moments than specimens reinforced with steel bars. This is because the bending stiffness of a SEA section is much higher than the bending stiffness of steel bar with the similar cross-sectional area.

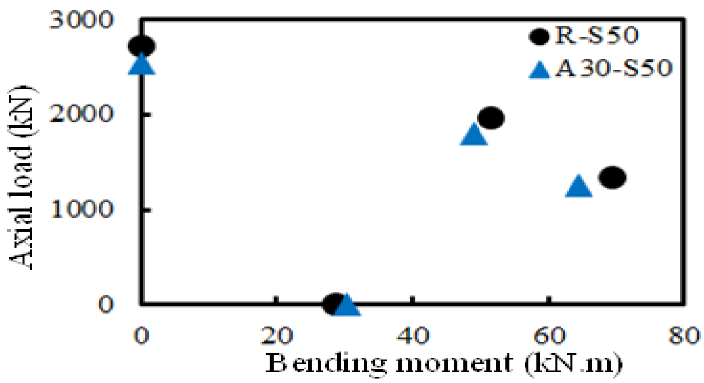

Figure 3 Experimental axial load-bending moment interaction diagram of specimens

5. CONCLUSIONS

The behaviour of 8 square HSC specimens reinforced longitudinally with either steel bars or SEA sections was experimentally investigated. Six specimens were tested as columns under concentric, 25 mm eccentric and 50 mm eccentric axial loads, the remaining two specimens were tested as beams under four-point bending. The test results presented that the maximum axial load of SEA RC column specimens were slightly lower than steel bar RC column specimens because the yield strength of SEA sections was 49% lower than the yield strength of steel bars. However, the improvement in the ductility capacities of the SEA RC specimens was higher than steel bar RC column specimens.

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