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Behavior of Reactive Powder Concrete Hollow Core Columns Strengthened with Carbon Fiber Reinforced Polymer Under Eccentric Loading

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ABSTRACT: The behavior of hollow-core columns composed of reactive powder concrete (RPC) contained by a circular carbon fiber reinforced polymer (CFRP) tube is investigated numerically in this work. This research used circular hollow core column samples with an outside diameter of 20.6 cm, an interior diameter of 9cm, and a height of 80cm. These examples have been created utilizing 116 MPa reactive powder concrete. Nine groupings of specimens were created. A control set of nine unconfined hollow columns with stirrups strengthened by 12mm longitudinal bars (HCRPC). Groups two through five have been produced up of RPC hollow column specimens with similar reinforcement but were externally confined with CFRP of 0.131, 0.262, 1.2, and 2.4mm thick (These thicknesses are commercially available (0.131 for CFRP one layer sheet, 0.262 for two layers of CFRP sheet; 1.2 for one layer of CFRP plate. And 2.4 for two-layer of CFRP plate) respectively, placed at mid-length of the columns. Sets six to nine, on the other hand, are identical to the previous sets, but the CFRP restriction has been put at both columns' ends. Axial load thru the column center and uniaxial loading with 2.5 and 5 cm eccentricities from the center were applied to all columns. According to the findings, CFRP confinement boosted the strength of HCRPC columns marginally. Also, column samples confined at mid-height with CFRP wrapping achieved a higher ultimate strength than those confined at both ends.

Keywords: Carbon fiber reinforced polymer, confinement, hollow columns, finite element method.

1 INTRODUCTION

Reinforced concrete (RC) is one of the widely used materials worldwide. Due to the availability of its base constituents, economy, strength, and flexibility, reinforced concrete is usually preferred more than steel, timber, and masonry in building construction. However, from a design and structural perspective, RC is not a simple composite material as it comes to mind (Ali et al., 2022; Hamad et al., 2021; A. Shubbar et al., 2021; SHUBBAR et al., 2020). On the contrary, it is a complex material that provides a special bond between two materials (steel and concrete) that differ in their properties. However, during the last twenty years, researchers enhanced concrete's mechanical and physical properties by introducing reactive powder concrete, producing concrete with ultra-high strength, high ductility, and lower porosity than normal concrete (Z.S. Al-Khafaji & Falah, 2020; Tuama et al., 2020). Regardless of its type (modern or traditional), RC is used to produce a variety of structural members such as beams, columns, slabs, joints, and foundations. Columns, by far, are the most important among structural members due to their task of transferring the loads from the superstructure to the substructure and soil (Z S Al-Khafaji et al., 2018; Zainab S Al-Khafaji et al., 2018; Lignola et al., 2008; Sharma & Singh, 2018).

Like other industries, the construction industry has seen its share of development over the past years. One of these developments is the introduction of hollow columns. Researchers have found that the utilization of hollow columns in construction could lead to a reduction in execution time, amount of concrete as well as cost (Lignola et al., 2008; A. A. Shubbar et al., 2020; A. A. F. Shubbar et al., 2017). Furthermore, hollow columns increase the member's ability to resist seismic loads due to the low contribution of the light self-weight of the column to the internal vibration mode during an earthquake (Kraav & Lellep, 2017). Therefore, hollow columns are widely used in areas that suffer seismic action, such as Japan, Italy, and the United States (Z S Al-Khafaji et al., 2018).

Due to their low seismic mass and increased moment of inertia, hollow columns are widely used in the industrial and civic sectors (Theofanous & Gardner, 2009). A greater moment of inertia and torsional strength of the columns per unit weight of material affords an advantage over solid columns, according to the fundamental characteristics of hollow columns. Lower seismic mass also ensures the superstructure's security and safety (Falah et al., 2022). As a result, hollow section columns increase both the efficiency and cost-effectiveness of the building. Building bridges, tall buildings, exposing structural applications, long-span enclosure structures, and other structures use hollow steel sections as columns, beams, and bracing (Al-Salman et al., 2022; Jabbar et al., 2021).

Generally, various factors could affect the properties of columns and cause their deterioration. These factors include environmental factors (rain, wind, and earthquakes), accidents (fire, gas explosion, and direct impact by an object), and overloading the column beyond its strength capacity. New ones could replace damaged columns; however, this process is neither time-efficient nor cheap, and it has a high expectancy of waste. Due to its drawbacks, researchers have endeavored to find alternative methods to replace damaged columns. Repairing the columns was found to be a better option than replacing them. Repairing methods include enlarging the column cross-section (jacketing) and column confinement using steel plates, glass, or carbon fiber (Johnson et al., 1995). (Rutledge et al., 2012) suggested another column repairing method by adding additional columns to prevent future failure. Steel jacketing is another method of column repair. It strengthens the damaged column against compression loads and deformations; however, low corrosion resistance, high cost, and heavy dead weight hinder it from being a more efficient repair method (Johnson et al., 1995).

In recent years, newly developed materials such as fiber-reinforced composites have been utilized in strengthening technologies. These materials have high ratios of strength and stiffness to weight and are highly resistant to corrosion (Al-Baghdadi et al., 2021). The introduction of such materials made the repairing method an efficient alternative to the earlier methods. The repairing method using fiber-reinforced composite materials is done by covering the deteriorated column with wraps or jackets made from these materials (Abbas et al., n.d.; Alwanas et al., 2019; Keshtegar et al., 2019; Mirmiran et al., 2001; Mohammed et al., 2020). Carbon sheets are an example of such materials. They increase the reinforced concrete column's loading and confinement resistance.

Fiber-reinforced polymers (FRP) jackets depend on various parameters for effectiveness when used as external confinement. These parameters are concrete type, steel reinforcement, the thickness of the FRP jacket (number of layers), stiffness (FRP type), and loading conditions (Alwanas et al., 2019; Bisby & Ranger, 2010; Bogdanovic, 2002; Keshtegar et al., 2019; Micelli et al., 2018). In addition, both the cross-sectional shape of the column and its edges directly affect the FRP jacket's effectiveness when used as externally bonded confinement. Furthermore, there is a strong relationship between the confined concrete's strength and the FRP wrapping's strength. The ruptured CFRP-wrapped confined concrete strain is lower than the obtained ultimate strain for the CFRP tensile strength (Ali et al., 2020; Micelli et al., 2018). Fitzwilliam et al. (Fitzwilliam & Bisby, 2010) stated that the utilization of longitudinal CFRP wraps reduced the lateral deflections in the columns and increased the ability to use slender columns to achieve greater strengths (Olivova & Bilcik, 2009; Wang et al., 2012).

(Hadi et al., 2018) experimentally investigated CFRP confined effects for hollow core Reactive Powder Concrete columns. They use sixteen samples of a circular hollow core column with dimensions (D=206 mm, h= 800 mm, and internal D= 90 mm) prepared by Reactive Powder Concrete (RPC) with 105 MPa compressive strength. The samples were classified into four groups to investigate the effect of (being externally confined with a CFRP tube. Externally confined with a CFRP tube and internally confined with a Polyvinyl chloride (PVC) tube, no steel reinforcement and were only made with an external CFRP tube and an internal steel tube) on the columns that were prepared by (RPC) and reinforced by 10mm longitudinal steel bars. The samples were tested under different loading conditions: concentric, eccentric (25 and 50) mm, and four-point bending. The final experimental results have been proofed that the use of CFRP increased the strength of columns slightly while the ductility was enhanced significantly.

The effect of CFRP confinement on hollow columns made using reactive powder concrete was experimentally investigated (Hadi et al., 2018). The authors used sixteen samples of circular hollow-core columns. The column dimensions were D=206mm, h=800mm, and internal D=90mm. These columns were prepared using reactive powder concrete having a compressive strength of 105MPa. The samples were confined externally with CFRP tubes, internally with Polyvinyl Chloride (PVC) tubes, reinforced and non-reinforced with longitudinal bars of 10mm diameter. The column samples were loaded axially and uniaxially with 25 and 50 mm eccentricities from the column's center. Furthermore, the samples were tested for their bending strength using the four-point bending test. Results show that using CFRP confinement slightly increased the columns' strength but enhanced their ductility significantly.

This work endeavors to study the effect of CFRP confinement with different thicknesses (0.131, 0.262, 1.2, and 2.4mm). And different placements (at both ends and mid-height of the column) on the strength of hollow columns reinforced with 12mm longitudinal reinforcement and subjected to loadings with (0, 25, and 50mm) eccentricities where the eccentricity changes lead to change failure from compression to flexural. On the other hand, this research reduces the required cost and time for investigating the effect of using different CFRP thicknesses and locations.

2 MODELING AND ANALYSIS

Figure 1 shows the dimension of the column samples studied in this article. Longitudinal and horizontal reinforcement with 12 and 10mm diameters were used.

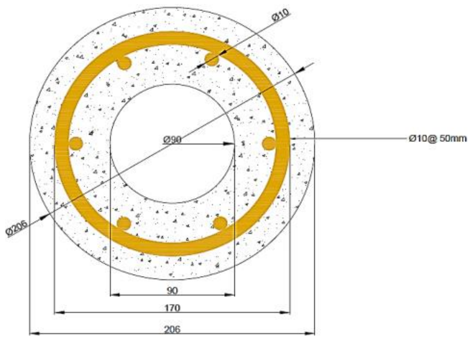


Figure 1. The cross-sectional details of the hollow column samples

In order to find the accuracy of the numerical model used in this study, the results obtained for the control specimen with CFRP strengthening at the ends and without eccentricity of loading compared with the experimental results of (Hadi et al., 2018) for the same specimens. The comparison showed a good agreement in both ultimate load and maximum deflection, as shown in Figure 2 and 3 shows the similarity in the type of failure between the experimental specimen of (Hadi et al., 2018) and the numerical model for the same specimen.

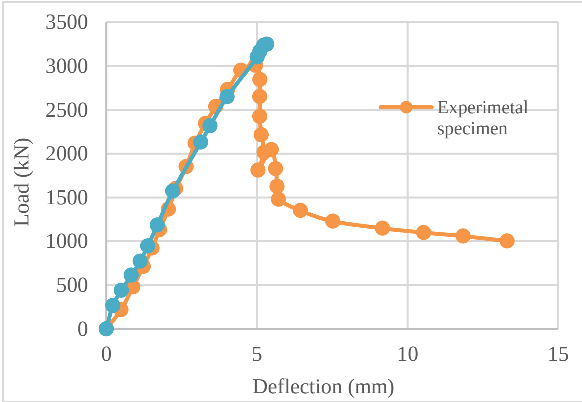


Figure 2. Numerical and Experimental Load-Deflection of the control Specimen

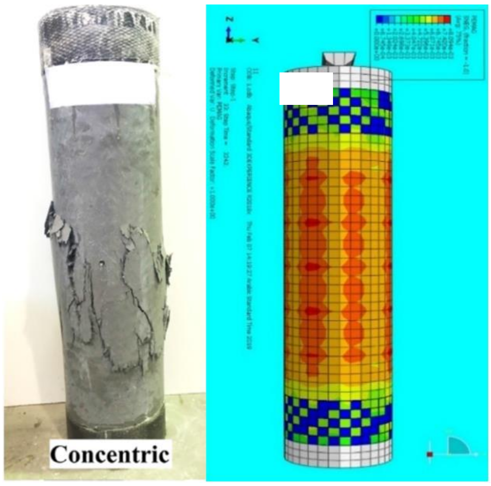


Figure 3. Failure of the control specimen in the numerical model and experimental specimen (Hadi et al., 2018)

The authors studied nine groups of column samples in this study. The first group is the control group, consisting of 9 samples with the dimensions shown in Figure 1, unconfined by CFRP and loaded using three eccentricities (0, 25, and 50mm). The remaining groups differ from the control group by their CFRP confinement thicknesses and location. In order to study the effect of CFRP location on the load capacity of hollow columns, two locations were used for the confined column samples. The second group of hollow columns was confined at mid-height of the column's length, with the CFRP having a 100mm width. The third group was confined with CFRP at both ends, with each CFRP confinement having a width of 50mm. To study the effect of CFRP thickness on the load capacity and deflection of the column samples, four CFRP thicknesses were used, namely 0.131, 0.262, 1.2, and 2.4mm. Similar loading schemes were used throughout the study. Table 1 lists the details for the studied groups.

Table 1. Details of the column groups studied

Group ID	Group	Sample ID	Sample Details
Group 1	Hollow Col. Without CFRP	H1	Hollow column reinforced by Ø= 12mm with a central load
		H2	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=25mm)
		H3	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=50mm)
Group 2	Hollow Col. With CFRP at mid thickness (0.131mm)	HM1	Hollow column reinforced by Ø= 12mm with central load treated with CFRP (thickness=0.131mm) placed on both column sides
		HM2	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=25mm) treated with CFRP (thickness=0.131mm) placed on both column sides
		HM3	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=50mm) treated with CFRP (thickness=0.131mm) placed on both column sides
Group 3	Hollow Col. With CFRP at mid thickness (0.262mm)	HM4	Hollow column reinforced by Ø= 12mm with central load treated with CFRP (thickness=0.262mm) placed on both column sides
		HM5	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=25mm) treated with CFRP (thickness=0.262mm) placed on both column sides
		HM6	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=50mm) treated with CFRP (thickness=0.262mm) placed on both column sides
Group 4	Hollow Col. With CFRP at mid thickness (1.2mm)	HM7	Hollow column reinforced by Ø= 12mm with central load treated with CFRP (thickness=1.2mm) placed on both sides.
		HM8	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=25mm) treated with CFRP (thickness=1.2mm) placed on both column sides
		HM9	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=50mm) treated with CFRP (thickness=1.2mm) placed on both column sides
Group 5	Hollow Col. With CFRP at mid thickness (2.4mm)	HM10	A hollow column was reinforced by Ø= 12mm with a central load treated with CFRP (thickness=2.4mm) placed on both sides.
		HM11	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=25mm) treated with CFRP (thickness=2.4mm) placed on both column sides
		HM12	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=50mm) treated with CFRP (thickness=2.4mm) placed on both column sides
Group 6	Hollow Col. With CFRP at ends, thickness (0.131 mm)	HE1	Hollow column reinforced by Ø= 12mm with central load treated with CFRP (thickness=0.131mm) placed on column middle part.
		HE2	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=25mm) treated with CFRP (thickness=0.131mm) placed on column middle part.
		HE3	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=50mm) treated with CFRP (thickness=0.131mm) placed on column middle part.
Group 7	Hollow Col. With CFRP at ends, thickness (0.262 mm)	HE4	Hollow column reinforced by Ø= 12mm with central load treated with CFRP (thickness=0.262mm) placed on column middle part.
		HE5	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=25mm) treated with CFRP (thickness=0.262mm) placed on column middle part.
		HE6	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=50mm) treated with CFRP (thickness=0.262mm) placed on column middle part.
Group 8	Hollow Col. With CFRP at ends, thickness (1.2 mm)	HE7	The hollow column was reinforced by Ø= 12mm with a central load treated with CFRP (thickness=1.2mm) placed on the middle column.
		HE8	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=25mm) treated with CFRP (thickness=1.2mm) placed on column middle part.

Group 9	Hollow Col. With CFRP at ends, thickness (2.4 mm)	HE9	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=50mm) treated with CFRP (thickness=1.2mm) placed on column middle part.
		HE10	Hollow column reinforced by Ø= 12mm with central load treated with CFRP (thickness=2.4mm) placed on column middle part.
		HE11	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=25mm) treated with CFRP (thickness=2.4mm) placed on column middle part.
		HE12	Hollow column reinforced by Ø= 12mm with un-central load (eccentricity=50mm) treated with CFRP (thickness=2.4mm) placed on column middle part.

3 MATERIAL CHARACTERISTICS

ABAQUS/ finite element standard package is used for the numerical simulation of the CFRP RC columns. The nonlinear material behavior of concrete, bilinear load-deflection curves of steel, and CFRP tubes' elastic behavior have been used for the finite element model (Salman Al-Taai et al., 2018; Yin et al., 2019). The materials for the analyzed structural elements include concrete, steel reinforcement bars, and CFRP. Table 2 lists the parameters for each structural element adopted for the finite element models. Figure 4 shows the column simulation details.

Table 2. Parameters used for finite element modeling for the column samples

Item	Element Type	Characteristics
Concrete	C3D8R	compressive strength (fc')=116 MPa Tensile strength(ft'=18) Poisson's ratio=0.2 modulus of elasticity=44500 MPa dilation angle= 36 viscosity= 0 eccentricity= 0.1 k=0.667 fb0/fc0=1.16
Steel Reinforcement	T3D2	modulus of elasticity=200000 MPa Poisson's ratio=0.3 yielding strength (fy)= 460 MPa
CFRP	C4R	modulus of elasticity=165000 MPa yielding strength (fy)= 2800

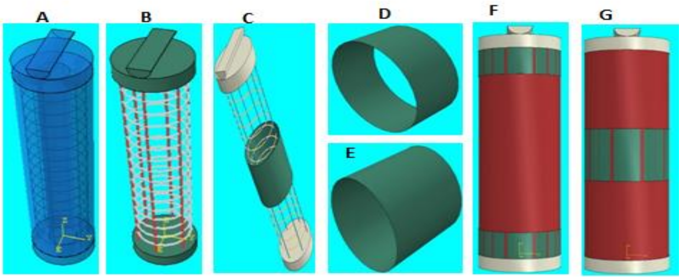


Figure 4. The column simulation details: A) Hollow column, B) Reinforcement details, C) Confining the column with CFRP, D) & E) CFRP tube in different width, F) & G) Confined columns at both ends and middle, respectively.

4 RESULTS AND DISCUSSION

Ultimate loads before failure and the shown deflection for each column sample are recorded when subjected to the loading scheme illustrated above. Comparisons will be made between the control samples with samples confined with CFRP. In addition, the effect of confinement location (at mid-height or both ends) will be listed and analyzed. Furthermore, the behavior of the confined column samples when loaded with increasing eccentricity will be studied and analyzed.

4.1 *Effect of load eccentricity on the columns*

Figure 5 shows the effect of the eccentricity of loading on the ultimate load capacity for the control column samples. The figure shows that an increase in load eccentricity leads to a reduction in column ultimate load capacity. The central loading condition distributes the load on the whole cross-sectional area of the column sample, as shown in Figure 6.

Figure 5. Ultimate load-deflection relationship for group 1 at different eccentricities

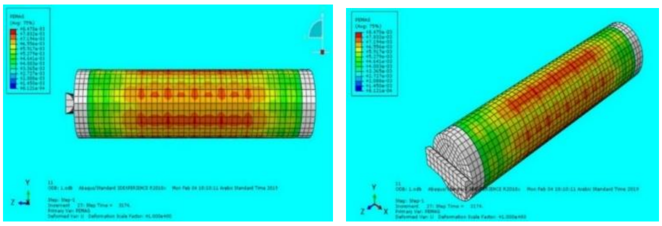
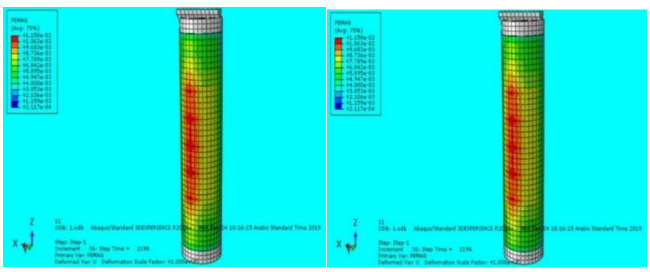


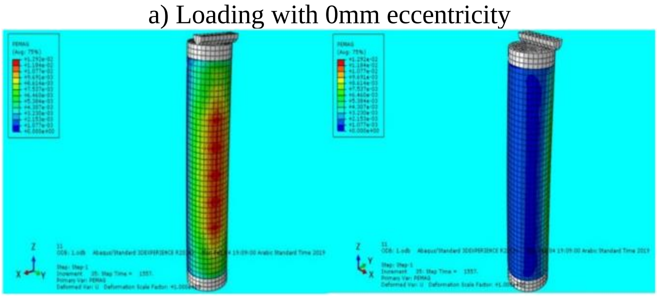
Figure 6. Stress distribution due to loading at 0mm eccentricity

A slight movement of the load from the center of the cross-section will alter the stress distribution, where it will affect positively on one side and negatively on the other side of the column sample, as shown in Figs. 7(a), (b), (c) & (d). The inequality of load distribution leads to a speed-up in column failure in the area nearer to the concentration of the load (Abbassi & Dabbagh, 2014).

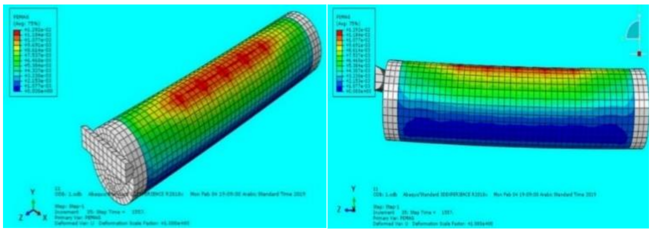
An increase in load eccentricity from 0 to 25mm reduced the load capacity of the column sample by 27%. Furthermore, increasing the eccentricity to 50mm reduced the load capacity to more than half at 51.96%. These numerical results are compatible with the experimental results stated b (Hadi et al., 2018; Jiang et al., 2014). Although the load capacity is decreased due to an increase in eccentricity, the column samples' deflection is reduced by nearly 2mm when a 50mm eccentricity is used.



a) Loading with 0mm eccentricity



b) Loading with 25mm eccentricity

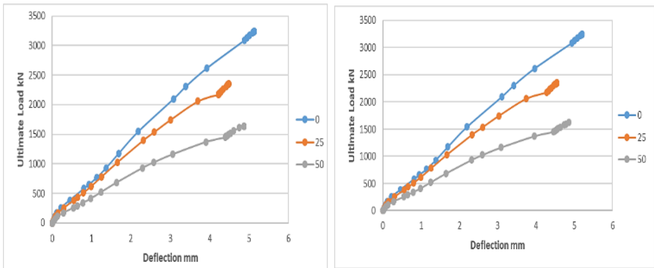


c) Loading with 50mm eccentricity

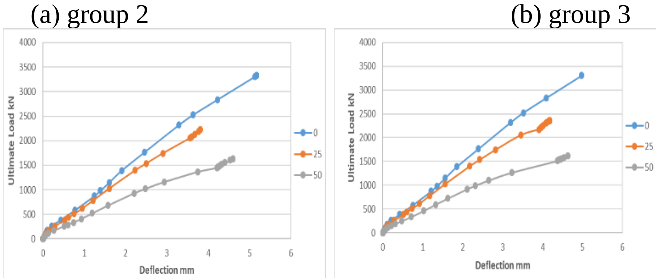
Figure 7. Load eccentricity effect on stress distribution

4.2 *Effect of CFRP regardless of location & thickness*

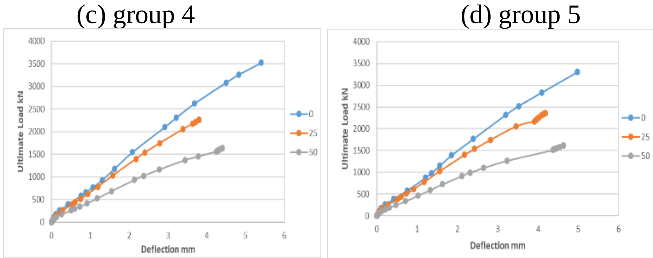
In general, the utilization of CFRP confinement in strengthening the column samples increased their ultimate loading capacity compared to the control samples. Figure 8 shows the ultimate load-deflection relationships for the column samples with confinement at both ends and mid-height.



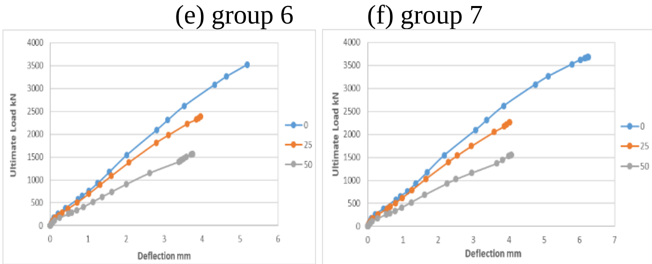
(a) group 2 (b) group 3



(c) group 4 (d) group 5



(e) group 6 (f) group 7



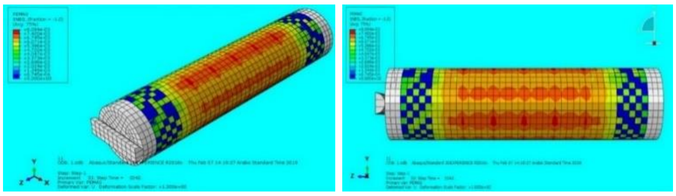
(g) group 8 (h) group 9

Figure 8. Ultimate load-deflection relationships for confined column samples at different locations and with various thicknesses

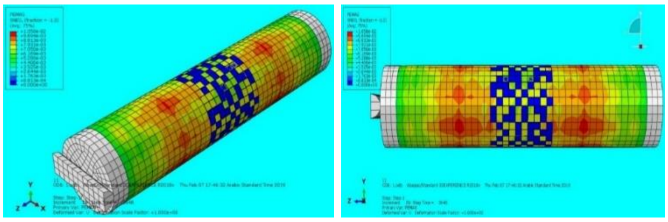
Even with loading eccentricity, confined column samples achieved higher ultimate load capacities than their control counterparts. However, it is noticed that column samples confined at mid-height with CFRP wrapping achieved a higher ultimate strength than those exhibited by the samples confined at both ends, which will be discussed in detail next.

4.3 *Effect of CFRP location*

Figure 9. shows the stress distribution of confined columns at mid-height and both ends.



a) 3D and 2D stress distribution for a column confined at both ends



b) 3D and 2D stress distribution for a column confined at mid-height

Figure 9. 2D and 3D illustrations for stress distribution of confined columns' samples.

The CFRP confined column samples at mid-height showed higher ultimate load capacities than their control and confined at both ends counterparts at different load eccentricities. Column samples with confinement at mid-height and 0 load eccentricity achieved 12.7, 13.89, 8.98, and 9.35% higher than the ultimate load capacity achieved by the control column samples at thicknesses of 0.131, 0.262, 1.2, and 2.4mm respectively. The column samples with the same loading eccentricity and thicknesses are 0.22, 0.036, 2.87, and 2.19%. The earlier percentages show that hollow column samples confined with CFRP wrapping at mid-height are better than the same hollow column samples confined at both ends.

4.4 *Effect of CFRP thickness*

The study sheds light on the effect of CFRP thickness on the column samples' ultimate load capacity. Four thicknesses have been investigated, namely 0.131, 0.262, 1.2, and 2.4mm. Table 3 lists the ultimate load capacities for the column samples confined at mid-height and both ends.

Table 3. Ultimate load capacity and deflection of confined column samples

Description	Group Name	Ultimate Load (kN)	Deflection (mm)
	HM1	3648.40	6.305218
Group 2	HM2	2519.5	4.205902
	HM3	1586.34	4.964258
	HM4	3684.00	6.254446
Group 3	HM5	2561.5	4.021664
	HM6	1626.80	4.068226
	HM7	3525.10	5.406017
Group 4	HM8	2525.89	3.801597
	HM9	1630.40	4.401073
	HM10	3537.10	5.195784
Group 5	HM11	2570.95	3.963403
	HM12	1640.13	3.755424
	HE1	3241.70	5.209888
Group 6	HE2	2345.65	4.546947
	HE3	1621.87	4.863965
	HE4	3235.88	5.134756
Group 7	HE5	2350.71	4.494847
	HE6	1632.94	4.872744
	HE7	3327.57	5.172937
Group 8	HE8	2362.10	3.80658
	HE9	1631.64	4.598442
	HE10	3305.66	4.978817
Group 9	HE11	2394.41	4.182486
	HE12	1616.13	4.635329

Table 3 shows that the effect of CFRP thickness does not follow a specific trend. Column samples confined at mid-height show a higher ultimate load capacity when the thickness of the CFRP wrap is 0.262mm, and the load eccentricity is 0. However, at a load eccentricity of 25mm, the column sample with a 2.4mm CFRP wrap exhibited a higher load capacity when compared with other mid-height confined samples. The 2.4mm CFRP wrapped column sample also achieved a higher ultimate load capacity than the thinner CFRP at 50mm load eccentricity.

Hollow column samples confined with CFRP wrapping at both ends exhibited a different behavior. A column sample confined at both ends with a 1.2mm thick CFRP exhibited the highest ultimate load capacity compared to the other both-ends confined samples. With an increased load eccentricity of 25mm, a CFRP of 2.4mm exhibited a higher ultimate load capacity of 2394.41kN compared to the remaining column samples. When the eccentricity is increased to 50mm, the column with both ends confined with 0.262mm thick CFRP showed the highest ultimate load capacity of 1632.94kN.

It is safe to say that the thickness of the CFRP confinement does not conclude that thicker CFRP would lead to higher ultimate load capacities, which is accurate, especially when there is no load eccentricity. However, load eccentricity will pressure the column to extreme stresses, in which confinement with a thick CFRP helps reduce these stresses.

4.1 Deflection of column samples

Table 3 lists the deflection readings exhibited by each column sample. The results show that the column shows higher deflection readings with confinement. The CFRP confinement allows the column sample to withstand loading even with showing signs of deflection. If a comparison is made between control and confined samples, it is obvious that the confined column samples, although high in load capacity, show higher deflection readings. Deflection readings decrease with increased load eccentricity regardless of confinement, thickness, and location. Column samples confined at mid-height with CFRP showed higher deflection readings than those confined at both ends.

5 CONCLUSIONS

This study has presented a numerical investigation of CFRP confinement effects on the load capacity of hollow columns. Column samples were confined with CFRP wrapping at mid-height of the sample, using different thicknesses and increasing load eccentricity. The following conclusions can be drawn:

- The addition of CFRP increased the column samples' ultimate load capacity by 12.7% higher than the control samples when confined at mid-height.
- Confined samples at mid-height achieved higher ultimate load capacities than control and were confined at both ends.
- Increasing the thickness of CFRP confinement did not show a significant trend. However, a 0.262 thick CFRP wrap at mid-height and central loading showed the highest ultimate load capacity. Column samples confined at both ends with 2.4mm thick CFRP exhibited a higher ultimate capacity when compared to the remaining other thicknesses used for samples at both ends.
- Column samples confined with CFRP exhibited higher deflection readings than the control samples. The confinement enhances the ability of the confined column samples to withstand extra load even when showing deflection.
- Adding CFRP to columns will increase their ultimate load capacity regardless of location and thickness.

6 ACKNOWLEDGMENTS

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