Effect of cross section aspect ratio and load eccentricity on the behavior of large scale RC columns wrapped with different CFRP layers

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ABSTRACT
This paper investigates the effect of cross-section aspect ratio and the effect of load eccentricity on the behavior of RC short columns with large-scale specimens wrapped with external carbon fiber polymers (CFRP) using finite element. Firstly, to study the effect of cross-section, six models have been conducted with various aspect ratios defined as the depth per the width of the cross-section with a constant number of carbon fiber layers. While the behavior of each aspect ratio in both axial and transverse directions was investigated, the results demonstrate that while the CFRP jackets increase the efficiency of square sections significantly, however, CFRP jacket's effect reduces when cross-section aspect ratio becomes more than 2.0. Secondly, twelve finite element models have been built to study the effect of load eccentricity on the behavior of RC short columns wrapped with external CFRP. The results showed that external confinement can significantly increase the strength of columns under concentric loading, while the enhancement in columns under eccentric loading is not the same.

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Introduction
FRP materials effectively have been utilized to improve the capacity and deformation of circular concrete columns with geometrical configurations that enable uniform getting stressed of the fibers, ensuring that the concrete is highly effective throughout the cross-section in terms of confinement. The effectiveness of confinement for the square and rectangular section is significantly reduced as the confinement stress is uniform across the cross-section [1]. Several parameters like concrete strength, load eccentricity, fiber type, and the bond between the cross-section and the carbon fiber layers have an
effect on the effectiveness of the confinement of RC columns wrapped with CFRP [1].

Whereas many researchers have investigated the behavior of circular columns wrapped with CFRP [2], however, the use of square and rectangular sections in the field has become widespread compared to circular section [3]. Moreover, in the last decade, the investigation of confined rectangular sections has been increased with small-scale specimens. While almost all existing FRP design equations were investigated in the case of concentric axial loads, few exceptions in recent years have been discovered [1]. In reality, the highest proportion of RC columns is subjected to axial load with eccentricity. Although reinforced concrete columns resist eccentric loads, many researchers have studied the behavior of reinforced concrete columns with external confinement under concentric load [1]. In recent years, many investigations have been tested on circular concrete columns with external carbon fibers under eccentric loads [4–7]. In this investigation, the effect of cross-section aspect ratio and load eccentricity on large-scale RC columns will be tested.

**Finite element analysis**

**Finite element model**

The 3D model has been built using finite element software (ANSYS). We selected appropriate materials from the ANSYS program library to simulate concrete, adhesive, longitudinal reinforcements, transverse stirrups, and CFRP strips [8]. Whilst Solid65 was utilized to simulate concrete and adhesive mesh because this component can resist plastic deformation, cracking in three orthogonal directions, and crushing, longitudinal and transverse reinforcement were simulated using element link180 due to its ability to carry out tension and compression force. Moreover, a layered solid element, Solid185, was utilized to model carbon fiber laminates because of the ability to withstand against plasticity, elasticity, deflection, and large strain capabilities. Furthermore, the Solid186 component is utilized for supporting steel plates in the top and the bottom of each column due to the ability to resist translation in its three different directions [8].

**De-bonding model using cohesive zone model**

Cohesive Zone Material Model (CZM) was utilized to allow separation between the epoxy and the concrete which is the weakest layer [3]. CZM has two distinct approaches; a bilinear traction separation law and an exponential traction separation law [3].

The contribution of the concrete-adhesive interface was taken into consideration in the model by recognizing interface fracture energies and suitable bilinear shear stress slips curve and normal stress gap curve. Bringing this
into thought, both models provide to have a precise analyze the debonding conduct; The shear-slip model generally leads to an integrated mode of separation, wherein the standard transition to interface is dominated by relative tangent displacement [3]. Taking into consideration the pressure gap model of the tension causes a failure mode where the normal separation from the interface controls the tangent of the slip to the interface. Using debonding based on just one of these two models leads to ignoring the other. While TARG170 element was utilized to model the concrete surface, the adhesive surface was modeled using CONTA174 element [3]. In this research, Cohesive zone model has been conducted using the traction and separation option with six input which are maximum normal contact stress \( \sigma_{\text{max}} \), contact gap at the completion of bonding \( U^c_n \), maximum tangential stress \( \tau_{\text{max}} \), tangential slip at the completion of bonding \( U^c_t \), artificial damping coefficient \( \eta \), and an option indicator for tangential slip under compressive normal contact stress \( \beta \) (Figure 1) [3].

**Normal contact stress – gap model.** The tensile resistance is assumed to be equal to the concrete tensile strength. Consequently, failure occurs when the bonding strength under stress exceeds the tensile force of the concrete. Thus, the fracture energy of the interface is supposed to be equal to the concrete fracture energy [3].

\[
\tau_t = k_t u_t (1 - d_m) \text{(MPa)}
\]

\[
\sigma_n = k_n u_n (1 - d_m) \text{(MPa)}
\]

\[
\chi = \left( \frac{U^c_n}{U_n - U_n} \right) = \left( \frac{U^c_t}{U_t - U_t} \right)
\]

\[
G_{cn} = G_{fo} \left( \frac{\tau^t}{f_c} \right)^{0.7} \text{ (N/mm)}
\]

**Figure 1.** (a) Normal stress – gap and (b) Shear stress – slip models [3].
\[ d_m = \left( \frac{\Delta_m - 1}{\Delta_m} \right) \chi \]  \hspace{1cm} (5)

\[ \Delta_m = \sqrt{\left( \frac{U_n}{U_t} \right)^2 + \left( \frac{U_t}{U_t} \right)^2} \]  \hspace{1cm} (6)

\[ \sigma_{\text{max}} = 0.6 \sqrt{f'_c} \text{(MPa)} \]  \hspace{1cm} (7)

\[ U'_n = G_{fo} \left( \frac{\sqrt{10f'_c}}{24.3} \right)^{0.2} \text{(mm)} \]  \hspace{1cm} (8)

Where \( G_{fo} \) is calculated as 0.03475 N/mm \[3\].

**Shear contact stress – gap model.**

\[ \tau_{\text{max}} = (0.802 + 0.078\varphi)f'_c^{0.6} \text{(MPa)} \]  \hspace{1cm} (9)

\[ G_{ct} = \frac{0.976 \varphi^{0.526} f'_c^{0.6}}{2} \text{(N/mm)} \]  \hspace{1cm} (10)

\[ U'_t = \frac{0.976 \varphi^{0.526}}{0.802 + 0.078\varphi} \text{(mm)} \]  \hspace{1cm} (11)

\[ \varphi = \frac{\text{Groove depth} + 1 \text{ mm}}{\text{Groove width} + 2 \text{ mm}} \]  \hspace{1cm} (12)

**Finite element verification**

*Validation of finite element models with experimental reference models*

Firstly, to verify the finite element modeling, three reference models were created to be compared with three tests by Xiao and Wu \[9\] with various carbon fiber layers. Three cylinders with a diameter of 150 mm and a height of 300 mm wrapped with one, two and three carbon fiber plies with nominal thickness 0.381 mm per layer. Whilst the concrete compressive strength was 43.8 MPa, carbon fiber modulus of elasticity, tensile strength and tensile strain were 105 GPa, 1577 MPa and 0.015 respectively. The comparison between experimental stress-strain curves and finite element reference models for each specimen is shown in Figure 2. While the right curve represents the response of axial confined stress versus the axial confined strain, the left curve
represents the response of the axial confined stress versus the laterally confined strain.

Secondly, finite element reference model is compared to a square column which was tested by Diego et al. [10]. This model is (150 x150) mm and 600 mm high with a corner radius of 25 mm. While the unconfined strength of concrete was 17.5 MPa, 1 carbon fiber layer was wrapped the cross-section with 0.3 mm thickness. Moreover, according to the manufacture, the elastic modulus and tensile strength of fibers are 242 GPa, 3,800 MPa respectively. In addition, four longitudinal steel bars with diameter of 6 mm and distributed stirrups each 100 mm with 6 mm diameter.

Figure 2. Comparison of FE and experimental stress–strain curves by Xiao and Wu [9].

Figure 3. Comparison of FE and experimental stress–strain curves by Diego et al. [10].
models. While the Y-axis represents the confined axial stress, the left X-axis presents the lateral confined strain and the right X-axis simplify the axial confined strain. The comparison shows agreement between Diego et al. and the reference model.

**Validation of finite element models with theoretical models**

Finite element models which have been investigated were verified by comparing results obtained from the FE analysis with results obtained from corresponding Mander et al. model [13], and ACI Committee 440 2 R-02 [1] (Table 2).

**Mander et al model[13]**

\[
f_{cc} = f'_{co} \left( -1.254 + 2.254 \sqrt{1 + \frac{7.94 f'_l}{f'_{co}}} - 2 \left( \frac{f'_l}{f'_{co}} \right) \right) \tag{13}
\]

\[
f_l = \frac{2 E_f \varepsilon_{clu} t_f}{D} \tag{14}
\]

\[
\varepsilon_{cc} = \varepsilon_{co} \left( 1 + 5 \left( \frac{f'_{cc}}{f'_{co}} - 1 \right) \right) \tag{15}
\]

\[
f'_l = K_e f_l \tag{16}
\]

\[
\varepsilon_{clu} = 0.004 < 0.75 \varepsilon_{fu} \tag{17}
\]

\[
D = \frac{2bd}{(b + d)} \tag{18}
\]

**ACI 440.2 R.2002[1]**

This model calculates the compressive strength \( f_{cc} \) and the ultimate strain \( \varepsilon_{cc} \) for FRP for the apparent confined concrete strength \( f_{cc} \) for a rectangular concrete member wrapped with an FRP jacket providing a confining pressure \( f_l \).

\[
f'_{cc} = f'_{co} \left( 2.25 \sqrt{1 + \frac{7.9f'_l}{f'_{co}}} - 2 \left( \frac{f'_l}{f'_{co}} \right) - 1.25 \right) \tag{19}
\]

\[
f'_l = K_e f_l \tag{20}
\]
\[ f_i = \frac{2E_f \varepsilon_{clu} t_f}{D} \]  
(21)

\[ \varepsilon_{cu} = \frac{1.71(5f'_cc - 4f'_co)}{E_c} \]  
(22)

\[ E_c = 4730\sqrt{f'_co} \]  
(23)

\[ \rho_{sg} = \frac{A_s}{A_g} \]  
(24)

\[ b' = b - 2r \]  
(25)

\[ d' = d - 2r \]  
(26)

\[ K_e = \frac{A_e}{A_c} = 1 - \frac{b'^2 + d'^2}{3A_g (1 - \rho_{sg})} \]  
(27)

**Effect of cross-section aspect ratio**

To investigate the effect of cross-section aspect ratio, six models with six different cross-section aspect ratios are chosen which are 1.0, 1.2, 1.4, 1.6, 1.8 and 2.0 with a constant height equals 3000 mm and rounded corners with radius of 25 mm to overcome stress concentration at corners which effect CFRP efficiency [12] (Figure 4). The four corners of each model were rounded to prevent premature failure and to prepare appropriate effect on column

![Figure 4. Cross-section aspect ratio.](image-url)
confinement. On each side, the concrete cover was 25 mm. While the radius of each corner is 25 mm, concrete compressive strength is 40 MPa for all models. Four longitudinal steel bars with diameter 12 mm and 8 mm as a transverse steel bars with 100 mm spaced in the middle and 50 mm spaced at top and bottom of each column (Figure 5).

The CFRP jacket has an elastic modulus of 225 GPa, a tensile strength of 4300 MPa and an ultimate tensile strain of 0.018; and its nominal thickness is 0.13 mm per layer (Figure 6). Each model name is identified by a combination of numbers and letters. The first number 1.0, 1.2, 1.4, 1.6, 1.8 and 2.0 denotes

**Figure 5.** Longitudinal and transverse reinforcement.

**Figure 6.** CFRP and epoxy elements.
the cross-section aspect ratio, the second character is C which refers to the column, the third number denotes the number of fiber reinforcement plaites and the fourth character refers to the direction of FRP which is horizontal (H).

**Finite element results and discussion**

All models have been tested under concentric load. The compressive strengths and strains which were obtained from models are abstracted in Table 1 which illustrates the values of \( \frac{f_{cc}}{f_c} \), \( \frac{f_i}{f_c} \), \( \frac{\varepsilon_{cc}}{\varepsilon_c} \) and \( \frac{\varepsilon_i}{\varepsilon_c} \). On one hand, as shown in Table 1, the value of \( \frac{f_{cc}}{f_c} \) for square model is 2.79, whereas the values for rectangular section with (t/b) ratio from 1.2 to 2.0 are ranging from 2.70 to 2.03. As the same, the value of \( \frac{f_i}{f_c} \) for square model is 1.98, while the values for rectangular models are ranging from 1.89 to 1.03.

On the other hand, for strains ratio results the value of \( \frac{\varepsilon_{cc}}{\varepsilon_c} \) for square model is 6.13, whereas the values for rectangular section with (t/b) ratio from 1.2 to 2.0 are ranging from 5.83 to 2.93. Similarly, the value of \( \frac{\varepsilon_i}{\varepsilon_c} \) for square model is 3.47, while the values for rectangular models are ranging from 3.47 to 1.27 (Figures 7–8). While these observations obviously demonstrate that confinement with CFRP can improve concrete efficiency, CFRP wrapping, however, is more efficient in square cross-sections than in rectangular cross-sections. Moreover, the ultimate confined strength reduces as the aspect ratio rises whilst the ultimate axial and lateral strains decrease as the aspect ratio increases (Figures 9–26) [13].

**Table 1. Stresses and strains results.**

| Model | \( f_{cc} \) (MPa) | \( f_i \) | \( \varepsilon_{cc} \) | \( \varepsilon_i \) | \( \frac{f_{cc}}{f_i} \) | \( \frac{f_i}{f_c} \) | \( \frac{\varepsilon_{cc}}{\varepsilon_i} \) | \( \frac{\varepsilon_i}{\varepsilon_c} \) |
|-------|------------------|-----|-----------------|-------|----------------|-------------|----------------|----------------|
| 1.0C3H | 111.70           | 79.19 | 0.0184         | 0.0104 | 2.79           | 1.98        | 6.13           | 3.47           |
| 1.2C3H | 108.22           | 75.94 | 0.0175         | 0.0104 | 2.70           | 1.89        | 5.83           | 3.47           |
| 1.4C3H | 102             | 65.76 | 0.015          | 0.0078 | 2.55           | 1.64        | 5.00           | 2.60           |
| 1.6C3H | 100             | 63.58 | 0.014          | 0.0078 | 2.50           | 1.59        | 4.67           | 2.60           |
| 1.8C3H | 99              | 62.15 | 0.014          | 0.0073 | 2.47           | 1.55        | 4.67           | 2.43           |
| 2.0C3H | 81              | 41.18 | 0.0088         | 0.0038 | 2.03           | 1.03        | 2.93           | 1.27           |

**Table 2. Stresses and strains comparison with theoretical models.**

| Model Code | Finite Element Results | Mander et al Model | ACI 440 2 R.02 |
|------------|------------------------|--------------------|-----------------|
|            | \( f_{cc} \) (MPa) | \( \varepsilon_{cc} \) | \( f_{cc} \) (MPa) | \( \varepsilon_{cc} \) | \( f_{cc} \) (MPa) | \( \varepsilon_{cc} \) |
| 1.0C3H     | 111.70             | 0.018             | 88.97           | 0.0163         | 88.75           | 0.0162         |
| 1.2C3H     | 108.22             | 0.0175            | 85.97           | 0.0154         | 85.70           | 0.0153         |
| 1.4C3H     | 102                | 0.015             | 82.94           | 0.0146         | 82.74           | 0.0145         |
| 1.6C3H     | 100                | 0.014             | 80.00           | 0.0137         | 79.82           | 0.0137         |
| 1.8C3H     | 99                 | 0.014             | 77.05           | 0.0129         | 76.88           | 0.0128         |
| 2.0C3H     | 81                 | 0.0088            | 74.02           | 0.012          | 73.86           | 0.012          |
Figure 7. Axial stress versus axial strain.

Figure 8. Axial stress versus lateral strain.

Figure 9. 1.0C3H axial stress.
Figure 10. 1.0C3H axial strain.

Figure 11. 1.0C3H lateral strain.

Figure 12. 1.2C3H axial stress.
**Figure 13.** 1.2C3H axial strain.

**Figure 14.** 1.2C3H lateral strain.

**Figure 15.** 1.4C3H axial stress.
Figure 16. 1.4C3H axial strain.

Figure 17. 1.4C3H lateral strain.

Figure 18. 1.6C3H axial stress.
**Figure 19.** 1.6C3H axial strain.

**Figure 20.** 1.8C3H lateral strain.

**Figure 21.** 1.8C3H axial stress.
Figure 22. 1.8C3H axial strain.

Figure 23. 1.8C3H lateral strain.

Figure 24. 2.0C3H axial stress.
Effect of load eccentricity

Twelve models with dimensions $250 \times 250 \times 3000$ mm and round corners with radius of 25 mm have been used to investigate the impact of eccentricity and the number of FRP layers. The e/t ratio was 0.0, 0.1, 0.2 and 0.3 for three different eccentricities with 0, 25, 50 and 75 mm. With variable number of FRP layers, unwrapped columns, two layers, and three layers.

The four corners of the samples were rounded to prevent premature failure and to prepare appropriate effect on column confinement. On each side, the concrete cover was 25 mm. While the radius of each corner is 25 mm. Concrete compressive strength is 40 MPa for all models. Four longitudinal steel bars with diameter 12 mm and 8 mm as a transverse steel bar with 100 mm spaced in the middle and 50 mm spaced at top and bottom of each column (Figure 5). CFRP jacket has an elastic modulus of 225 GPa, a tensile strength of 4300 MPa and an ultimate tensile strain of 0.018; and its nominal thickness is 0.13 mm per layer. Each model name is identified by a combination of numbers and letters. The first number 0, 25, 50 and 75
denotes load eccentricity, the second character is C which refers to the
column, the third number denotes the number of fiber reinforcement platies
and the fourth character refers to the direction of FRP which is horizontal (H)
or vertical (V).

**Finite element results and discussion**

Table 3 illustrates the ultimate load, corresponding axial and lateral displacements. For concentric columns, columns have equivalent conduct before the peak load was reached. It is noticeable that a column which is wrapped with three layers of CFRP achieves the highest load and the maximum axial displacement between the three columns. On the other hand, not only does the peak load rise enormously while there is an increase in CFRP layers, but also the efficiency of the columns will be increased by increasing their displacement at failure, which means more ductility.

Firstly, for concentric columns, model 0C1V1H has a 13.58% maximum load than Column 0C0, while 0C3H model has a 5.6% maximum load than Column 0C1H1V. As shown in Table 3, model 0C3H has a higher ductility than model 0C1V1H and model 0C0 with 15% and 34% respectively. Figure 27 shows the deflection results obtained from the finite element analysis for the concentric models at failure, Figures (31–33) [13]. Secondly, for the eccentric models with (e/t = 0.1) at failure, it can be noticed from Figure 28 and Table 3 that model 25C3H has a higher ductility than model 25C1V1H and model 25C0 with 7.7% and 27% increase, Figures (34–39). Thirdly, for eccentric columns with (e/t = 0.2), Figure 29 illustrates the axial and lateral

**Table 3.** Finite element results.

| FE Model | Maximum Load (KN) | Axial (mm) | Lateral (mm) | Load at yield stage (KN) | Axial disp. at yield stage (D<sub>yield</sub>) (mm) | Ductility = D<sub>max</sub> / D<sub>yield</sub> |
|----------|-------------------|------------|-------------|--------------------------|-----------------------------------------------|---------------------------------------------|
| 0C0      | 2650              | 9.12       | 0           | 1128                     | 1.50                                          | 6.10                                        |
| 25C0     | 2177              | 5.32       | 3.90        | 990                      | 1.51                                          | 3.52                                        |
| 50C0     | 1737              | 4.37       | 4.27        | 1087.5                   | 1.96                                          | 2.24                                        |
| 75C0     | 1321              | 3.73       | 4.37        | 878.13                   | 1.77                                          | 2.10                                        |
| 0C1V1H   | 3010              | 16.09      | 0           | 1135                     | 1.46                                          | 7.11                                        |
| 25C1V1H  | 2464              | 7.16       | 6.19        | 899.22                   | 1.32                                          | 4.15                                        |
| 50C1V1H  | 2089              | 6.83       | 7.07        | 1089                     | 1.88                                          | 3.63                                        |
| 75C1V1H  | 1764              | 6.64       | 7.87        | 943.75                   | 1.84                                          | 3.61                                        |
| 0C3H     | 3179              | 16.44      | 0           | 1499                     | 2.01                                          | 8.18                                        |
| 25C3H    | 2635              | 8.57       | 8.19        | 1089.1                   | 1.60                                          | 4.47                                        |
| 50C3H    | 2250              | 7.76       | 8.45        | 1135                     | 1.94                                          | 4.01                                        |
| 75C3H    | 1781              | 7.04       | 8.55        | 962                      | 1.84                                          | 3.83                                        |
Figure 27. Load displ. curve for e/t = 0.

Figure 28. Load displ. curve for e/t = 0.1.

Figure 29. Load displ. curve for e/t = 0.2.
displacements versus the applied load curves for models which were tested under 50 mm eccentric load (e/t = 0.2). For column 50C1V1H a 20.26% increase in maximum load was recorded by reaching a maximum load of nearly 2090 KN in comparison with the unwrapped column with a maximum load equal to 1737 KN, whereas the figures for the maximum load for model 50C3H reaches 2250 KN with 29.5% increase compared to the unwrapped model. Furthermore, model 50C3H has a higher ductility than model 50C1V1H and model 50C0 with 62.05% and 96.8% increase, Figures (40–45). Fourthly, for eccentric columns with (e/t = 0.3), Figure 30 and (46–51) illustrate axial and lateral displacements versus the applied load curves for columns which were tested under 75 mm eccentric load (e/t = 0.3). It can be noticed from Figure 30, Model 75C3H has a better performance than the unwrapped column with 34.8 % increase in maximum load by reaching a value equal to 1764 KN, while a similar raise in maximum load of 33.5%
Figure 32. 0C1V1H axial displacement.

Figure 33. 0C3H axial displacement.

Figure 34. 25C0 axial displacement.
Figure 35. 25C0 Lateral displacement.

Figure 36. 25C1V1H axial displacement.

Figure 37. 25C1V1H Lateral displacement.
Figure 38. 25C3H axial displacement.

Figure 39. 25C3H Lateral displacement.

Figure 40. 50C0 Axia.
Figure 41. 50C0 Lateral.

Figure 42. 50C1V1H Axial.

Figure 43. 50C1V1H Lateral displacement.
Figure 44. 50C3H axial displacement.

Figure 45. 50C3H Lateral displacement.

Figure 46. 75C0 Axial displacement.
Figure 47. 75C0 Lateral displacement.

Figure 48. 75C1V1H Axial displacement.

Figure 49. 75C1V1H Lateral displacement.
was recorded for model 75C1V1H. The presence of passive confining reinforcement has a crucial effect on the value of ductility. As it can be highlighted, FRP jacket has the privilege of enhancing ductility. Thus, model 75C3H has a higher ductility than model 75C1V1H and model 75C0 with 71.9 % and 82.4% increase [13].

For the unwrapped models, there is a sharp decline in the axial deflection value as long as the value of eccentricity is increased. By contrast, there is an enormous increase in the value of lateral deflection while the value of eccentricity has been increased. Moreover, for the wrapped columns, there is a gradual upsurge in both axial and lateral deflection as long as CFRP layers have been increased. This can been seen in column 25C3H where the maximum axial deflection is 8.57 mm, while the maximum axial deflection for column 25C1V1H is 7.16 mm. The figure for the axial deflection for model 25C0 is 5.32 mm. Furthermore, for the lateral deflection the figures for models 25C3H, 25C1V1H and 25C0 are 8.19, 6.19 and 3.90 mm in a row. In addition,
for column 50C3H, the maximum axial deflection is 7.76 mm, whereas the maximum axial deflection for column 50C1V1H and 50C0 is 6.83 mm and 4.37 mm. Moreover, for the lateral deflection the figures for columns 50C3H, 50C1V1H and 50C0 are 8.45, 7.07 and 4.27 mm in a row. On the contrary, for column 75C3H, the maximum axial deflection is 7.04 mm, compared to 6.64 mm for column 75C1V1H and 3.73 mm for column 75C0. However, for the lateral deflection, the figures for columns 75C3H, 75C1V1H and 75C0 are 8.55, 7.87 and 4.37 mm in a row [13].

**Conclusion**

This paper investigates the influence of cross-section aspect ratio and load eccentricity on the behavior of on the behavior of RC short columns with large-scale specimens wrapped with external carbon fiber polymers (CFRP) using finite element software (ANSYS). Based on the finite element results, the following conclusions were drawn:

1. Although CFRP jackets increase the performance of square sections significantly, CFRP jackets performance decreases incase of cross-section aspect ratio of more than 2.0 at a constant corner radius.
2. As the cross-section aspect ratio increases from 1.0 to 2.0 the ratio of axial confined stress per unconfined stress decreases until it becomes slightly more than 1.0.
3. CFRP rupture strain decreases significantly as the cross-section aspect ratio increases from 1.0 to 2.0.
4. The external confinement can significantly increase the strength of columns under concentric loading, while the enhancement in columns under eccentric loading is not as significant as columns under concentric loading.
5. Columns with external FRP could resist large deformation under concentric load.
6. Under eccentric load, the maximum load has an enormously decreased while the eccentricity magnitude increased.
7. Increasing the number of CFRP layers leads to an increasing in the load and the performance of columns under each case of loading.
8. There is a sharp decline in the axial deflection values as long as the value of eccentricity is increased which leads to decrease ductility. In contrast, there is a significant increase in the values of lateral deflection while increasing the value of eccentricity.


List of symbols

\[ f^e \] Confined concrete axial stress.
\[ f^u \] Unconfined concrete axial stress.
\[ f_l \] Confined concrete lateral stress.
\[ E_c \] Concrete modulus of elasticity.
\[ \varepsilon_{ec} \] Confined concrete axial strain.
\[ \varepsilon_{ec} \] Confined concrete axial strain.
\[ d_m \] The Debonding parameter.
\[ u_t \] The contact slip.
\[ u_n \] The contact gap.
\[ U_n \] The contact gap at the maximum normal stress.
\[ \sigma_{max} \] The maximum normal stress.
\[ K_s \] The confinement effectiveness factor.
\[ D \] The equivalent diameter of rectangular cross section.
\[ E_l \] Confined concrete lateral strain.
\[ E_{FRP} \] Ultimate tensile strain for FRP.
\[ \tau_c \] The shear contact stress.
\[ \sigma_n \] The normal contact stress.
\[ k_s \] The shear contact stiffness.
\[ k_n \] The normal contact stress.
\[ G_{fn} \] The total value of the normal fracture energy.
\[ U_{t} \] The contact slip at the maximum shear stress.
\[ U_{f} \] The contact slip at the completion of debonding.
\[ A_g \] The gross cross sectional area.
\[ r \] The radius of corner.

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