Behavior of composite columns repaired by CFRP and subjected to uniaxial and biaxial eccentric load

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ABSTRACT

This paper presents an experimental program to study the behavior of short high strength concrete composite columns subjected to either uniaxial or biaxial eccentric loading. The paper also includes a study on a suitable repairing technique for those columns by using carbon fiber reinforced polymers. The experimental program divided into two phases, the first consists of studying the behavior of six high strength reinforced concrete composite columns, three of them subjected to uniaxial eccentric loading as well as the other three subjected to biaxial eccentric loading, while the second phase deals with the behavior of five columns from the first phase after repairing them by carbon fiber reinforced polymers and subjecting them to the same eccentric loading. The main variables were the load direction, the number of sheets of carbon fiber reinforced polymers used and their arrangements. A comparison between the behavior of each column before and after repairing, using different numbers and arrangements of sheets of carbon fiber reinforced polymer layers was made. The comparison showed that wrapping composite steel columns with carbon fiber reinforced polymers is considered a very effective technique for repairing.

ARTICLE HISTORY

Received 23 February 2021; Revised 30 May 2021; Accepted 1 June 2021

KEYWORDS

RC columns; composite steel; repair; load eccentricity; CFRP; H.S.C

1. Introduction

A concrete composite column is a structural system that combines steel sections and reinforced concrete to give a structure with adequate carrying higher load capacity. Recently, high-strength concrete (H.S.C) composite columns were used in high-rise buildings due to their unique advantages compared to traditional normal strength concrete columns for higher load capacity. High strength concrete can be defined as concrete with a specified characteristic cube strength ranged between 60 and 100 N/mm², with a modulus of elasticity that is much higher than
that of normal strength concrete (N.S.C), but with less ductility. Fiber-reinforced polymers have also recently proved their effectiveness in repairing damaged buildings. FRP is a high-strength fiber embedded in the polymer resin matrix where fibers can be made from carbon, glass, or aramids, while the resin used can be epoxy, polyester thermosetting plastic, or vinyl ester. Recently, some papers studied the use of high-strength concrete composite columns to give extra advantages for the structural element. Despite that, few papers studied repairing of that new hybrid columns, while almost no paper has studied the use of fiber-reinforced polymers in that repairing technique. A study conducted by Jian C. Lim and Togay Ozbakkaloglu (2014) focused on determining the factors affecting the behavior of H.S.C and N.S.C. concrete column confined by FRP and subjected to axial compressive load. He conducted an extensive experimental database consisted of a total of 1063 axial compressive FRP confined concrete test results, 237 of them were on high-strength concrete, while the other 739 tests were on normal-strength concrete, with unconfined compressive strengths ranged from 6.2 to 169.7 MPa, which showed that unconfined concrete compressive strength is directly proportional to the confinement requirement, but it is inversely proportional to the confinement strength enhancement and FRP hoop rapture strain. In Xiaobin Song and Xianglin Gu conducted a numerical analysis to study the behavior of short square columns strengthened by FRP laminates and subjected to concentric and eccentric loading. Compression load capacity enhancement is directly proportional to the number of FRP layers used, while it is inversely proportional to the load eccentricity value.

Also, in 2013, Bai Y. 2013 & J. F. Chen. and L. A. Bisby (2013) conducted an analytical study to investigate the different factors affecting FRP’s ultimate conditions. The FRP failure could be due to either rapture of FRP layers or de-bonding of FRP layers at the overlap zone. The main factors affecting FRP ultimate conditions were FRP material, concrete materials, adhesive agent material used in attaching the FRP, load position, and contributory factors. Recommendations to minimize the affecting factors such as appropriately gluing the FRP, overlapping the FRP layers with sufficient size, and wrapping the FRP with suitable procedures.

Saadatmanesh et al (1994), and Halim NHA, Alih SC, Vafaei M. (2018) conducted an analytic model to estimate the strain and ductility improvement gained for circular concrete columns after wrapped by different types of FRP and the effect of different test parameters in that improvement. The key variables in that analytical study were the compressive strength of used concrete, types, and arrangement of FRP used. The author concluded that; enhancement in column load capacity, ductility and moment capacity gained
by wrapping FRP are inversely proportional with concrete compressive strength, enhancement in column axial load capacity and column ductility gained by strengthening by FRP is more than the enhancement in column moment capacity, ductility of the columns is directly proportioned with FRP strap thickness, but inverse proportion with the FRP spacing, the author also concluded that CFRP has more considerable energy absorbing capacity than E-glass FRP, but with lower elongation at failure.

Neale et al. (19971997), Comprehensive tests were conducted on a 300mm cross-section diameter column with a 1200mm clear height. The columns were axially loaded with varies load values, which lead to varies damage conditions. The author’s objective was to study the effectiveness of using FRP to repair several damaged reinforced concrete columns. A repairing technique was conducted to repair the damage columns by using carbon fiber wrapping sheets, and then the columns were reloaded under the same case of loading of the original colms. The study conclusion was that repairing reinforced concrete columns by using carbon fiber reinforced polymers is exceptionally effective in restoring column stiffness not only that but increasing its ductility also.

In (2011) Antonio De Luca, Fabio Nardone investigated the ability of FRP confinement to improve the behavior of different columns shapes and the effect of using different kinds of GFRP in column performance, and the ductility enhancement achieved using different types of FRP and the confinement effect of the new hybrid FRP sheets, Wael M. Hassan, Osama A. Hodhod, Mohamed Sameh Hilal, Heba H. Bahnsawy (2004), El-Afandy et al. (2002) conducted studies to estimate the behavior of H.S.C columns strengthened by different numbers and arrangements of GFRP layers and subjected to small biaxial eccentric loading, and compared that behavior with those obtained from strengthening N.S.C. Test variables was compressive strength of the used concrete, number, arrangement, and types of FRP layers used. Azadeh Parvin and Wei Wang. studied the behavior of eccentric loaded concrete columns strengthened by FRP jackets. Almost there is no research studied the use of FRP laminates in repairing high strength concrete composite columns, to fill these gaps, intensive experimental research is carried out in this paper to determine the feasibility and effectiveness of a proposed polymer to rapidly repair high strength concrete composite columns subjected to uniaxial and biaxial eccentric loading Karim Salah Al-Adawy (2019). The objectives of this study are summarized at the following: to Investigate the difference in behavior between uniaxial and biaxial eccentric loaded H.S.C composite columns before and after repairing by carbon fiber reinforced polymers, to compare between the original and repaired columns to evaluate the enhancement gained in the structure performance from repairing by CFRP laminates, and to Investigate the optimum arrangement and number of CFRP layers to achieve the best performance with optimum cost.
Experimental Program

Two comprehensive experimental programs were conducted to achieve the targeted objectives. The first experimental specimens were divided into three identical uniaxial eccentric loaded H.S.C composite square columns and three identical biaxial eccentrically loaded columns. The columns were loaded with up to 90% of their failure load, while the second experimental program was consisted of retesting five columns from the first experimental program until failure under the same load conditions after repairing them by different numbers and arrangement of CFRP layers. Table 1 shows the summary for the experimental program before and after repair.

Table 1. Experimental program before and after repair.

| Experimental Program | Uniaxial Loading | Biaxial Loading |
|----------------------|------------------|-----------------|
| Column’s cross-section | 250 × 250 mm, clear height of 1650 mm with top and bottom uniaxial corbel heads either of 400 × 250 × 400 mm dimensions for uniaxial columns or 400 × 250 × 400 mm dimensions for biaxial column loaded up to 90% of its failure load |

| Repaired Columns Experimental Program | Uniaxial Loading | Biaxial Loading |
|--------------------------------------|------------------|-----------------|
| UN-02 Specimen with 1 full CFRP layer | UN-02-1 F |
| UN-03 Specimen with 1 full and 1 partial CFRP layer | UN-03-1 F + 1P |
| BI-02 Specimen with 1 full and 1 partial CFRP layer | BI-02-1 F + 1P |
| BI-03 Specimen with 2 full CFRP layers | |

Materials used

The concrete mix designed to achieve characteristic cube strengths of 85 MPa, the cement used was 500 kg/m³ ordinary Portland cement grade 52.5, the fine aggregate used was 600 Kg/m³ nature clean coarse siliceous sand, while the coarse aggregate used was 1150 kg/m³ crushed dolomite with a nominal aggregate size of 5 mm. The silica fume used was 60 kg/m³ ferroalloys by-product, while the super-plasticizer used was 10:16 kg/m³ synthetic polymers.
Reinforcement used were Broad Flange I-Beam No10 and Longitudinal Reinforcement bars as a longitudinal reinforcement diameter 16, 18 and 22 mm with yield strength 440; 460 N/mm², while plain stirrups diameter 8 mm with yield strength 350 N/mm², in columns and high tensile steel bars for corbel heads were used as transverse reinforcement.

Carbon fiber with uni-direction fabric (SikaWrap-230 C) used in the second columns experimental program, with adhesion agent to bond the CFRP laminates tensile strengthen 4000 N/mm² and tensile modulus of elasticity 230,000 N/mm² with the concrete surface “Sikadur-330”, tensile strengthen 30 N/mm² and tension modulus of elasticity 4,500 N/mm², while Concrete Surface Leveling Agent (Sikadur-30) tensile strengthen 15 to 20 N/mm² and tension modulus of elasticity 4,300 N/mm² with was used to fill the cracks and level the damaged concrete surface.

First experimental program

Figures 1 and 2 show the details of the specimen used to determine the behavior of uniaxial and biaxial eccentric-loaded column, respectively, it consists of a column with a square cross-section of 250 x 250 mm, with a clear height of 1650 mm with top and bottom uniaxial corbel heads either of 400 x 250 x 400 mm dimensions for uniaxial columns or 400 x 250 x 400 mm for biaxial columns. The main role of the top corbel head was to transfer the eccentric load to the column with an e/t ratio of 0.9. Two electric strain gauges produced by Kyowa Measuring Instrument Co. Ltd., Tokyo, Japan, of type “KFG-
10-120-C1-11” were attached to the steel, one at the tension side of the broad flange I-beam and the other at the compression side to measure the longitudinal tensile and compression steel strain at different load stages, while one electrical strain gauge was attached at mid-height of the columns tension and compression concrete surface sides, in addition to a mechanical strain gauge, consisted of seven datum discs were attached along with the column height at tension and compression concrete surface with 20 cm between them to measure the concrete strain. To measure the lateral deflection of concrete four linear variable displacement transducers (LVDTs) was used with 100 mm stroke length three of them were attached to the concrete surface at the tension side at a distance of 0.25%, 0.5%, and 0.75% of the clear column height, while one was attached to concrete surface at compression side at mid-uniaxial columns height, while eight (LVDTs) were used in biaxial columns, three of them were attached to the concrete surface at each tension side at a distance 0.25%, 0.5% and 0.75% of the clear column height, while one was attached to each concrete surface at compression side at the columns mid-height. Figures 3 and 4 show the interaction diagram for the uniaxial and biaxial columns, which were obtained to identify the point of 90% failure load for both columns. Columns were prepared and tested on an AMSLER compression testing machine of 500-ton maximum capacity. The reinforcement cages were fabricated externally as shown in Figure 5 concrete was mixed and poured inside the form, electrical rod vibrator was used to give sufficient vibration to avoid honeycomb in concrete, especially in corbel head due to heavy reinforcement as shown in Figure 6; then, specimens were carried and left in laboratory ready for the test, as shown in Figure 7.
Figure 3. Interaction diagram for uniaxial specimens.

Figure 4. Interaction diagram for biaxial specimens.

Figure 8 shows the experiment load location for uniaxial and biaxial columns, while Figure 9 shows the column on the loading machine. The machine starts
loading with a rate of loading equal to 0.1 ton/sec. Electric strain gages and LVDTs readings were taken automatically by the loading machine computer with every change in load value, while mechanical strain gages readings were taken manually for every 1-ton increase in load. The experiment was ended at a load of 60 tons for uniaxial specimens and 55 ton in biaxial specimens which represent 90% of the specimen’s failure load estimated.

**First experiment columns behavior**

**Behavior of uniaxial specimens**

Specimen ‘UN-01’ was accidentally tested until failure. An unexpected failure occurred at 14.85 m.ton uniaxial moment, while the estimated ultimate
moment of the column that was conducted from the interaction diagram was 15.3 m.ton. The failure moment achieved at 60-ton eccentric load that failure can be due to specimen verticality tolerance, which leads to additional unexpected secondary moment.

Table 2 shows specimens’ results. The first crack was at load 11, 10, and 10 tons for UN-01, UN-02, and UN-03, respectively, and located at column mid-height on the tension side. Then, cracks started to appear along with column height at the tension side starting from column mid-height to its top and bottom and concentrated at the middle third of the tension side of the column. At 60-ton load, brittle concrete compression failure occurred at the mid-height of the UN-01 column as shown in Figure 10. The applied load and the longitudinal tensile steel strain for the uniaxial specimen’s curve as given in Figure 11. The longitudinal tensile steel strain relation at failure load for UN-

**Figure 6.** Specimen after concrete casting.
01 was 6900µε, while the maximum longitudinal tensile steel strain at 60-ton load for UN-02 and UN-03 was 6500µε and 6700µε, respectively.

Yielding phenomena occurred at loads 43, 45 and 43 tons for specimens UN-01, UN-02 and UN-03, respectively. The applied load and the longitudinal compressive steel strain for uniaxial specimens are given in Figure 12. The longitudinal compressive steel strain relation at failure load for UN-01 was 2300µε, while the maximum longitudinal compressive steel strain at 60-ton load for UN-02 and UN-03 was 1640µε and 1600µε, respectively, which indicates that the compressive steel strain did not reach the yielding point at that stage for specimens UN-02 and UN-03.

The applied load and the longitudinal tensile concrete surface strain for uniaxial specimens are as given in Figure 13. The longitudinal tensile concrete surface strain relation at failure load for UN-01 was 5600µε, while the maximum longitudinal tensile steel strain at 60-ton load for UN-02 and UN-03 was 4300µε and 4490µε, respectively, which means that a lot of wide cracks occurred on the concrete tensile surface at that stage.
The applied load and the longitudinal compressive concrete surface strain for uniaxial specimens are as given in Figure 14. The longitudinal compressive concrete surface strain relation at failure load for UN-01 was 3600µε, while the maximum longitudinal tensile steel strain at 60-ton load for UN-02 and UN-03 was 2300µε and 2770µε, respectively, which is smaller than the allowable concrete strain.

The applied load and the maximum lateral deflection for uniaxial specimens are as given in Figure 15. UN-02 and UN-03 were 12 and 11.5 mm, respectively, which gives ΔL/H ratio of 1.36%, 0.73% and 0.7% for specimens UN-01, UN-02 and UN-03, respectively.

**Behavior of biaxial specimens**

Table 3 shows the specimen’s results. The first crack was at load 10, 10, and 13 tons for BI-01, BI-02 and BI-03, respectively, and located at column mid-height tension side. Then, cracks started to appear along with column height at the tension side starting from mid-height of the column to its top and bottom and concentrated at the middle third of the tension side of the column. Loading was stopped at load 55 ton, which represents almost 90% of the specimen’s failure load.

*Figure 8. Experiment loading position.*
The relation between the applied load and the longitudinal tensile steel strain for biaxial specimens is as given in Figure 16. The maximum longitudinal tensile steel strain at 55-ton load for BI-01, BI-02, and BI-03 was 6970µε, 6700µε and 6800µε, respectively, while yielding strain occurred at load 38, 40, and 43 tons for specimens BI-01, BI-02, and BI-03, respectively.

The relation between the applied load and the longitudinal compressive steel strain for biaxial specimens is given in Figure 17. The maximum longitudinal compressive steel strain at 55-ton load for BI-01, BI-02, and BI-03 were
1620µε, 1580µε and 1700µε, respectively, which indicates that the compressive steel strain did not reach the yielding point at that stage for biaxial specimens.

The relation between the applied load and the longitudinal tensile concrete surface strain for biaxial specimens is given in Figure 18. The maximum

**Figure 10.** Crack pattern for uniaxial specimens.

**Figure 11.** Load-longitudinal tensile steel strain for uniaxial specimens.
longitudinal tensile steel strain at 55-ton load for BI-01, BI-02 and BI-03 were 4450µε, 4370µε and 4870µε, respectively, which means that a lot of wide cracks occurred on the concrete tensile surface at that stage.

The relation between the applied load and the longitudinal compressive concrete surface strain for biaxial specimens is given in Figure 19. The maximum longitudinal tensile steel strain at 55-ton load for BI-01, BI-02 and BI-03 were 2510 µε, 2470 µε and 2740 µε, respectively.

The relation between the applied load and the lateral deflection for biaxial specimens is given in Figure 20. The maximum lateral deflection at 55-ton load for BI-01, BI-02, and BI-03 were 8, 8 and 7.5 mm, respectively, which gives $\Delta L/H$.
ratio of 0.48%, 0.48% and 0.45% for specimens BI-01, BI-02 and BI-03, respectively.

Second experimental program

Specimens ‘UN-02’ and ‘UN-03’ were repaired by CFRP and tested again under the same loading conditions as the original columns to determine the behavior of the repaired short H.S.C composite columns repaired by different arrangements of CFRP laminates and subjected to uniaxial eccentric loading,
Table 3. Test results for biaxial specimens.

| Properties                                | BI-01  | BI-02  | BI-03  |
|-------------------------------------------|--------|--------|--------|
| First Crack Load                          | 10 ton | 10 Ton | 13 Ton |
| Primary Moment Value                      | 12.4 m.ton | 12.4 m.ton | 12.4 m.ton |
| Secondary Moment Value                    | 0.42 m.ton | 0.42 m.ton | 0.42 m.ton |
| Tensile Steel Yielding Load               | 38 Ton | 40 Ton | 43 Ton |
| (63%)                                      | (67%)  | (66%)  |        |
| Longitudinal Tensile Steel Strain at 90 % Failure Load | 6970 µε | 6700 µε | 6800 µε |
| Longitudinal Compressive Steel Strain at 90% Failure Load | 1620 µε | 1580 µε | 1700 µε |
| Tensile Concrete Surface Strain at 90% Failure Load | 4450 µε | 4370 µε | 4870 µε |
| Compressive Concrete Surface Strain at 90% Failure Load | 0.251% | 0.247% | 0.274% |
| Maximum Column Deflection at 90% Failure Load | 8 mm | 8 mm | 7.5 mm |

Figure 16. Load-longitudinal tensile steel strain for biaxial specimens.

Figure 17. Load-Longitudinal Tensile Concrete Strain for biaxial.
while specimens ‘BI-01’, ‘BI-02’ and ‘BI-03’ were repaired by CFRP and tested again under the same loading conditions as the original columns to determine the behavior of the repaired short H.S.C composite columns repaired by different arrangements of CFRP laminates and subjected to biaxial eccentric loading. Table 3 shows the repaired column experimental program specimen’s details.

**Repairing technique**

The material used in that repairing scheme were CFRP, Sikadur-30, and sikadure-330. The wrapping of CFRP laminates is applied as recommended
by the (ECFRP 2004) and Sika company instructions. First of all, irregular lugs were removed and column corners were smoothed and rounded to a radius of 3 cm to avoid local CFRP fabric rupture due to stress concentration, and then dust was cleaned by a blower to ensure the effective bond between column surface and the adhesion agent. Cracks and any irregularities in the concrete surface were filled with epoxy paste (Sikadur-30), as shown in Figure 21. The fabric was attached to the column surface using epoxy resin adhesive material (Sikadur-330) and rolled by a special laminating roller to ensure that no air voids between the fabric and the concrete surface, as shown in Figure 22. In specimen ‘UN-03-1 F + 1P’ and ‘BI-03-1 F + 1P’ an additional strip of CFRP with width 20 cm was wrapped at column mid-height and 10 cm strips arranged throw column height with 10 cm space between every two strips as shown in Figure 23, while in specimen ‘BI-02-2 F’ additional full layer of CFRP was wrapped above the first layer. Finally, an external layer of epoxy resin (Sikadur-330) was applied onto the CFRP laminates to protect it during specimen handling and testing as shown in Figure 24. The measuring instruments used in the second experimental program can be summarized as follows: The same electric strain gauge used to measure tensile and compressive steel strains at the original columns experimental program was used in the repaired column experimental program, additional electric strain gauge used in each specimen to measure CFRP transverse strains at different load stages, as shown in Figure 25. The same LVDTs were used to measure the lateral deflection along with column height in the original columns used in repaired columns with the same arrangement for uniaxial and biaxial specimens.
Experiment specimens and test setup

Figures 26–29 present that the isometric of specimen UN-02-1 F, UN-03-1 F + 1P, BI-01-1 F, BI-02-1 F + 1P, and BI-03-2 F, respectively, while Figures 30–34 illustrate the real specimens after repairing. The test setup for the repaired columns was almost the same as the original columns with almost no changes in the test setup for the repaired columns was almost the same as in the original columns except that the experiment when the specimen failed.

Behavior of the repaired columns

Behavior of uniaxial repaired specimens
Table 4 shows specimen results. The maximum load capacity for specimen “UN-02-1 F” was 82ton, while for specimen “UN-03-1 F + 1P” was 86 ton, which shows that repairing columns by using CFRP laminates significantly enhances the ultimate load capacity of uniaxial eccentric loaded columns and that enhancement increases e by increasing the number of wrapped CFRP layers in which despite that the column was previously loaded by 90% of its failure load which leads to yielding of the tension steel, repairing the column
Figure 22. Attaching CFRP.

Figure 23. Partial CFRP strips.
by one full layer of CFRP increased the ultimate load capacity by 22.4% compared to the original column while repairing the column by one full layer in addition to one partial layer of CFRP increased the ultimate load capacity by 28.4% compared to the original column.

After reaching the failure load a loud sound due to the crushing of concrete under the CFRP layers was heard in both specimens followed by a sudden drop in load value with excessive strain and lateral deflection values, but no CFRP rapture was observed. The maximum bending moment capacity for specimen “UN-02-1 F” was 20.2 m.t, while for specimen “UN-03-1 F + 1P” was 21.2 m.t, which shows that repairing uniaxially loaded column by using CFRP laminates significantly enhances the total bending moment capacity of the column and that enhancements were increased by increasing number of wrapped CFRP layers in which repairing the column by one full layer of CFRP increased the total bending moment capacity by 27.2% compared to the original column while repairing the column by one full layer in
addition to one partial layer of CFRP increased the total bending moment capacity by 33.8% compared to the original column.

Figure 5 shows load-longitudinal tensile steel strain relation for specimens ‘UN-02-1 F’, ‘UN-03-1 F + 1P’ and the original column, it is clear from the graph that the slope of the three columns was almost similar at the first part of the graph, the effect of wrapping the specimen by CFRP appeared at the second part of the graph after tensile steel yielded which was at 50ton and 53 ton load, respectively.

The graph also shows that repairing by CFRP decreased tensile steel strain increment, which leads to an increase in the yielding load of the tensile steel strain such that increases in the yielding load are in direct proportion with the number of wrapped CFRP layers. It is clear from the graph that adding a partial layer did not affect tensile steel strain as the graphs of specimens ‘UN-02-1 F’ and ‘UN-03-1 F + 1P’ were almost the same. Figures 35 and 36 illustrates load-longitudinal compressive steel strain relation for specimens ‘UN-02-1 F’, ‘UN-03-1 F + 1P’ and the original column, it is clear from the graph that the slope of the three columns was almost similar at the first part of the graph, the effect of wrapping the specimen by CFRP appeared at the second
part of the graph after tensile steel yielded which was at 68 ton and 1 ton load, respectively.

The graph proves that the repaired column compressive strain exceeds the yielding point. Compressive steel strain for specimens 'UN-02-1 F' and 'UN-03-1 F + 1P' reached 0.42% and 0.44%, respectively, which means that strain enhancement reached values of 156% and 175%, respectively, compared to compressive steel strain for the original column at 90% of its failure load that significant enhancement reflects the high strength and ductility the columns gained after wrapping by CFRP. Figure 37 shows load-CFRP transverse strain relation for specimens “UN-02-1 F” and “UN-03-1 F + 1P”. As shown in the graph, the behavior of the CFRP was non-linear, the load-CFRP transverse

![Figure 26. UN-02-1 F.](image-url)
strain was with small slope until about 69% of the failure load, in that stage, the column was capable of carrying the load, and the tensile steel was just entered the plastic region after that CFRP transverse strain slope increased until reached 0.43% and 0.46%, respectively. Figure 38 shows load-lateral deflection relation for specimens “UN-02-1 F”, “UN-03-1 F + 1P” and the original column; it is clear from the graph how wrapping the columns by CFRP enhances column ductility.

Repairing the column by one full layer of CFRP increased the maximum lateral deflection of the column by 75% compared to those of the original column, while repairing the column by one full layer in addition to one partial
layer of CFRP increased the maximum lateral deflection of the column by 85% compared to the original column.

**Behavior of biaxial repaired specimens**

During testing of the first repaired biaxial column, as the load reached the original specimen failure load (60 ton) premature failure of the upper corbel occurs, and the test stopped before repaired column failure. Figure 39 shows the corbel just before its failure, as shown in the photo vertical shear crack was the reason for failure. Grout was cast to repair the upper corbel; then, an external steel jacket was applied to confine the corbel and to resist splitting force. The objective was to design a temporary steel confining jacket that can be applied to the specimen under test and then can be removed when the test is finished, so we can use it in other specimens. The steel jacket consisted of 10 mm steel plates, high-strength steel bolts, and Akmon bolts. Figure 40
shows the steel jacket details, while Figure 41 shows specimens after repairing the corbel.

Table 5 shows specimen results. The maximum load capacity for specimen “BI-01-1 F”, “BI-02-1 F + 1P” and “BI-03-2 F” was 76.5-ton, 79 to, and 96 ton, respectively, which shows that repairing columns by using CFRP laminates significantly enhances the ultimate load capacity biaxial eccentric loaded column and that enhancement increased by increasing number of wrapped CFRP layers in which despite that the column was previously loaded by 90% of its ultimate load which led to yielding of the tension steel.

Repairing the column by one full layer of CFRP increased the ultimate load capacity by 28% compared to the original column, while repairing the column by one full layer in addition to one partial layer of CFRP increased the ultimate load capacity by 31.6% and repairing by two full layers increases the load capacity by 60%. The maximum moment capacity for specimen “BI-01-1 F”,

**Figure 29.** BI-02-1 F + 1P.
“BI-02-1 F + 1P” and “BI-03-2 F” was 18.74 m.t, 19.5 m.t, and 23.84 m.t., respectively, which shows that repairing biaxial eccentric loaded column by using CFRP laminates significantly enhances the total moment capacity of the column, and that enhancement increased by increasing number of wrapped CFRP layers.

The effect of adding a partial layer of CFRP can be seen in total moment capacity enhancement values; the partial layer increased the secondary moment capacity of the column, which increased the total moment capacity. Repairing the column with one full layer of CFRP increase the total moment capacity by 34% compared to the original column, while repairing the column by one full layer in addition to one partial layer of CFRP increases the total moment capacity by 52% and repairing by two full layers increase the load capacity by 70.9%.

As the longitudinal tensile steel strain of the repaired uniaxial specimens increases, the tensile steel strain of the repaired biaxial specimens reaches very high illogical values, so in that subsection, we will limit the tensile strain
to value 1% and will neglect any readings exceeded that. Figure 42 shows load-longitudinal tensile steel strain relation for specimens ‘BI-01-1 F’, ‘BI-02-1 F + 1P’, ‘BI-03-2 F’ and the original column, as in uniaxial specimens, the slopes of the original and repaired columns were almost similar at the first part of the graph, the effect of wrapping the specimen by CFRP appeared at the second part of the graph after tensile steel yielded which was at 45-ton, 45 ton and 53-ton load, respectively. The role of the partial layer was not observed also as in uniaxial specimens as it had minimal effect while adding an extra one full layer gave a great enhancement. The graph also shows that repairing by CFRP delays tensile steel strain increment, which leads to an increase in the yielding load of the tensile steel strain that increases in the yielding load is directly proportional to the number of wrapped CFRP layers. Figure 43 shows load-longitudinal compressive steel strain for specimens ‘BI-01-1 F’, ‘BI-02-1 F + 1P’,” BI-03-2 F” and the original column, as in tensile steel the slope of the repaired and original columns was almost similar in the first part of the graph, the effect of wrapping the specimen by CFRP appeared at
the second part of the graph. Repairing the column by using CFRP laminates allowed higher longitudinal compressive steel strain. The graph shows that the repaired columns’ compressive strain exceeds the yielding point. Compressive steel strain for specimens “BI-01-1 F”, “BI-02-1 F + 1P” and “BI-03-2 F” reached 0.4%, 0.42% and 0.5%, respectively, which mean that strain enhancement reached values of 150%, 163% and 213%, respectively, compared to compressive steel strain for the original column at 90% of its failure load, that big enhancement reflects the high strength and ductility the columns gained after wrapping by CFRP. Figure 44 shows load-CFRP transverse strain relation for specimens “BI-011 F”, “BI-021 F + 1P” and “BI-03-2 F”. As shown in the graph, the behavior of the CFRP was non-linear, the load-CFRP transverse strain was with small slope until about 65% of the failure load, in that stage, the column was capable of carrying the load and the tensile steel was just entered the plastic region after that CFRP transverse strain slope increased until reached 0.43% and 0.46%, respectively. Figure 45 shows load-lateral deflection relation for specimens “BI-01-1 F”, “BI-02-
1 F + 1P”, “BI-03-2 F” and the original column. It is clear from the graph how wrapping the columns by CFRP enhances column ductility. Repairing the column by one full layer of CFRP increased the maximum lateral deflection of the column by 150% compared to the original column, while repairing the column by one full layer in addition to one partial layer of CFRP increased the maximum lateral deflection of the column by 172% and 210% for two full layers compared to the original column, which means that adding one partial layer of CFRP increased the maximum lateral deflection of the column by only 22% while adding one additional full layer increased the maximum lateral deflection by 60%.

**Conclusions**

Based on the test results for the uniaxially and biaxially loaded column experimental program, it showed that the first cracks were almost the same
at load 10.3 and 11 ton, respectively, with the first crack location at mid-height of columns tension side.

The maximum tensile steel strain; compressive steel strain, tensile concrete surface strain, and compressive concrete surface strain in both uniaxial, and biaxial specimens were almost the same in uniaxial and biaxial columns; but the only difference was in the load values to which those maximum strains were reached. The maximum lateral deflection in uniaxial and biaxial columns was

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**Table 4.** Test results for uniaxial repaired specimens.

| Items                          | UN-02-1 F | UN-03-1 F + 1P |
|-------------------------------|-----------|----------------|
| Load Capacity                 | 82 ton    | 86 ton         |
| Moment Capacity               | 20.2 m.t  | 21.2 m.t      |
| Tensile Steel Yielding Point  | 50 ton    | 53 ton         |
| Compressive Steel Yielding Point | 68 ton | 71 ton         |
| Longitudinal Compressive Steel Strain at Failure | 0.42% | 0.44%          |
| Max. CFRP Transverse Strain   | 0.43%     | 0.46%          |
| Maximum Column Lateral Deflection | 21 mm | 21.4 mm        |
11.7 mm ($\Delta/H = 1/140$) and 7.8 mm ($\Delta/H = 1/210$), respectively, which means that lateral deflection in uniaxial was 53% higher than that in biaxial specimens.

It was evident that repairing columns by CFRP jackets is significantly efficient in restoring and enhancing short H.S.C composite columns stiffness and ductility either for uniaxial or biaxial eccentric loaded columns as summarized as follows:

**Figure 35.** Load-longitudinal tensile steel strain for uniaxial specimens.

**Figure 36.** Load-longitudinal compressive steel strain for uniaxial specimens.


**Uniaxial eccentric loaded repaired columns**

Repaired H.S.C composite columns by CFRP subjected to uniaxial eccentric loading showed:

(a) columns Stiffness was not affected by repairing the columns by CFRP laminates,

(b) compressive strain for original and repaired columns was similar.

(c) The load capacity of repaired columns is directly proportional to the amount of CFRP layers used as the load capacities were 22.4% and
28.4% higher for columns repaired by one full CFRP layer and one full in addition to one partial CFRP layer, respectively.

(d) The moment capacity was 27.2% and 33.8% higher for columns repaired by one full CFRP layer and one full in addition to one partial CFRP layer, respectively.

(e) Repairing columns by CFRP laminates increased columns maximum longitudinal tensile steel strain, as it reached up to 0.92% strain at 80% of repaired columns failure load which represent about 42% higher strain than the maximum longitudinal tensile steel strain of the original column but adding partial layer almost did not affect the maximum strain value reached.

(f) Columns maximum longitudinal compressive steel strain, reach up to 0.44% strain of repaired columns failure load, which represents about 177% higher strain than the maximum longitudinal compressive steel strain of the original column. However, adding the partial layer almost did not affect the maximum strain value reached.

Figure 39. Corbel shear crack.
Repaired mid-span lateral deflection by 75% and 85% for columns repaired by one full layer and one full in addition to one partial layer of CFRP, respectively, that big enhancement proves the efficiency of CFRP in decreasing the brittleness of H.S.C.

**Biaxial eccentric loaded repaired columns**

(a) As in uniaxial specimen’s columns, stiffness was not affected by repairing the columns by CFRP laminates,
(b) Compressive strains for original and repaired columns were similar.
(c) The load capacity of the repaired columns subjected to biaxial load was 28%, 31.6%, and 60% for columns repaired by one full CFRP layer, one full in addition to one partial CFRP layer, and two full layers of CFRP, respectively.
(d) The total moment capacity of the repaired columns was 34%, 52%, and 70.9% for columns repaired by one full CFRP layer, one full in...
addition to one partial CFRP layer, and two full layers of CFRP, respectively.

(e) Repaired columns’ maximum longitudinal tensile steel strain, increases as it reached up to 0.96% strain at 82% of repaired columns failure load, which represents about 41% higher strain than the maximum longitudinal tensile steel strain of the original column. Repaired columns maximum longitudinal compressive steel strain, reach up to

Figure 41. Specimen after corbel repair.

Table 5. Test results for biaxial repaired specimen.

| Items                              | BI-01-1 F | BI-02-1 F + 1P | BI-03-2 F |
|------------------------------------|-----------|---------------|-----------|
| Load Capacity                      | 76.5ton   | 79 ton        | 96 ton    |
| Moment Capacity                    | 18.74 m.t | 19.5 m.t      | 23.84 m.t|
| Tensile Steel Yielding Point       | 45 ton    | 45 ton        | 53 ton    |
| Compressive Steel Yielding Point   | 63 ton    | 66 ton        | 77 ton    |
| Longitudinal Compressive Steel Strain at Failure | 0.4%    | 0.42%         | 0.5%      |
| Max. CFRP Transverse Strain        | 0.51%     | 0.55%         | 0.65%     |
| Maximum Column Lateral Deflection  | 20 mm     | 21.74 mm      | 23.3 mm   |
0.5% strain at repaired columns failure load which represents about 215% higher strain than the maximum longitudinal compressive steel strain of the original column.

(f) Columns maximum mid-span lateral deflection in repaired columns by CFRP laminates increases by 150%, 172%, and 210% for columns repaired by one full layer, one full in addition to one partial layer of CFRP and two full layers, respectively, that huge enhancement proves the efficiency of CFRP in decreasing the brittleness of H.S.C.
Some recommendations for suitable number and arrangement of the CFRP layers used in repairing technique to give the desired outcome with the lowest cost.

**Recommendations**

Figure 44. Load-transverse CFRP strain for biaxial specimens.

Figure 45. Load-maximum lateral deflection for biaxial specimens.
**Repairing a uniaxial eccentric loaded short H.S.C composite columns by CFRP**

(1) For load capacity and moment capacity enhancement, it is recommended to use one full layer of CFRP which can improve the load and moment capacity by 22.4% and 28.4%, respectively, those values are slightly affected by adding a partial CFRP layer while repairing by two full layers of CFRP is estimated to improve the load and moment capacity by more than 50% which can be recommended if high load and moment capacity is needed.

(2) For ductility enhancement with optimum cost, it is recommended to use one full layer of CFRP. This is because the difference in steel strains and columns maximum deflection between using only one full layer and using one full layer plus one partial layer of CFRP is relatively small (5%) in comparison with FRP cost (25%).

**Repairing biaxial eccentric loaded short H.S.C composite columns by CFRP**

(1) For load capacity, it is recommended to use one full layer of CFRP if less than 30% enhancement needed while using two full layers of CFRP is recommended as it can enhance load capacity up to 60%. Using an additional partial layer of CFRP is not recommended.

(2) For moment capacity, the effect of adding a partial layer of CFRP can be significant. If up to 30% moment enhancement is needed, it is recommended to use one full layer of CFRP, while if from 30% to 50% enhancement is needed, adding a partial CFRP layer can be a suitable solution. In addition, if more than 50% enhancement is needed using two full CFRP layers is recommended as it can give moment enhancement up to 71%.

(3) For ductility, it is recommended to use two full layers of CFRP as it greatly increased steel strains and columns’ maximum deflection, although using one full layer also gave good enhancement with less cost.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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