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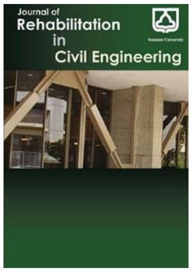

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Nonlinear Finite Element Modeling of Different Cross-Sectional Shapes of Slender RC Columns Confined with CFRP Wraps

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ABSTRACT

In the present study, nonlinear finite element analysis is carried out on the slender reinforced concrete columns wrapped using CFRP composite with different cross-sectional shapes having the same area. Thickness of the CFRP wraps, concrete compressive strength, corner radius, loading condition, slenderness ratio and column size are the main parameters of this study. According to this, four different eccentricity-to-section-height ratios, four different levels of the CFRP thickness in the strengthened specimens, the slenderness ratios of the length to the section-height (l/h) from 6 to 12, three various types of column size, concrete compressive strength values from 20 to 50 MPa and corner radiuses from 10 to 40 mm are considered. This paper presents a comparison of a numerical simulation using ABAQUS software, with the results of experimental tests by previous researchers to validate finite element models. It is shown that the predicted results by this numerical study are in reasonable agreement with the results of experimental studies. The results of this investigation also represented a considerable enhancement on the performance of strengthened columns with CFRP compared to unstrengthened columns.

1. Introduction

Strengthening of RC columns through lateral confinement provided by external fiber-reinforced polymer jackets (or wraps) has become an increasingly popular technique over the past decade. An important application of fiber-reinforced polymer composites is to provide confinement to reinforced concrete (RC) columns to enhance their load-carrying capacity. Mirmiran et al. [1] investigated that the confinement effectiveness of FRP jackets in concrete columns depends on several parameters such as, concrete strength, types of fibers and resin, fiber orientation, jacket thickness, length-to-diameter (slenderness) ratio of the

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column and the interfacial bond between the concrete core and the jacket.

Rochette and Labossi`ere [2] considered that the confinement effect is directly related to the shape of the section. They concentrated on the behavior of square and rectangular columns confined with carbon and aramid fiber sheets and also showed that confinement increased the strength and ductility of the concrete columns loaded axially. Wu et al. [3] studied that the corner radius ratio, which is defined as the ratio of the corner radius to the half width of the column, is the single most important factor that affects the confinement across the cross-section. Smith et al. [4] presented an experimental investigation on the strength and behavior of large 250 mm diameter concentrically loaded unreinforced fiber-reinforced polymer (FRP)confined concrete cylinders. They studied the effect of the number of layers of the FRP and different overlap locations on the effectiveness of the FRP wrap.

Parvin and Wang [5] performed small-scale strengthened square concrete columns with varying layers of carbon fiber reinforced polymer CFRP composites and tested subjected to an axial load at different eccentricities. Li and Hadi [6, 7], and Hadi [8-11] tested several FRP-wrapped concrete columns with a circular section under eccentric loading at different conditions. They investigated the effects of the concrete strength, wrap type, fiber orientation, and eccentricity. The experimental results clearly indicated that the FRP wrapping can enhance the strength and ductility of concrete columns under eccentric loading. The method of strengthening with FRP composite materials is being used for bending, shearing and compressed members.

Barros et al. [12] presented a strengthening technique method by using CFRP material to improve the flexural capacity of columns subjected to bending and compression.

Saadatmanesh et al. [13] presented the technique of wrapping flexible and high strength fibre composite straps around the column for seismic strengthening, to improve the confinement and also ductility and strength of the column. Malik and Foster [14] performed an experimental study to investigate the behavior of ultra-high strength concrete columns confined by CFRP, subjected to concentric and eccentric loading. Tao et al. [15] and Bisby & Ranger [16] studied the behavior of FRP confined circular RC columns subjected to compression with different eccentricities. They demonstrated that the longitudinal CFRP not only decreases the lateral deflection, but also increases the strength of the long RC columns. Toutanji and Deng [17] investigated the performance of concrete columns externally wrapped with aramid fiber reinforced polymer composite sheets. They also represented the performance of the wrapped concrete specimens subjected to severe environmental conditions, such as wet-dry and freeze-thaw cycles. Results showed that specimens wrapped with aramid fibers experienced no reduction in strength due to wet/dry exposure, but some reduction was observed due to freeze/thaw exposure. Teng and Lam [18] presented the results of an experimental study on FRP-confined concrete in elliptical columns. They investigated that the axial compressive strength of FRP-confined concrete in elliptical specimens was controlled by the amount of confining FRP and the major to minor axis length ratio of the column section.

In recent years, many researchers used commercial software such as ATENA, ANSYS and ABAQUS for finite element analysis.

Al-Kamaki et al. [19] investigated an experimental and numerical study of the behavior of RC columns, damaged by heating and subsequently wrapped by CFRP. Finite element analysis (FEA) was conducted using ATENA-GiD software, which is only applicable to RC elements. It was found that the CFRP can significantly increase the strength and ductility of unheated and heat-damaged columns. The finite element models (FEMs) were able to reasonably predict the experimental behavior. Mirmiran et al. [20] focused on developing a nonlinear FE model for the analysis of FRP-wrapped concrete. A parametric program was developed inside ANSYS software to automatically generate the mesh for various geometric shapes and material properties. Solid elements were used for the concrete core, along with a non-associative Drucker-Prager (DP) [21] plasticity model, which takes into account the pressure sensitivity of the material. Zaman Kabir et al. [22] presented a numerical study on FRP-wrap strengthened reinforced concrete columns subjected to eccentric axial loads using ABAQUS. Presented numerical predictions, were in close agreement with existing experimental results. The results of this study recommend taking fiber angles between zero (circumferential) and 30° can improve ultimate strength and ductility of confined short concrete columns. However, for slender concrete columns the optimum fiber orientation can be set between 15° and 30°.

According to this literature review, a considerable amount of research has been devoted to circular columns that are retrofitted with FRP, and FRP wrapping of existing circular columns has proven to be an effective retrofitting technique. In additional to these previous researches extensive studies are available on small size short specimens without longitudinal and transverse reinforcement and the unconfined concrete strengths of almost all of the tested specimens are in the range of medium to high. This study presents the results of the numerical investigation of circular, square and rectangular reinforced concrete (RC) slender columns confined with CFRP wraps. The main parameters of this work are the thickness of the CFRP wraps, concrete compressive strength, corner radius, loading condition, and slenderness ratio and column size. According to this, four different eccentricity-to-section-height ratios, four different levels of the CFRP thickness in the strengthened specimens, the slenderness ratios of the length to the section-height (l/h) from 6 to 12, three various types of column size, concrete compressive strength values from 20 to 50 MPa and corner radiuses from 10 to 40 mm are considered. This paper presents a comparison of a numerical simulation using ABAQUS [23] software with the results of experimental studies by previous researchers to validate finite element models.

2. Finite Element Modeling

Finite element analysis is conducted with ABAQUS [23] software. The simulated specimens include RC columns with circular, square and rectangular cross-sectional shapes having same area. In this study, a 3-D model of the CFRP-confined reinforced concrete columns is established. The damaged plasticity concrete model defined in Standard ABAQUS is used in the analysis. In CDP model, ψ is the dilation angle measured in the p-q plane at high confining pressure. This parameter with the value of $\psi = 31^o$ is used in this study. ϵ is an eccentricity of the plastic potential surface with default value of 0.1. The ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress, fb0/fc0, with default value of 1.16. Finally, K_c is the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian at initial yield with default value of 0.667.

Thus, default values are accepted in this study [23].

The stress-strain model of selected RC columns is required to describe the behavior of specimens. Lam & Teng [24] model is adopted as the compressive constitutive law of concrete in this study for circular cross-sectional RC column as shown in Fig. 1. Additionally, confinement Kent & Park [25] stress-strain model proposed in the last decade is selected and used for nonlinear finite element modeling of square and rectangular RC columns in this work as shown in Fig. 2. In CDP model, two concrete damage parameters in tension and compression (d_t and d_c) are selected to consider the effect of elastic stiffness degradation on the strain softening branch of the stress-strain curve. These damage parameters can take values from zero to one. Zero represents the undamaged material where one represents total loss of strength [23].

Also, for concrete in tension, the stress strain behavior is assumed to be linear elastic with slope of E_c up to tensile strength of concrete. The post failure behavior is modeled with tension stiffening, which allows for the strain softening behavior of cracked concrete. The tension behavior of concrete is shown in Fig. 3. The steel bar is assumed as a hardening elastic-plastic material. The parameters used to define this model are elastic modulus E_s, yield stress, F_y, and Poisson's ratio ν. Perfect bond is assumed between the steel and the concrete. The stress-strain curve used in the numerical analysis is shown in Fig.4.

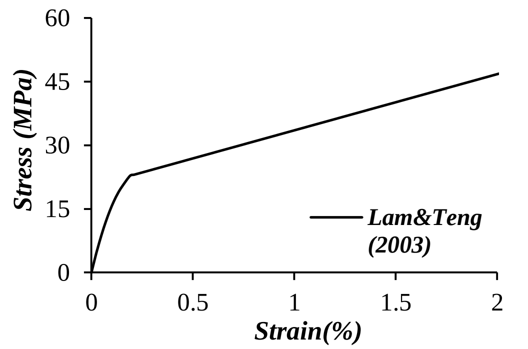

Fig. 1. Constitutive model in compression for circular RC column.

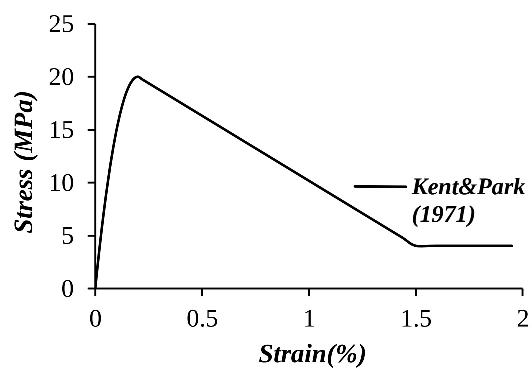

Fig. 2. Constitutive model in compression for square/rectangular RC columns.

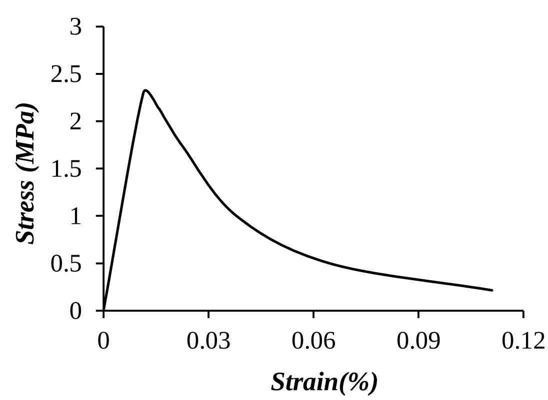

Fig. 3. Concrete constitutive model in tension.

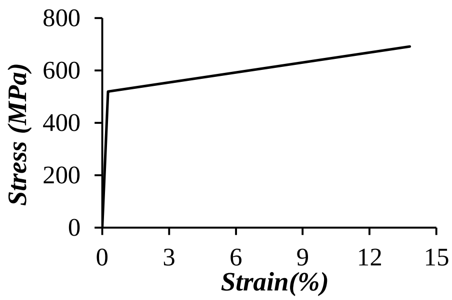

Fig. 4. Steel constitutive model.

CFRP wraps are defined as an elastic lamina in ABAQUS. The mechanical properties of the SikaWrap-230C product are given by the manufacturer [26]. The stress-strain behavior of CFRP is shown in Fig. 5. For the lamina material model E_1 is set to 230 GPa. In addition to this, E_2 =15 GPa and ν_{12} = 0.23. G_{12}, G_{13} and G_{23} are set to 3.40, 3.40 and 1.80 GPa, respectively. In this study, Hashin damage model in the CFRP wraps is used. It is primarily intended for use with fiber-reinforced composite materials. According to this, longitudinal tensile and compressive strength are both set to 3450 MPa. Also, transverse tensile and compressive strength are both equal to 280 MPa. Longitudinal and transverse shear strength of the CFRP wraps are 90 MPa.

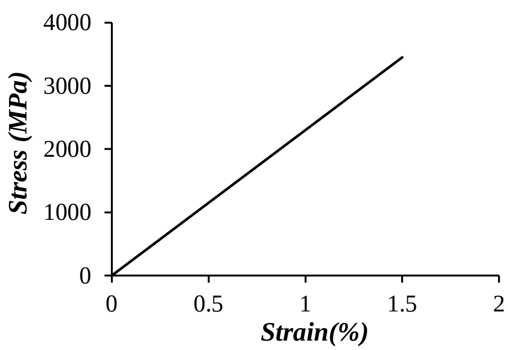

Fig. 5. CFRP constitutive model.

In the finite element (FE) model, the fixed-end boundary condition is assigned to the bottom end node of the circular and noncircular RC columns.

The CFRP composite sheets and reinforced concrete columns need to be connected to each other. This connection is modeled as a tie constraint, which ties the CFRP composite sheets to the surface of the columns. One surface in the constraint is designated to be the slave surface and the other surface is the master surface. In this study, all specimens are tested under monotonically increasing load with a nominal eccentricity to section-height ratio (e/h) of 0.46. This eccentric load is applied to the top end node of the circular and noncircular RC columns, and the nonlinear geometry is included in this analysis. Full Newton technique and automatic increment control provide convergence, within tolerance limits, for this nonlinear finite element analysis.

An 8-node 3-D solid element (C3D8R) is used to model concrete. The longitudinal and transverse steel bars are simulated by truss element (T3D2). Reduced integration doubly curved thin or thick shell element with 4-node (S4R) is used to define CFRP.

The finite element mesh of the circular and noncircular slender reinforced concrete columns wrapped with CFRP composite sheet are shown in Figs. 6-8.

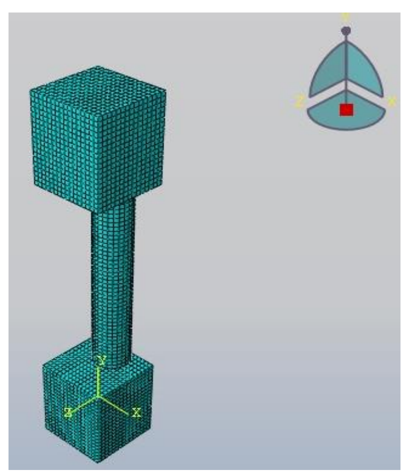

Fig. 6. A schematic view of the finite element mesh for circular slender RC column confined by CFRP sheet.

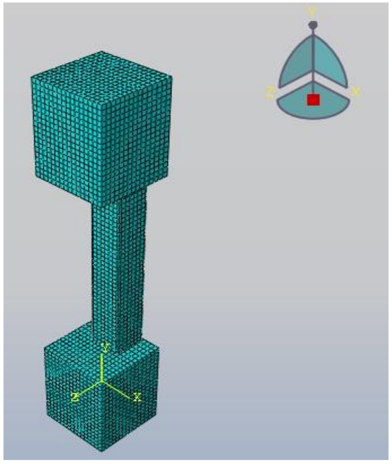

Fig. 7. A schematic view of the finite element mesh for square slender RC column confined by CFRP sheet.

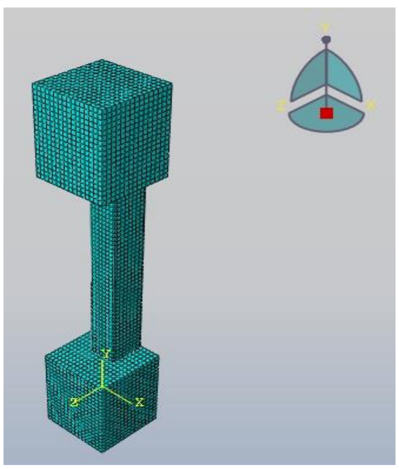

Fig. 8. A schematic view of the finite element mesh for rectangular slender RC column confined by CFRP sheet.

3. Description of Experimental RC Columns

Table 1 and 2 show the details of all columns that are analyzed in this study. Experimental results of circular, square and rectangular RC columns with Carbon Fiber Reinforced Polymer tested by Maaddawy et al. [27] are selected to compare with the predictions from the nonlinear finite element analysis. Three different cross-sectional shapes, as indicated in Table 1, are used in the study: circular, 150 mm diameter; square, 135×135 mm and rectangular (Rect. 1), 120×150 mm. The cross-sectional dimensions are selected so that all sections have almost the same cross-sectional area. All specimens tested under eccentric loading, have end corbels, each having a cross-section of 300×300 mm and a length of 380 mm.

The ratio of the length of the test region between the end corbels to the section-height (l/h) is a constant value of four for all cross-sectional shapes. The corners of the specimens with the square and rectangular cross-sections are rounded to a radius of about 10 mm. A concrete with an average compressive strength of f'_c=20 MPa and the modulus of elasticity of E_c= 21.02 GPa is used in the present study to simulate a poor concrete that can be encountered in a repair condition. The materials used for concrete included Type I Portland cement, local sand, medium aggregate (10 mm), and large aggregate (19 mm).

The longitudinal steel reinforcement is No. 10 Grade 520 deformed bars, and the shear reinforcement is 6 mm diameter Grade 300 plain bars. Young's modulus of steel rebar is equal to 200 GPa. The CFRP fabric used for wrapping is unidirectional with fibers oriented in the hoop or transverse direction of the specimen (Sika-Wrap Hex 230C). The fabric is bonded to the specimen with an epoxy resin (Sikadur 330). Typical mechanical properties of a dry carbon fiber fabric, epoxy resin and a cured CFRP composite sheet as provided by the manufacturer are summarized in Table 2 [26].

Table 1. Details of the test specimens.

Specimen designation[a]	Loading condition	Slenderness ratio	Section shape	Confinement condition
CF-e1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 4)	Circular	CFRP-confinement
SF-e1			Square	CFRP-confinement
R1F-e1			Rect. 1	CFRP-confinement

[a] C, S and R1, refer to Circular (150 mm diameter), Square (135 × 135 mm) and Rect. 1 (120 ×150 mm) respectively and F refer to Full CFRP-confinement.

Table 2. Mechanical properties of CFRP [26].

Type	Tensile modulus (GPa)	Tensile strength (MPa)	Ultimate elongation (%)
Sika Wrap Hex 230C dry fabric	230	3450	1.5
Sikadur 330 resin	------	30	1.5
SikaWrap Hex 230C cured with Sikadur 330[a]	65.4	894	1.33

[a] Thickness of a typical cured composite sheet is 0.381 mm.

4. Results of the Finite Element Analysis

The load versus deflection curves of the nonlinear FE analysis for circular, square and rectangular RC columns are compared with the results of the experimental tests to validate the accuracy of FE models for confined concrete, see Figs. 9-11.

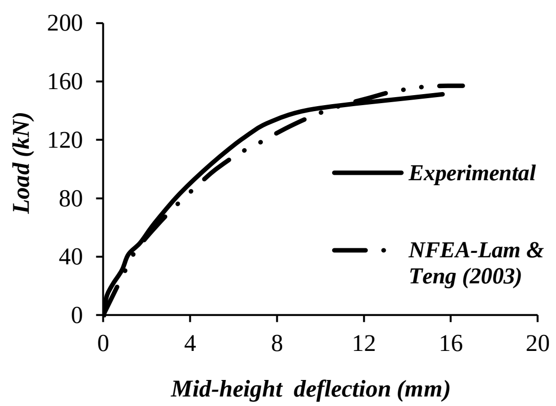

Fig. 9. Comparison of predicted results with test data for the circular column.

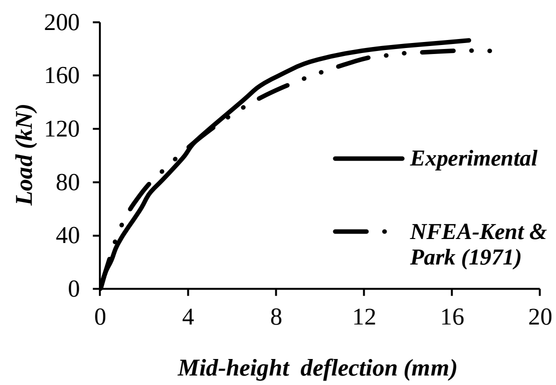

Fig. 10. Comparison of predicted results with test data for the square column.

As shown in Figs. 9-11, it is observed that the NFEA results obtained using Lam & Teng (2003) model for circular column and confinement Kent & Park (1971) model for square and rectangular columns correlate well with the results of the experimental tests.

This means that the finite element models can be used to analyze the behavior of CFRP-confined RC columns.

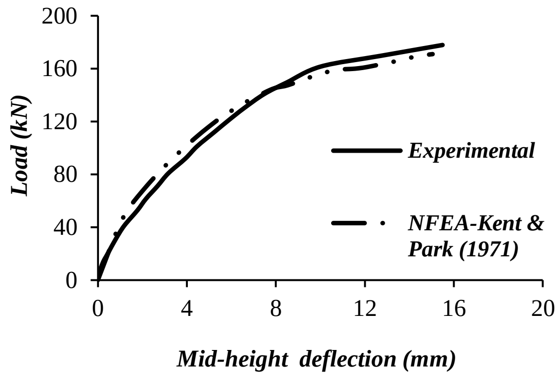

Fig. 11. Comparison of predicted results with test data for the rectangular column.

The finite element analysis results to experimental ratio and error in prediction in terms of peak load are obtained for the comparison, see Table .3.

5. Parametric Studies Based on Finite Element Analysis

In this paper, a parametric study using the validated finite element models is focused on six factors. They are the column size, thickness of the CFRP wrap, concrete compressive strength, corner radius, loading condition and slenderness ratio. According to this, four different eccentricity-to-section-height ratios, four different levels of the CFRP thickness in the strengthened specimens, the slenderness ratios of the length to the section-height (l/h) from 6 to 12, three various types of column size, concrete compressive strength values from 20 to 50 MPa and corner radiuses from 10 to 40 mm are considered.

Table 3. Comparison of experimental results with finite element analysis results.

Model	Test specimens	Peak Load, (kN)			
		EXP	FEA	FEA/EXP	Error (%)
Lam & Teng (2003)	CF-e1	149.2	157.6	1.05	5.6
Kent & Park (1971)	SF-e1	186.3	178.9	0.96	4.1
Kent & Park (1971)	R1F-e1	177.7	171.8	0.97	3.4

5.1. Effect of CFRP Wraps Thickness

In this investigation, to evaluate the effect of CFRP wraps thickness on the behavior of confined circular, square and rectangular columns having the same cross-section area, the finite element analysis is performed for four groups. Ranges of the CFRP wraps thickness considered are from 0.381 to 1.524 mm for four groups respectively. The material properties and geometric of different cross-sectional slender columns that used to study the effect of CFRP wraps thickness are summarized in Table 4.

Considering the cases of 1 to 4 CFRP layers, from results displayed in Table 5 and Figs. 12-14, it can be evaluated that the load as well as lateral displacement capacity increase when the thickness of CFRP enhances.

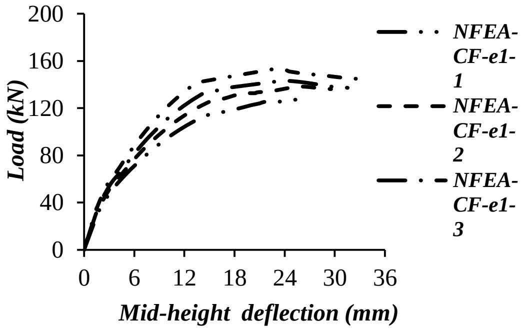

Fig. 12. Effect of CFRP wraps thickness on the behavior of slender confined circular RC column.

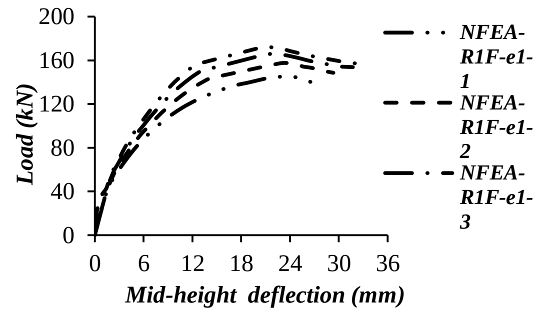

Fig. 13. Effect of CFRP wraps thickness on the behavior of slender confined rectangular RC column.

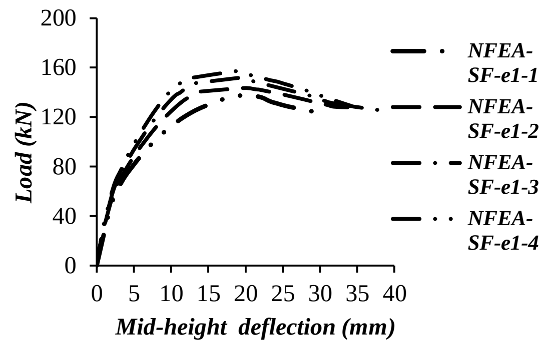

Fig. 14. Effect of CFRP wraps thickness on the behavior of slender confined square RC column.

Table 4. Material properties and geometric.

Specimen designation	Loading condition	Slenderness ratio	Section shape	Thickness of FRP (mm)
CF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	Circular	0.381
SF-e1-1			Square	0.381
R1F-e1-1			Rect. 1	0.381
CF-e1-2	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	Circular	0.762
SF-e1-2			Square	0.762
R1F-e1-2			Rect. 1	0.762
CF-e1-3	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	Circular	1.143
SF-e1-3			Square	1.143
R1F-e1-3			Rect. 1	1.143

CF-e1-4	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	Circular	1.524
SF-e1-4			Square	1.524
R1F-e1-4			Rect. 1	1.524

According to this, increasing the thickness of CFRP from 0.381 to 1.524 mm enhances the load capacity roughly from 8% to 20% for slender circular column, 9% to 18.7% for slender rectangular column and 4.2% to 14% for slender square column in comparison with CF-e1-1, R1F-e1-1 and SF-e1-1, respectively.

The increase of the number of layers from 1 to 4 generates an increase of lateral displacement capacity roughly from 15% to 29% for slender circular column, 12% to 29% for slender rectangular column and 16% to 31% for slender square column as compared to the CF-e1-1, R1F-e1-1 and SF-e1-1 specimens of different cross-sectional CFRP-confined RC columns.

Table 5. Results of finite element analysis for four different CFRP thicknesses.

Specimen designation	Loading condition	Slenderness ratio	Load capacity (kN)	Lateral displacement capacity (mm)
CF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	128.07	26.04
SF-e1-1			137.70	28.90
R1F-e1-1			144.95	26.14
CF-e1-2	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	138.30	29.84
SF-e1-2			143.42	33.60
R1F-e1-2			157.49	29.33
CF-e1-3	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	143.31	31.53
SF-e1-3			151.57	35.92
R1F-e1-3			166.05	31.73
CF-e1-4	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	153.20	33.64
SF-e1-4			157.09	37.95
R1F-e1-4			172.10	33.85

5.2. Effect of Concrete Compressive Strength

To consider the effect of concrete compressive strength on the behavior of confined circular, square and rectangular columns having the same cross-section area, the finite element analysis is presented for four groups. The concrete compressive strength varies from 20 to 50 MPa for four groups respectively. The material properties and geometric of different cross-sectional slender columns that used to study the effect of concrete compressive strength are listed in Table 6.

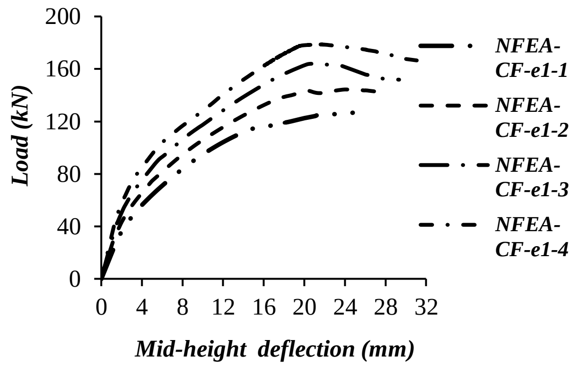

Fig. 15. Effect of concrete compressive strength on the behavior of slender confined circular RC column.

Table 6. Material properties and geometric.

Specimen designation	Loading condition	Slenderness ratio	F'_c (MPa)	Thickness of FRP (mm)
CF-e1-1			20	0.381
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	20	0.381
R1F-e1-1			20	0.381
CF-e1-2			30	0.381
SF-e1-2	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	30	0.381
R1F-e1-2			30	0.381
CF-e1-3			40	0.381
SF-e1-3	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	40	0.381
R1F-e1-3			40	0.381
CF-e1-4			50	0.381
SF-e1-4	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	50	0.381

R1F-e1-4	50	0.381

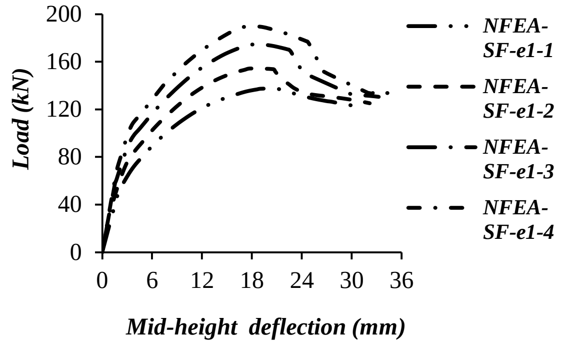

Fig. 16. Effect of concrete compressive strength on the behavior of slender confined square RC column.

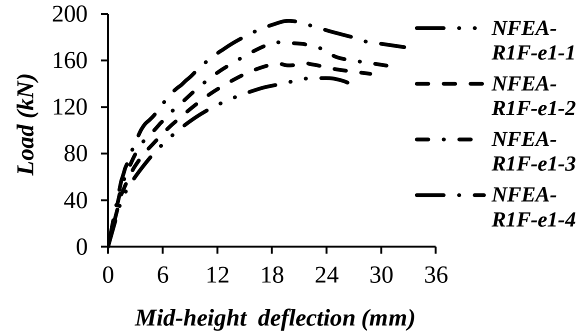

Fig. 17. Effect of concrete compressive strength on the behavior of slender confined rectangular RC column.

Table 7. Results of finite element analysis for four different concrete compressive strengths.

Specimen designation	Loading condition	Slenderness ratio	Load capacity (kN)	Lateral displacement capacity (mm)
CF-e1-1			128.07	26.04
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	137.70	28.90
R1F-e1-1			144.95	26.14
CF-e1-2	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	144.40	28.31
SF-e1-2			154.35	32.17
R1F-e1-2			157.66	28.81
CF-e1-3	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	164.05	29.34
SF-e1-3			174.64	33.25
R1F-e1-3			175.82	30.66
CF-e1-4	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	178.75	31.07
SF-e1-4			189.79	35.98
R1F-e1-4			194.11	32.54

As seen in Figs. 15-17, in all cases the increase of concrete compressive strength generates an increase of load capacity as well as lateral deformation capacity. According to Table 7, increasing the concrete compressive strength from 20 to 50 MPa enhances the load capacity roughly from 13% to 40% for slender circular column, 9% to 34% for slender rectangular column and 12% to 38% for slender square column in comparison with CF-e1-1, R1F-e1-1 and SF-e1-1, respectively. Additionally, the increase of concrete compressive strength generates an increase of lateral displacement capacity roughly from 9% to 19% for slender circular column, 10% to 25% for slender rectangular column and 11% to 25% for slender square column as compared to the CF-e1-1, R1F-e1-1 and SF-e1-1 specimens of different cross-sectional CFRP-confined RC columns.

5.3. Effect of Corner radius

To evaluate the effect of corner radius on the response of the slender columns, four different corner radiuses are considered: 10, 20, 30, and 40 mm. The material properties and geometric of slender column that used to study the effect of corner radius are given in Table 8.

From Figs. 18 and 19 and Table 9, it is clearly seen in the noncircular RC specimens, the load capacity enhances whereas the lateral displacement capacity is decreased.

Table 8. Material properties and geometric.

Specimen designation	Loading condition	Slenderness ratio	Corner radius	Thickness of FRP (mm)
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	10	0.381
R1F-e1-1			10	0.381
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	20	0.381
R1F-e1-1			20	0.381
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	30	0.381
R1F-e1-1			30	0.381
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	40	0.381
R1F-e1-1			40	0.381

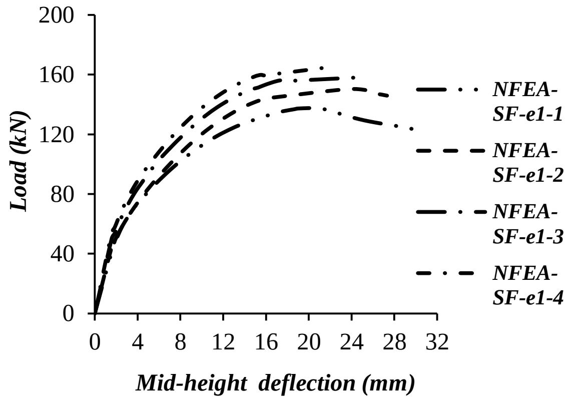

Fig. 18. Effect of corner radius on the behavior of slender confined square RC column.

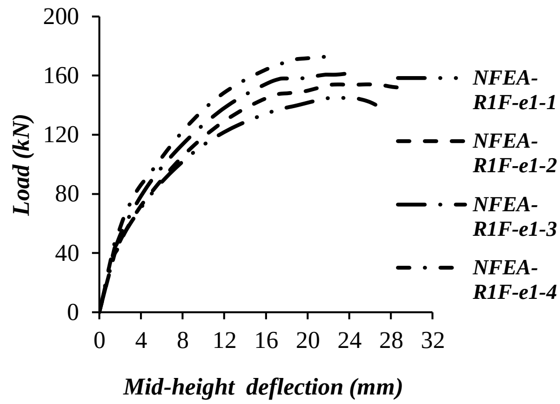

Fig. 19. Effect of corner radius on the behavior of slender confined rectangular RC column.

For slender confined square RC column with corner radiuses from 10 to 40 mm, lateral displacement capacity is decreased from 6% to 29% whereas the load capacity enhances from 9% to 20% in comparison with SF-e1-1 specimen. Additionally, in the rectangular RC specimen, when the corner radiuses increases from 10 to 20 mm, the lateral displacement capacity of the specimen enhances roughly 11% while for the corner radius from 20 to 40 mm, the lateral displacement capacity is decreased from 21% to 33% whereas the load capacity increases from 6% to 20% in comparison with R1F-e1-1 specimen.

Table 9. Results of finite element analysis for four different corner radiuses.

Specimen designation	Loading condition	Slenderness ratio	Load capacity (kN)	Lateral displacement capacity (mm)
SF-e1-1			137.70	28.90
R1F-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	144.95	26.14
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	150.32	27.31
R1F-e1-1			154.04	29.10
SF-e1-1			158.11	25.22
R1F-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	161.77	24.12
SF-e1-1			165.44	22.36
R1F-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	173.10	21.90

According to this, it can be concluded that for columns with a relatively small corner radius ratio (2r/b≤0.4), lateral displacement capacity and the ductility of columns enhances but for columns with a relatively large corner radius ratio (2r/b>0.4), the confinement reduces the ductility as well as lateral displacement capacity of specimens. This conclusion is consistent with the experimental results provided by Wang et al. [28].

5.4. Effect of Loading Condition

In this paper, to study the effect of loading condition on the behavior of circular as well as noncircular slender columns, four different eccentricity-to-section-height ratios ranges from 0.46 to 0.88 are evaluated. The detailed geometric and material properties of these columns are given in Table 10.

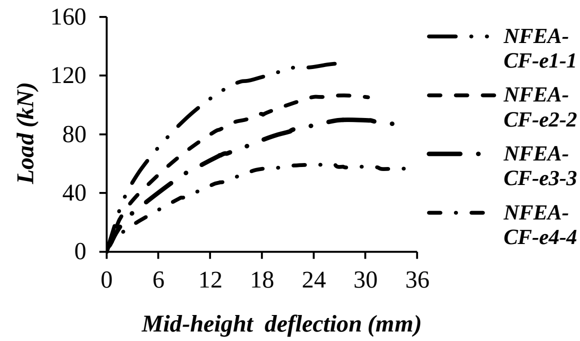

Fig. 20. Effect of loading condition on the behavior of slender confined circular RC column.

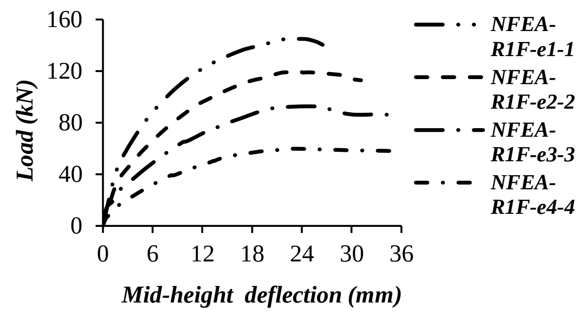

Fig. 21. Effect of loading condition on the behavior of slender confined rectangular RC column.

Table 10. Material properties and geometric.

Specimen designation	Loading condition	Slenderness ratio	F'_c (MPa)	Thickness of FRP (mm)
CF-e1-1			20	0.381
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	20	0.381
R1F-e1-1			20	0.381
CF-e2-2			20	0.381
SF-e2-2	Eccentric e2 (e/h = 0.6)	Length to the section-height (L/h = 6)	20	0.381
R1F-e2-2			20	0.381
CF-e3-3			20	0.381

SF-e3-3	Eccentric e3 (e/h = 0.74)	Length to the section-height (L/h = 6)	20	0.381
R1F-e3-3			20	0.381
CF-e4-4			20	0.381
SF-e4-4	Eccentric e4 (e/h = 0.88)	Length to the section-height (L/h = 6)	20	0.381
R1F-e4-4			20	0.381

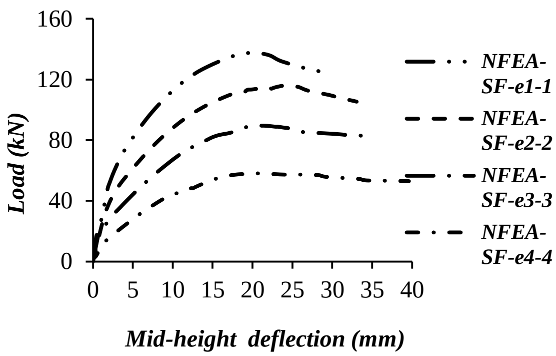

Fig. 22. Effect of loading condition on the behavior of slender confined square RC column.

The comparison of results, as seen in Figs. 20-22 and Table 11 for different eccentricity-to-section-height ratios ranges from 0.46 to 0.88; show an important decrease in the load capacity and a moderate enhancement in the lateral displacement capacity for different cross-sectional wrapped RC specimens. When the eccentricity-to-section-height ratios enhances from 0.46 to 0.88, the load capacity is decreased roughly from 20% to 114.5% for slender circular column, 21% to 142.5% for slender rectangular column and 19% to 137% for slender square column in comparison with CF-e1-1, R1F-e1-1 and SF-e1-1, respectively. In addition to this, the increase of the eccentricity-to-section-height ratios from 0.46 to 0.88 generates an increase of lateral displacement capacity roughly from 16.5% to 37.5% for slender circular column, 19% to 37.5% for slender rectangular column and 15% to 37% for slender square column as compared to the CF-e1-1, R1F-e1-1 and SF-e1-1 specimens of different cross-sectional CFRP-confined RC columns.

Table 11. Results of finite element analysis for four different loading conditions.

Specimen designation	Loading condition	Slenderness ratio	Load capacity (kN)	Lateral displacement capacity (mm)
CF-e1-1			128.07	26.04
SF-e1-1	Eccentric e1	Length to the section-	137.70	28.90

	(e/h = 0.46)	height (L/h = 6)		
R1F-e1-1			144.95	26.14
CF-e2-2			106.50	30.31
SF-e2-2	Eccentric e2 (e/h = 0.6)	Length to the section-height (L/h = 6)	115.96	33.10
R1F-e2-2			119.80	31.17
CF-e3-3			89.90	33.50
SF-e3-3	Eccentric e3 (e/h = 0.74)	Length to the section-height (L/h = 6)	89.50	35.03
R1F-e3-3			92.63	34.23
CF-e4-4			59.70	35.80
SF-e4-4	Eccentric e4 (e/h = 0.88)	Length to the section-height (L/h = 6)	58.10	39.61
R1F-e4-4			59.75	35.92

5.5. Effect of Slenderness Ratio

As noted previously, three different cross-sectional confined columns used for demonstrating the effect of slenderness ratio have the same cross-section area but different slenderness ratios. To consider the effect of slenderness ratio on the response of considered columns, four different lengths to the section-height are considered: 6, 8, 10, and 12. The dimensions and material properties of these columns that used to study the effect of slenderness ratio are listed in Table 12.

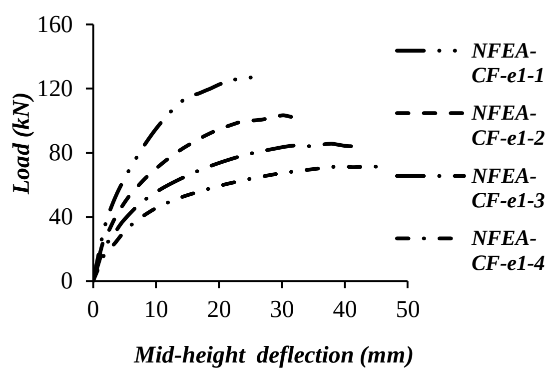

Fig. 23. Effect of slenderness ratio on the behavior of slender confined circular RC column.

Table 12. Material properties and geometric.

Specimen designation	Loading condition	Slenderness ratio	F'c (MPa)	Thickness of FRP (mm)
CF-e1-1			20	0.381
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	20	0.381
R1F-e1-1			20	0.381
CF-e1-2			20	0.381
SF-e1-2	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 8)	20	0.381
R1F-e1-2			20	0.381
CF-e1-3			20	0.381
SF-e1-3	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 10)	20	0.381
R1F-e1-3			20	0.381
CF-e1-4			20	0.381
SF-e1-4	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 12)	20	0.381
R1F-e1-4			20	0.381

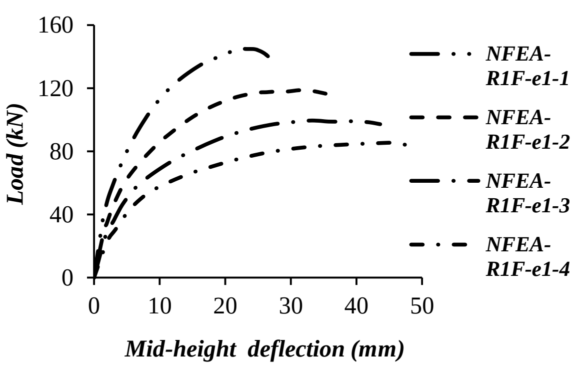

Fig. 24. Effect of slenderness ratio on the behavior of slender confined rectangular RC column.

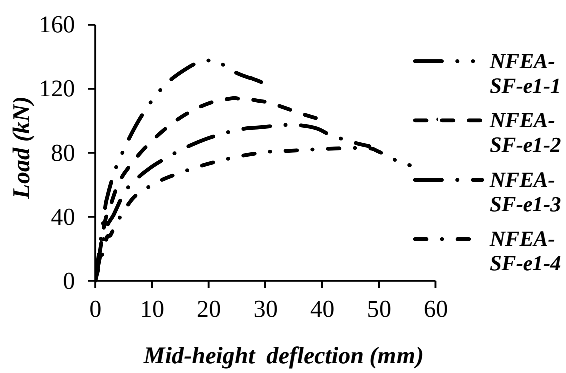

Fig. 25. Effect of slenderness ratio on the behavior of slender confined square RC column.

Table 13. Results of finite element analysis for four different slenderness ratios.

Specimen designation	Loading condition	Slenderness ratio	Load capacity (kN)	Lateral displacement capacity (mm)
CF-e1-1			128.07	26.04
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	137.70	28.90

R1F-e1-1			144.95	26.14
CF-e1-2			103.35	33.42
SF-e1-2	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 8)	114.12	40.20
R1F-e1-2			118.78	35.30
CF-e1-3			85.65	41.51
SF-e1-3	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 10)	97.63	48.32
R1F-e1-3			99.57	43.62
CF-e1-4			71.56	47.24
SF-e1-4	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 12)	83.01	55.46
R1F-e1-4			85.53	49.50

Figs. 23, 24 and 25 show the effects of increasing slenderness on the applied load versus lateral displacement responses of both circular and noncircular CFRP wrapped columns. According to results in Table 13, it can be concluded that increased slenderness causes a decrease of load capacity whereas increases lateral deflection at failure. In addition to this, the increase of slenderness ratios from 6 to 12 generates a significant increase of lateral displacement capacity roughly from 28% to 81% for slender circular column, 35% to 89% for slender rectangular column and 39% to 92% for slender square column as compared to the CF-e1-1, R1F-e1-1 and SF-e1-1 specimens of different cross-sectional CFRP-confined RC columns.

However, the increase of slenderness ratio of these columns generates an important decrease of load capacity roughly from 24% to 79% for slender circular column, 22% to 70% for slender rectangular column and 21% to 66% for slender square column in comparison with CF-e1-1, R1F-e1-1 and SF-e1-1 specimens of different cross-sectional CFRP-confined RC columns.

5.6. Effect of column size

The structural behavior of these different cross-sectional shape RC columns, subjected to different column sizes are evaluated for parametric study in this investigation. To enable a comparative study of the influence of different column sizes on structural behavior, the finite element analysis is performed for three groups. Figs. 26-28 and Table 15 show the results of the simulations of slender columns subjected to different column sizes. Additionally, the geometric and material properties of the analyzed CFRP-confined RC columns to consider the size effect are given in Table 14.

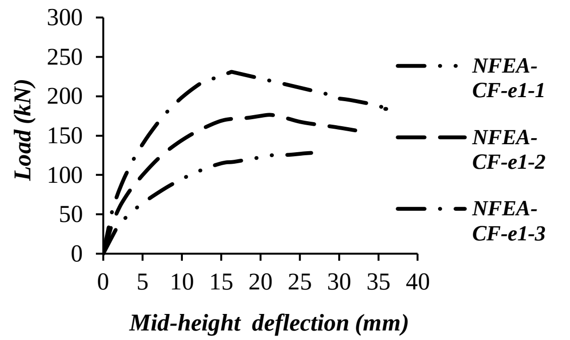

Fig. 26. Effect of column size on the behavior of slender confined circular RC column.

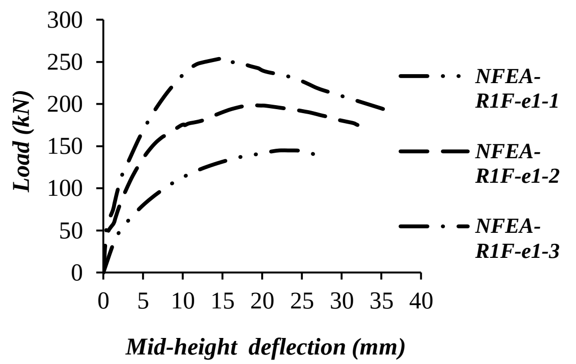

Fig. 27. Effect of column size on the behavior of slender confined rectangular RC column.

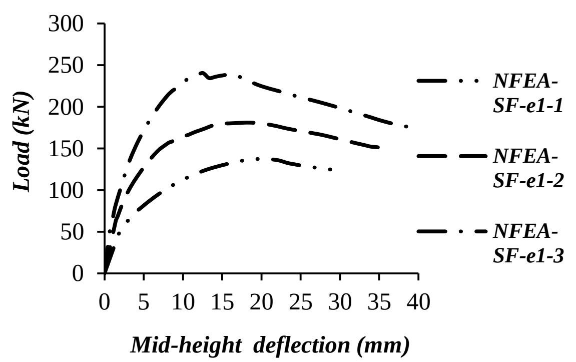

Fig. 28. Effect of column size on the behavior of slender confined square RC column.

To describe the influence of column size on the behavior of the circular, square and rectangular slender columns load-displacement curves of the RC columns in relation to the column size are plotted as shown in Figs. 26-28. It can be clearly seen that the column size increasing the load capacity, lateral displacement capacity and performance of the columns. It is evident from Figs. 26-28 that the response of circular and noncircular CFRP-confined slender columns is dependent on the cross-section size. In this regard, enhancement of cross-section increases the load capacity about 38% to 81%, 37% to 75.5% and 32% to 75% for slender circular, rectangular and square columns, respectively. Furthermore, the lateral displacement capacity of the confined columns due to the enhancement of cross-section increases roughly from 23% to 38% for slender circular column, 23% to 40% for slender rectangular column and 24% to 38.5% for slender square column as compared to the CF-e1-1, R1F-e1-1 and SF-e1-1 specimens of different cross-sectional CFRP-confined RC columns.

Table 14. Material properties and geometric.

Specimen designation	Loading condition	Slenderness ratio	Column dimensions (mm)	Thickness of FRP (mm)
CF-e1-1			150	0.381
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	135×135	0.381
R1F-e1-1			120×150	0.381
CF-e1-2			170	0.381
	Eccentric e1	Length to the section-		

SF-e1-2	(e/h = 0.46)	height (L/h = 6)	155×155	0.381
R1F-e1-2			150×170	0.381
CF-e1-3			190	0.381
SF-e1-3	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	175×175	0.381
R1F-e1-3			170×190	0.381

Table 15. Results of finite element analysis for three different column sizes.

Specimen designation	Loading condition	Slenderness ratio	Load capacity (kN)	Lateral displacement capacity (mm)
CF-e1-1			128.07	26.04
SF-e1-1	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	137.70	28.90
R1F-e1-1			144.95	26.14
CF-e1-2			176.44	32.10
SF-e1-2	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	181.15	35.90
R1F-e1-2			198.90	32.10
CF-e1-3			230.95	35.90
SF-e1-3	Eccentric e1 (e/h = 0.46)	Length to the section-height (L/h = 6)	240.77	39.89
R1F-e1-3			254.43	36.72

6. Conclusion

In this paper, nonlinear finite element analysis was carried out on the circular and noncircular slender reinforced concrete columns wrapped with CFRP composite having same cross-sectional area. In the present study, the influence of the CFRP wrap thickness, concrete compressive strength, corner radius, loading condition, slenderness ratio and column size on the performance of slender reinforced concrete columns were considered. The following conclusions can be drawn from this study:

1. The load as well as lateral displacement capacity of different cross-sectional shape confined columns increases when the thickness of CFRP enhances. No significant increase in peak load generates when the both circular and noncircular columns are wrapped with one layer of CFRP.

2. The performance of both circular and noncircular slender reinforced concrete columns is dependent on concrete compressive strength with different concrete grades. Increasing concrete compressive strength results with an increase in the load capacity of slender RC columns.

3. The ductility of slender confined RC columns enhances with the increase in the concrete compressive strength.

4. For slender confined noncircular RC columns with corner radius, while the load capacity increases, the lateral displacement capacity is decreased.

5. For both square and rectangular slender confined columns with sharp or relatively small corner radius ratio (2r/b≤0.4), lateral displacement capacity and the ductility of columns increases but for these columns with a relatively large corner radius ratio (2r/b>0.4), the confinement reduces the ductility as well as lateral displacement capacity of specimens.

6. When the eccentricity-to-section-height ratio of slender circular, square and rectangular columns enhances, the load capacity is decreased significantly. In addition to this, the increase of the eccentricity-to-section-height ratio generates a moderate increase of lateral displacement capacity and ductility of these columns.

7. The effects of increasing slenderness on the applied load versus lateral displacement responses of both circular and noncircular CFRP wrapped columns are considered. According to this, increased slenderness causes a decrease of load capacity whereas increases lateral deflection at failure. The rate of lateral deflection enhancement is more important for noncircular specimens.

8. Enhancement of column cross-section increases the load capacity as well as the lateral displacement capacity. While the load capacity increase is more considerable for the specimens with circular cross section, specimens with square and rectangular cross sections displayed higher lateral displacement capacity.

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