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Performance Evaluation of Square High Strength Concrete (HSC) Columns Reinforced with Steel Equal Angle (SEA) Sections under Axial Compression

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Abstract

This paper reports the results of an experimental investigation on the behaviour of square High Strength Concrete (HSC) columns reinforced longitudinally with either steel bars or Steel Equal Angle (SEA) sections under concentric axial compression. The use of SEA sections as longitudinal reinforcement may enhance the load carrying capacity and ductility of concrete columns. These enhancements are because for a given cross-sectional area, a SEA section has a higher second moment of area and radius gyration than a steel bar. Also, the SEA sections provide a greater confinement area for the concrete core of columns. A total of 6 column specimens with a square cross section of 210 mm and 600 mm height were tested under concentric axial compression. The specimens were divided into two groups and each group contains three specimens. The specimens in the first group (Group 1) were reinforced longitudinally with four N12 (12 mm diameter) deformed steel bars and served as reference specimens. The remaining four specimens in the second group (Group 2) were reinforced longitudinally with four A30 (29.1 mm x 29.1 mm x 2.25 mm) SEA sections. The lateral reinforcement spacing in each group of specimens varied between 50 mm and 200 mm. The influence of the type of longitudinal reinforcement (steel bars and SEA sections) and the spacing of the lateral reinforcement on the performance of the column specimens were investigated and discussed. The results of this investigation showed that for specimens reinforced with SEA sections, the ductility significantly enhanced compared to corresponding specimens reinforced with steel bars. The test results also indicated that as the lateral reinforcement increased from 50 mm to 200 mm, specimens reinforced with SEA sections showed better enhancement in ductility and strength than the specimens reinforced with steel bars.

Keywords: Columns, Steel equal angle sections, High strength concrete, Axial compression, Ductility.

1. INTRODUCTION

The use of high-strength concrete (HSC) in buildings has increased over the last decades. However, HSC reinforced concrete (RC) columns exhibit a lower ductility than normal strength concrete (NSC) (Razvi and Saatcioglu 1999). Therefore, many studies attempted to investigate the ductility and the strength of HSC columns (Bhowmick et al. 2006). Most of these studies indicated that more lateral reinforcement is required in HSC columns than in NSC columns to achieve a similar ductility. Also, it was reported that HSC columns under concentric compression experience premature concrete cover spalling, which can lead to decreasing the column strength due to reducing its cross-section (Cusson and Paultre 1994; Samani et al. 2015).

The lateral reinforcement may be in the form of helices or ties. The mechanism of confinement by lateral reinforcement can be demonstrated by reviewing the behaviour of reinforced concrete (RC) columns under axial compressive load. When the columns are subjected to an axial compressive load, these columns will be shortened axially and expanded laterally. As the applied load increases and reach the maximum strength of columns, the concrete cover cracks and spalls due to the stress concentration produced at the interface between the lateral reinforcement and the surrounding concrete (Bresler and Gilbert 1961), then the longitudinal reinforcement buckles outwards. The use of sufficient lateral reinforcement to confine concrete under axial compressive load can restrain the lateral expansion of the concrete. When the reinforced concrete (RC) column is axially loaded, the concrete core starts to expand outwards. At this stage, the lateral reinforcement tends to prevent the lateral expansion of the concrete core. This process can generate a reactive confining pressure against the concrete core of the column. When the concrete core is confined by lateral square ties, the concrete expands laterally and bears against the lateral ties. This study summarizes the results of an experimental program investigating the behaviour SEA reinforced square HSC columns under pure concentric axial compression. The main parameters investigated included the type of longitudinal reinforcement and the spacing of lateral ties.

2. EXPERIMENTAL WORK

2.1 Design of Specimens

In this study, a total of six square reinforced high strength concrete (HSC) column specimens were cast and tested under concentric axial load. In this study, concrete compressive strength greater than 50 MPa is referred to as high-strength concrete (HSC). All specimens had 210 mm square cross-section and 600 mm height. Table 1 presents the reinforcement details of the tested specimens. Specimens N12-S50, B-S100 and N12-S200 served as reference specimens and reinforced longitudinally with four N12 (12 mm diameter) deformed steel bars. Specimens SEA-S50, SEA-S100, and SEA-S200 were reinforced longitudinally with four A30 (29.1 mm x 29.1 mm x 2.25 mm) steel equal angle (SEA) sections. All specimens were reinforced laterally with R10 (10 mm diameter) plain steel bars with a spacing that varied between 50 mm and 200 mm at centres (centre-to-centre). Also, the spacing of lateral reinforcement was decreased to 40 mm at the top and bottom ends of specimens to prevent failure during testing. The column specimens are labelled by the type of longitudinal reinforcement and the lateral tie spacing. For instance, Specimen N12-S200 is reinforced longitudinally with four N12 steel bars and laterally with square ties at 200 mm spacing centre-to-centre.

Table 1. Test matrix.

Group	Specimen	Longitudinal Reinforcement			Lateral Reinforcement	
		Type	ρ^a %	$f_y{}^b$ (MPa)	Diameter (mm)	Spacing (mm)
1	N12-S50	N12 steel bars	1.03	556	10	50
	N12-S100		1.03	556	10	100
	N12-S200		1.03	556	10	200
2	SEA-S50	A30 SEA sections	1.11	374	10	50
	SEA-S100		1.11	374	10	100
	SEA-S200		1.11	374	10	200

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

2.2 Preliminary Tests

Preliminary testing involved testing concrete cylinder samples, steel bars, and steel equal angle (SEA) sections. The concrete cylinder samples were 100 mm in diameter and 200 mm in height. The concrete compressive strength was 68.5 MPa. Three pieces of each bar diameter N12 and R10 were tested to determine the mechanical properties of the reinforcing steel bars according to Australian Standard AS 1391 (2007), and the results were 556 MPa and 323 MPa, respectively. Also, three coupon pieces of each SEA A30 sections were tested to determine the average yield strength of the reinforcing SEA section according to AS 1391(2007), and the result was 374 MPa.

2.3 Test Procedure

The column specimens were tested under displacement controlled pure axial compression at a displacement rate of 0.3 mm/min. Two Linear Variable Displacement Transformers (LVDTs) were mounted at 180-degrees around the tested column specimen to monitor axial deformation. Two of LVDTs were mounted on the lower steel plate of the 5000 kN Denison testing machine (Figure 1). The top and bottom end of each specimen were wrapped with a double layer of Carbon Fiber Reinforced Polymer (CFRP) sheets to avoid premature failure of the specimens ends under pure axial loads. The width of CFRP sheet was 90 mm.

Figure 1 Test setup of specimen

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 General Behaviour

Figure 2 presents the failure modes of the tested specimens after failure. The SEA and steel bar reinforced concrete (RC) column specimens had a similar behaviour up to their maximum axial load. During testing, vertical hairline cracks started to appear before reaching their maximum axial loads. It can also be seen that the failure of the SEA and the steel bar RC specimens were characterised by spalling of the concrete cover, followed by outward buckling of the longitudinal reinforcement (steel bars and SEA sections). The ductility of the tested specimens was calculated as the ratio of the areas under the axial load-axial deformation curves (Hadi et al. 2016). The ductility (μ) of the tested specimens was measured using Equation (1).

$$\mu = \frac{A_2}{A_1} \tag{1}$$

where A_1 and A_2 are the areas under the axial load-deformation curve up to the yield deformation and to the ultimate deformation, respectively. The ultimate deformation was computed at 85% of maximum axial load in the descending part of the axial load-axial deformation curves.

Figure 2 Failure modes of the tested specimens

3.2 Influence of Longitudinal Reinforcement Type

The type of longitudinal reinforcement was one of the main parameters investigated in this study. The effect of longitudinal reinforcement type (N12 steel bars and SEA sections) was examined by comparing experimental results of four pairs each of N12 steel bar specimens and A30 SEA specimens (Figure 3). The compared specimens of each pair had the same spacing of lateral tie, but a different type of longitudinal reinforcement (N12 steel bars or A30 SEA sections). From Table 2, it can be observed that Specimen N12-S50 exhibited about 11.6% higher maximum axial load compared to Specimen SEA-S50. Specimens N12-S100 and SEA-S100 had similar ductilities. However, the increase in the maximum axial load was 2.9% for Specimens SEA-S200 relative to the maximum axial loads of Specimens N12-S200. Also, the increase in the ductility of Specimens SEA-S50, SEA-S100 and SEA-S200 was 44.4%, 12.5% and 6.7%, respectively, relative to the ductilities of Specimens N12-S50, N12-S100 and N12-S200. This indicates that the use of A30 SEA sections instead of the steel bars led to increasing the strength and ductility of the HSC specimens.

Table 2. Test results of the tested specimens.

Specimen	Maximum axial load P_{max}, kN	Deformation at P_{max}, mm	Ductility
N12-S50	2929	2.3	1.8
N12-S100	2626	2.1	1.6
N12-S200	2399	1.8	1.5
SEA-S50	2625	2.2	2.6
SEA-S100	2619	2.3	1.8
SEA-S200	2469	1.9	1.6

[a]The ductility was not calculated as the specimen failed prematurely.

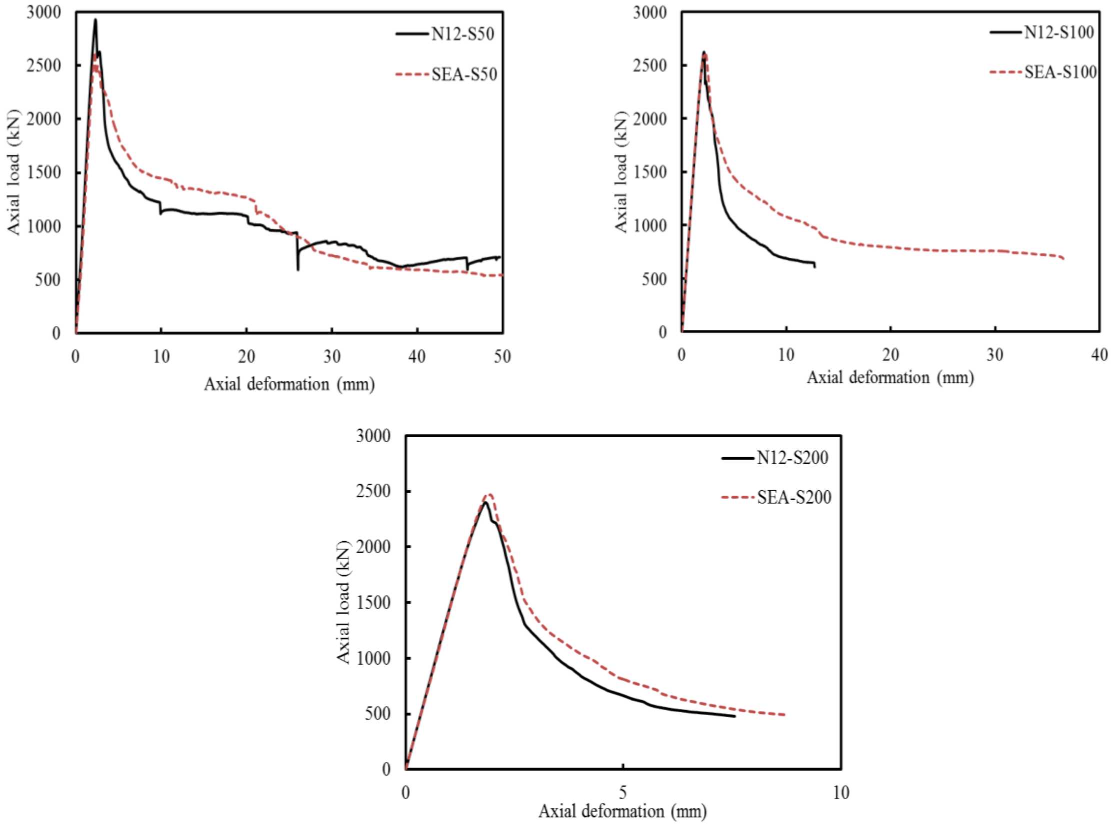

Figure 3 Influence of the longitudinal reinforcements (steel bars and SEA sections)

3.3 Influence of Lateral Tie Spacing

The spacing of lateral ties was the most significant and one of the main variables investigated extensively in this study. The lateral confining pressure in the concrete core is significantly affected by an increase in the spacing of the lateral tie. Also, the spacing of lateral ties is one of the most important variables that impact on the distribution of the laterally confining pressure on the concrete core as well as controlling of the stability of the longitudinal reinforcement. Figure 4 presents comparisons of N12 steel bar specimens and A30 SEA specimens with different lateral tie spacing, which ranged from 50 mm to 400 mm. From this figure, it can be observed that as the spacing of lateral ties increased, the post-peak behaviour of the specimens became steeper. Also, from Table 2, it was found that the decrease in the maximum axial load was 11.5% and 22.1% for Specimens N12-S100 and N12-S200 respectively, relative to the maximum axial load of Specimen N12-S50. Also, the decrease in the ductility was 12.5% and 20.0% for Specimens N12-S100 and N12-S200 respectively, compared to the ductility of Specimen N12-S50. This is because as the spacing of lateral ties increases, the effective confinement of concrete core decreases.

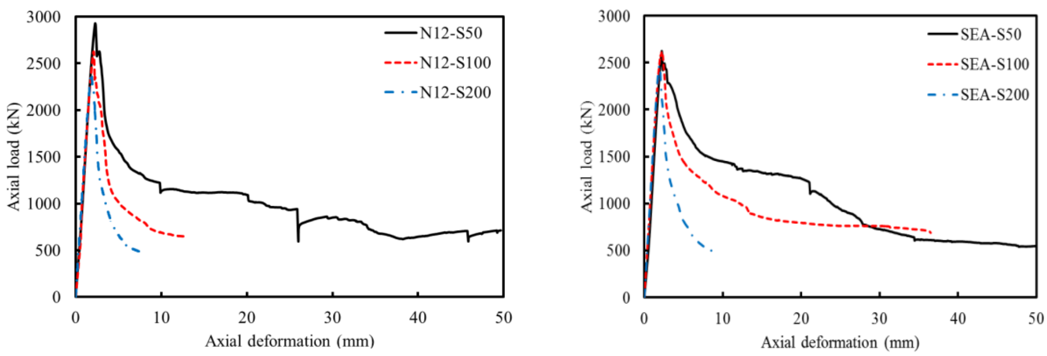

Figure 4 Influence of lateral tie spacing of the tested specimens

It was also observed that the decrease in the maximum axial load was only 0.2% and 6.3% for Specimens SEA-S100 and SEA-S200, respectively, relative to the maximum axial load of Specimen SEA-S50. Also, the decrease in the ductility was 44.4% and 62.5% for Specimens SEA-S100 and SEA-S200, respectively, compared to the ductility of Specimen SEA-S50.

4. CONCLUSIONS

In this study, an experimental program was carried out on eight square HSC columns under axial compression. The main objective of this study was to investigate the behaviour and efficiency of specimens reinforced longitudinally with steel equal angle (SEA) sections. The effect of longitudinal reinforcements and spacing of lateral ties were investigated. From the test results, it can be concluded that the improvements in the strength and ductility of the specimens reinforced longitudinally with SEA sections are because the SEA sections increase the effectively confined concrete core. Also, the use of SEA sections as longitudinal reinforcement led to increasing the buckling resistance of the specimens, in particular for specimens with high lateral tie spacing.

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