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Behavior of R.C. Columns Strengthened by CFRP Sheets Reinforced Partially by GFRP Bars

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R.C. Columns; GFRP bars; Concentric; Eccentric; CFRP sheets.

Highlights:

- *Structural Behavior of Strengthened Reinforcement Concrete Columns with CFRP Sheets.*
- *Structural Behavior of Concrete Columns Reinforced Partially by GFRP Bars.*
- *Reinforcement Concrete Columns Test Under Concentric and Eccentric Compression Load.*

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Abstract: This paper investigates the behavior of column specimens' reinforcement by partially and fully GFRP bars and strengthened by CFRP sheets subjected to concentric and eccentrically applied loading. 12 half-scale column specimens reinforced with varied ratios of GFRP (36%, 64%, and 100%) were investigated, besides the control specimen. The specimens were reinforced with traditional steel bars strengthened with CFRP sheets and investigated under load with different eccentric ratio e/h (0, 0.66, and 1). The failure mode, the axial load, and the average axial displacement relation were tested. A comparison between the experimental results and the theoretical interaction diagram for strengthened and un-strengthened columns was conducted. The results showed that the experimental results for the strengthening specimens by CFRP sheets were higher than the theoretical results, indicating that the theoretical design was conservative according to the ACI code. CFRP sheets improved the specimens' performance and increased the moments value. The average axial bearing capacity of the columns strengthened by CFRP sheet in the groups where the GFRP bars were used as a partial or complete replacement in the main reinforcement was reduced with increasing the number of GFRP bars. Furthermore, the percentage of dropping the average axial bearing capacity for columns with GFRP bars was tested under eccentric load reduced by increasing the number of GFRP bars.

السلوك الانشائي لتقوية الأعمدة الخرسانية المسلحة بصفائح الياف الكاربون البوليمرية (CFRP) والمسلحة جزئيًا بقضبان الياف الزجاج البوليمرية (GFRP)

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الخلاصة

يعرض هذا البحث النتائج التي تم الحصول عليها من الفحوصات المختبرية والتي تم إجراؤها للتحقق من السلوك الانشائي لتقوية نماذج الأعمدة بألياف الكاربون البوليميرية (CFRP) والمسلحة جزئياً وكلياً بواسطة قضبان الياف الزجاج البوليمرية (GFRP) والمعرضة لتحميل الانضغاط المركزي (Concentric) وتحميل الانضغاط اللامركزي (Eccentric). ١٢ نموذج من الأعمدة المسلحة جزئياً وكلياً بقضبان الياف الزجاج البوليمرية (GFRP) وبنسب (٣٦٪، ٦٤٪، ١٠٠٪) فضلاً عن نموذج العينة المرجعية والمسلحة بالقضبان الحديد التقليدية والتي تم تقوية هذه النماذج بألواح الياف الكاربون (CFRP) والتي تم فحصها تحت ظروف مختلفة من مسافات اللامركزية (eccentricities) (e/h) (٠، ٠,٦٦، ١). تم مناقشة وعرض نتائج كل من أنماط الفشل الحاصلة في العينات بعد الفحص، وعلاقات حمل الفشل مع معدل الازاحة العامودية فضلاً عن عرض مقارنة للنتائج النظرية بين مخططات تفاعل الفشل (Interaction diagram) للعينات التي تم تقويتها بواسطة الياف الكاربون والعينات غير المقواة ومقارنتها مع النتائج العملية المختبرية والتي تم الحصول عليها للنماذج التي تم تقويتها. بينت النتائج أن النتائج التجريبية لعينات الاعمدة المقواة بواسطة الواح الياف الكاربون البوليمرية (CFRP) أعطت نتائج أعلى من النتائج النظرية، وهذا يدل على أن التصميم النظري، وفقًا لكود ACI، متحفظ. وقد حسنت ألواح (CFRP) من أداء ومقاومة العينات وزادت من قيمة العزوم. وانخفض متوسط قدرة التحمل المركزية للأعمدة المقواة بألياف الكاربون البوليمرية (CFRP) في المجموعات التي استخدمت فيها قضبان GFRP كبديل جزئي أو كامل في التسليح الرئيسي مع زيادة عدد قضبان GFRP. علاوة على ذلك، انخفضت النسبة المئوية لانخفاض متوسط مقاومة التحمل المركزية للأعمدة بقضبان GFRP التي تم فحصها تم احمال لامركزية مع زيادة عدد قضبان GFRP.

الكلمات الدالة: أعمدة خرسانية مسلحة، قضبان الياف الزجاج البوليمرية، مركزي، لا مركزي، صفائح الياف الكاربون البوليمرية.

1.INTRODUCTION

Fiber-reinforced polymer (FRP) composites, such as GFRP and CFRP, have emerged as more reliable materials for the construction of new concrete structures and rehabilitation of existing ageing infrastructure in the civil engineering field over the last two decades. FRP composites have provided long-term durability, sufficient resistance against crack growth, corrosion, shock, and fatigue loadings. FRP composites increased the energy absorption capacity of the structure [1, 2]. Also, the (FRP) composite bars have been used in construction as an alternative to traditional steel reinforcing bars (rebars) in concrete structures where high corrosion resistance, high tensile strength, and low weight are required [3]. Over time, FRP reinforcement became an acceptable material for many regulatory authorities and building agencies. Glass-FRP (GFRP) bars have been employed to build the deck slabs of several bridges, which remarkably led to the successful construction of over 200 bridge structures. Moreover, the use of GFRP bars has been extended to various concrete structures, such as tunnels, seawalls, water tanks, and parking garages [4-7]. Also, the majority of FRP-reinforced concrete (RC) structures were built near coastal regions in North America, Japan, and Europe [8-10]. Nowadays, rehabilitation and strengthening of the concrete structural elements are becoming very important in construction. The risk of structural deterioration due to uncertain seismic, excessive and impact loadings and increasing loading causes serious threats to the integrity and reliability of the concrete structures [11]. Due to the operation of structures in variable negative conditions, their operational reliability is reduced, and the bearing capacity is quickly lost [12-14]. According to general engineering experience, rehabilitation and strengthening of existing structures is economically more efficient than the reconstruction and construction of new buildings [15-17]. To repair, retrofit, and strengthen the slight and severe damages, various research efforts have been made, such as concrete, steel, GFRP, and CFRP jacketing, to restore the capacity and ductility of the damaged RC columns [11, 18-21]. Among these, CFRP jacketing is the most famous method of repairing and confining concrete columns. Also, it is required to maintain the actual size of the structural member in the rehabilitation process. CFRP laminate installation around the vertical structure provides an effective strengthening or rehabilitation because they are very thin [22]. Different studies have been performed in repairing the damaged and strengthening concrete columns by employing CFRP sheets [21, 23-27]. Previous studies have been conducted on columns containing GFRP bars [8, 28-30] and the strength of these bars to corrosion and increased tensile stress compared to conventional steel rebars [14, 31-33]. Columns reinforced with fully GFRP bars or reinforced partially with GFRP bars were also studied under different loads (concentric or eccentric) to determine the effect of the eccentricity ratio on strength [34-36]. The high eccentricity (e/h) ratio reduced the strength of specimens containing GFRP bars, however, to a lesser extent than specimens containing conventional steel reinforcement [35, 37-40]. Also, experimental studies have been conducted on using CFRP in strengthening concrete columns [41-43]. These studies showed that CFRP confinement can significantly improve circular concrete columns' strength response and ductility [44-

46]. However, for square and rectangular section columns, the confinement efficiency is much less due to stress concentration at the corners than in circular columns [39, 47, 48]. Rounding the corners of square columns is one of the experimental techniques used to reduce the effect of stress concentration at the corners and improve strength and displacement [35, 49, 50]. Studies began on specimens containing different types of FRP bar reinforcements [27, 47, 51-55], then other studies on columns containing GFRP bars retrofitted with CFRP sheets [56-58]. Studies also demonstrated improved strength to failure and an increase in lateral displacement, especially for specimens subjected to eccentric loads [59-61]. However, "based on the author's knowledge", few studies were conducted on strengthening concrete columns with CFRP sheets partially reinforced with GFRP bars and subjected to concentric and eccentric loading. In the present study, twelve half-scale reinforcement square concrete columns were tested. These specimens were reinforced with 36%, 64%, and 100% of GFRP bars in addition to the control specimen of steel rebar. Then, they were strengthened with one layer of CFRP sheets and subjected to varied e/h ratios (0, 0.66, and 1). The objective of the present study is to investigate load-buckling behavior, as well as its deformation and interaction diagram.

2.EXPERIMENTAL PROGRAM

2.1.Concrete

The concrete strength was constant for all studied specimens in the present study. This assumption was adopted because the presented work was part of an experimental investigation focused on simulating real-world conditions and the inaccuracy in some work sites in selecting the appropriate concrete or achieving the basic requirements for standard concrete. A concrete mix has been designed, and the suitable proportions of the mix ingredients satisfy the required compressive strength of 25 MPa according to the ACI code [62]. The average concrete strength was determined at 7 days (19.86 MPa) and 28 days (29.72 MPa) based on testing three concrete cubes (150 mm × 150 mm × 150mm) according to BS EN 12390-1:2000 [63].

2.2.Reinforcements

2.2.1.Steel Bars

Two types of deformed reinforcing steel bars were used in the present study. Steel bars with a diameter of 10 mm, 8 mm, and 6 mm were used in longitudinal and corbel columns reinforced. Also, steel bar with a diameter of 8 mm was used as transverse ties for all columns. The tensile test results of the reinforcement steel bars are summarized in Table 1.

2.2.2.Glass Fiber Reinforcement Polymer Bars (GFRP bars)

Fibers commonly used in FRP bars are glass, carbon, aramid, and basalt. GFRP composites offer an economic balance between cost and specific strength properties that make them the favorite in most RC applications [64-66]. The GFRP rebar with diameters of 10mm, 8mm, and 6mm, as shown in Fig. 1, was used for longitudinal reinforcement. The properties of GFRP are summarized in Table 2.

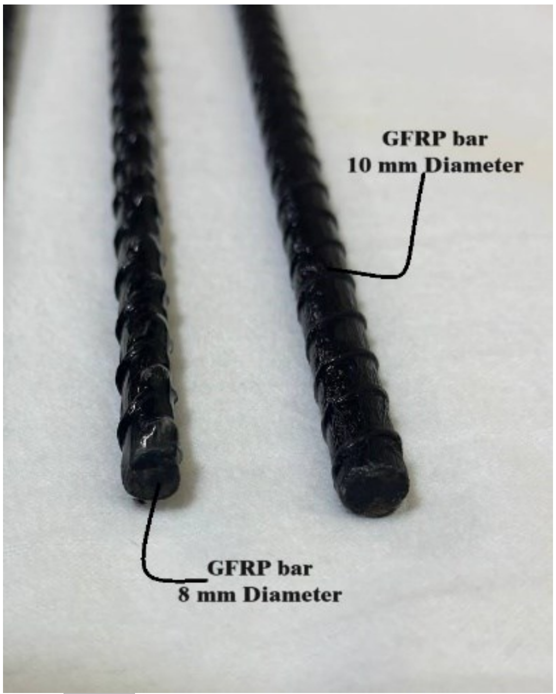


Fig. 1 GFRP Bars Used in the Study.

Table 1 The Tensile Test Results of the Reinforcement Steel Bars Used in the Present Study.

Diameter (mm)	Yield stress (*Fy*) (MPa)	Ultimate strength (*Fu*) (MPa)	Elongation (%)
6	524	602	9.0
8	541	631	9.0
10	629	708	9.2

Table 2 Properties of GFRP Bars Used in the Present Study According to the Manufacturer's Data.

NO.	Diameter (mm)	Initial Area (mm²)	Elongation (%)	Specific Gravity (gr/23 °C)	Tensile Strength @ Break (MPa)
1	6	28.26	2.1	2.094	1209
2	8	50.27	2.0	2.094	1215
3	10	78.53	2.4	2.093	1207

2.3.Carbon Fiber Reinforcement Polymer (CFRP) Sheets

Carbon fiber-reinforced polymer (CFRP) is a composite material commonly used in strengthening construction members. It is a favorite in most RC applications because of the economic balance between cost and specific strength properties [57, 67-69]. In the present study, one layer of CFRP sheets was used to fully strengthen R.C. columns, as shown in Fig. 2. The properties of these sheets, according to the manufacturer's data sheet, are shown in Table 3.

2.4.Tested Specimens

The 12 concrete columns were cast using wooden molds in two main groups: the first group was 4 molds for normal columns without corbel (CF-N), and the second group was 8 molds for columns with corbel (CF-C) shown in Fig. 3. The length of the molds was 1700 mm and the cross section dimensions of mold at the length of the ends was (150 mm × 150 mm) for normal columns without corbel and the cross section dimensions of mold at the length of the ends was (300 mm × 150 mm) for columns with corbel. A total of twelve medium-scale columns were prepared and tested under compressive load in three main groups according to loadings (concentric or eccentric). Each group consisted of four reinforcements (steel only, steel and GFRP (hybrid), and GFRP only). For the axial compressive load, the square cross-section 150 mm × 150 mm was used, and for the Uniaxial compressive load, the rectangular cross-section 300 mm × 150 mm with two eccentricity ratios (e/h) (0.66, and 1) was used. The dimensions and reinforcements of specimens are shown in Figs. 4 and 5 and Table 4. All ingredients of the concrete mixture were prepared by electronic balance in the concrete factory according to the quantity in the ACI-Code mix design [62]. A central mixer with a capacity of 7 m^3 was used to mix concrete ingredients and transport them to the casting place. Also, all wooden molds were prepared and painted using oil, and the reinforcement of the column specimens was placed in molds. The casting began by placing the concrete in molds, and the mechanical vibrator was used to compact the concrete specimens. Also, the upper surface of all the column specimens was smoothly finished after the casting was completed by the hand steel trowel. All specimens were de-molded after 24 hours from casting and then cured by water, as shown in Fig. 6. Then, the RC column specimens were painted white to have a clear vision of the crack initiation and propagation during the test.

Table 3 Properties of CFRP Sheets Used in Strengthening R.C. Columns According to the Manufacturer's Data.

No.	Pro-fiber CW450	
1	Fiber area weight	450 g/m^2
2	Design thickness	0.255 mm
3	Tensile strength	4800 MPa
4	Tensile E-Modulus	230 GPa
5	Elongation at break	2.1%
6	Fabric length	50 m
7	Fabric width	0.5 m

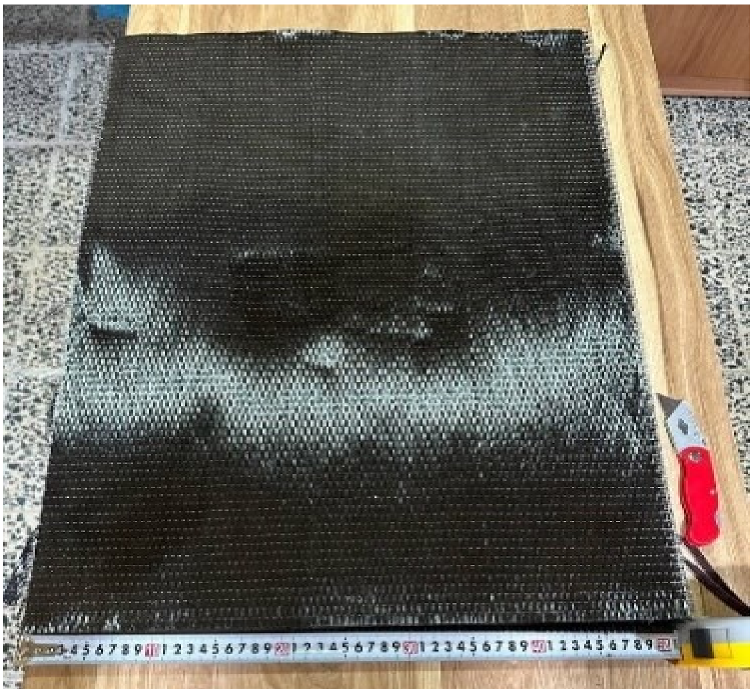


Fig. 2 CFRP Sheets Used in Strengthening R.C. Column.

(a) [CF -N] Columns specimens (b) [CF -C] Columns specimens

Fig. 3 The Wooden Molds and Reinforcement of Concrete Columns Used in the Present Study.

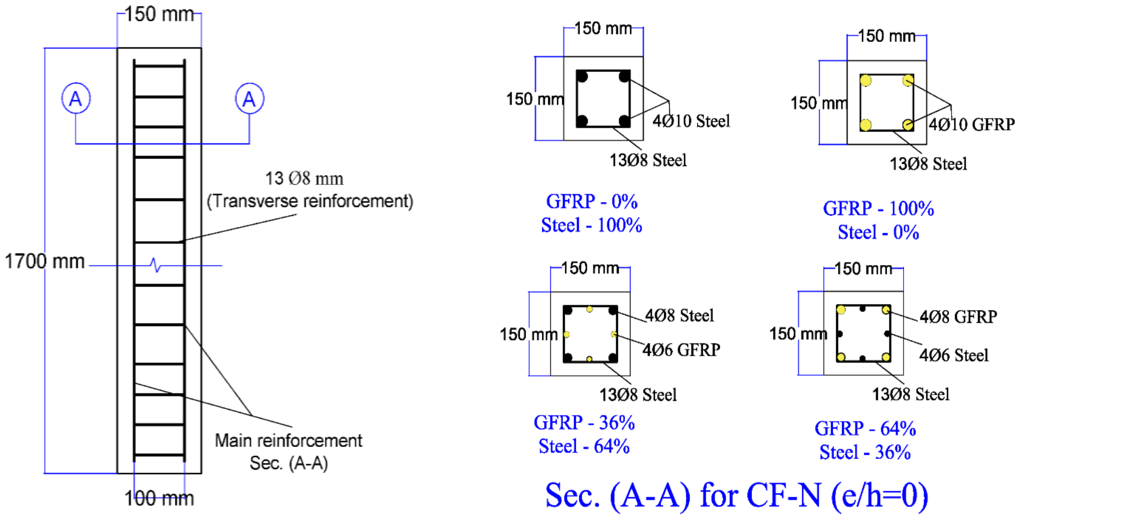


Fig. 4 Dimension and Reinforcement Details (Sec A-A) of R.C. Columns [CF-N] Used in the Present Study.

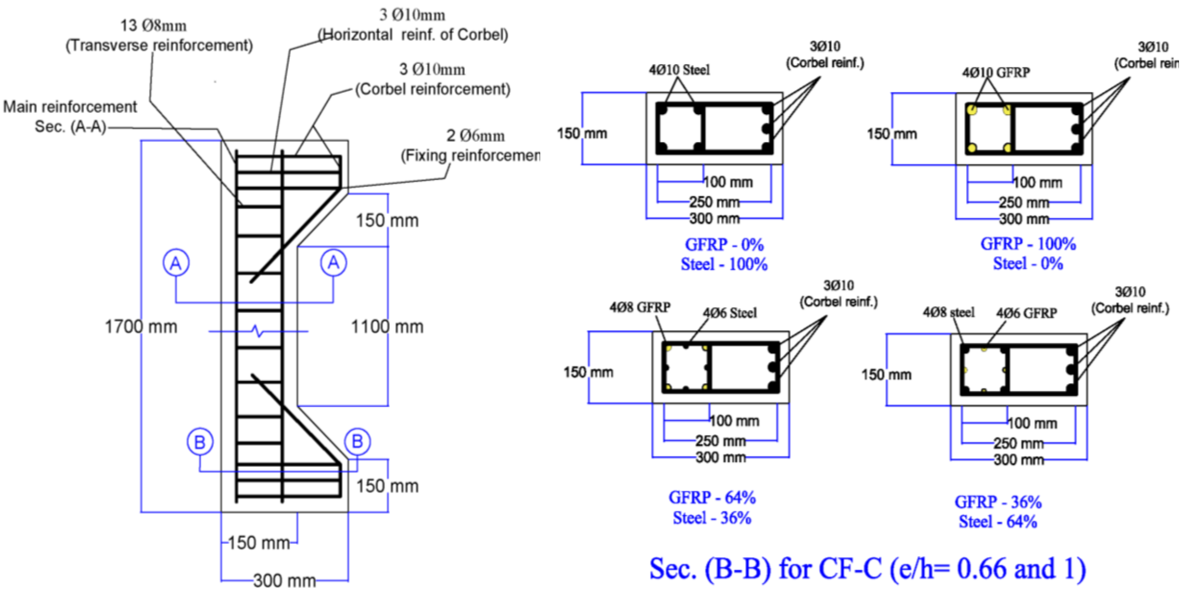


Fig. 5 Dimension and Reinforcement Details (Sec B-B) of R.C. Columns [CF-C] Used in the Present Study.

Table 4 Reinforcement Details, Ratios, Eccentricity, and Details of the R.C. Columns [CF-N] and [CF-C] Used in the Present Study

No.	Name	Corbel	Reinforcement Percentage of GFRP %	Reinforcement Percentage of steel %	Eccentricity value (e) mm	Eccentricity ratio(e/h)	Longitudinal reinforcement
1	CF-N	no	0	100	0 mm	0	4Ø10 steel
		no	100	0	0 mm	0	4Ø10 GFRP
		no	36	64	0 mm	0	4Ø8 steel & 4Ø6 GFRP
		no	64	36	0 mm	0	4Ø6 steel & 4Ø8 GFRP
2	CF-C	yes	0	100	100 mm	0.66	4Ø10 steel
		yes	100	0	100 mm	0.66	4Ø10 GFRP
		yes	36	64	100 mm	0.66	4Ø8 steel & 4Ø6 GFRP
		yes	64	36	100 mm	0.66	4Ø6 steel & 4Ø8 GFRP
3	CF-C	yes	0	100	150 mm	1	4Ø10 steel
		yes	100	0	150 mm	1	4Ø10 GFRP
		yes	36	64	150 mm	1	4Ø8 steel & 4Ø6 GFRP
		yes	64	36	150 mm	1	4Ø6 steel & 4Ø8 GFRP

(a) (b)

Fig. 6 R.C. Columns Specimens (a) After Casting, (b) After De-Molded.

2.5.Strengthening of R.C. Columns Specimens by CFRP Sheets

Strengthening R.C. columns by (CFRP) involves several steps to ensure proper adhesion. The most prominent steps and details necessary to apply and strengthen the columns by CFRP are detailed below: The surface is prepared by thoroughly cleaning the surface of the concrete columns to remove any dirt, dust, grease, or loose particles. Mechanical methods are used to achieve a roughened surface profile, promoting better CFRP material adhesion. After applying primer (primer base and hardener mixed well, according to the datasheet from the supplier), a suitable primer was applied to the prepared concrete surface using rollers at a rate of 0.25 to 0.30 kg/m² and allowed to cure for 24 hours. The primer enhances the bond between the concrete and the CFRP material, ensuring the effective transfer of loads. Then, CFRP Sheets were cut to the required dimensions based on the design specifications. Appropriate tools, such as a utility knife, were used to shape the CFRP sheets to fit the contours of the concrete columns. After the adhesive application, a high-strength epoxy adhesive was applied to the prepared concrete surface, mixed well with the base and hardener, using a roller at the rate of 0.275 kg/m² to ensure uniform coverage of the adhesive layer, especially in areas where the CFRP sheets could be bonded. Then, the CFRP sheets were placed carefully onto the adhesive-coated concrete surface, ensuring proper alignment and orientation according to the design requirements. Then, the CFRP sheets were pressed firmly onto the adhesive to remove any air pockets and achieve good contact. Then, the CFRP sheets were consolidated and cured using a roller to remove excess adhesive, ensuring intimate contact between the CFRP and concrete surface and allowing the adhesive to cure according to the manufacturer's recommendations, providing adequate time for full bond strength development. Fig. 7 shows the steps and details of applying and strengthening the columns' specimens using CFRP sheets.

(a) (b) (c)

(d) (e)

Fig. 7 Strengthening R.C. Columns Specimens [a] Preparation of the Surface and Rounded the Corner, [b] Application of Primer (Quickmast CW) and Epoxy Adhesive (Quickmast ER 350), [c] Placement of One Layer CFRP Sheets, [d] R.C. Column Specimens (CF-C) after Strengthening, [e] R.C. Column Specimens (CF-N) after Strengthening.

2.6.Test Setup and Instrumentations

All R.C. column specimens were tested using the universal testing machine available at the structural laboratory of the College of Engineering /University of Baghdad, as shown in Fig. 8. The R.C. columns specimens were tested vertically under compressive concentric and eccentric loading up to failure. The monolithic load was applied to the surface of the bottom end of the columns at a rate of 7 kN/sec, and it was measured using a hydraulic pressure gauge with a maximum capacity of 2000 kN. Many measurements and data were recorded and monitored: the ultimate failure load, the axial displacement at the bottom end of the column, and the lateral displacement at the tension side of the mid-height of the column. The present study considered three eccentricity ratios (e/h), i.e., 0, 0.66, and 1, to investigate the behavior of the RC columns under concentric and eccentric loads. To achieve the required eccentricity value, the dimensions and location of the bearing rod steel were selected such that the distance from the center lines of the plate and the column section was equal to the intended eccentricity, as shown in Fig. 9. Four electronic LVDTs were prepared to measure each column specimen's lateral and axial displacement until failure. Two LVDTs were placed at the middle height of the tension zone to measure the lateral displacement, and one LVDT was also placed at the mid-height but perpendicular to the others. Another LVDT was placed at the bottom end of the column to measure the axial displacement.

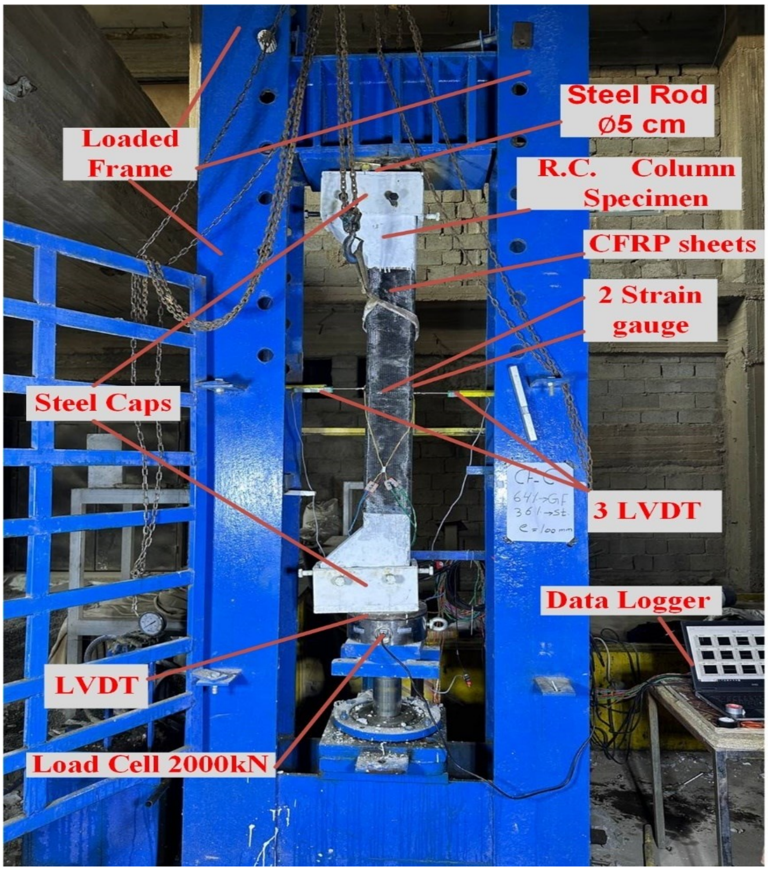
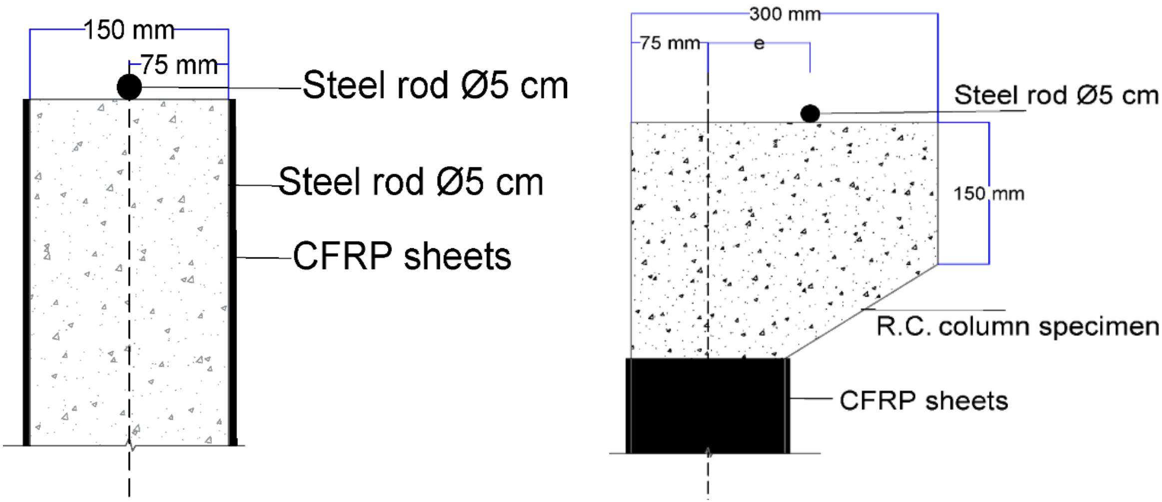


Fig. 8 Test Machine with All Details Used in the Experimental Test of the Present Study.



(a) e/h=0. **(b)** e/h=0.66 and =1.

Fig. 9 Location of the Bearing Rod Steel Used to Achieve the Required Eccentricity Ratio.

3.RESULTS AND DISCUSSION

3.1.Failure Mode

Figure 10(a) shows the modes of failure that occurred in the specimens. In the first group subjected to a compression loading (concentric) at (e/h=0), the failures that occurred in these specimens were concrete crushing failures in the first third of the height. The damage was observed in the regions near the places where the concentric load was applied, as well as ruptures in CFRP sheets and GFRP bars in the compression zone. The main reason for the rupture in the CFRP sheet is that the carbon fibers confine the specimen to the maximum strain and rupture. Moreover, the GFRP bars were completely damaged in the compression zone. This phenomenon proves that the confined concrete in the compression zone reached its maximum strain. In addition, the GFRP bars cannot resist the compressive stresses, as shown in Fig. 10 and Fig. 13. Figures 11 and 12 show the modes of failure that occurred in the specimens in the second and third groups. These groups were subjected to an eccentric load (e=100mm) (e/h=0.66) and (e=150mm) (e/h=1). The failure modes in these specimens occurred at the point where the end of the corbel intersects with the column. The failure initiation happened when the concrete next to the edge of the CFRP sheet confinement reached its ultimate compressive strength. Increasing the size of the damaged concrete due to crashing exposed the CFRP sheets to tensile force, consequently, ruptures the CFRP at its edge, as shown in Fig. 11 and Fig. 12. In the case of considering the rehabilitation columns of content FRP bars it was concluded that there is no available a practice method of rehabilitating these columns duo to completely crashing of the bars in the compression zone and rupture of the bars in the tension, based on available mode failure.

[a] ST 100% [b] GFRP 100% [c] ST 64% + GFRP 36% [d] ST 36% + GFRP 64%

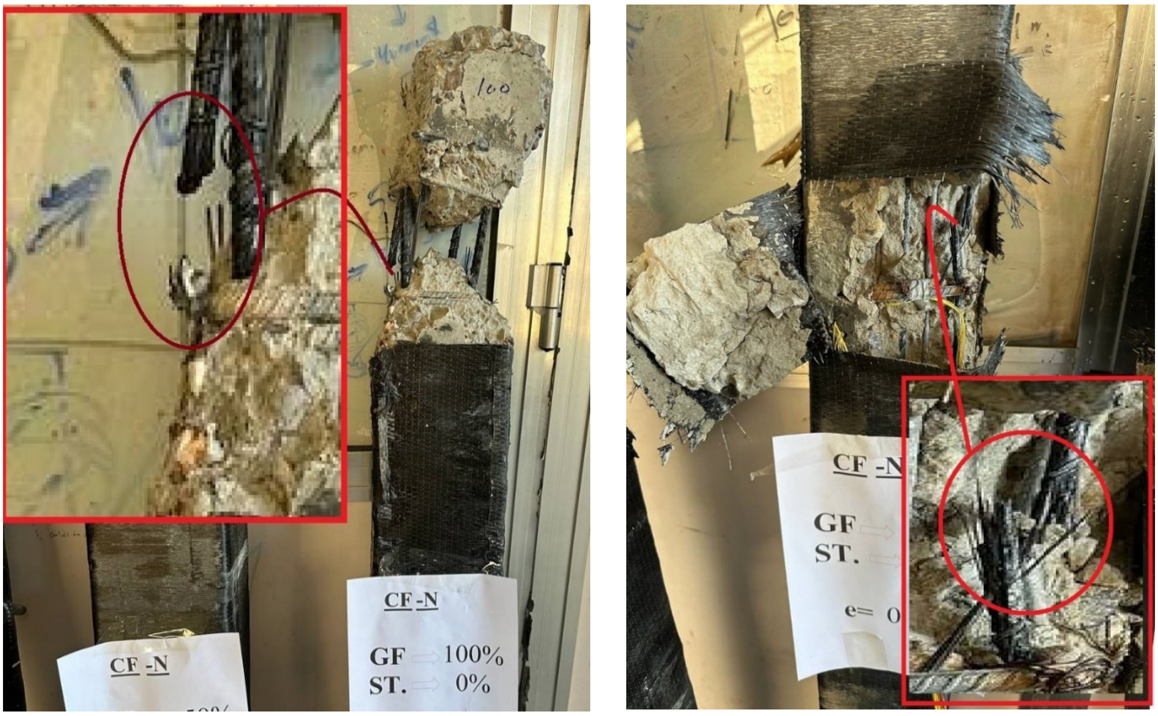
Fig. 10 Failure Modes for Strengthening R. C. Columns Specimens with Eccentricity Ratio e/h=0.

[a] ST 100% [b] GFRP 100% [c] ST 64% + GFRP 36% [d] ST 36% + GFRP 64%

Fig. 11 Failure Modes for Strengthening R. C. Columns Specimens with Eccentricity Ratio e/h=0.66.

[a] ST 100% [b] GFRP 100% [c] ST 64% + GFRP 36% [d] ST 36% + GFRP 64%

Fig. 12 Failure Modes for Strengthening R. C. Columns Specimens with Eccentricity Ratio e/h=1.



[a] Specimen CF–N (GFRP=100% + St=0%), e/h=0 [b] Specimen CF–N (GFRP=36% + St =64%), e/h=0

Fig. 13 Rupture and Cutting CFRP Sheets and GFRP Bars in the Compression Zone for Specimens with Eccentricity Ratio e/h=0.

3.2.Axial Load–Axial Displacement Relationship

Table 5 shows the failure axial load and maximum axial displacement at failure for all tested column specimens. Figure 14 presents the load—axial displacement relationships for all specimens. The strength responses of the column specimens in Fig. 14 to Fig. 17 show concentric loads (e/h = 0), (e/h = 0.66), and (e/h = 1). The failure load and axial displacement started dropping with an increase in the ratio of eccentricity. It was noticed that increasing the GFRP bars in the internal reinforcement decreased the ultimate load and increased deformation compared to the control specimen. This behavior is because the fact that the elastic modulus of elasticity of GFRP was lower than the elastic modulus of steel rebars by (3-4 times) and the inability of GFRP to resist the stresses in the compression zone during loading [7]. This behavior can be seen clearly from the curves in Fig. 18. The control specimens began linearly in the initial loading. Then, they started the plasticity at the second stage to failure, which is, in contrast to specimens containing partial reinforcement with GFRP, if the behaviors are close to linear. The ultimate vertical displacement value for strengthening columns at (e/h = 0.66) (e/h = 1) decreased by (67.7%) and (92.6%) compared to the control specimen in the same reinforcement in axial load with (e=0) (St 100% / CF-N). It was decreased by (41.8%) and (64.4%) compared to e=0 (GFRP 100% / CF-N). It was decreased by (61.7%) and (89.6%) compared to (e=0) (St 64% + GFRP 36%/ CF-N), and it was decreased by (55.2%) and (84.3%) compared to (e=0) (St 36% + GFRP 64% / CF-N). Through the results, the average axial bearing capacity of the columns in the groups where the GFRP bars were used as a partial or complete replacement in the main reinforcement decreased with increasing the amount of the GFRP bars. However, the percentage of dropping the average axial bearing capacity for columns with GFRP bars tested under eccentric load decreased with increasing the amount of GFRP bars. Based on the measured axial strain obtained from the strain gauge mounted on the GFRP bars, it was concluded that all GFRP bars were damaged under compression when the axial strain reached (0.0024). The designer must be conservative when using GFRP bars as a main reinforcement in the R.C. columns. The average axial strain for all specimens under concentric load was observed to be between (0.003-0-0035). It was expected that the CFRP sheet in the region where the rupture occurred would exceed its ultimate tensile strain. This behavior indicates that the failure of the columns occurred in concrete before the reinforcement reached ultimate strain.

Table 5 Experimental Results: Values Recorded During the Tests for Columns Specimen Strengthening by CFRP.

No.	Name	Reinforcement Percentage of GFRP %	Reinforcement Percentage of steel %	Eccentricity value (e) mm	Eccentricity ratio (e/h)	Max. load Failure [kN]	Moment at load failure [kN.m]	Max. axial displacement [mm]
1	CF - N strengthen	0	100	0 mm	0	880	0	5.2
		100	0	0 mm	0	706	0	6.1
		36	64	0 mm	0	811	0	5.5
		64	36	0 mm	0	721	0	5.9
2	CF - C strengthen	0	100	100 mm	0.66	194	19.4	3.1
		100	0	100 mm	0.66	161	16.1	4.3
		36	64	100 mm	0.66	173	17.3	3.4
		64	36	100 mm	0.66	159	15.9	3.8
3	CF - C strengthen	0	100	150 mm	1	93	13.95	2.7
		100	0	150 mm	1	77	11.55	3.6
		36	64	150 mm	1	82	12.3	2.9
		64	36	150 mm	1	69	10.35	3.2

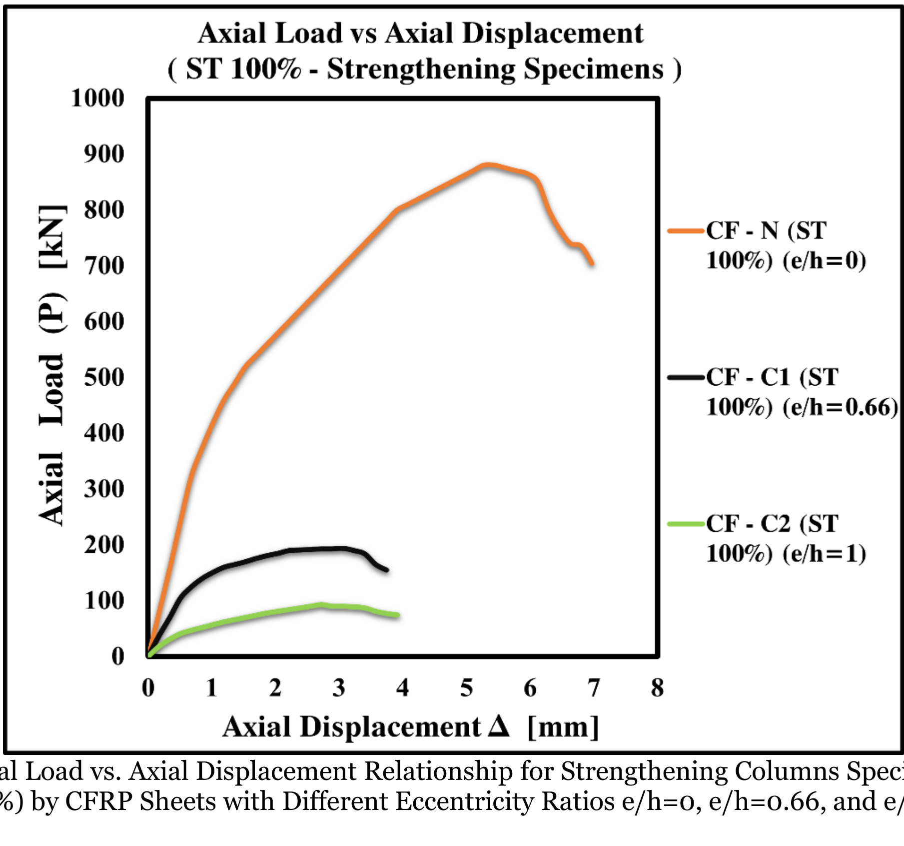


Fig. 14 Axial Load vs. Axial Displacement Relationship for Strengthening Columns Specimens (ST = 100%) by CFRP Sheets with Different Eccentricity Ratios e/h=0, e/h=0.66, and e/h=1.

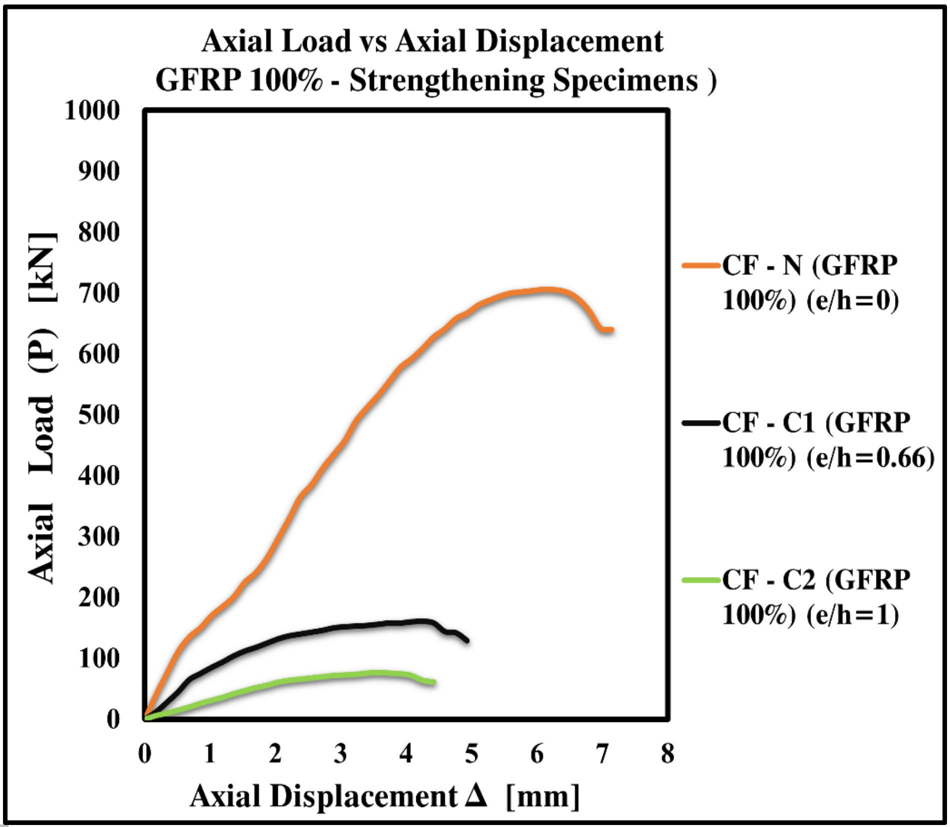


Fig. 15 Axial Load vs. Axial Displacement Relationship for Strengthening Columns Specimens (GFRP= 100%) by CFRP Sheets with Different Eccentricity Ratios e/h=0, e/h=0.66, and e/h=1.

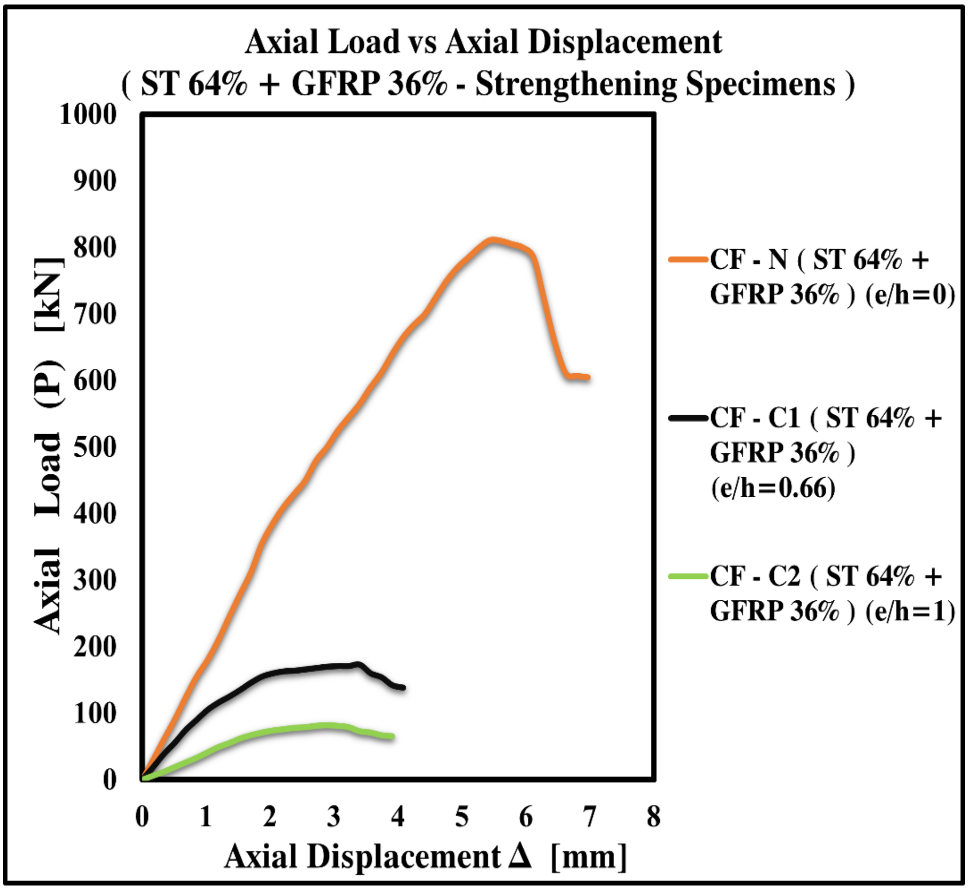


Fig. 16 Axial Load vs. Axial Displacement Relationship for Strengthening Columns Specimens (ST 64% + GFRP 36%) by CFRP Sheets with Different Eccentricity Ratios e/h=0, e/h=0.66, and e/h=1.

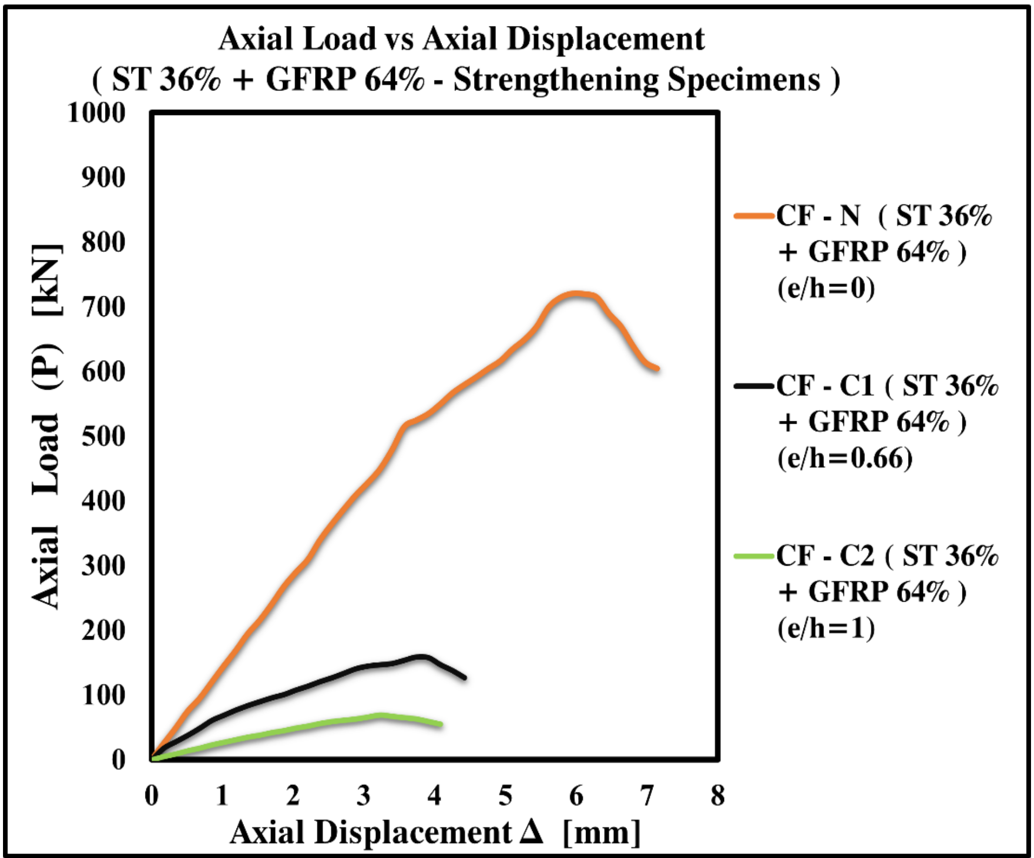


Fig. 17 Axial Load vs. Axial Displacement Relationship for Strengthening Columns Specimens (ST 36% + GFRP 64%) by CFRP Sheets with Different Eccentricity Ratios e/h=0, e/h=0.66, and e/h=1.

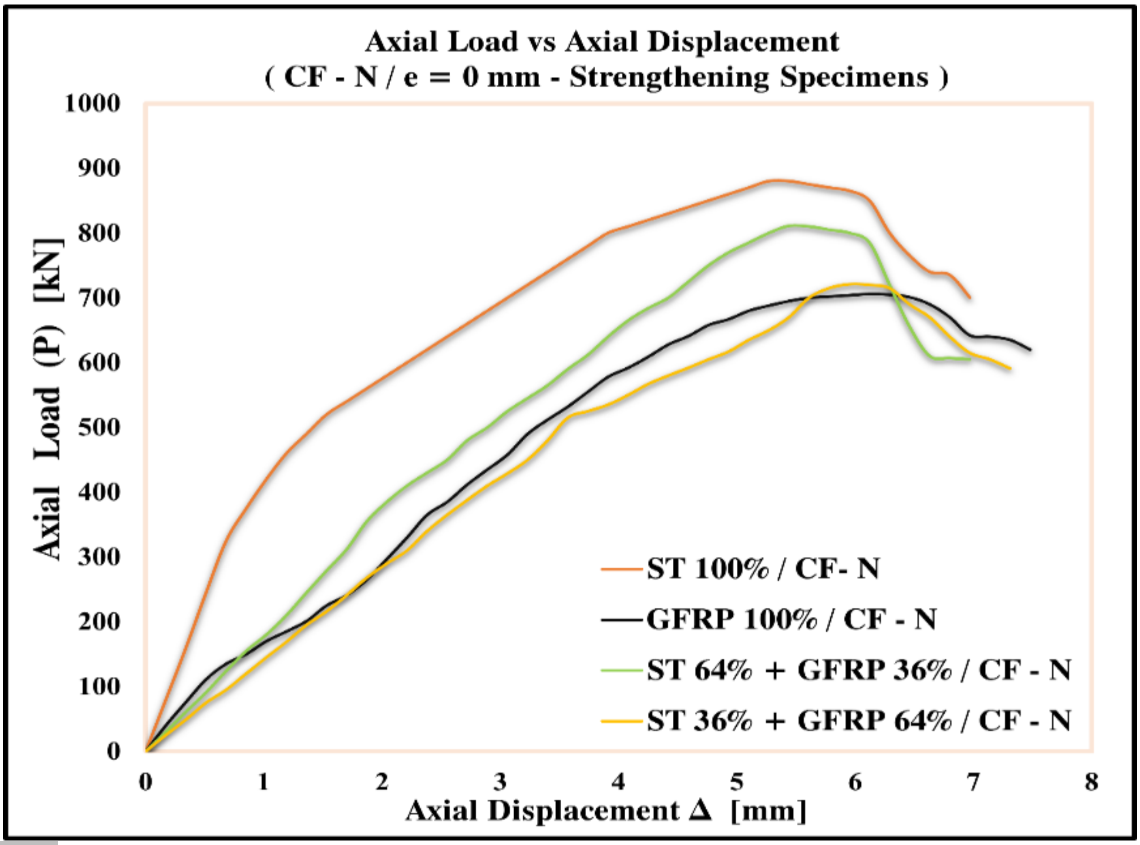


Fig. 18 Axial Load vs. Axial Displacement Relationship for Strengthening Columns Specimens (CF-N) by CFRP Sheets with e/h=0.

3.3.Interaction Diagram Behavior

Figure 19 shows the theoretical interaction diagram calculated according to (ACI 440.2R) [70] for columns strengthened by CFRP sheets. These calculations are based on the theoretical interaction diagram for control columns without strengthening [73, 74]. Specimens containing full GFRP were calculated according to [75, 76], while specimens that contained hybrid reinforcement (steel and GFRP) were calculated according to [71, 72]. From Fig. 19, when the GFRP ratio increased, the ultimate axial load and bending moment decreased. However, when GFRP was fully used as a main reinforcement in the specimen, the moment improved compared to the partial replacement. It was concluded that the existing steel and GFRP bars simultaneously affected the distribution of the stresses in the main reinforcement. Therefore, based on the observations, alternatives like GFRP bars were recommended as a full replacement without partial reinforcement. The reduction in the values of the load axial as the replacement ratios increase was because the tensile strength of GFRP bars is higher than the tensile strength of steel rebars; however, the modulus of elasticity was lower. Its strength to compressive stresses was small or could be neglected in the compression zone.

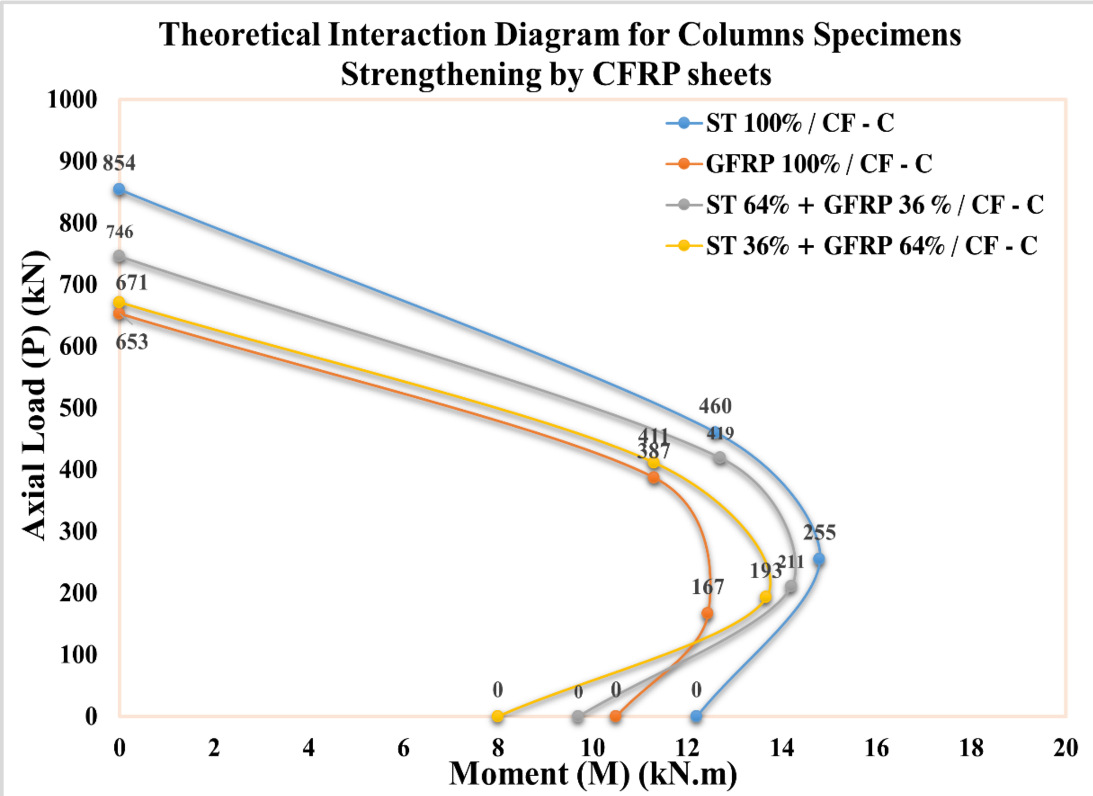


Fig. 19 Theoretical Interaction Diagram for Columns Specimens Strengthening by CFRP Sheets [70].

Table 5 shows the experimental axial load results of column specimens strengthened by CFRP sheets. Moreover, Fig. 20 to Fig. 23 show CFRP's theoretical interaction diagram for column strengthening and columns without strengthening. In addition, the experimental results of column strengthening by CFRP for different eccentricities (e/h = 0), (e/h = 0.66), and (e/h = 1) were plotted for comparison. According to the theoretical results, Fig. 20, the axial load capacity for strengthening the control specimen improved by (24.3%) compared to the control specimen without strengthening. Furthermore, all points fall outside the boundaries of the theoretical interaction diagram. CFRP's concentric load for column strengthening improved by (3%) from the theoretical concentric load. Figure 21 shows the theoretical results for the specimens fully reinforced with GFRP bars strengthened and un-strengthened by CFRP sheets. It is clear that the axial capacity improved by (16.8%). Moreover, the values of the experimental results showed that all points fall outside and on the boundaries of the theoretical interaction diagrams. The concentric load for column strengthening by CFRP improved by (8.11%) from the theoretical concentric load. In addition, Fig. 22 shows the theoretical results for the specimens partially reinforced with 36% GFRP bars strengthened and un-strengthened by CFRP sheets. It is clear that axial capacity improved by (16.1%). Moreover, the values of the experimental results showed that all points fall outside and on the boundaries of the theoretical interaction diagrams. The concentric load for column strengthening by CFRP improved by (8.7%) from the theoretical concentric load. Figure 23 also shows the theoretical results for the specimens partially reinforced with 64% GFRP bars strengthened and un-strengthened by CFRP sheets. It is clear that the axial capacity improved by (10.5%). Moreover, the values of the experimental results showed that all points fall outside and on the boundaries of the theoretical interaction diagrams. The concentric load for column strengthening by CFRP improved by (7.4%) from the theoretical concentric load. The experimental results for the strengthening specimens above are higher than the theoretical results, indicating that the theoretical design, according to ACI, is conservative. CFRP sheets improved the specimens' performance and increased the moments value. The failure loads for specimens with partial reinforcement were higher than the failure loads for specimens containing GFRP. Still, this ratio can be used when moments and high vertical displacement are desired.

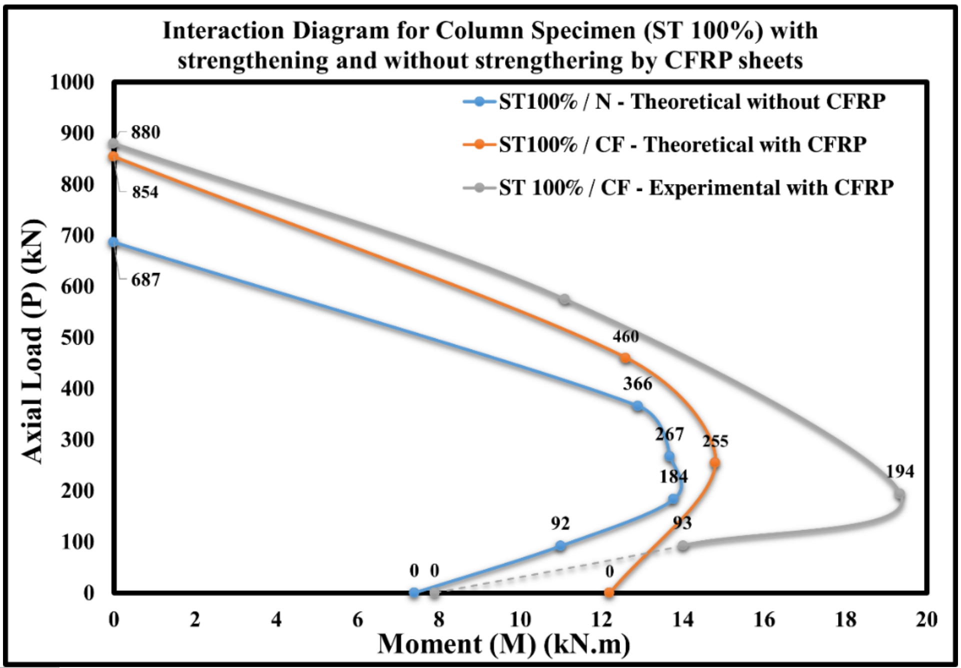


Fig. 20 Comparison between the Theoretical Interaction Diagram for Column ST 100% Strengthening by CFRP and Un-Strengthening and the Experimental Results of Column Strengthening.

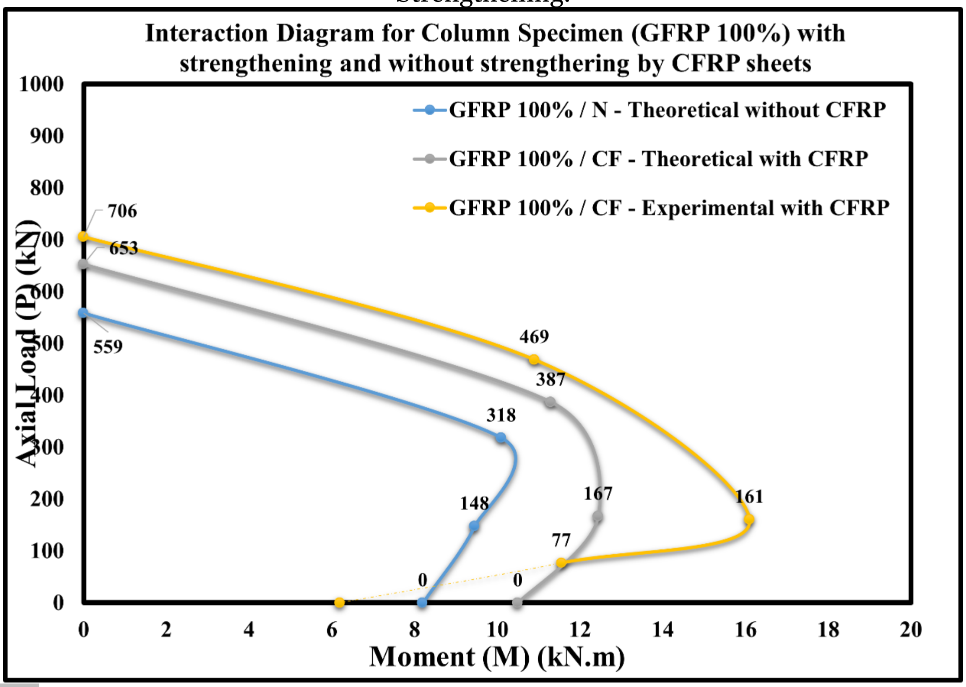


Fig. 21 Comparison between the Theoretical Interaction Diagram for Column GFRP 100% Strengthening by CFRP and Un-Strengthening and the Experimental Results of Column Strengthening.

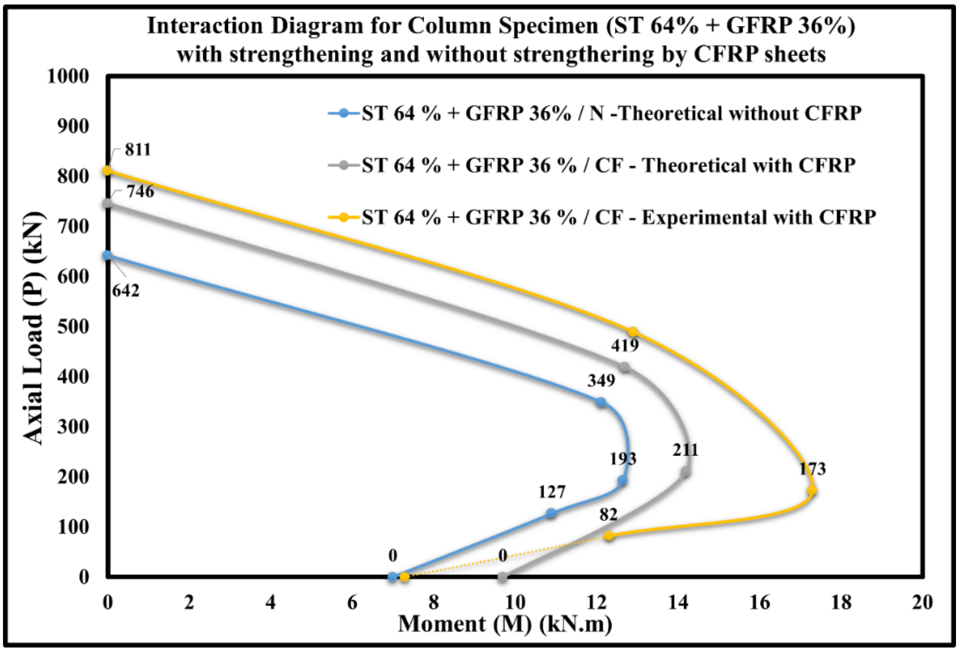


Fig. 22 Comparison between the Theoretical Interaction Diagram for Column ST64%+GFRP36% Strengthening by CFRP and Un-Strengthening and the Experimental Results of Column Strengthening.

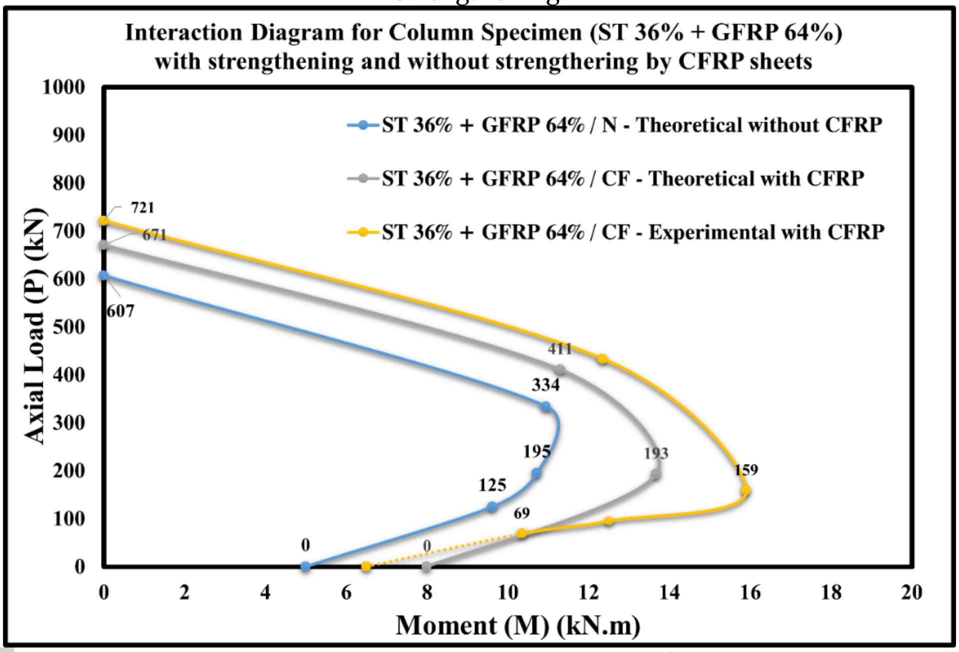


Fig. 23 Comparison between Theoretical Interaction Diagram for Column ST36%+GFRP64%-Strengthening by CFRP and Un-Strengthening, as Well as the Experimental Results of Column Strengthening.

4.CONCLUSIONS

The following conclusions can be drawn based on the test results reported in the present study:

- The failure of strengthened columns by CFRP sheets was dominated by a reinforcement bars failure in terms of gradual concrete cover spalling and rupture in CFRP sheets at the maximum load.
- The ultimate vertical displacement value for strengthening columns at (e/h = 0.66) (e/h = 1) decreased by (67.7%) and (92.6%) compared to the control specimen in the same reinforcement in axial load with (e/h=0) (St 100% / CF-N). It was decreased by (41.8%) and (64.4%) compared to (e/h=0) (GFRP 100% / CF-N). It was decreased by (61.7%) and (89.6%) compared to (e/h=0) (St 64% + GFRP 36%/ CF-N), and it was decreased by (55.2%) and (84.3%) compared to (e/h=0) (St 36% + GFRP 64% / CF-N).
- The experimental results for strengthening specimens with CFRP sheets are higher than the theoretical results. They improved by (3%) from the theoretical concentric load for the control

specimen, (8.11%) for fully GFRP bars reinforcement, (8.7%) for (ST 64% + GFRP 36%) reinforcement, and (7.4%) for (ST 36% + GFRP 64%) reinforcement. The CFRP sheets improved the specimens' performance and increased the moments value.

- The GFRP reinforcement concrete columns exhibited lower strength capacity than partially replaced GFRP bars and steel reinforcement concrete columns. This reduction in column capacity must be considered in the design.
- The consequences of using GFRP bars in the R.C. columns were more pronounced with e/h =0.66 and e/h =1 compared to the conventional reinforced R.C. column.
- When considering the rehabilitation of the columns containing FRP bars, it was concluded that no available practice method exists due to the complete crashing of the bars in the compression region and rupture of the bars in the tension region.

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