

A Comparative Study on Behavior of RC Columns Strengthened by CFRP and Steel Jacket

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Abstract. This paper studies the behavior of axially loaded RC columns which are confined with carbon fiber reinforced polymers' sheet (CFRP) and steel jackets (SJ). The study is based on twelve axially loaded RC columns tested up to failure. It is divided into three schemes based on its strengthening type; each scheme has four columns. The main parameters in this study were the compressive strength of the concrete and steel reinforcement ratio. Furthermore, the results of the experimental test showed a substantial enhancement in the column's load-carrying capacity. When compared to the original columns, the CFRP sheet had a significant effect on improving the ductility of the column by increasing the axial deformation by about 59.2 to 95.7%. On the other hand, the SJ contributed mostly to the column load-carrying capacity, which increased the capacity of RC concrete from 75 to 107%; because of its composite action comparing with the CFRP sheet action in which unidirectional lateral confinement is provided. Both methods produced completely different failure modes. The columns strengthened with CFRP sheet failed by rupture occurring in the sheet fibers. The strengthened with SJ failed due to the buckling that occurred in the steel angles due to the direct contact with the head of the column, and crushing in the concrete has occurred.

Keywords: Strengthening; steel jacket; carbon fiber reinforced polymer; composite column.

Introduction

Columns are compression members and are the most important structural members. Their failure can lead to a total collapse of the building. Causes of deterioration could range from the use of poor quality construction materials, defective structural practices, or increased demand in the loading of structure, due to natural causes, such as earthquakes, tornados, or human causes, for example, road traffic accidents [1]. Most columns are designed with a rectangle or square cross-section for architectural requirements [2,3]. The use of composite materials for strengthening and rehabilitating deficient RC systems has increased worldwide in the past few years. The CFRP has been widely used in externally strengthening for different structural members such as beams, columns, and slabs [4]. This application gained popularity due to the lightweight, corrosion-resistant, and tensile strength of FRP materials which was used in the seventies in the space industry. The CFRP jacket provides the RC columns with passive confinement and is stressed only when an additional axial load is applied to a column that causes dilation. The degree of confinement and the overall strength enhancement of confined concrete is influenced by several factors: fiber modulus, fiber thickness, fiber rupture strain, column size, and column shape (circular, square, or rectangular) [5]. In addition to the FRP method, a steel jacket can improve the load-carrying capacity of the RC column. This is achieved by producing a lateral confinement system with four steel angels. Said angles are connected to the concrete using adhesive material with discontinuous strips welded transversely at a specific spacing.

The investigation of carbon fiber reinforced polymer was thoroughly examined by many researchers [6-9]. They studied the effect of corner roundness, the column height, the cross-section shape, the number of layers, and the method of wrapping (partially or complete) on the strength and ductility of the RC column. They found that the strength enhanced as the rounding of the corner radius increased until it reached the circular section and increased as the thickness of the CFRP increased. Moreover, the ultimate strength and ductility have decreased as the slenderness ratio (l column height/h long side of column section) increased. Others [10-13] investigate the effect of steel jackets on the behavior of RC columns with some parameters controlled such as the size of angels and battens,

the spacing between battens, the shape of steel section used. They concluded that the decrease in spacing between battens and increase in the size of vertical angle section enhanced the behavior of strengthened concrete column.

Experimental Test

Work Plan: Laboratory work is accomplished by casting 12 columns divided into four groups and three schemes, the groups divided according to two parameters; concrete compressive strength (24.2 and 31.7 MPa) and reinforcement steel ratio (1.4 and 2%). According to these parameters, there are three columns of different types of strengthening (without strengthening as a reference specimen, strengthening with CFRP, and strengthening with steel jacket).

Details of Tested Specimen: All the specimens were designed by a cross-section of (150 mm × 150 mm) with a height of 1000 mm. These dimensions were selected to satisfy the requirement of ACI 318-19 [14] to the slenderness ratio for the short column. Two different longitudinal steel reinforcements were used (4 ϕ 10 mm and 4 ϕ 12 mm) with a tie of (ϕ 8 mm) provided at 80 mm spacing at the column ends and 107 mm at the middle part of the column. The column is detailed as shown in Figure 1. The column specimens were concentrically loaded until failure using the compression machine shown in Figure 2. Table 1 shows the details of all tested column specimens through this study. one CFRP layer was applied by wrapping the column with an overlap of 120 mm. The application of the CFRP layer was such that the direction of carbon fibers is perpendicular to the column's longitudinal axis, as shown in Figure 1(b). The steel jacket was executed using four steel angle sections (L40×40×4) mm erected at the corners of the column specimen using the adhesive material: Nitomortar TC-2000 and steel battens of (40×4) mm spaced at 240 mm c/c in all column specimens.

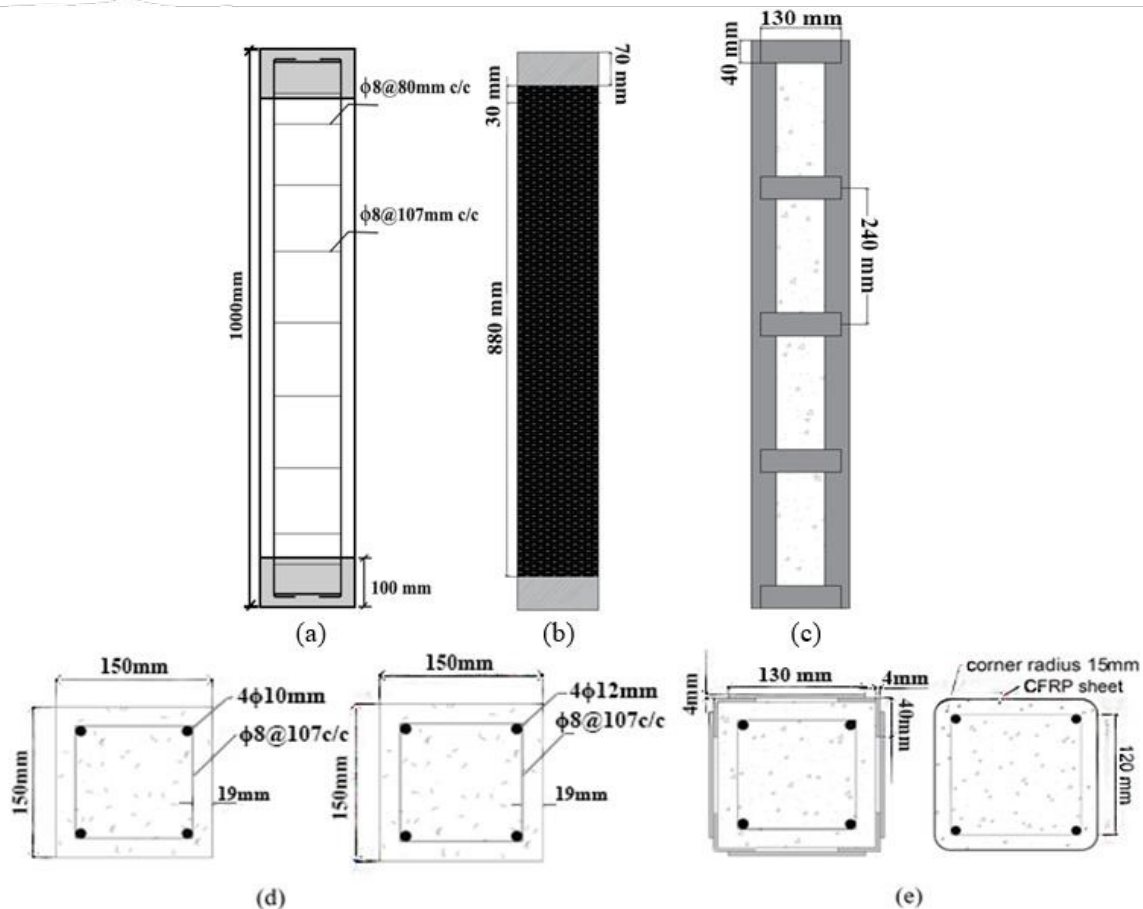


Figure 1. (a) Reference columns details, (b) Column strengthened with CFRP, (c) Column strengthened with SJ (d) Column sections (e) Details of strengthening techniques.

Table1. Details of all specimen tested.

Specimen	Type of strengthening	f'_c (MPa)	Longitudinal reinforcement	ρ_s
24CN1	Non	24.2	4 ϕ 10	1.4%
24CC1	CFRP	24.2	4 ϕ 10	1.4%
24CS1	SJ	24.2	4 ϕ 10	1.4%
32CN1	Non	31.7	4 ϕ 10	1.4%
32CC1	CFRP	31.7	4 ϕ 10	1.4%
32CS1	SJ	31.7	4 ϕ 10	1.4%
24CN2	Non	24.2	4 ϕ 12	2%
24CC2	CFRP	24.2	4 ϕ 12	2%
24CS2	SJ	24.2	4 ϕ 12	2%
32CN2	Non	31.7	4 ϕ 12	2%
32CC2	CFRP	31.7	4 ϕ 12	2%
32CS2	SJ	31.7	4 ϕ 12	2%

Material Properties: Ordinary Portland cement (OPC) Type I (trademark: Mass Group Holding) was used to cast all column specimens. The results of chemical and physical properties for a cement sample tested in the Building Research Center of the Ministry of Construction, Housing, Municipalities, and Public Works are shown in Table 2 and Table 3. The results show that the cement sample conforms with IQS NO.5 (1984) [15]. The gradient of the sand used in the concrete mixture was appropriate according to the specification IQS NO.45 (1980)[16]. The crushed gravel was used with a maximum size of 12.5 mm. The gradient of nominal aggregate was accepted according to IQS NO.45 (1980) [16].

Table 2. Chemical composition of the cement-based on Iraqi Standard No. (5) of 1984.

Chemical Formula	L.O.I	SO ₃	MgO	L.S.F	I.R
Results of Test	2.48	2.49	2.54	0.95	0.55
Limit of IQS No.5:1984	Max. 4	Max. 8	Max.5	0.66-1.02	Max.1.5

Table 3. Physical properties of cement-based on Iraqi Standard No. (5) of 1984.

Test	Result	Limits
Fineness cm ² /gm	3925	At least 2300
Setting Time	Initial	150 min.
	Final	4.30 hour
Compressive Strength	3 days	18
	7 days	27

The test results of sand and gravel are shown in Table 4 and Table 5. The superplasticizer (Flocrete W52) from the DCP company was used to reduce the water content and improve the workability.

Table 4. Properties of fine aggregate.

Characteristic	Value	IQS 45:1981
Specific Gravity	2.75	-----
SO ₃	0.11%	0.5%
Fineness modulus	2.5	-----

Table 5. Properties of coarse aggregate.

Type of aggregate	Total density (g/cm ³)	Bulk Specific Gravity	SO ₃ (%)
Crushed gravel	1.54	2.7	0.01

The properties of CFRP sheets shown in Table 6 were taken from the manufacturer’s technical datasheet (Nitowrap FRC– Fosroc). The physical properties, yield stress, ultimate strength, and elongation of reinforcing steel bars are shown in Table 7.

Table 6. Properties of CFRP sheets (Nitowrap FRC – Fosroc).

Grade	FRC300
Fiber area weight (g/m ²)	300
Design thickness (mm)	0.167
Ultimate elongation	1.5%
Fiber density	1.8 g/cm ³
Tensile strength (kgf/cm ²)	3480
Tensile E-modulus (kgf/cm ²)	2.30×10 ⁵

Table 7. Physical properties of reinforcing steel bars.

Nominal bar diameter (mm)	Yield strength (N/mm ²)	Ultimate strength (N/mm ²)	Elongation %
φ8	345.3	499.6	16.5
φ10	616.6	681.0	10.0
φ12	629.2	701.2	10.6

Finally, the physical properties of steel angles and battens are shown in Table 8. (ACI 211.1-91) [17] was adopted to calculate the proportions of concrete components for two normal strength concrete (NSC) mixes. The proportions of the concrete mixture are shown in Table 9.

Table 8. Physical properties of steel shapes.

Shape	Yield strength (N/mm ²)	Ultimate strength (N/mm ²)	Elongation (%)
Steel angle (L40×40×4 mm)	441	510	25.5
Steel battens (40×4 mm)	337	491	24.3

Table 9. Mixture proportions.

Mix component (m ³)	Quantity for $f'_c = 31.7$ MPa	Quantity for $f'_c = 24.2$ MPa
Cement (kg)	400	278
Water (liter)	160	158
Gravel (kg)	893	893
Sand (kg)	967	1095
FW52 (liter)	5.7	3.5

Test Set-up and Procedure: The test set-up is illustrated in Figure 3. The hydraulic compression machine used to test column specimens shown in Figure 2 was available at the structural laboratory at the College of Engineering at UOB. The load is applied by increasing the hydraulic press pressure incrementally with an equal load increment of 45.216 KN till failure. The lateral and axial displacement of the columns were recorded by used dial gauges of Accuracy (0.01 mm). Two lateral dial gauges were located at the mid-height of the tested specimens, while the axial dial gauge was located on the top face of the lower plate of the compression machine.

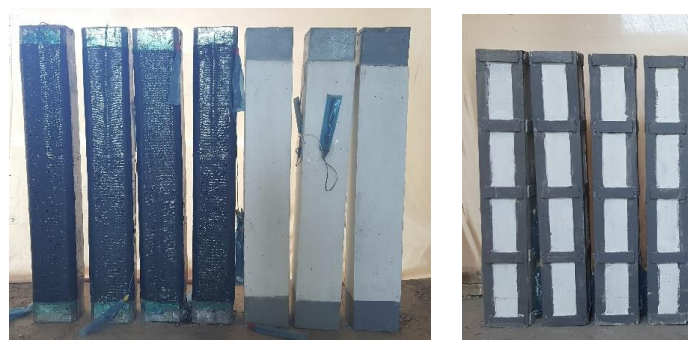


Figure 2. Column specimens.

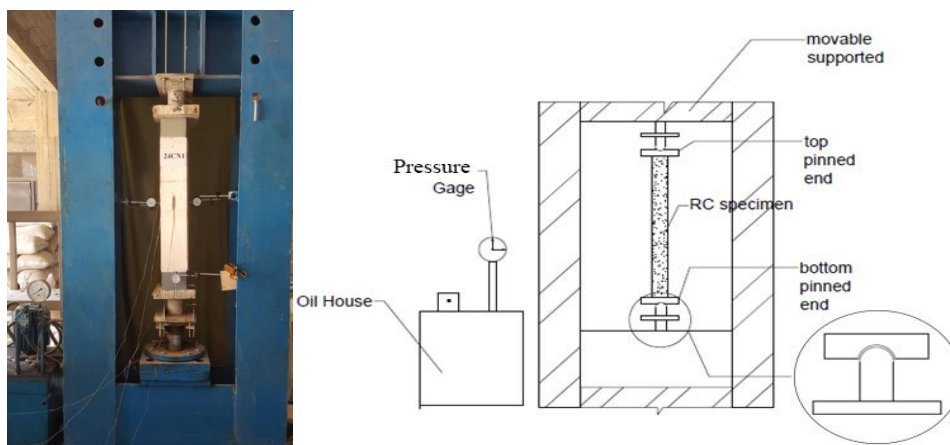


Figure 3. Testing set-up.

Experimental Results and Discussions

Column Behavior and Failure mode: Figure 4(a) illustrated the unstrengthened column specimens after testing. These columns were referred to as reference specimens since they are considered as the control specimens to study the effectiveness of the two strengthening techniques. It was observed that the failure mode of these columns was crushing at the top. This type of failure is the most common failure mode for short columns. Then, it was followed by buckling in the top region of longitudinal steel reinforcement. This is maybe a result of occurrences of high stresses at both ends of the column. Figure 4(b) and Figure 4(c) show the failure modes of columns strengthened with CFRP and SJ, respectively. The column specimens strengthened with CFRP exhibited a failure by CFRP rupture. The concrete cracks cannot be noticed inside the sheet during the test. However, a slight buckling in steel reinforcement was observed after failure as shown in Figure 4(b). The failure of SJ strengthened columns began with a crack occurring in the concrete. Then concrete crushing was taking place, followed by a slight buckling of the vertical steel angles. With increasing the load, concrete crushing continued, and a high buckle on the vertical steel angles was taking place.

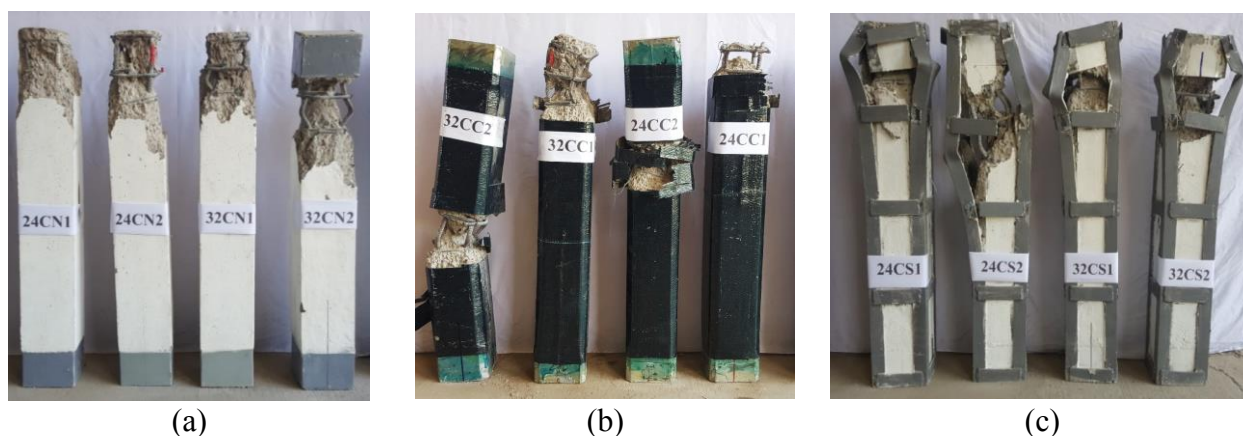


Figure 4. The failure modes of the column specimens: (a) reference, (b) CFRP strengthened, (c) SJ strengthened.

Load-Displacement Curves: Table 10 comprises the comprehensive results of all the tests conducted through this study. Obviously, the CFRP axial displacement reached a higher value than other strengthening techniques, which indicates the increase in ductility. This may be due to the effect of confinement of the CFRP wrapping during the dilation of the column. It is important to mention that the CFRP wrapping increased the concrete compressive strength in a range more than the SJ did. This is the reason to list the confined compressive strength f'_{cc} . Only for columns strengthened with CFRP. However, SJ increased the load-carrying capacity higher than CFRP wrapping because the SJ is

working with the concrete column as a composite member in which the vertical angles work as axial stiffness and the battens provide lateral support. The compressive strength of the column strengthened with CFRP was calculated using the equation adopted by ACI 440.2R-17 [18], as shown in Eq. 1.

$$P_{CC} = 0.85f'_{cc}A_C + f_yA_S \quad (1)$$

Where,

P_{cc} = is the ultimate strength capacity of the column strengthened with CFRP,

f'_{cc} = is the confined compressive strength of concrete,

A_c = is the area of concrete-section,

A_s = is the area of steel reinforcement, and

f_y = is the yield stress for steel reinforcement.

Figure 5 shows the load-axial displacement relationships for all types of columns. An improvement in the behavior of strengthened specimens concerning original columns can be seen. The load-carrying capacity of columns constructed with concrete compressive strength of 24MPa and reinforced by a steel ratio of 1% and strengthened with CFRP wrapping reached 768.67 kN. This increase in the carrying capacity represents 1.21 times compared with the unstrengthened reference column. While the same column reached 859.10 kN, i.e., 1.19 times when the steel reinforcement ratio was increased to 2%. This slight decrease can be attributed to the effect of longitudinal steel bars in reducing the concrete share of compressive stress, which reduces the dilation and, in turn, limits the efficiency of the CFRP confinement. The above trend can also be seen in columns with compressive strength of 32 MPa. They resist ultimate loads of 949.54 kN and 1039.97 kN with steel reinforcement ratios of 1% and 2%, respectively. Hence, the enhancement ratios were 1.17 and 1.15 when comparing with reference columns. On the other hand, the SJ technique enhanced the carrying load capacity for columns better than the CFRP wrapping technique. The ultimate load for the columns strengthened by SJ with compressive strength 24MPa reached about 1311.3 kN for the column with a steel ratio 1% and 1446.9 kN for the column with a steel reinforcement ratio of 2%. This means that SJ enhanced the load-carrying capacity by 2.07 and 1.90 compared with reference columns. While SJ-strengthened columns with compressive strength 32 MPa reached 1446.9 kN and 1582.6 kN for columns reinforced with steel reinforcement ratio 1 and 2%, respectively. The calculated enhancement in carrying capacity was 1.78, 1.75 times the ones of reference columns. These results revealed a concept that the CFRP works better with low values of compressive strength, while the effect of the increase in the area of steel reinforcement was small compared with the effect of compressive strength.

In addition, it was noticed that the axial displacement in columns strengthened with CFRP was large compared with columns strengthened by SJ. This is maybe due to the effect of the confinement provided by CFRP wrapping, leading to increased ductility because the ratio of lateral confinement stress provided from the CFRP wrapping to the compressive strength of the column increased. However, the SJ technique enhanced the carrying load capacity for columns better than the CFRP wrapping technique. The ultimate load for the columns strengthened by SJ with compressive strength 24MPa reached about 1311.3 kN for the column with steel ratio 1% and about 1446.9 kN for the column with steel ratio 2%. SJ enhanced the load-carrying capacity by 2.07 and 1.90 compared with reference columns. While SJ-strengthened columns with compressive strength 32 MPa reached 1446.9 kN and 1582.6 kN for columns reinforced with steel reinforcement ratio 1% and 2%, respectively. The calculated enhancement in carrying capacity was 1.78, 1.75 times the ones of reference columns.

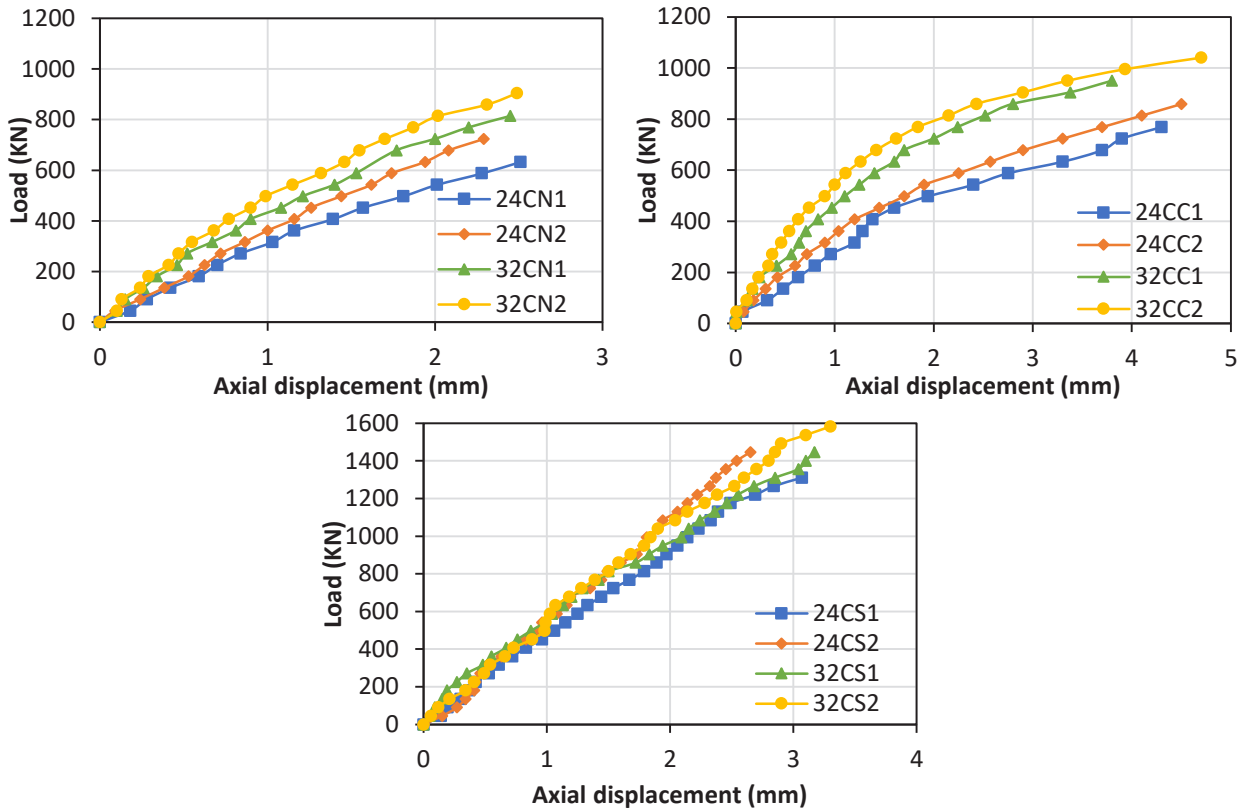


Figure 5. Load-axial displacement relationships.

Figure 6 shows the relationship between load and lateral deformation. Most of the columns fail with a small value of lateral deformation that means no considerable buckling occurred during the test because the column specimens were designed as short columns. Finally, Figure 7 illustrates the values of maximum load and axial deformation for all types of columns.

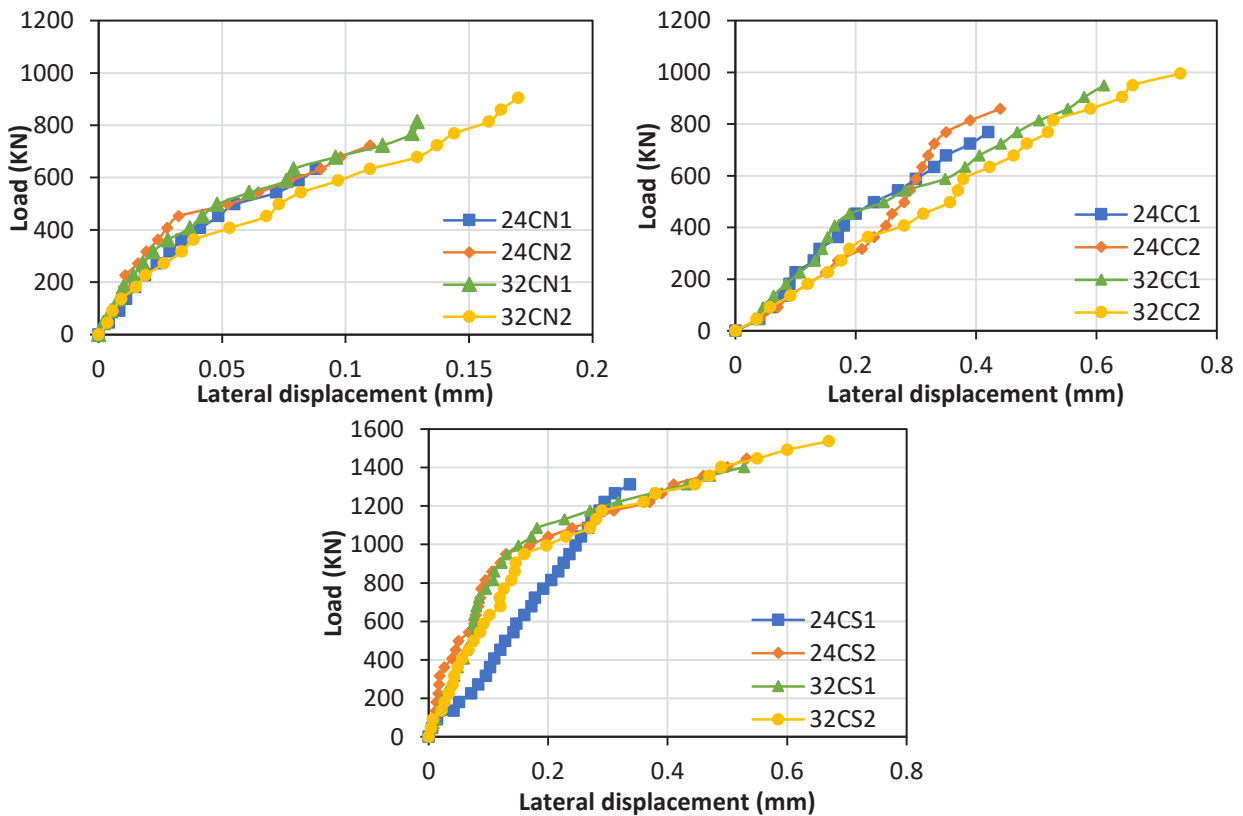


Figure 6. Load-lateral displacement relationships.

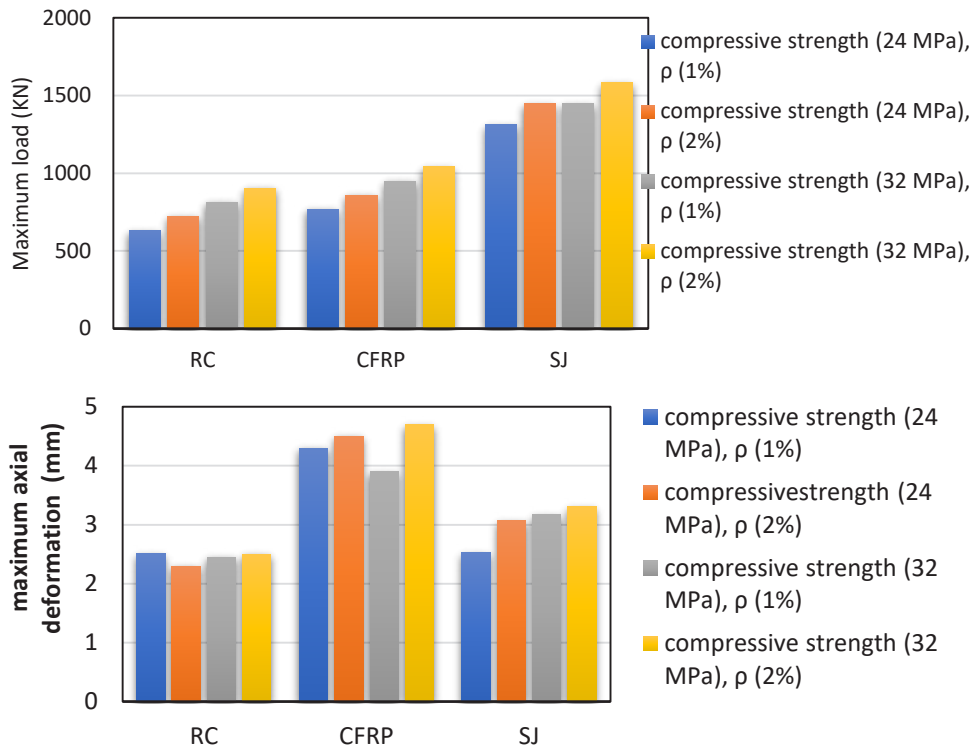


Figure 7. Maximum load and axial deformation for all types of columns.

Load-Strain Curves: The strains in steel and concrete were measured by means of strain gages. The results mounted using a special data logger program. Figure 8 shows the locations of strain gauges mounted on steel reinforcement, concrete, and steel jacket. Figure 9 illustrates the relationship between a load- strain in all tested columns. It was found that the ultimate strain value at the failure of columns strengthened with CFRP was relatively higher than the other columns. The steel angles were overpast the yield strain (0.00221) that was obtained by the laboratory tests. The vertical angle in this research is connected with the head of the column, which means the load transfer directly to the angle of the jacket instead of transfer with friction which occurred in the case of partially strengthening with SJ; this is why the steel jacket reached yielding before column failure.

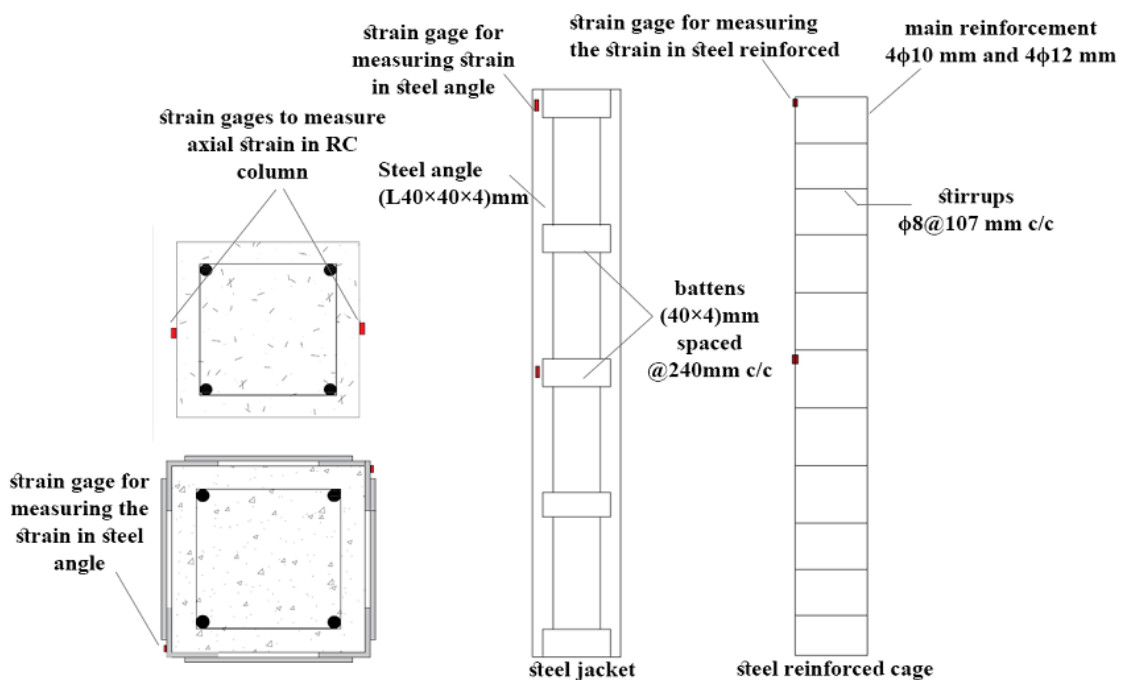


Figure 8. Strain gauges locations.

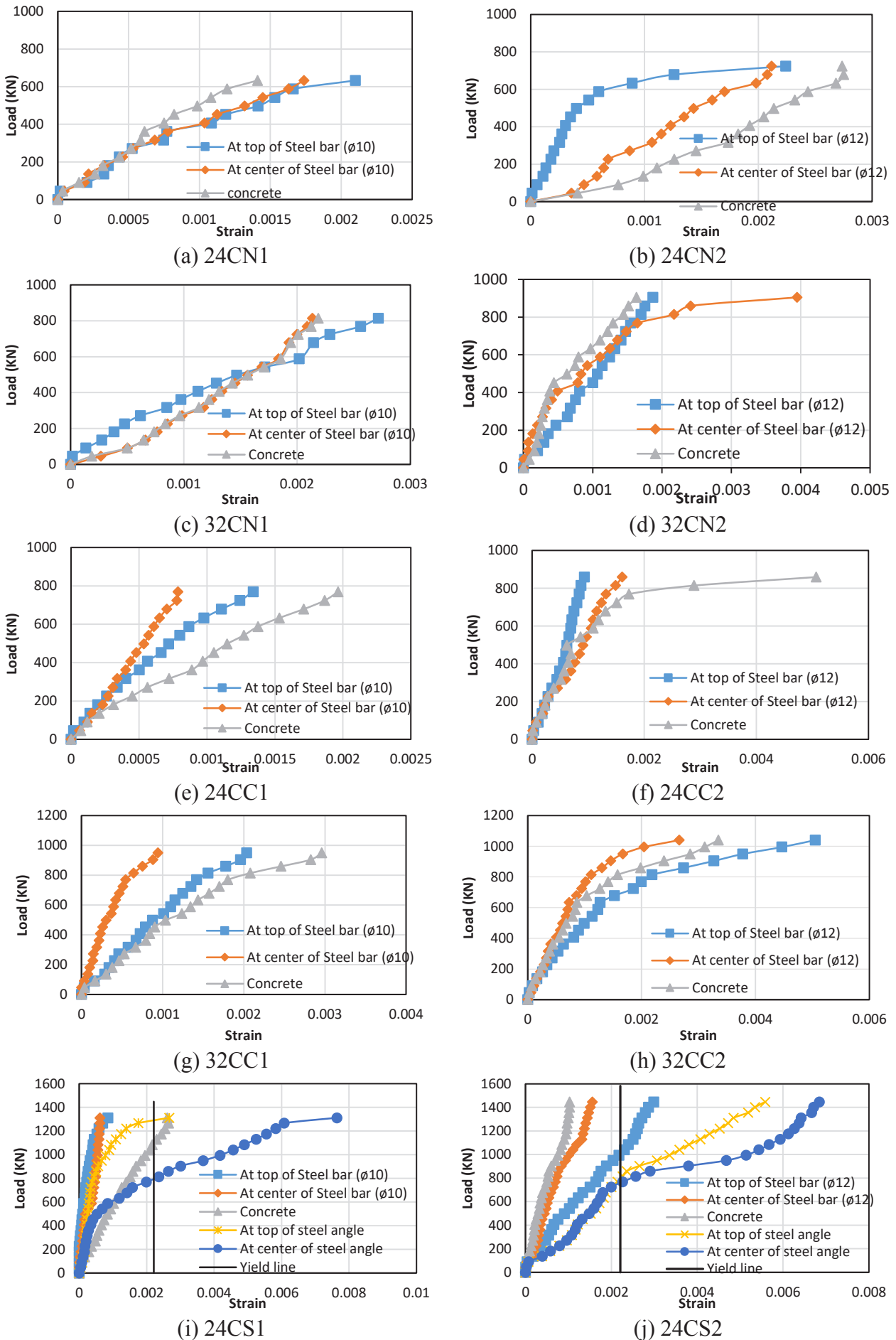


Figure 9. Load-strain relationships.

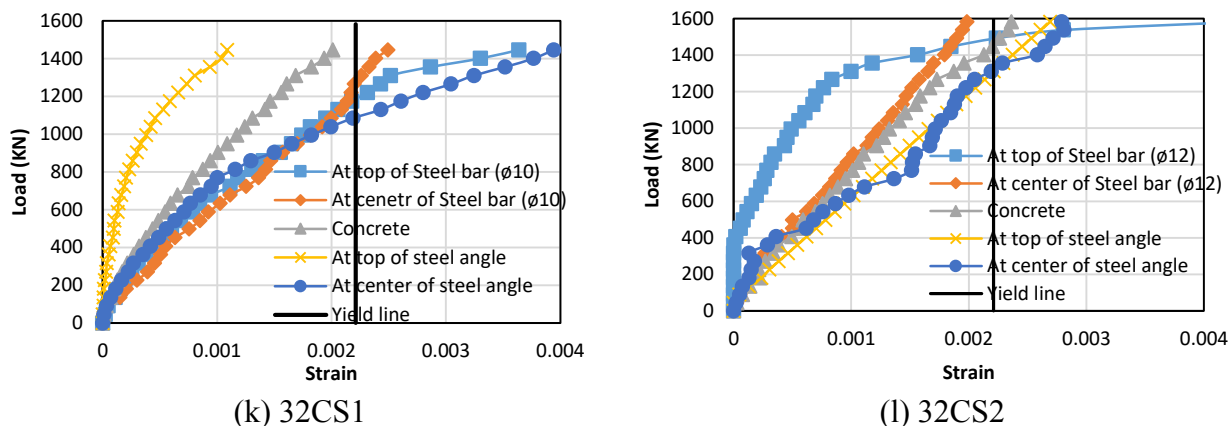


Figure 9. Continued.

Table 10. The summary of results for all columns.

Column code no.	Strengthening type	f'_c (MPa)	ρ_s (%)	Ultimate strength (kN)	Axial deformation (mm)	Calculated confined compressive strength f'_{cc} (MPa)	Load Increment ratio %	$\frac{f'_{cc}}{f'_c}$	Failure mode
24CN1	Non	24.2	1.4	633.02	2.51	—	—	—	Crushing
24CC1	CFRP			768.67	4.30	31.5	1.21	1.30	Rupture of CFRP
24CS1	SJ			1311.30	2.53	—	2.07	—	Total buckling
24CN2	Non	24.2	2	723.46	2.30	—	—	—	Crushing
24CC2	CFRP			859.10	4.50	31.8	1.19	1.31	Rupture of CFRP
24CS2	SJ			1446.90	3.07	—	1.90	—	Total buckling
32CN1	Non	32.7	1.4	813.89	2.45	—	—	—	Crushing
32CC1	CFRP			949.54	3.90	41.4	1.17	1.26	Rupture of CFRP
32CS1	SJ			1446.90	3.17	—	1.78	—	Total buckling
32CN2	Non	32.7	2	904.32	2.50	—	—	—	Crushing
32CC2	CFRP			1039.97	4.70	41.7	1.15	1.28	Rupture of CFRP
32CS2	SJ			1582.60	3.30	—	1.75	—	Total buckling

Conclusions

The following was concluded from the experimental studies presented in this paper:

- Both strengthening methods, CFRP wrapping, and SJ increased the load-carrying capacity when compared with the reference columns. The enhancement ratio, which ranged between (1.15 to 2.07) was found to be decreasing when increasing both steel reinforcement ratio and concrete compressive strength
- The SJ techniques enhanced the column carrying capacity more than the CFRP technique by about 1.65 and 1.52 for concrete with 24 and 32 MPa compressive strength.
- The CFRP wrapping increased the ultimate concrete strain, increasing the column ductility higher than the SJ method.
- The axial deformation for columns strengthened with the CFRP technique increased when compared with original columns by 83.5 and 73.6% for concrete with 24 and 32 MPa compressive strength, respectively.

- The column specimens strengthened with CFRP exhibited a failure by CFRP rupture, while the failure of SJ strengthened columns began with a crack occurring in the concrete, which developed to concrete crushing, then was followed by a slight buckling of the vertical steel angles.
- Finally, further studies are needed to examine the structural performance of these types of columns under various loading conditions.

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