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Finite element modeling of square high-strength concrete short columns longitudinally reinforced with steel equal-angles under axial loading

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ABSTRACT

Conventional steel bars in Reinforced Concrete (RC) square columns are utilized as longitudinal reinforcement and steel ties are utilized as transverse reinforcement for concrete confinement. The concrete confinement in RC columns with square section is less than that with circular section. Recently, Steel-Equal Angle (SEA) as longitudinal reinforcement has been investigated for square RC columns. The RC columns with SEA as longitudinal reinforcement exhibit higher strength and ductility than the RC columns with conventional steel bars as longitudinal reinforcement. However, experimental and computational investigations have been very limited on RC columns with SEA as longitudinal reinforcement. Existing studies investigated only the effects of lateral tie spacing on the performance of RC columns reinforced with SEA sections. However, the effects of the other important column parameters, such as the width and thickness of SEA sections, yield stress of SEA sections, and the concrete compressive strength, on the axial performance of RC columns reinforced with SEA sections have not been fully investigated yet. This study develops finite element (FE) models for quantifying the behavior of axially loaded square RC short concrete columns reinforced with SEA. The inelastic buckling of SEA cross-sections and the effects of concrete confinement are considered in the simulation. The accuracy of the FE analysis is verified using available test results. The influences of material and geometric properties on the compressive behavior of square RC short concrete columns incorporating SEA are studied. The results show that the model accurately estimates the behavior of square SEA reinforced concrete short columns. Moreover, the width of the SEA sections, the concrete compressive strength, and the lateral tie spacing have the most significant effects on the performance of SEA reinforced concrete columns subjected to axial loads.

1. Introduction

A recent development in the field of composite construction is the use of High-Strength Concrete (HSC) instead of Normal-Strength Concrete (NSC). In the design of Reinforced Concrete (RC) columns, axial strength and ductility are two main design factors that are used to assess the performance of the columns. The use of HSC in an RC column increases its axial strength, offering an opportunity to reduce the size of the columns. On the other hand, the RC column with HSC exhibits less ductility compared with the NSC column. It is noted that HSC columns require more lateral reinforcement than NSC columns to achieve the same ductility [1–3]. Therefore, the application of HSC is still limited in the construction of RC columns in low to mid-rise buildings [4,5].

Traditionally, the steel bars are used as longitudinal reinforcement in square RC columns and steel ties are utilized as the transverse reinforcement for providing concrete confinement. The concrete confinement provided by the lateral steel ties increases the overall strength and ductility of circular RC columns. The longitudinal reinforcement also provides concrete confinement and stability to the transverse steel cages. The concrete confinement in square RC columns is less than that in circular RC columns [6–8]. The lateral concrete confining pressure in square RC columns is not uniform, whereas the concrete confinement in

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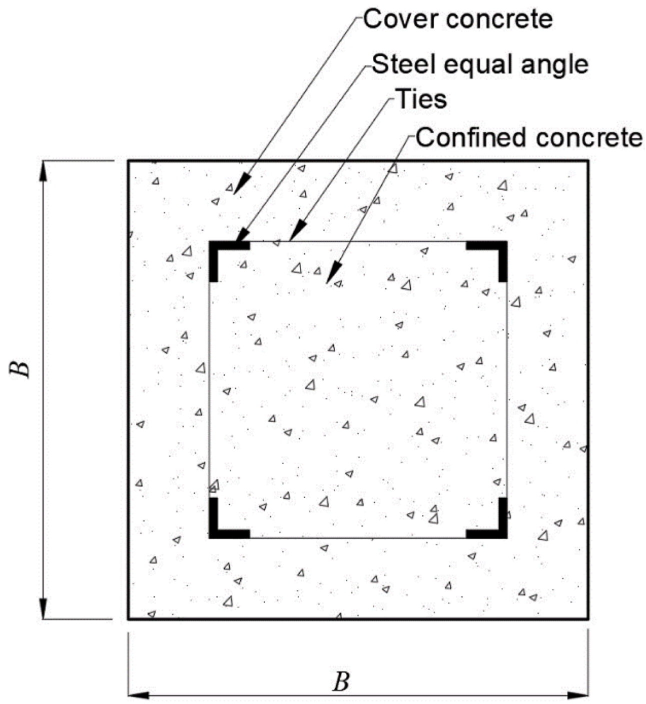


Fig. 1. Cross-section of square concrete columns reinforced with SEA sections.

RC columns with circular sections is uniform [9,10]. Therefore, the performance of circular RC columns is better than that of square RC columns for the same transverse reinforcement ratio. The structural performance of RC columns also depends on the other parameters including the concrete compressive strength, lateral tie spacing, volumetric ratio, and types of reinforcement. Previous studies indicated that increasing the concrete compressive strength increases the strength of the RC column but reduces its ductility [11–13]. This is because of the brittleness of the HSC. It was showed that the ductility of RC columns with HSC is less than that of RC columns with NSC [11–13]. Similarly, the increase in the tie spacing decreases the confining pressure to concrete, thereby reducing the ultimate axial strength and ductility of RC columns.

Recently, steel equal-angle (SEA) has been proposed for RC columns as an alternative to the traditional longitudinal steel bars to improve the structural performance of square RC columns as illustrated in Fig. 1 [14]. As depicted in Fig. 2, the effectively confined concrete area of a RC column reinforced with SEA section is larger than that of the RC column reinforced with traditional steel bars. Therefore, the strength and ductility of RC columns with SEA are higher than those of RC columns reinforced with traditional steel bars. Some preliminary studies on the effectiveness of SEA sections in reinforcing RC columns under different loading conditions were performed by researchers. Ibrahim et al. [14] investigated the effects of SEA as longitudinal reinforcement and lateral tie spacing on the performance of square RC short columns. To decrease the possible slippage of the SEA sections in the specimens reinforced with SEA sections, Ibrahim et al. [14] and Hadi et al. [15] welded two short plain steel bars of 8-mm diameter and 40-mm long to the top and bottom of the SEA sections laterally. In addition, two short steel bars of 16-mm diameter and 70-mm length were welded to the top and bottom of each SEA section in longitudinal direction. They found that the specimens with a smaller tie spacing failed by the fracture of the ties, followed by the local buckling of SEA sections. In addition, the buckling of SEA sections occurred before the failure of lateral ties when the tie spacing was greater than 100 mm. It was concluded that the ultimate axial strength of square RC columns can be increased by increasing the cross-sectional area of SEA sections or reducing the tie spacing. After the experimental study conducted by Ibrahim et al. [14], Hadi et al. [15] conducted research on RC columns with SEA as longitudinal reinforcement subjected to axial and eccentric loading and pure bending. Hadi et al. [15] reported that increasing the loading eccentricity significantly decreased the axial and bending resistance of RC columns.

Although the application of SEA can improve the strength and ductility of HSC columns, there are challenges to be addressed to ensure the practicality of such a reinforcement system. For example, the flowability and high-passing ability are important criteria of concrete that ensure the concrete to pass through the narrow gaps of reinforcement and reach the corners of formwork. Although normally vibrated concrete (NVC) is often used to construct RC columns, it is difficult to cast concrete in columns with a significant amount of longitudinal and lateral reinforcements, such as bridge piers. The self-compacting concrete (SCC) has high flowability, passing ability, and segregation

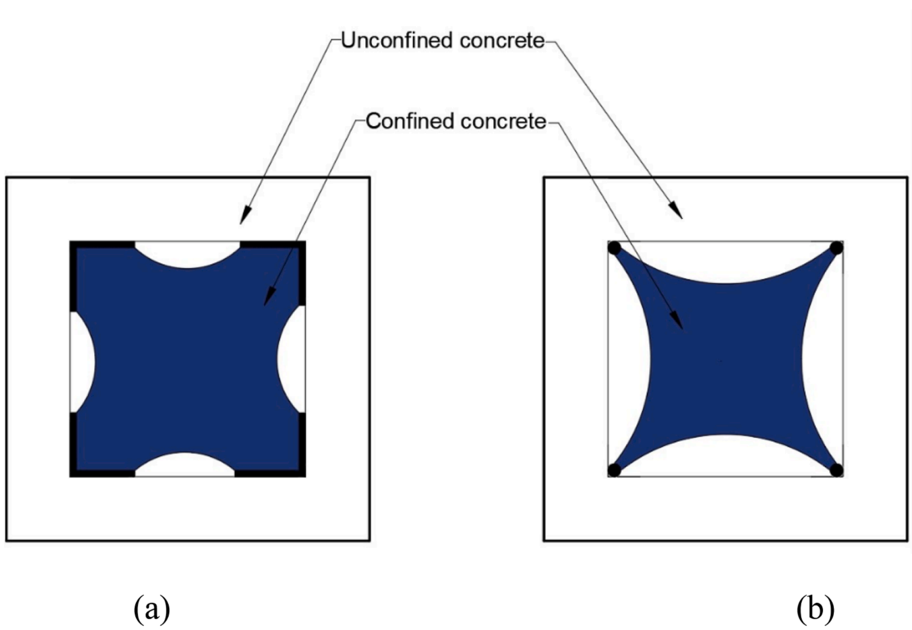


Fig. 2. The effective confined concrete area concrete columns reinforced with (a) SEA sections and (b) traditional longitudinal bars.

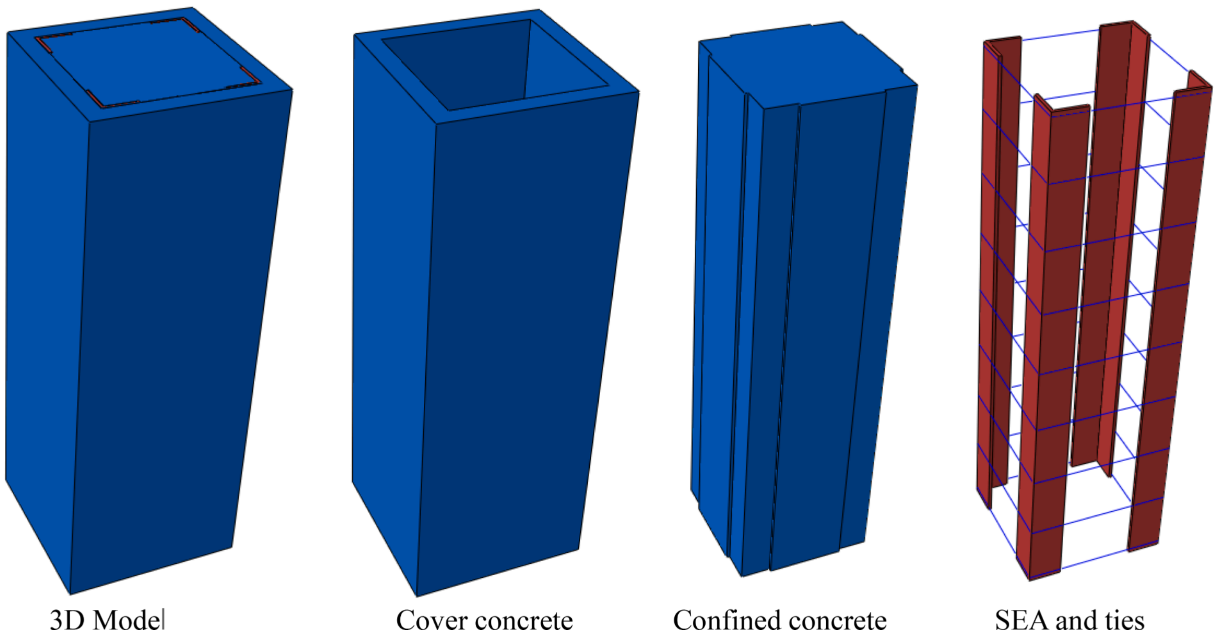


Fig. 3. Finite element modeling of square concrete columns reinforced with SEA sections.

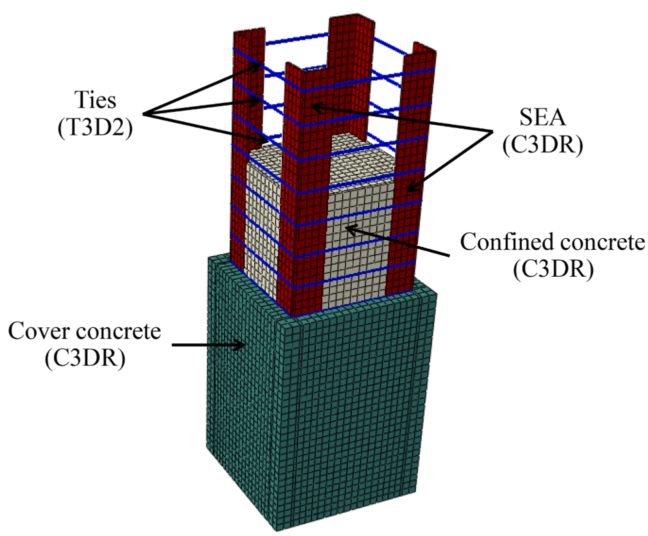


Fig. 4. Meshing of square concrete columns reinforced with SEA sections.

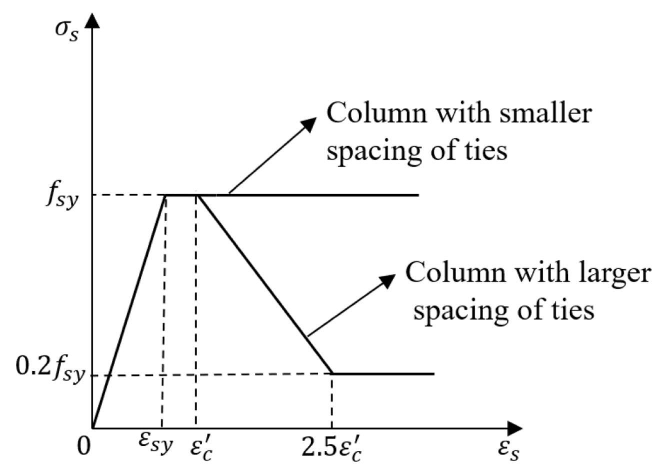


Fig. 5. Stress–strain relationships of structural steel.

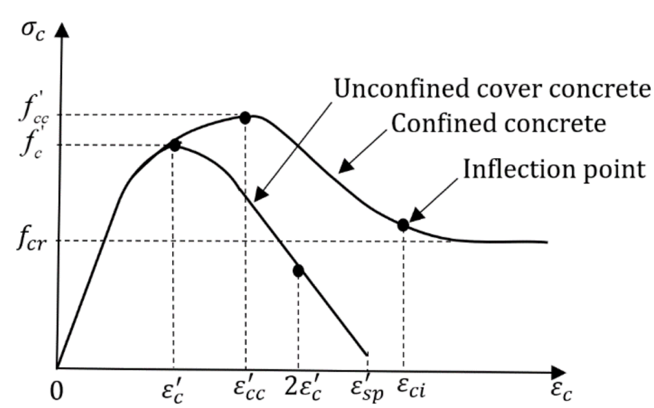


Fig. 6. Stress–strain relationships of confined and unconfined concrete.

resistance; therefore, it can be cast in congested or complex structures without the need for vibration. Moreover, the flowability and passing ability of concrete in composite columns can be improved by using cementitious fillers and inert filler proposed by Lai et al. [16]. It was found that the concrete cover of the tested columns reported by Ibrahim et al. [14] and Hadi et al. [15] spalled off upon reaching the first peak load which led to the drop of the axial load of approximately 1.1–7.7% of the first peak axial load. However, for the columns under eccentric loading of 25 and 50 mm carried out by Hadi et al. [15], at first, the cracks started on the tension side at the column mid-height followed by buckling of the longitudinal reinforcement and crushing of concrete in the compression zone. As the idea of the application of SEA section to longitudinally reinforce concrete columns is still in an early stage, there is need to investigate the performance of RC columns with SEA section subjected to minimum eccentricity to account for the construction tolerance.

Numerical models were also developed to study the performance of SEARC columns. Hadi et al. [15] developed a simplified analytical model to simulate the axial load-moment interaction curves of SERAC columns under eccentric loading. However, the inelastic buckling of SEA sections and the concrete confinement by the SEA sections were not

Table 1
Validation of the accuracy of the FE model by comparing the test and predicted ultimate axial strength of square concrete columns reinforced with SEA sections.

Specimen	Length of the column (mm)	Dimension $B \times B$ (mm)	$f_c^{'}$(MPa)	Steel equal-angle		Ties		$P_{u,exp}$(kN)	$P_{u,FE}$(kN)	$\frac{P_{u,FE}}{P_{u,exp}}$	Ref.
				Width × thickness (mm)	$f_{sy,s}$ (MPa)	Diameter @Spacing (mm)	$f_{sy,t}$ (MPa)				
A30-S50	600	210 × 210	68.5	29.1 × 2.25	374	10@50	323	2625	2601	0.99	[14]
A30-S100	600	210 × 210	68.5	29.1 × 2.25	374	10@100	323	2619	2481	0.95	
A30-S200	600	210 × 210	68.5	29.1 × 2.25	374	10@200	323	2469	2373	0.96	
A30-S400	600	210 × 210	68.5	29.1 × 2.25	374	10@400	323	2446	2469	1.01	
A40-S50	600	210 × 210	68.5	39.3 × 3.7	473	10@50	323	3009	2878	0.96	
A40-S100	600	210 × 210	68.5	39.3 × 3.7	473	10@100	323	2836	2677	0.94	
A40-S200	600	210 × 210	68.5	39.3 × 3.7	473	10@200	323	2791	2656	0.95	
A40-S400	600	210 × 210	68.5	39.3 × 3.7	473	10@400	323	2614	2686	1.03	
A30-S50-C	800	210 × 210	68.5	29.1 × 2.25	374	10@50	323	2548	2640	1.04	[15]
A30-S75-C	800	210 × 210	68.5	29.1 × 2.25	374	10@75	323	2749	2612	0.95	
A40-S50-C	800	210 × 210	68.5	39.3 × 3.7	473	10@50	323	2977	2987	1.01	
A40-S75-C	800	210 × 210	68.5	39.3 × 3.7	473	10@75	323	2747	2934	1.07	
Mean										0.99	
Standard Deviation (SD)										0.04	
Coefficient of Variance (CoV)										0.04	

Note: B=width of the column, $f_c^{'}$= unconfined compressive strength of concrete, $f_{sy,s}$=yield stress of SEA section, $f_{sy,t}$= yield stress of stirrups, $P_{u,exp}$= test ultimate axial strength and $P_{u,FE}$ = ultimate axial strength obtained from FE analysis.

considered in the simplified analytical modeling. Furthermore, the effects of important column parameters on the axial performance of RC columns reinforced with SEA sections have not been fully investigated yet.

The performance of RC columns reinforced with SEA sections is influenced by the lateral tie spacing, the width and thickness of SEA sections, yield stress of SEA sections, and the concrete compressive strength. These parameters need to be studied thoroughly in order to facilitate the practical applications of such columns and develop design methods. However, only few studies have been performed on the axial performance of RC columns reinforced with SEA sections. Therefore, further research works are needed to fully understand their structural behavior. Nonlinear inelastic numerical models are cost-effective tools that can be used to conduct parametric studies compared to expensive experiments. Based on the extensive review of literature, no publications on 3D finite element (FE) modeling of RC columns reinforced with SEA sections were found. This paper rectifies the lack of 3D finite element (FE) models and computational results of square RC short columns with SEA as longitudinal reinforcement. The influences of inelastic buckling of SEA reinforcement and confinement are considered in the FE modeling. A verification of the model using the available experimental results is presented. The numerical model developed is utilized to investigate the influences of important parameters on the structural performance of RC columns. The benchmark numerical data presented can be used to design guidelines for their practical applications. It should be noted that one of the objectives of this study is to validate the constitutive models of steel and concrete for use in the inelastic analysis of axially loaded HSC short columns reinforced with SEA sections where the member length-to-width *(L/B)* ratio is less than 4. The validated FE model can be employed to investigate the performance of HSC slender columns reinforced with SEA sections subjected to combined axial and biaxially loads. Furthermore, bond behavior of concrete and SEA sections of such a column should be studied in the future study and propose a novel system to improve anchorage and bond between SEA sections and concrete. However, examining the bond behavior of such a column is out of the scope of this paper.

2. Development of FE model

The FE model was built by employing the simulation software Abaqus/CAE 2020. Fig. 3 depicts the finite element model of RC composite columns with SEA longitudinal reinforcement. The 8-node solid element with reduced integration (C3D8R) was assigned for confined concrete, cover concrete, and SEA sections, while the 2-node 3D linear truss element was used for steel ties as presented in Fig. 4. Although the C3D8R element has only a single integration point, it is capable of solving the integral problem with high accuracy in a minimal computational time. The 2-node 3D linear truss element transmits only axial force and offers simplicity in the development of FE models.

2.1. Selection of mesh size

A sensitivity analysis was undertaken to study the optimal element size. Several sizes were examined, revealing that the 10-mm mesh provides accurate results while maintaining a suitable computational time. For a typical specimen, there were 53,856 elements.

2.2. Interaction properties and boundary conditions

The interaction between the confined concrete and SEA sections and between confined concrete and cover concrete is important to ensure that the finite element model accurately represents the true mechanical behavior of composite columns. For the interaction property, a penalty friction formulation using a friction coefficient of 0.6 was assigned for the tangential contact behavior, while a hard contact was employed for the normal behavior. Previous studies conducted by Hassanein et al. [17] and Dai and Lam [18] showed that the friction coefficient had an insignificant effect on the load-deformation curves of columns. However, the value of a friction coefficient less than 0.25 caused difficulty in the convergence when modeling the post-peak behavior of the columns. The interaction between concrete and steel ties was simulated through the embedded constraints, in which concrete and ties were defined as the host region and embedded region, respectively. Moreover, full bond was considered at the overlapping between ties and SEA to simulate the real specimen at which ties were bent of a radius of 6 mm at four corners and then welded to the SEA. The axial loading was applied as a monotonic displacement at the reference point connected to the top surface of the column. The top point was restrained except in the column axial direction at which the displacement load was applied. On the other hand, to simulate the fixed support at the bottom of the column, all degrees of freedom were fully restrained in all directions. The axial stress-axial deformation curves of RC columns reinforced with SEA sections were recorded during the analysis. The axial stress-axial deformation curves can be converted to axial stress-axial strain curves

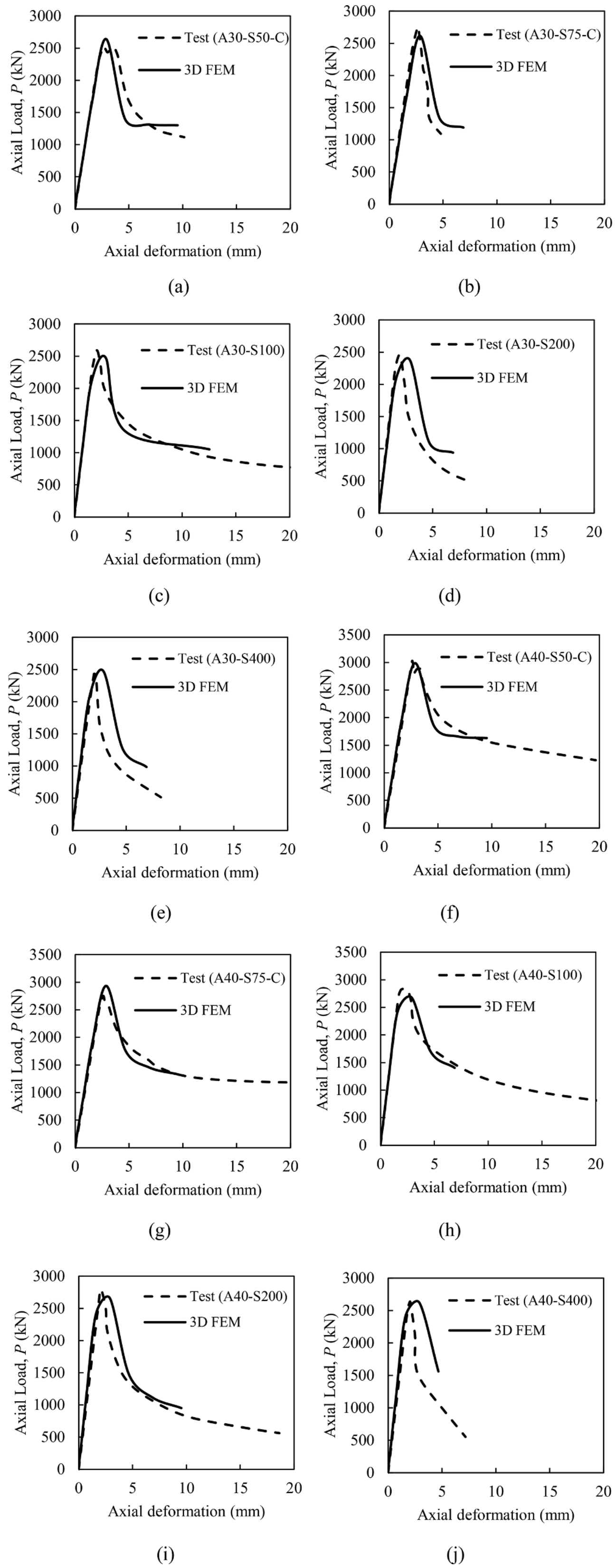


Fig. 7. Comparison of test and predicted axial load-axial deformation curves of square concrete columns reinforced with SEA sections.

by dividing the axial deformation with the length of the columns.

3. Stress–strain curves of structural steel

Fig. 5 depicts the stress–strain relationships of steel-equal angles. As discussed above, experimental studies on RC columns reinforced with SEA sections showed that the localized buckling of SEA sections could be minimized by using transverse steel ties with small spacing. However, for columns with a larger spacing of ties, the SEA sections underwent localized buckling followed by the crushing of cover concrete. The stress–strain response of SEA sections was assumed to be elastic-perfectly plastic for columns with a tie spacing up to 100 mm and beyond that, the inelastic buckling of SEA sections was simulated based on the stress–strain relationships of steel developed by Chen and Lin [19]. According to the stress–strain relationship of structural steel depicted in Fig. 5, the strength of SEA sections decreases linearly to 20% of their yield stress ($f_{sy,s}$) from the concrete strain $\varepsilon_c^{'}$ to $2.5\varepsilon_c^{'}$ and remains constant thereupon [19]. In the FE model, the elastic modulus was taken as 200 GPa while Poisson's ratio of 0.3 was used.

4. Stress–strain relationships of unconfined and confined concrete

There are two regions in an RC column reinforced with SEA sections: (a) unconfined cover concrete and (b) confined concrete. Fig. 6 presents the stress–strain relationships of confined and unconfined concrete. The stress–strain relationships depicted in Fig. 6 consists of two parts: (a) an ascending response and (b) a descending curve. The axial concrete stress (σ_c) at the ascending response was obtained using the equations proposed by Mander et al. [7] as:

$$\sigma_c = \frac{f_{cc}^{'}(\varepsilon_c/\varepsilon_{cc}^{'})\lambda}{(\varepsilon_c/\varepsilon_{cc}^{'})^{\lambda} + \lambda - 1} \quad for \quad 0 \leqslant \varepsilon_c \leqslant \varepsilon_{cc}^{'} \tag{1}$$

$$\lambda = \frac{E_c\varepsilon_{cc}^{'}}{E_c\varepsilon_{cc}^{'} - f_{cc}^{'}} \tag{2}$$

where, ε_c is the corresponding strain at σ_c; $f_{cc}^{'}$ denotes the concrete compressive strength; $\varepsilon_{cc}^{'}$ denotes the corresponding strain at $f_{cc}^{'}$; and E_c represents the concrete elastic modulus calculated as [20]:

$$E_c = 4400\sqrt{\alpha_1 f_c^{'}} \text{ (MPa)} \tag{3}$$

where α_1 is the reduction factor, calculated according to AS3600 [21] to consider the column size effects on the unconfined concrete compressive strength ($f_c^{'}$) as:

$$\alpha_1 = 1 - 0.003f_c^{'} \quad 0.72 \leqslant \alpha_1 \leqslant 0.85 \tag{4}$$

For the unconfined cover concrete, the concrete compressive stress in the descending branch (Fig. 6) decreases from the ultimate strain ($\varepsilon_c^{'}$) to the spalling strain ($\varepsilon_{sp}^{'}$), passing through the inflection point of ($2\varepsilon_c^{'}$). In this study, the spalling strain of 0.006 was used as suggested by Zhao et al. [22]. The formula proposed by Razvi and Saatcioglu [8] was used to predict the unconfined concrete strain ($\varepsilon_c^{'}$) as

$$\varepsilon_c^{'} = 0.0028 - 0.0008k_3 \tag{5}$$

$$k_3 = \frac{40}{\alpha_1 f_c^{'}} \leqslant 1.0 \tag{6}$$

The increase in the compressive load and ductility of the concrete confined by ties was simulated using the lateral pressure equation given by Razvi and Saatcioglu [8]. The compressive strength of confined concrete can be obtained using Eq. (7) [8] as:

$$f_{cc}^{'} = \alpha_1 f_c^{'} + k_1 f_{le,l} \tag{7}$$

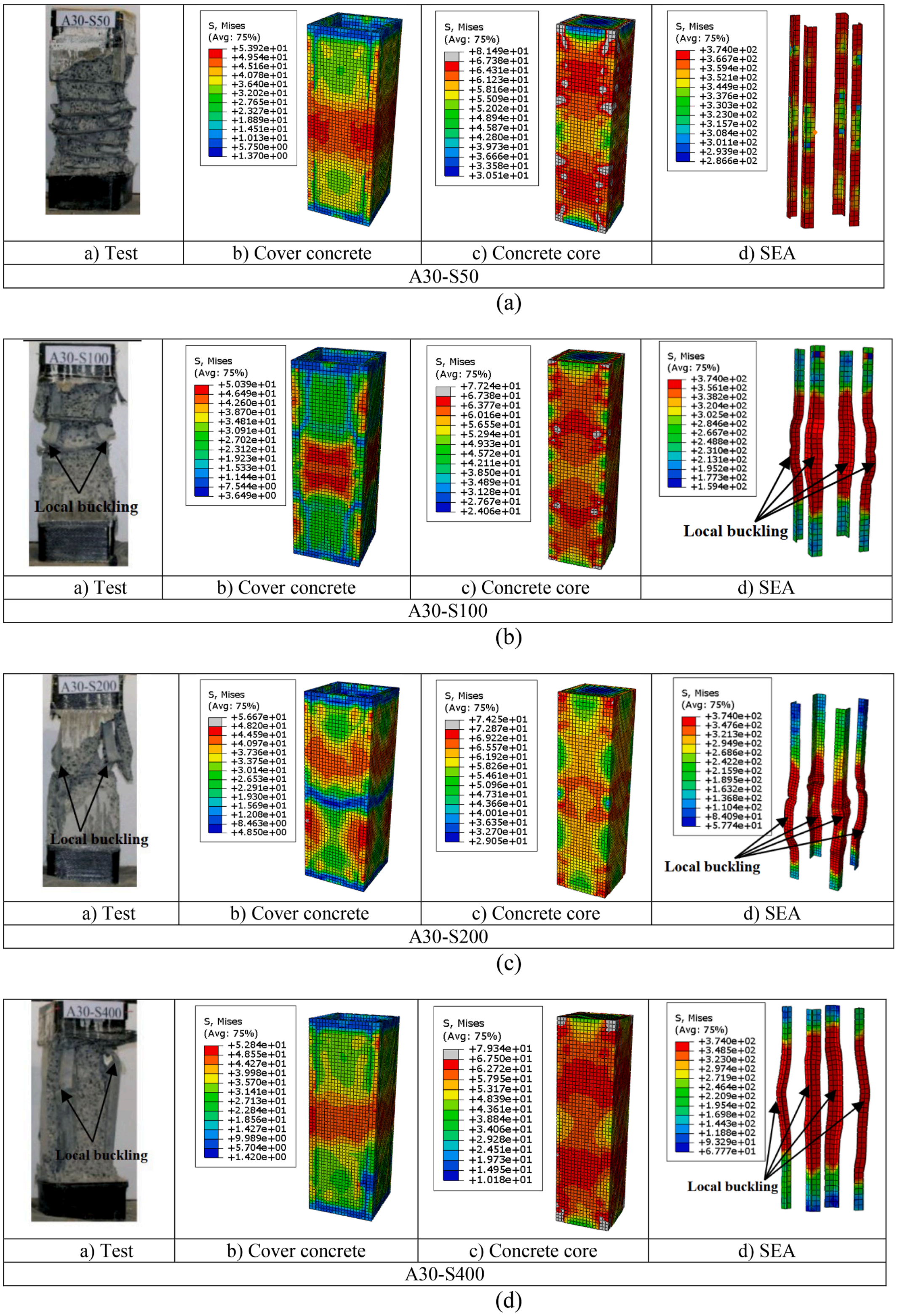


Fig. 8. Comparison of predicted failure modes of the columns obtained from FE analysis with the experimental observations.

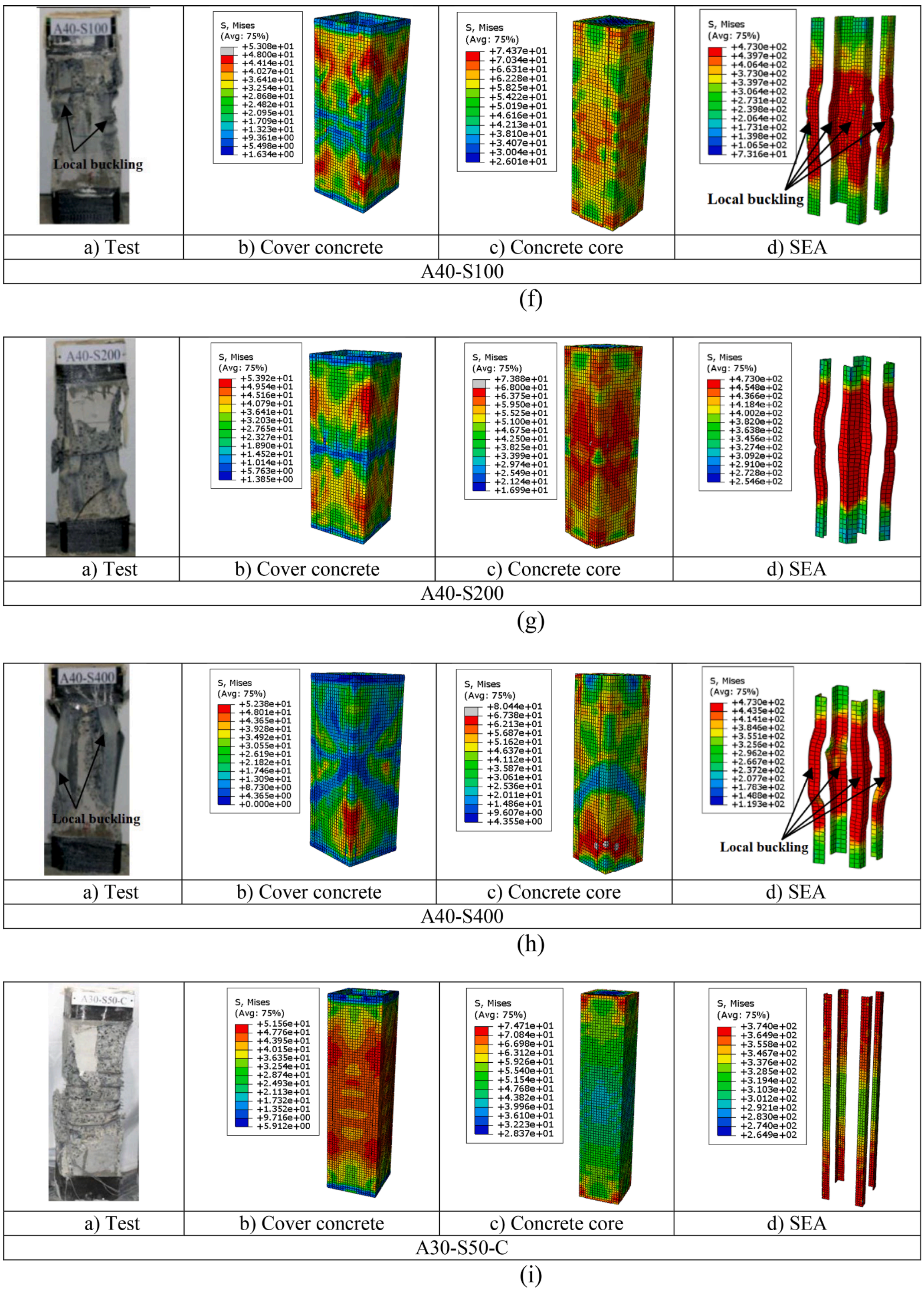
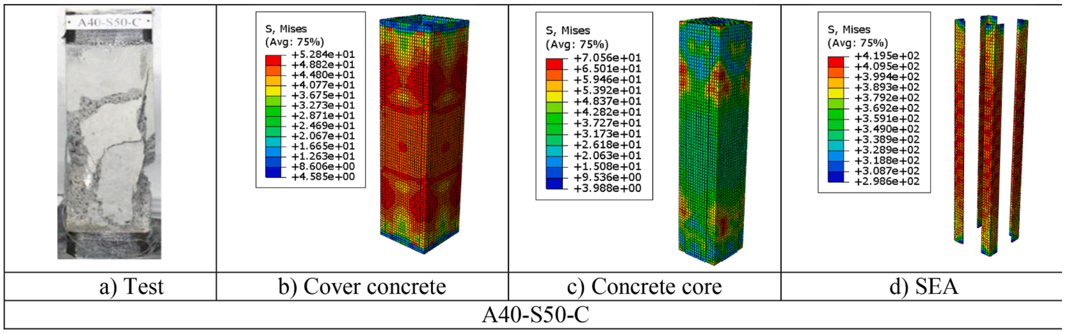


Fig. 8. (*continued*).



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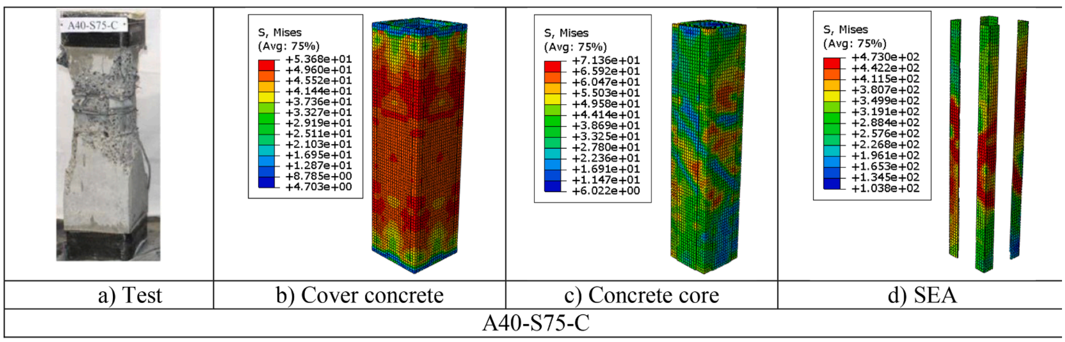

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Fig. 8. (*continued*).

Table 2
Parameters of the columns used for the FE parametric study.

Group	Column	Dimension $B \times B$ (mm)	Compressive strength of concrete f_c' (MPa)	Steel equal-angle		Ties	
				Width × thickness (mm)	$f_{sy,s}$ (MPa)	Dia-spacing (mm)	$f_{sy,t}$ (MPa)
G1	C1	240 × 240	60	40 × 3	350	10@40	350
	C2	240 × 240	60	40 × 4	350	10@40	350
	C3	240 × 240	60	40 × 5	350	10@40	350
	C4	240 × 240	60	40 × 6	350	10@40	350
G2	C5	240 × 240	60	40 × 3	350	10@40	350
	C6	240 × 240	60	45 × 3.5	350	10@40	350
	C7	240 × 240	60	50 × 3.9	350	10@40	350
	C8	240 × 240	60	55 × 4.2	350	10@40	350
G3	C9	240 × 240	60	65 × 2.5	350	10@40	350
	C10	240 × 240	60	75 × 2.1	350	10@40	350
	C11	240 × 240	60	85 × 1.9	350	10@40	350
	C12	240 × 240	60	95 × 1.7	350	10@40	350
G4	C13	240 × 240	60	40 × 3	350	10@40	350
	C14	240 × 240	60	40 × 3	350	10@80	350
	C15	240 × 240	60	40 × 3	350	10@120	350
	C16	240 × 240	60	40 × 3	350	10@160	350
G5	C17	240 × 240	40	40 × 3	350	10@40	350
	C18	240 × 240	60	40 × 3	350	10@40	350
	C19	240 × 240	80	40 × 3	350	10@40	350
	C20	240 × 240	100	40 × 3	350	10@40	350
G6	C21	240 × 240	60	40 × 3	250	10@40	250
	C22	240 × 240	60	40 × 3	350	10@40	350
	C23	240 × 240	60	40 × 3	450	10@40	450
	C24	240 × 240	60	40 × 3	550	10@40	550

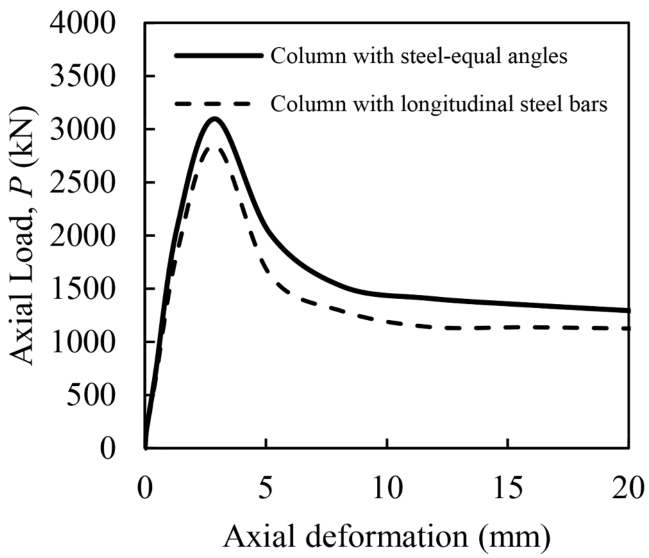


Fig. 9. The axial load-axial deformation curves of concrete columns reinforced with SEA sections and longitudinal steel reinforcing bars.

$$k_1 = 6.7(f_{le,l})^{-0.17} \tag{8}$$

where $f_{le,l}$ is the equivalent uniform lateral confinement stress, calculated as:

$$f_{le,l} = k_2 f_l \tag{9}$$

where f_l is the average uniform lateral confining stress, given by Mander et al. [7] as:

$$f_l = \frac{2A_{s,t} f_{sy,t}}{s b_c} \tag{10}$$

where $A_{s,t}$ represents the area of the ties; $f_{sy,t}$ denotes the yield strength of the ties; s denotes the center-center spacing of ties measured vertically; b_c is the core dimensions of the centerline of ties. In Eq. (9), k_2 represents the confinement coefficient of rectangular ties developed by Razvi and Saatcioglu [8] as:

$$k_2 = 0.15\sqrt{\left(\frac{b_c}{s}\right)\left(\frac{b_c}{s_l}\right)} \leqslant 1.0 \tag{11}$$

where, s_l is the clear spacing between the two SEA sections. Razvi and Saatcioglu [8] proposed formulae for determining the compressive strain (ε'_{cc}) of the confined concrete as

$$\varepsilon'_{cc} = \varepsilon'_c(1 + 5k_3 K) \tag{12}$$

$$K = \frac{k_1 f_{le,l}}{\alpha_1 f'_c} \tag{13}$$

The stress in the descending branch of confined concrete [23] was evaluated as

$$\sigma_c = f'_{cc} - \frac{f'_{cc} - f_{cr}}{1 + \left(\frac{\varepsilon_c - \varepsilon'_{cc}}{\varepsilon_{ci} - \varepsilon'_{cc}}\right)^{-2}} \text{ for } \varepsilon_c > \varepsilon'_{cc} \tag{14}$$

in which f_{cr} represents the residual strength of confined concrete. The residual strength f_{cr} was taken as $f_{cr} = 0.3f'_{cc}$ and ε_{ci} denotes the inflection strain. The inflection strain was specified as 0.007 [20].

The Drucker-Prager yield criterion model was used in the FE model for simulating the nonlinear responses of concrete. The yield stage of concrete was defined using two parameters including *DRUCKER PRAGER and *DRUCKER PRAGER HARDENING. The associate flow and isotropic rule were used for defining the linear Drucker–Prager model. The material angle of friction was taken as 20° and the ratio of flow stress was equal to 0.8 [24].

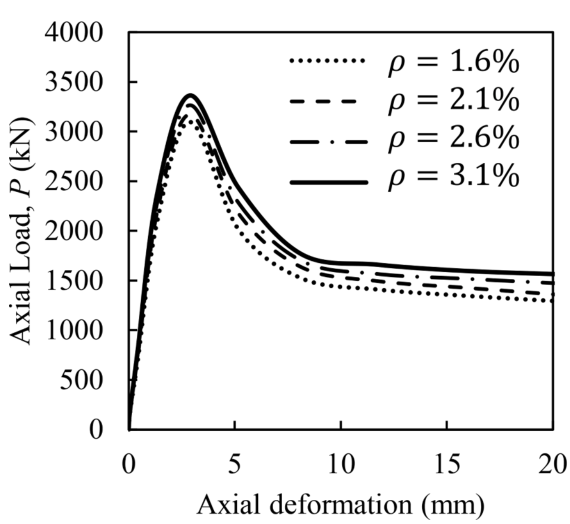
5. Validation of the FE model

5.1. Ultimate axial strength

The accuracy of the model is verified by comparing the ultimate axial strengths of the SEA reinforced concrete columns against the test data given by Ibrahim et al. [14] and Hadi et al. [15]. Table 1 shows the summary of the test specimens and the comparisons of the experimental data and the predicted ultimate axial strengths of the tested columns. As presented in Table 1, the FE model accurately predicts the ultimate axial strengths of the columns measured during the tests with ±10% accuracy. The mean $P_{u,num}/P_{u,exp}$ is 0.99 with a standard deviation of 0.04.

5.2. Load-deformation responses

The validation of the FE models developed is further performed by comparing the predicted load-deformation curves of the tested columns, as illustrated in Fig. 7. A good agreement between the FE results and



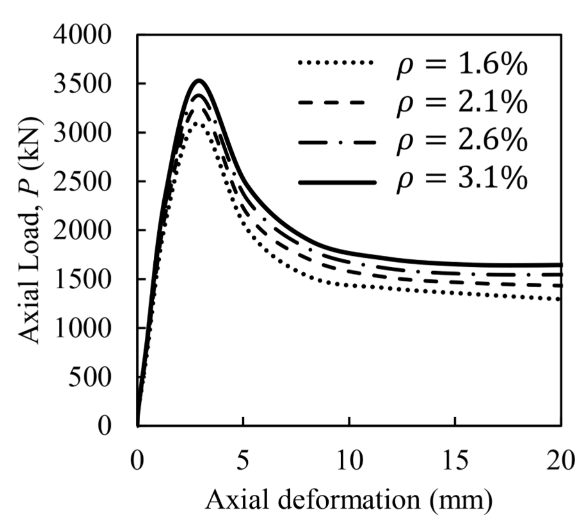


Fig. 10. Influences of longitudinal reinforcement ratio on the axial load-axial deformation curves of concrete columns reinforced with SEA sections by: (a) changing the thickness of SEA sections and (b) changing the width of SEA sections.

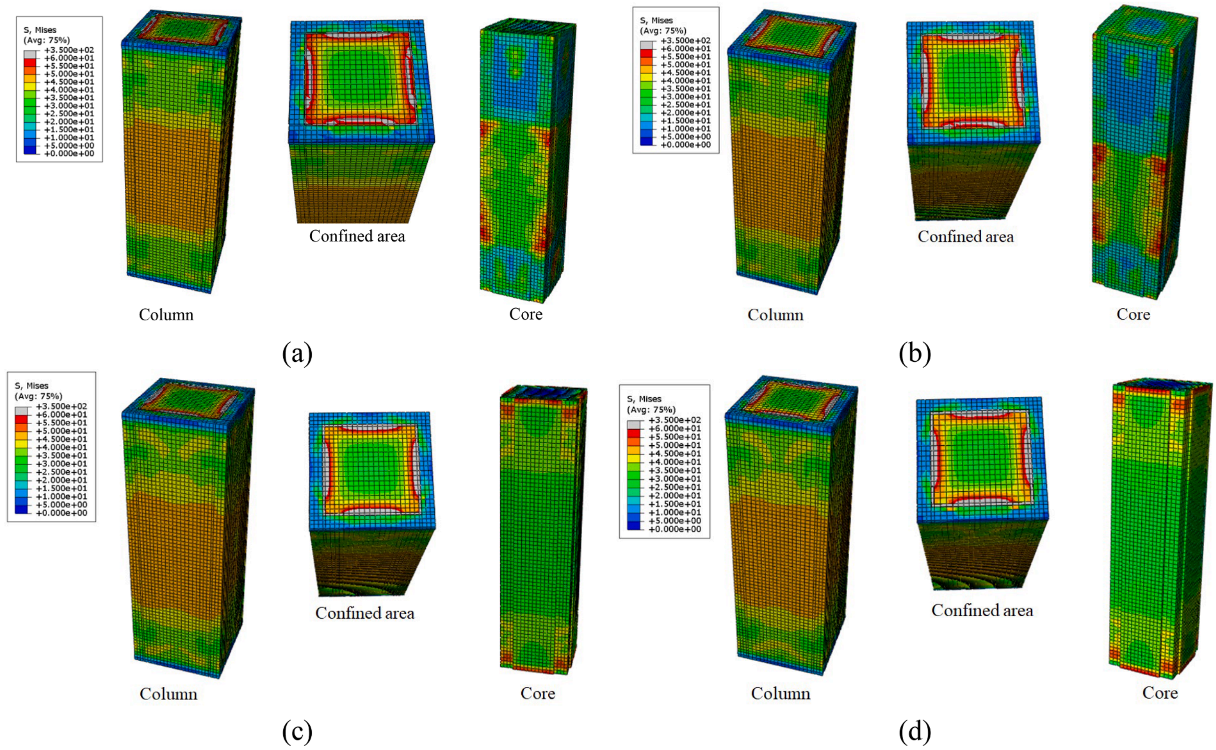


Fig. 11. Influences of longitudinal reinforcement ratio (by increasing the thickness) on the Von Mises stress of concrete columns reinforced with SEA sections: (a) ρ = 1.6%, (b) ρ = 2.1%, (c) ρ = 2.6%, and (d) ρ = 3.1%.

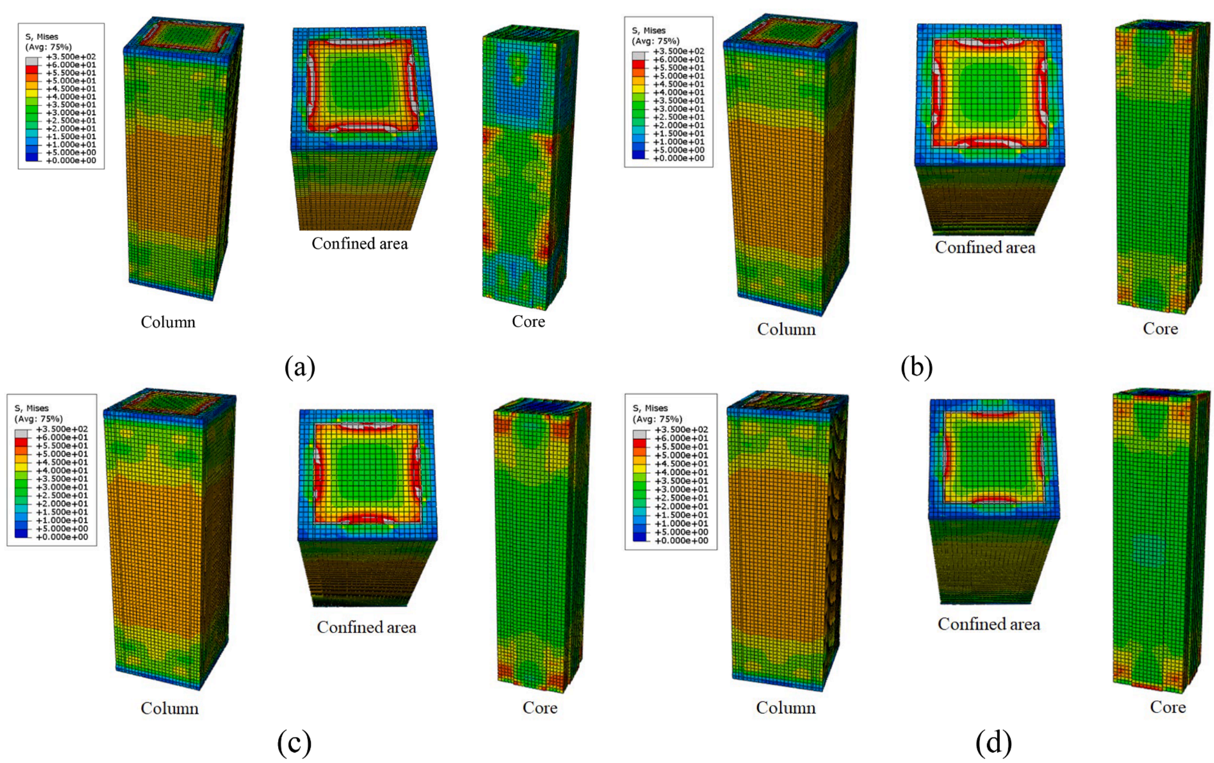


Fig. 12. Influences of longitudinal reinforcement ratio (by increasing the width) on the Von Mises stress of concrete columns reinforced with SEA sections: (a) ρ = 1.6%, (b) ρ = 2.1%, (c) ρ = 2.6%, and (d) ρ = 3.1%.

experimental data can be observed. As shown in Fig. 7, the FE model accurately determines the post-peak strength of the columns. Thus, the proposed stress–strain responses of the SEA sections incorporating the inelastic buckling can predict the behavior of such a column experimentally observed. This suggests that the proposed model can be used to parametrically study the performance of short concrete columns

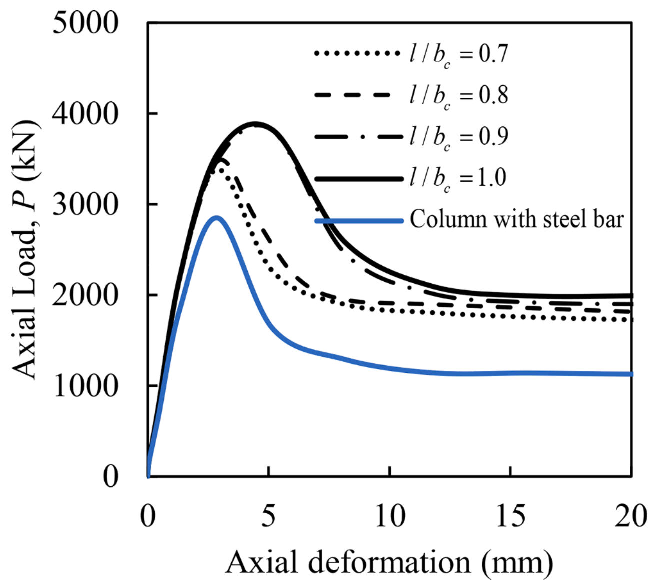


Fig. 13. Influences of l/b_c ratio on the axial load-axial deformation curves of concrete columns reinforced with SEA sections.

reinforced with SEA sections.

5.3. Failure modes

The predicted failure modes of the tested columns from the FE analysis are compared in Fig. 8 with the corresponding failure observed during the tests. It can be seen that the FE model predicts well the experimentally observed failure modes of the tested columns. It is seen from Fig. 8(d) and 8(h) that although SEA sections underwent significant buckling, the columns did not fail prematurely. This confirms the findings of Ibrahim et al. [14] who tested columns reinforced with SEA section with a tie spacing of 400 mm. However, Ibrahim et al. [14] reported that columns reinforced with conventional steel bars with a tie spacing of 400 mm failed due to premature failure. This is because SEA sections have a higher buckling capacity than conventional steel bars.

6. Parametric study

The reference specimen was a square column of 240 mm × 240 mm in cross-section, and to keep the short column characteristics, a height of

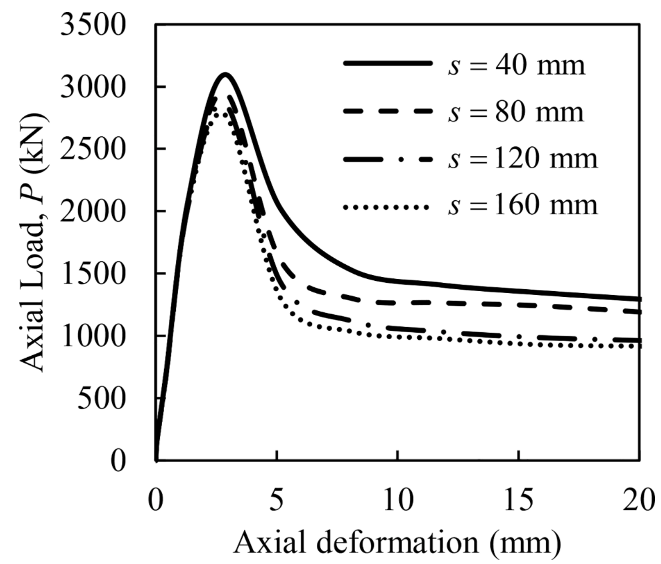


Fig. 15. Influences of tie spacing on the axial load-axial deformation curves of concrete columns reinforced with SEA sections.

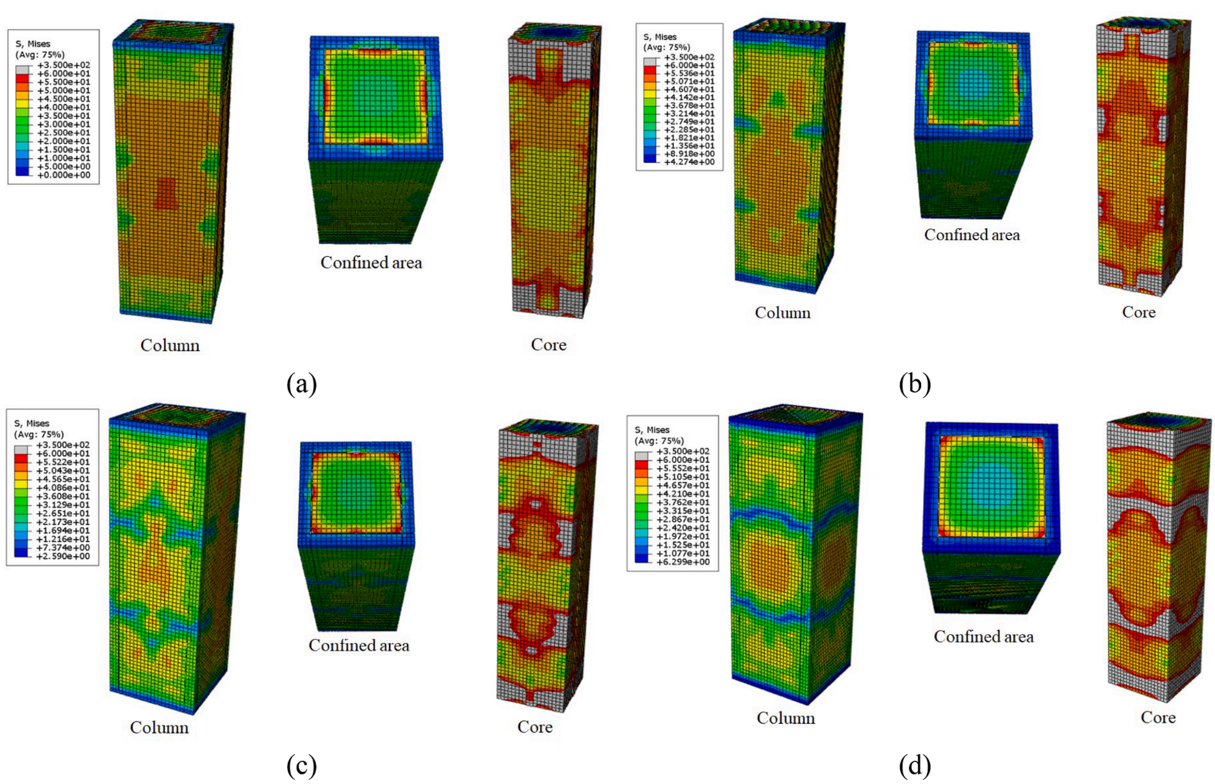


Fig. 14. Influences of l/b_c ratio on the Von Mises stress of concrete columns reinforced with SEA sections: (a) $l/b_c = 0.7$, (b) $l/b_c = 0.8$, (c) $l/b_c = 0.9$, and (d) $l/b_c = 1$.

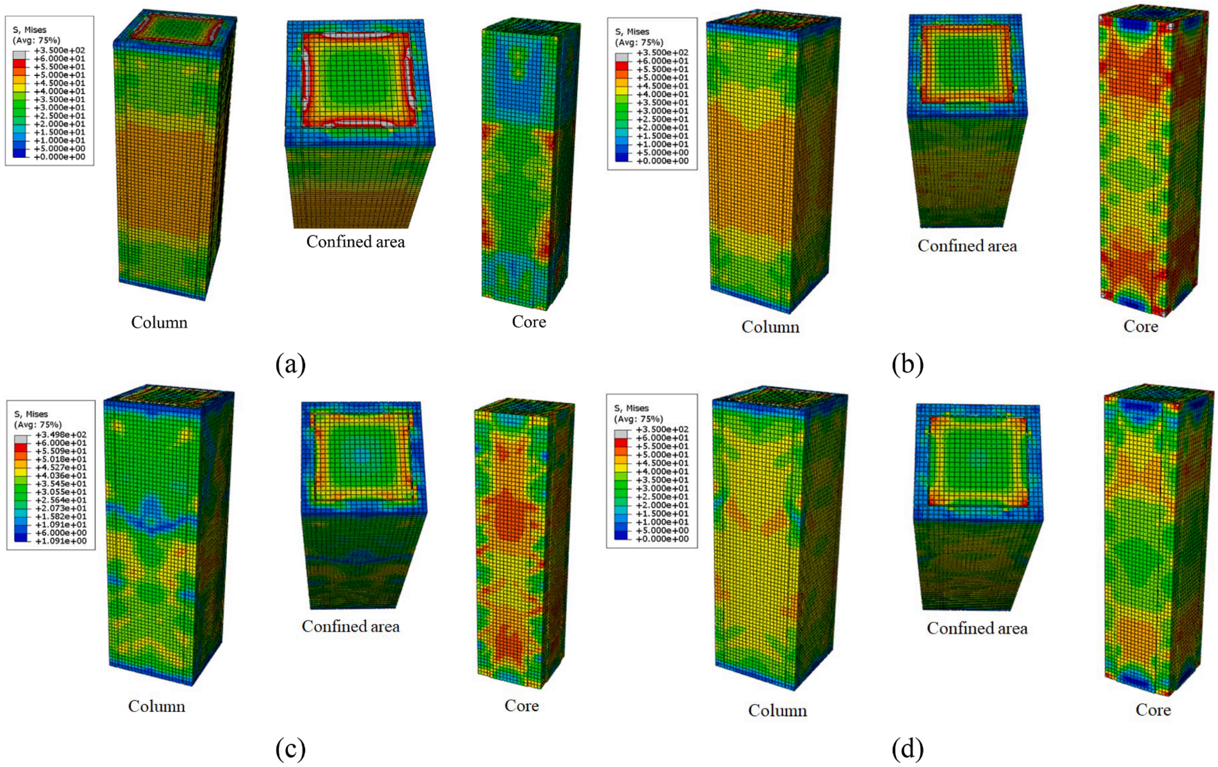


Fig. 16. Influences of tie spacing on the Von Mises stress of concrete columns reinforced with SEA sections: (a) $S = 40mm$, (b) $S = 80mm$, (c) $S = 120mm$, and (d) $S = 160mm$.

720 mm was selected (three times the column width). The concrete compressive strength was $f_c^{'} = 60$ MPa and the outer concrete cover was 25 mm. Four SEA of dimensions (width × thickness) = 40 mm × 3 mm and yield strength $f_{sy,s} = 350$ MPa were utilized as longitudinal reinforcement. Reinforcing steel of diameter equal to 10 mm and yield strength of $f_{sy,t} = 350$ MPa were utilized as transverse ties distributed along the column height with spacing $s = 40$ mm.

The parametric study was designed to examine the influence of geometry and material parameters that influence the behavior of short columns reinforced using SEA and subjected to axial compression. For this, twenty-four columns, divided into six groups, as shown in Table 2, were numerically investigated. The first two groups were selected to examine the influences of the longitudinal steel ratio (1.6%, 2.1%, 2.6%, and 3.1%) on the structural performance of composite columns with SEA. The examined ratios were predicted by varying the SEA thickness in the first group or the width of the SEA sections in the second group. In the third group, the width of the SEA sections was varied to investigate its effects on the performance of RC short columns. Moreover, the last three groups in Table 2 were used to study the influence of spacing between ties (40 mm to 160 mm with 40 increments), the compressive strength of concrete (40 MPa to 100 MPa with 20 increments), and the yield strength of SEA sections (250 MPa to 550 MPa with 100 increments) on the structural performance of composite columns with SEA.

6.1. Influences of SEA sections

To examine the efficiency of using SEA sections as longitudinal reinforcement, a concrete column reinforced with SEA sections was compared with another column having the same reinforcement ratio using four longitudinal deformed steel bars of 16 mm in diameter. Fig. 9 shows the simulation results in terms of axial load-deformation. It is revealed that the use of SEA sections considerably improves the overall behavior, ultimate strength by about 8.7%, and residual strength by 14.6% compared to columns reinforced using longitudinal steel bars. Therefore, SEA sections can be considered a good alternative to longitudinal steel bars in HSC columns.

6.2. Influences of longitudinal reinforcement ratio (ρ)

The ratio of the cross-sectional area of the reinforcing SEA sections to the total (gross) cross-sectional area of the concrete column is called the longitudinal steel ratio (ρ). As above mentioned, the impact of the ratio ρ was investigated through two approaches. In the first approach, the SEA thickness (3 mm, 4 mm, 5 mm, and 6 mm) was the main parameter of the study, while in the second approach, the width of SEA sections (40 mm, 45 mm, 50 mm and 55 mm) was the main parameter of the study. The load–displacement responses obtained for both approaches are presented in Fig. 10. As shown, increasing the ratio ρ by increasing the thickness of the SEA sections from 1.6% to 2.1% increases the ultimate strength by 2.5%. The ultimate strengths are increased by 5.5% and 8.6% by increasing ρ from 1.6% to 2.6% and from 1.6% to 3.1%, respectively. On the other hand, increasing the ratio ρ from 1.6% to 2.1% by increasing the width of the SEA sections increases the ultimate strength by 5.5%. Moreover, increasing the ρ from 1.6% to 2.6% and from 1.6% to 3.1% increases the ultimate strength by 9.2% and 14%, respectively. Fig. 10 depicts that the ductility of the column increases as the longitudinal steel ratio increases. Similar findings were reported by Ibrahim et al. [14] based on their experimental study. This is because increasing the ρ ratio increases the effective confinement on the concrete core, thereby improving the ultimate strength and ductility of the columns. As presented in Figs. 11 and 12, the confinement effect is more concentrated at the column mid-height. However, with increasing ρ, the region of the critical stress becomes smaller which represents the improvement of the stress distribution along the length of the columns. In a nutshell, for the same steel ratio, higher enhancement in the ultimate strength and stresses redistribution, as well as the overall behavior, can be achieved by increasing the width of SEA sections rather than the

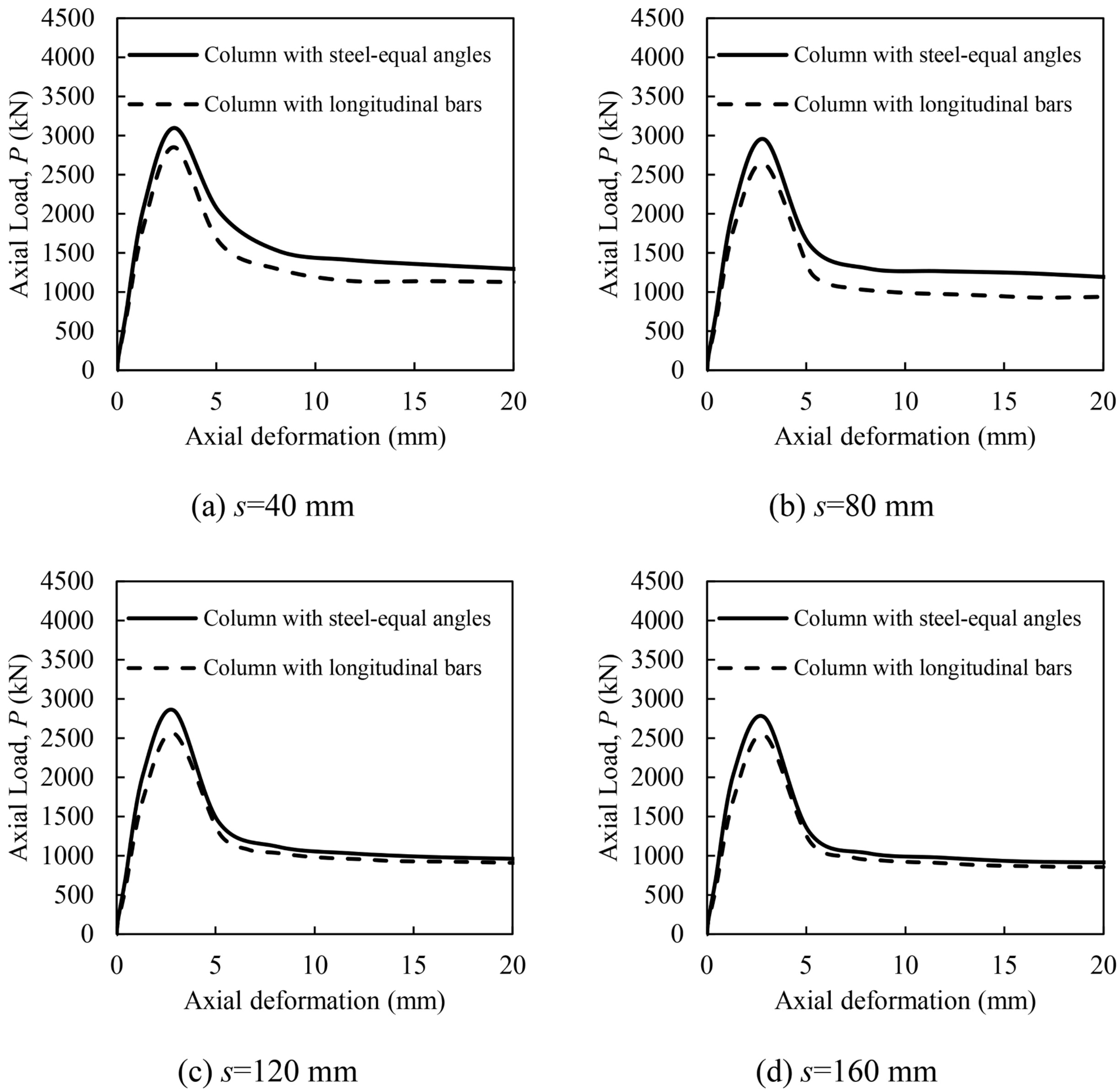


Fig. 17. Influences of tie spacing on the axial load-axial deformation curves of concrete columns reinforced with SEA sections and longitudinal reinforcing bars.

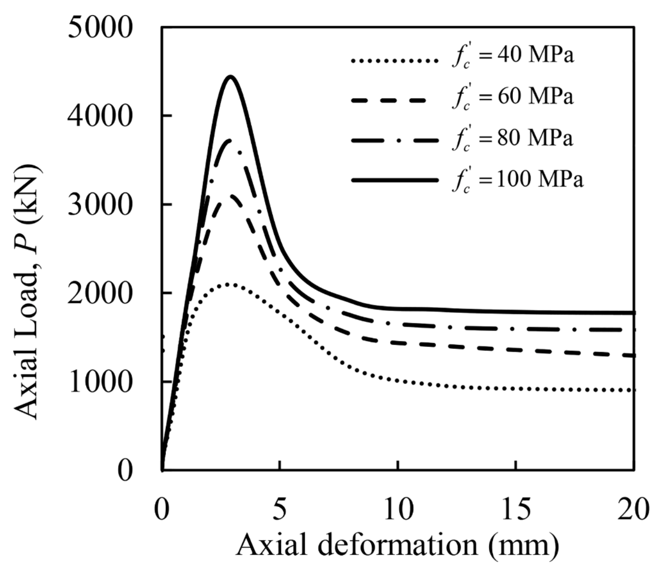


Fig. 18. Influences of concrete strengths on the axial load-axial deformation curves of concrete columns reinforced with SEA sections.

thickness of SEA sections, as shown in Figs. 10–12. This is because increasing the width of the SEA sections provides better confinement to the concrete than increasing the thickness of the SEA sections.

6.3. Influences of equal-angle width

Four different widths (65, 75, 85, and 95 mm) of the SEA sections were employed to examine the influence of the width of the SEA sections on the structural performance of composite columns reinforced with SEA sections. The thickness of the SEA sections was adjusted to ensure the same longitudinal reinforcement ratio. A l/b_c ratio is introduced herein, where l is the total width of two SEA sections placed in two opposite corners, calculated as $2w$, where w is the width of each SEA section, whereas b_c is the core dimension of the centerline of ties. For an identical steel ratio, the column with a larger width of the SEA sections has a larger concrete confinement area, which improves the concrete confinement. Fig. 13 presents the axial load–displacement curves for different ratios of l/b_c (0.7, 0.8, 0.9, and 1), showing that increasing the ratio from 0.7 to 0.8 increases the ultimate strength by 2.6%. Increasing the l/b_c ratio from 0.7 to 0.9 and 1 results in a significant increase of 12.5% and 12.8% in the ultimate strength, respectively, due to the enhanced confinement provided by these ratios. It is found that when l/b_c ratio is 1, the columns behave like concrete encased concrete-filled steel tubular (CFST) columns. A comparison with the performance of concrete columns reinforced with four deformed steel bars (traditional longitudinal steel bars) of 16 mm in diameter is also presented in Fig. 13. As shown in Fig. 13, all l/b_c ratios enhance the overall performance of concrete columns when compared to the column reinforced with longitudinal steel bars. Fig. 14 illustrates the stress distributions of the columns with various l/b_c ratio. As depicted, when the l/b_c ratio increases, the stress distribution of columns improves significantly. The arching action for the column with l/b_c ratio of 0.7 can be observed in Fig. 14(a). However, with the increase in the l/b_c ratio, this arching action is seen to be eliminated, indicating the better confinement to the concrete core. Therefore, the l/b_c ratio of concrete columns reinforced with SEA sections can be increased to improve the performance of the columns.

6.4. Influences of tie spacing

The influence of tie spacing on the compressive performance of composite columns with SEA was investigated by changing the spacing values within the range from 40 mm to 160 mm. As illustrated in Figs. 15 and 16, tie spacing is a major parameter that significantly influences the

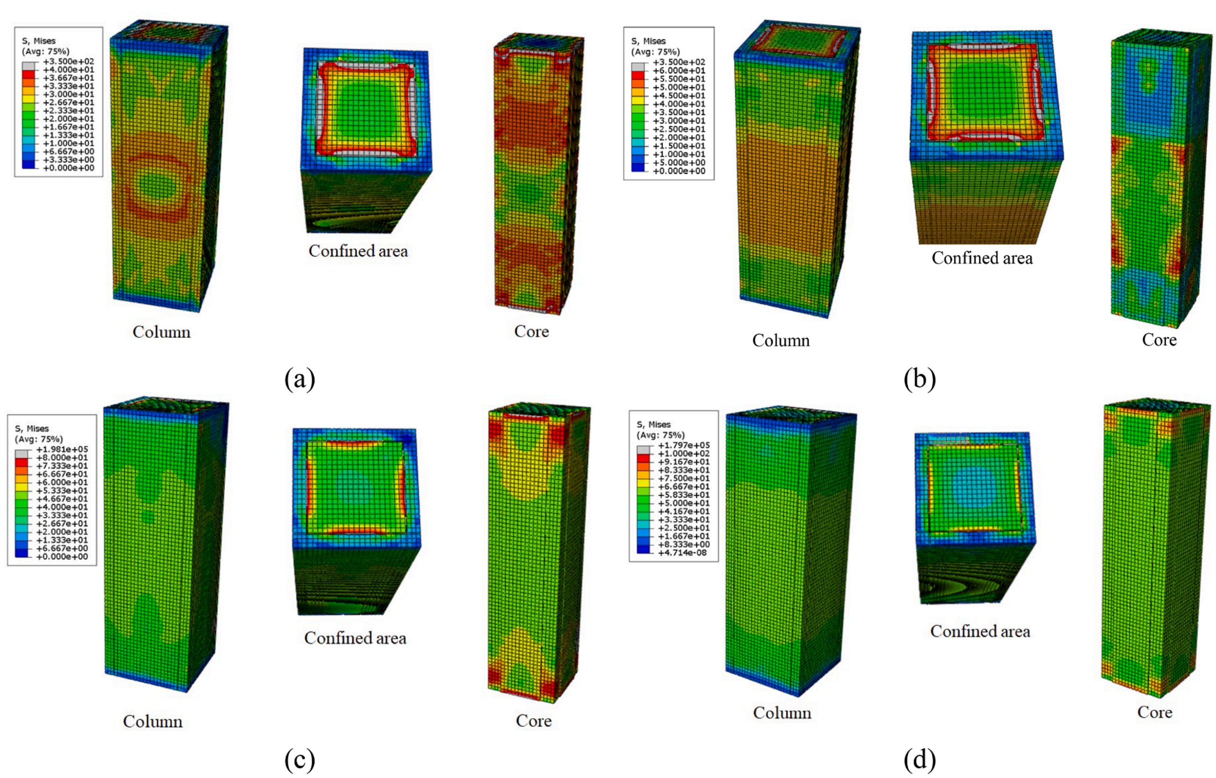


Fig. 19. Influences of concrete strengths on the Von Mises stress of concrete columns reinforced with SEA sections: (a) $f_c' = 40\ MPa$, (b) $f_c' = 60\ MPa$, (c) $f_c' = 80\ MPa$, and (d) $f_c' = 100\ MPa$.

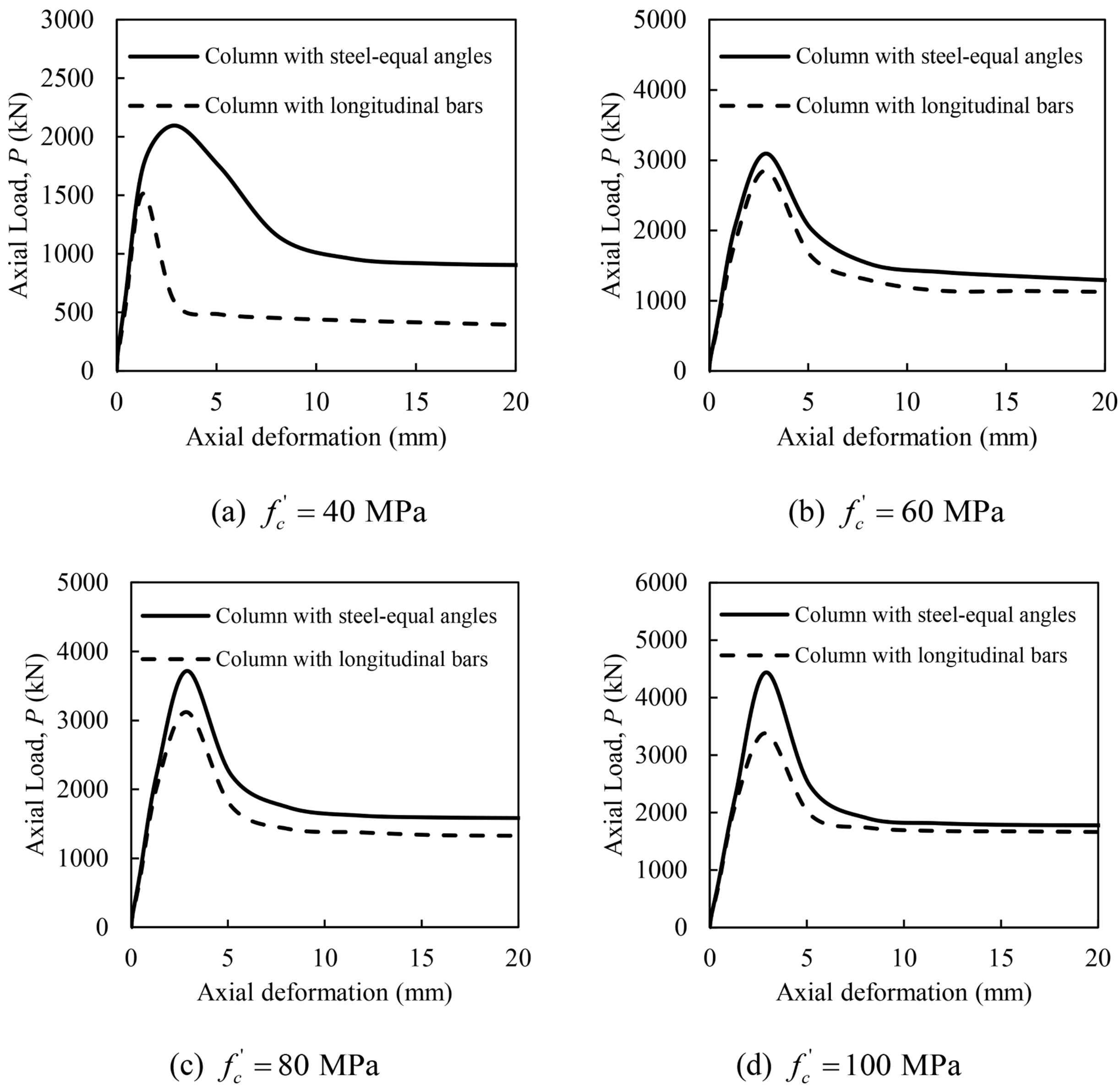


Fig. 20. Influences of concrete strength on the axial load-axial deformation curves of concrete columns reinforced with SEA sections and longitudinal reinforcing bars.

behavior of columns. The smaller the spacing, the higher the ultimate and residual strengths. This is because reducing the spacing of ties increases the lateral confining stress on the concrete core. However, the improvement in the ultimate and residual strengths of the columns becomes insignificant when the tie spacing is greater than 120 mm. Changing the tie spacing from 40 mm to 160 mm reduces the ultimate strength of the column by 10.6%. As presented in Fig. 16, an increase in the tie spacing influences the stress distribution of the columns. When the spacing of the ties was 40 mm, the stress was more concentrated at the center of the columns due to effective confinement. However, when the tie spacing increases, the confinement effect is less effective, as can be evident from Fig. 16. The influences of tie spacing on the axial load-axial deformation curves of concrete columns reinforced with SEA sections and longitudinal reinforcing bars for the same reinforcement ratio are shown in Fig. 17. It can be seen that for columns with a smaller tie spacing, the ultimate strength and residual strength of RC columns with SEA sections are significantly higher than those of traditional RC columns. However, for the columns with a large tie spacing, the behavior of concrete columns reinforced with SEA sections and longitudinal reinforcing bars for the same reinforcement ratio is found to be very similar.

6.5. *Influences of concrete compressive strength*

To study the effect of the compressive strength of concrete, the concrete strength ranging from 40 MPa to 100 MPa was considered in the analysis. As illustrated in Figs. 18 and 19, the concrete compressive strength can be considered one of the major parameters that significantly affects the performance of short concrete columns. Increasing compressive strength from 40 to 60, 80, and 100 MPa increases the ultimate strength of the columns by 47.7%, 77.7%, and 111.8%, respectively. From the stress distribution of the columns presented in Fig. 19, it can be seen that the confinement effect is the most effective for the column with a compressive strength of 40 MPa. However, with the increase in the concrete compressive strength, the confinement effect tends to diminish. To improve the confinement to the core concrete in HSC columns, either the spacing of ties should be reduced or the l/b_c ratio should be increased Fig. 20 illustrates the influences of concrete strength on the axial load-axial deformation curves of concrete columns reinforced with SEA sections and longitudinal reinforcing bars for the same reinforcement ratio. It can be seen that the ultimate and residual strengths of RC columns with SEA sections are higher than those of

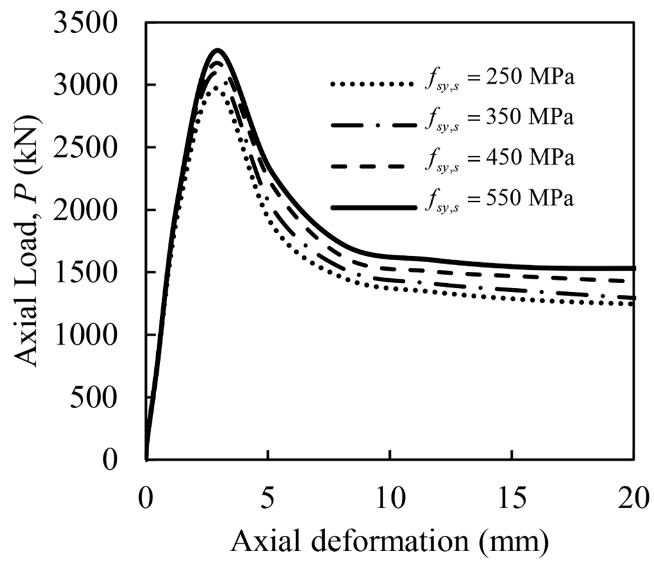


Fig. 21. Influences of steel yield stress on the axial load-axial deformation curves of concrete columns reinforced with SEA sections.

traditional RC columns. However, for the columns with normal strength, the improvement is much more significant as can be seen in Fig. 20.

6.6. Influences of SEA reinforcement yield stress

The effect of the yield strength of the SEA sections on the behavior of concrete columns reinforced using SEA sections was investigated using different values of the yield stress of the SEA sections ranging between 250 MPa and 550 MPa. Figs. 21 and 22 present the axial load-deformation curves and stresses on different elements, respectively. As depicted, increasing the yield stress of SEA sections increases the ultimate and residual strength. The increase in the ultimate strength is in the range from 4.2% to 10.2%. Fig. 22 illustrates the stress distribution. As shown, the yield stress of SEA sections has a moderate effect on the confinement to the concrete.

7. Conclusions

In this paper, a new FE model has been presented for the inelastic analysis of square high-strength concrete short columns with SEA sections as longitudinal reinforcements subjected to axial compression. The important outcomes from this study can be listed as follows:

1. The use of SEA sections is found to improve the ultimate strength and residual strength of HSC columns by 8.7% and 14.6%, respectively compared to the column reinforced using longitudinal steel bars. Therefore, SEA sections can be considered a good alternative to longitudinal steel bars in HSC columns.
2. The axial behavior of the columns can be improved by using larger widths of SEA sections. The ultimate strength of the column is found to increase by 12.8% by increasing the l/b_c ratio from 0.7 to 1.
3. The axial strength and ductility of the columns can be increased by reducing the spacing of ties. The ultimate strength of the column is found to reduce by 10.6% by increasing the tie spacing from 40 mm to 160 mm.
4. The increase in the longitudinal steel ratio of columns improves the axial strength and ductility. However, increasing the longitudinal steel ratio by increasing the width of the SEA sections is more effective. Increasing the ratio ρ from 1.6% to 3.1% by increasing the thickness of the SEA sections enhances the ultimate strength by 8.6%. However, increasing the ratio ρ from 1.6% to 3.1% by increasing the width of the SEA sections increases the ultimate strength by 14%. Furthermore, the width of SEA sections leads to a

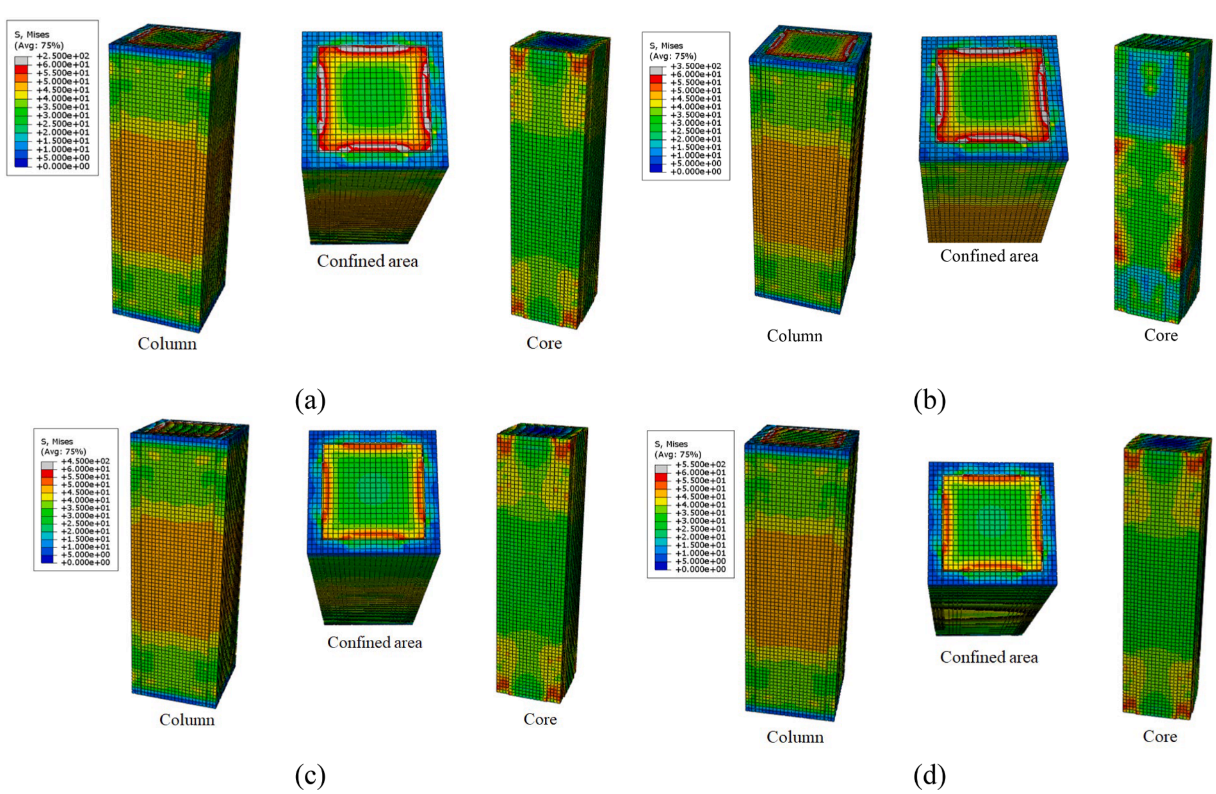


Fig. 22. Influences of steel yield stress on the Von Mises stress of concrete columns reinforced with SEA sections: (a) $f_{ys,s} = 250MPa$, (b) $f_{ys,s} = 350MPa$, (c) $f_{ys,s} = 450MPa$, and (d) $f_{ys,s} = 550MPa$.

higher ductility than increasing the thickness of the SEA sections for the same steel ratio.

5. The increase in the concrete compressive strength increases the ultimate axial strength of the columns but reduces the ductility of the columns. The ultimate strength of the columns is increased by 111.8% by increasing compressive strength from 40 to 100 MPa.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Mendis PA, Kovacic D, Setunge S. Basis for the design of lateral reinforcement for high-strength concrete columns. Struct Eng Mech: Int J 2000;9(6):589–600.
[2] Sharma UK, Bhargava P, Kaushik SK. Behavior of confined high strength concrete columns under axial compression. J Adv Concr Technol 2005;3(2):267–81.
[3] Awati M, Khadiranaikar RB. Behavior of concentrically loaded high performance concrete tied columns. Eng Struct 2012;37:76–87.
[4] Kwan AKH, Chau SL, Au FTK. Improving flexural ductility of high-strength concrete beams. Proc Instit Civil Eng – Struct Build 2006;159(6):339–47.
[5] Lam J, Ho J, Kwan A. Flexural ductility of high-strength concrete columns with minimal confinement. Mater Struct 2009;42(7):909–21.
[6] Sheikh SA, Uzumeri SM. Strength and ductility of tied concrete columns. J Struct Div 1980;106(5):1079–102.
[7] Mander JB, Priestley MJN, Park R. Theoretical stress-strain model for confined concrete. J Struct Eng 1988;114(8):1804–26.
[8] Razvi S, Saatcioglu M. Confinement model for high-strength concrete. J Struct Eng 1999;125(3):281–9.
[9] Al-Salloum YA. Influence of edge sharpness on the strength of square concrete columns confined with FRP composite laminates. Compos B Eng 2007;38(5–6):640–50.
[10] Maalej M, Tanwongsval S, Paramasivam P. Modelling of rectangular RC columns strengthened with FRP. Cem Concr Compos 2003;25(2):263–76.
[11] Razvi S, Saatcioglu M. Strength and deformability of confined high-strength concrete columns. ACI Struct J 1994;91(6):678–87.
[12] Bayrak O, Sheikh SA. Confinement reinforcement design considerations for ductile HSC columns. J Struct Eng 1998;124(9):999–1010.
[13] Paultre P, Eid R, Langlois Y, Lévesque Y. Behavior of steel fiber-reinforced high-strength concrete columns under uniaxial compression. J Struct Eng 2010;136(10):1225–35.
[14] Ibrahim A, Sheikh MN, Hadi MNS. Axial compressive behavior of steel equal angle section-reinforced square high-strength concrete column. ACI Struct J 2018;115(5):1431–42.
[15] Hadi MNS, Ibrahim AA, Sheikh MN. Behavior of high-strength concrete columns reinforced with galvanized steel equal-angle sections under different loading conditions. J Struct Eng 2018;144(7):04018070.
[16] Lai M, Hanzic L, Ho JC. Fillers to improve passing ability of concrete. Struct Concr 2019;20(1):185–97.
[17] Hassanein MF, Patel VI, El Hadidy AM, Al Abadi H, Elchalakani M. Structural behaviour and design of elliptical high-strength concrete-filled steel tubular short compression members. Eng Struct 2018;173:495–511.
[18] Dai X, Lam D. Numerical modelling of the axial compressive behaviour of short concrete-filled elliptical steel columns. J Constr Steel Res 2010;66(7):931–42.
[19] Chen C-C, Lin N-J. Analytical model for predicting axial capacity and behavior of concrete encased steel composite stub columns. J Constr Steel Res 2006;62(5):424–33.
[20] Ahmed M, Liang QQ, Patel VI, Hadi MNS. Nonlinear analysis of rectangular concrete-filled double steel tubular short columns incorporating local buckling. Eng Struct 2018;175:13–26.
[21] AS 3600. Concrete structures. Standards Australia, Sydney, NSW, Australia; 2018.
[22] Zhao X-M, Wu Y-F, Leung AYT. Analyses of plastic hinge regions in reinforced concrete beams under monotonic loading. Eng Struct 2012;34:466–82.
[23] Lim JC, Ozbakkaloglu T. Stress–strain model for normal-and light-weight concretes under uniaxial and triaxial compression. Constr Build Mater 2014;71:492–509.
[24] Hu HT, Huang CS, Wu MH, Wu YM. Nonlinear analysis of axially loaded concrete-filled tube columns with confinement effect. J Struct Eng 2003;129(10):1322–9.