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Effect of Fibrous Jacket on Behavior of RC Columns

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Abstract

This paper presented an extensive study about the strengthening of RC square short columns with high strength concrete jackets reinforced with steel fiber. The aim of this study is to investigate the effect of confinement by fibrous jacket on the behavior of RC column. A comparative study is performed on 23 square columns (six of them were unconfined columns where the remaining seventeen were confined columns) with varied parameters such as steel fibers ratio and type, jacket thickness, partial and full strengthening, type of confining jacket (hoop and composite), use of epoxy as bond material between the concrete column and strengthening jacket, and length parameter. The test results showed that the strengthened columns showed a significant improvement in the ultimate stress, load-carrying capacity, maximum strain, ductility, and energy absorption. Increase the steel fibers ratio (1, 1.5 and 2%) increased the ultimate stress by (22.5, 12.3 and 12.5%) respectively. The use of epoxy as bond material enhanced the ultimate stress by an average improvement by (55%). Composite case in the strengthening enhanced the load-carrying capacity larger than hoop case by (28.7 and 42%) for FRC jackets with hooked and straight fibers respectively but in case of stress capacity, hoop jacket carries stresses more than composite according to the stressed cross-sectional area. Increase jacket thickness (25 and 35 mm) enhanced the ultimate stress by (28.7 and 15.5%) respectively. Partial strengthening has a good enhancement in the ultimate load but was less than full strengthening. Increase the length by (25 cm) decreased the enhancement in load capacity of the column with hoop jacket by (45.3%). Concrete jackets enhanced Energy absorption and ductility which improved the deformation capacity. The compressive behavior of stub concrete columns was also modeled, simulated, and analyzed numerically by a 3D nonlinear finite element model. The verification process was performed against the reported data of the experimental test which proved the results of experimental results and showed a good agreement between experimental and numerical outcomes.

Keywords: Square Columns; Concrete Jackets; Steel Fibers; Jacket Thickness; Ductility; Finite Element.

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1. Introduction

Strengthening of the columns may be urgent need for some structures and find the most effective ways to retrofitting these columns is the challenge. Rehabilitation of some parts of the structures or the enhancement of the structural capacity of them may be necessary at some times, especially when damage occurs as a result of the deterioration due to environmental conditions, excessive loading, design errors, or significant damage caused by explosions or earthquakes [1]. In recent years, structures have become unable to meet the necessary design standards for many reasons, the most important of which are design errors or perhaps the low quality of engineering implementation of the facilities, as well as changing the purpose of buildings for another use that requires a high strength of the structure. Among the other reasons that weaken the structures is the corrosion of steel inside the concrete, which leads to cracking concrete because of its great importance in preserving the tensile strength of the concrete. As an action, these structures are strengthened by designing armor to support the designed load, or to

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reinforcing the damaged frames through the maintenance of some of its parts. The use of jackets has become a common strengthening method to increase the strength of the concrete member or to repair damaged concrete members in concrete structures [2]. Concrete is considered one of the most important building materials widely used around the world due to its high resistance to high loads. Despite this, concrete is in the loading stage, it loses the ability to load due to the appearance of cracks up to the partial or complete failure of concrete and to overcome these obstacles, steel fibers inside the concrete were used due to the effect of these fibers on the behavior of concrete [3-11].

The presence of fibers in concrete is a major factor in controlling concrete behavior in general, as it affects the appearance, direction, and quantities of cracks in concrete. In addition to this, the presence of steel fibers in concrete makes the structural member behave as if it were a composite material, and this behavior clearly and significantly differs from ordinary concrete. Many studies showed that fibrous concrete has very good properties such as compressive, bending, and tensile strength properties. Over the past decades, fibrous concrete has been used extensively in various concrete structures, including columns, beams, tunnels, floors, and industrial panels, where the strength and cracking is a source of great concern [12-16]. External strengthening jacket by using different materials had been commonly practical to enhance the total strength capacity frame columns and, also, the efficiency of the jacketing technique was investigated by many researchers [17-22]. Although some of the techniques are successful and effective in enhancing the compressive strength and general behavior of the concrete column, the disadvantages of these methods should not be disregarded which including high weight or corrosion of steel, the need for skilled labor, and high costs in general. Investigations have found that some jackets made of materials such as steel jackets and others are not sufficiently effective in providing good confinement pressure**.** Regarding the confinement of columns, many researchers investigated the effect of confining jacket on the column behavior with jacketed the column by many materials such as concrete, ferrocement, steel, and fibers reinforced polymers (FRP).

One of the important researchers that used the confinement by FRP was Demers and Neale [23] which presented an experimental study to assess the influence of confinement by CFRP sheets. When they jacketed sixteen circular columns by many layers of CFRP sheets. The outcomes exposed that CFRP jackets enhanced the whole performance of the circular concrete columns, including strength, and ductility. The use of FRP jacket strengthened the RC circular columns under centric and eccentric loads as presented by Seible et al. [24], Xiao and Ma [25], Mirmiran and Shahawy [26], Toutanji and Balaguru [27], and Teng and Lam [28]. Yaqub and Bailey [29] presented a study about retrofitting the concrete column by CFPR which concluded that CFRP enhanced the compressive of post heated columns and the jacket restored the original strength of non-heated columns. Siddiqui et al. [30] got that wraps of CFRP provided good confinement to concrete which enhanced the hoop strength pressure and increased the compressive strength of slender columns. Concerning ferrocement and steel jacket, ferrocement is a thin shell of concrete created from cement mortar and reinforced with very fine layers of wire mesh bonded together to make a strong and stiff structural form. While the steel jacket also thin steel used as a tube and the concrete-filled this tube inside. Many researchers [31-40] were used the jacketing by ferrocement and steel jackets which showed that the ferrocement and steel jackets considered a good way to enhance the strength capacity against different load types and improve the RC columns strength. Despite the multiplication of reinforcement methods and the effectiveness of some of them on the general performance of the column, some methods are expensive, such as reinforcement with the use of a steel jacket. Sometimes, the durability and high-temperature resistance of the FRP and steel are relatively poor. Strengthening by ferrocement and normal concrete jacket enhance the load-carrying capacity but cannot enhance the ductility in high percentage because these materials are brittle, thus the improvement in ductility is small.

In contrast, the use of fibrous concrete may be the best solution to get rid of these obstacles, besides, the reinforcement of fiber concrete is a very effective contribution as it contributes to raising the compressive strength and tensile strength of concrete as it contains steel fibers with a very high tensile strength. Over the past years, a lot of research has been done in terms of strengthening concrete columns by fibrous concrete, but this research has been limited in the used variables. In 2019, Xie et al. [41], presented an experimental investigation concerning strengthening the concrete column by ultra-high-performance concrete (UHPC) jacket. Outcomes of this study presented that the UHPC jacket affected the behavior of a concrete column which increased the ultimate stress capacity, maximum displacement, and ductility. Deng et al. [42] examined the influence of jacketing by FRC on the seismic behavior of concrete columns which showed that jackets offered a gaining in the ductility and maximum capacity of these columns. An experimental investigation by Hadi et al. [43] exhibited that using of R.P.C jacket (25 mm thick) affected the energy absorption capacity and maximum capacity. Studying the compressive behavior of a concrete-filled R.P.C cylinder was presented by Shan [44]. The results showed that the presence of these protective jackets that the effect had included effects and changes on the hoop confinement and the high resistance to R.P.C. Former researches such as Bafghi et al. [45], Kotsovos et al. [46], Soutsos et al. [47], Barros and Figueiras [48], and Campione and Mangiavillano [49] had shown that the existence of steel fibers in concrete prevents or delays concrete cover spalling with an increase in the deformation capacity. The compressive, splitting, and flexural strengths rise while adding more amount of steel fibers. Steel fibers are put into the specimens included silica fume, and sometimes with other additives so the ductility of the concrete is substantially increased.

The aim of this study is to investigate the effect of confinement by fibrous jacket and provide the most effective way to strengthen concrete columns through the use of several variables and different types of jackets**.** Based on the recent experimental works which showed little studies with strengthening by FRC jacket, HSC was used for strengthening short columns with normal strength concrete to enhance the strength and ductility of these short columns. In the present work, a total of 23 columns were fabricated, six of them were control specimens and seventeen were strengthened specimens by FRC jacket with different parameters. These parameters are steel fibers ratio, jacket thickness, type of strengthening, bond by epoxy in addition to the column height. The confined columns tested under static loading to investigate the effect of the confinement on the general behavior of the column. The results are discussed the effect of variables on the ultimate stress, maximum strain, ductility index, and energy absorption. The theoretical study was conducted by a simulation on 10 confined columns by finite element analysis (FEA) to prove the quality of the obtained results by experimental program.

2. Materials Properties and Concrete Mixes

The mixed proportions for the matrix of the NSC and HSC that used in this study are summarized in Tables 1 and 2. Normal concrete mix presented for the concrete core while the high strength concrete for the strengthening jacket.

The used materials include cement, natural gravel, natural silica sand, glassy sand, silica fume, water, steel fibers, and superplasticizer. To produce concrete for the concrete core or strengthening, urgent need to check the used material as follows; The physical and chemical properties of cement used in this study are issued according to the Iraqi standards while other properties such as the compressive strength, sieve analysis, and grading of sand are selected according to the ASTM C191 [50], ASTM C109 [51], ASTM C-136 [52], and Iraqi standards No. 45/1984 [53] respectively.

For high strength mixture was formed with a maximum size of glassy sand was 1 mm. The Iraqi Standard specification No. 45/1984 [53] used to confirm the chemical and physical properties of materials. In this study, a grey condenser grade 920 D silica fume was used. The sulfate content of fine sand is 0.13%. The fineness modulus for fine sand is 2.3. Normal potable water is used for mixing and treatment purposes, therefore, Flocrete pc 260 material (superplasticizer) was added to the mix which conformed to ASTM C494-99 [54]. Using the epoxy (Sikadur-32 LP) was used as a parameter for the bond purpose between the concrete column and the strengthening with flexural E-modulus 3600 N/mm^2 and tensile elasticity 4000 N/mm^2. Hooked end steel fibers with 30 mm length and straight fibers with 15 mm length are used in this study. Properties of steel fibers are presented in Table 3.

Table 1. Mix proportions of the normal strength concrete

	Cement	Sand	Silica fume/Gravel	w/c	Super plasticizer	SF %	f_{cu} 7 days *(MPa)*	f_{cu} 28 days *(MPa)*	f_t *(MPa)*
NSC	1	1.8	2.4	0.48	-	-	37	44.46	3.4

Table 2. Mix proportions of the high strength concrete.

Material /(kg/m^3)	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8
Cement	900	900	800	800	900	800	900	800
Sand	1000	1000	1000	1000	1000	1000	1000	1000
Silica fume	100	100	200	200	100	200	100	200
w/c	0.25	0.22	0.22	0.2	0.2	0.22	0.22	0.22
Super PS	2%	2%	3%	3%	3%	2%	3%	2%
Steel fiber%	1%	1.5%	1%	1.5%	1.5%	1%	2%	2%
f_{cu1}*	49.2	50.16	44.12	54.3	76.4	71.01	75.42	81.44
f_{cu2}**	61.56	71.56	67	78	80	80.72	78.3	91
f_t	5.5	5.6	4.74	6.16	6.33	4.38	8.36	8.13
f_r	9.7	12.52	12.1	13.43	13.14	11.74	13.95	12.65

* f_{cu1} = compressive strength after seven days.

** f_{cu2} = compressive strength after twenty-eight days.

Table 3. Properties of the Steel fibers

Type of steel fiber	Length (mm)	Diameter (mm)	Aspect Ratio (l/d)	Density kg/m^3	Tensile strength N/mm^2
hooked	30	0.55	55	7860	1345
Straight	15	0.2	75	7800	2850

3. Experimental Program

3.1. Concrete and Steel Bars

Used concrete with a design strength grade of C44 and C61-C91 for normal and high strength respectively. The average cylinder compressive strength of the concrete core was 37.4 MPa. Two sizes of steel reinforcing bars are used in the tested columns, deformed bars of size Ø8 mm with yield stress (464) are used as longitudinal reinforcement, and deformed steel bars of size (Ø6) mm with yield stress (432) MPa are used as closed stirrups (Table 4).

Table 4. Properties of the confined columns

Material	Compressive strength (MPa)	Steel grade (MPa)
Concrete Core	44	-
FRC Jacket	fcu_2	-
Main rebar Ø8	-	464
Secondary rebar Ø6	-	432
Hooked Fibers	-	1340
Straight Fibers	-	2850

Figure 1. Fabricating and casting the cubes, cylinders, and column specimens

3.2. Columns Details and Casting Procedure

A total of twenty-three short concrete columns were designed and fabricated. These columns included 6 unconfined columns and 17 confined columns with FRC jackets with different variables. Unconfined columns with dimensions of (150×150×500) mm and (150×150×750) mm were fabricated. Confined columns included casting normal strength concrete columns with the same dimensions of unconfined columns and casting the jacket over the concrete core. It should be noted that steel reinforcement for the concrete core was 6 Ǿ8 mm for the main reinforcement and Ǿ6 mm @ 100 mm as transverse reinforcement for columns. Figure 2 and Table 4 present reference square with variable cross-section dimensions which designed and fabricated for comparison with strengthened columns with the same dimensions. The confined columns strengthened by FRC jacket with variable thickness (25, and 35), two types (hooked and straight fibers) with three ratios of steel fibers (1%, 1.5%, and 2%) were used. Composite and hoop strengthening cases were used in which the composite case included jacketing the concrete column along the whole length while the hoop one involved jacketing the concrete core along the column by 94% (less than 15 mm from the top and bottom of column). Strengthening the columns in two and three faces only in addition to strengthening the columns with longer height is performed. Fabrication of confined columns was as following, an 80 kg mixer was used to mix the concrete for columns. Olivito and Zuccarello (2010) [8] were used in the forms and molds before putting the steel rebar and casting the columns. The steel bars were located inside molds by 1 cm square stock for a cover. Casting the concrete performed by plywood and steel forms for the square forms. After performing the mixing and casting, the forms can be removed after 24 hours and putting the specimens inside the water for 28 days for the saturation purpose. Then the strengthening can be used after this period.

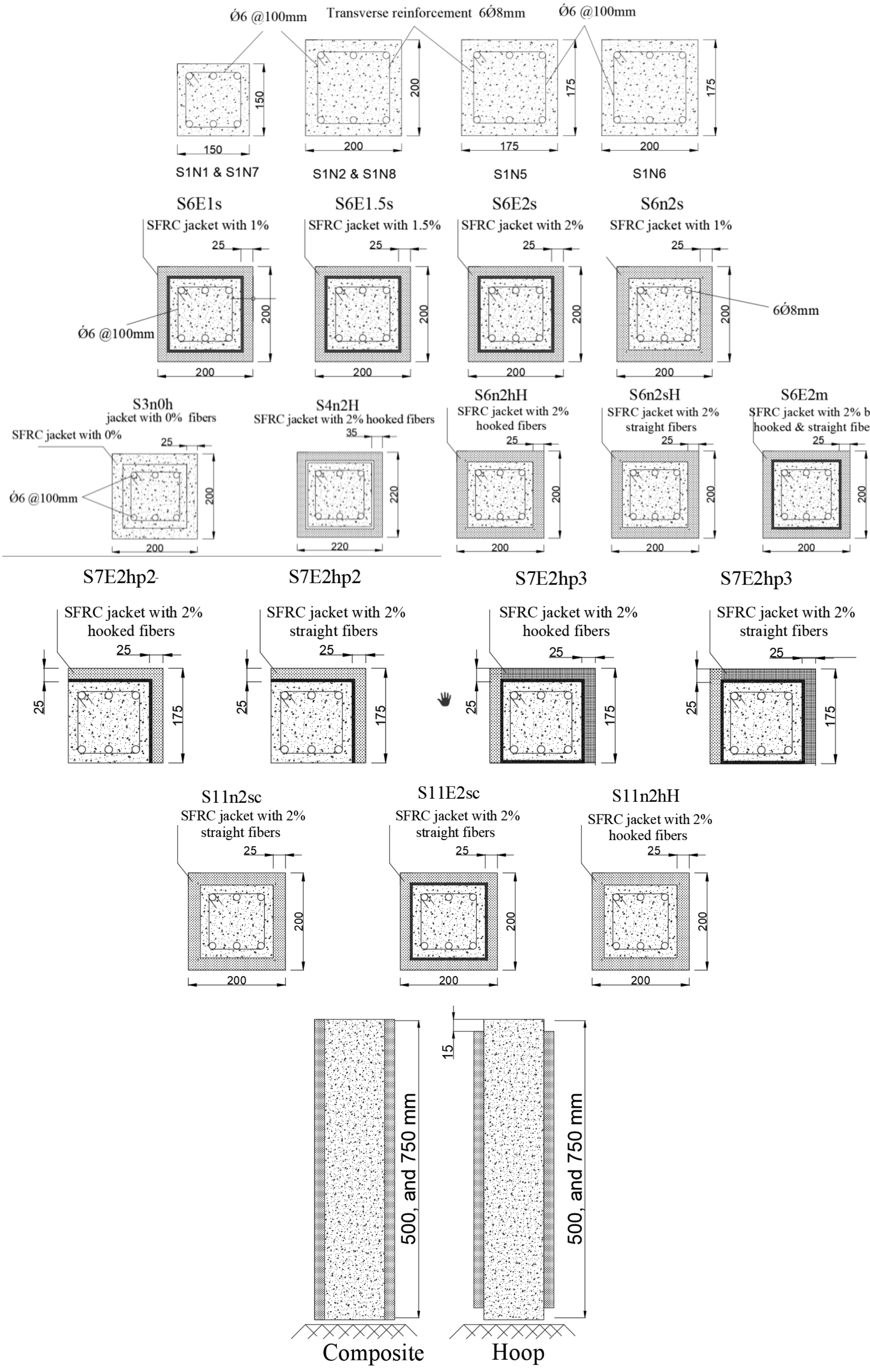


Figure 2. Details of test columns

Table 4. Summary of column test specimens

ID	Dimension (mm)	Jacket thickness (mm)	SF ratio	Epoxy	SF type	Jacketing Case
S1N1	150*150*500	-	-	-	-	-
S1N2	200*200*500	-	-	-	-	-
S1N5	175*200*500	-	-	-	-	-
S1N6	175*175*500	-	-	-	-	-
S1N7	150*150*750	-	-	-	-	-
S1N٨	200*200*750	-	-	-	-	-
S3E0h	200*200*500	25	0%	with	-	Composite
S4n2H	220*220*500	35	2%	without	hooked	Hoop
S6E1s	200*200*500	25	1%	with	straight	Composite
S6E1.5s	200*200*500	25	1.5%	with	straight	Composite
S6E2s	200*200*500	25	2%	with	straight	Composite
S6n2s	200*200*500	25	2%	without	straight	Composite
S6noH	200*200*500	25	0%	without	---	Hoop
S6n2hH	200*200*500	25	2%	without	hooked	Hoop
S6n2sH	200*200*500	25	2%	without	straight	Hoop
S6E2m	200*200*500	25	2%	with	Both	Composite
S7E2hp3	175*200*500	25	2%	with	hooked	Three side composites
S7E2sp3	175*200*500	25	2%	with	straight	Three side composites
S7E2hp2	175*175*500	25	2%	with	hooked	Two side composites
S7E2sp2	175*175*500	25	2%	with	straight	Two side composites
S11n2sc	200*200*750	25	2%	without	straight	Composite
S11E2sc	200*200*750	25	2%	with	straight	Composite
S11n2hH	200*200*750	25	2%	without	hooked	Hoop

4. Results and Discussions

4.1. Damage Progression and Failure Patterns

To investigate the occurred damage in the specimens, cracks were monitored at every stage of loading. Figure 3 shows the crack distributions for individual specimens at failure. Failure can be defined as a state of a rapid deterioration of resistance and fall of stiffness that leads to the imminent loss of full capacity to carry the loads.

The unconfined columns (control columns) showed a brittle failure which the concrete crushed. Large cracks started from the top corner to the bottom of the column. Reference columns with larger cross-section area showed more crushing in the concrete. Columns with length of 750 mm showed more brittleness than columns with length of 500 mm.

For the confined specimen with zero steel fibers ratio with epoxy (i.e., S3E0h) presented a brittle failure and break has occurred that has caused the jacket to splinter into several parts. Column (S6E1S to S6E2s) that included the use of an incremental ratio of straight steel fibers showed that the failure occurred in the jacket with inclined cracks started in the upper surface corner and extended towards the bottom surface of the column. The increase in steel fibers ratio made the cracked headed to the corner as if it has strengthened the cohesion between the concrete particles in the middle cross-section length to come back and focus on the corners. The column that strengthened with the FRC hoop jacket had the maximum strain among the strengthened columns. The failure occurred in these columns by vertical large crack. The cracks were generated from the center of the side surface of the column, causing a split in the jacket. The presence of steel fibers by their two types transferred the failure mode from sudden split to high deformation mode due to the offered ductility by steel fibers. The use of two and three direction strengthening caused the brittle failure and torn in FRC jacket as revealed in column (S7E2sp3) with a significant concentration on the stresses on the jacket. The failure mode of longer columns under effect the same parameters was different in comparison with the shorter ones. Steel fibers types affected the crack pattern of long columns which showed more deformation in the column with straight fibers than those in hooked ones. The existence of epoxy decreases the crack propagation in both straight and hooked fibers strengthening columns. Hoop jackets case (S11n2hH) failed in brittle failure which the loads applied directly on the concrete core, so the strains developed directly in the hoop jackets in the mid-length. Dichotomy occurred in the hoop jackets in columns (S11n2hH). Failure modes of the confined columns showed more deformation and decreases the brittleness of the concrete column by large percentages. A comparison with the previous study showed that the failure pattern is similar to the presented by Xie et al. [41].

Figure 3. Crack pattern and failure mode tested columns

Table 6. Test results of confined and unconfined columns

ID	P_{cr} (kN)	P_{cc} (kN)	Δ_{Vertical} (mm)	$\Delta_{\text{lateral.}}$ (mm)	ε_{cc}	$P_{cc}/P_{\text{Ref.1}}$	$P_{cc}/P_{\text{Ref.X}}$	$\varepsilon_{cc}/\varepsilon_{\text{Ref.1}}$	$\varepsilon_{cc}/\varepsilon_{\text{Ref.X}}$	DI	Tn (kN)
S1N1	902	992.3	3.69	0.721	0.00738	1	-	1	-	1.01	1990
S1N2	828	1142.6	3.88	0.002	0.00776	1.15	-	1.05	-	1.23	2035
S1N5	707	1177.5	4.45	1.057	0.0089	1.186637	-	1.2	-	1.09	2020
S1N6	582	895	3.64	0.657	0.00728	0.901945	-	0.98	-	1.07	2003
S1N7	646	1009.7	3.79	0.002	0.00758	1.02	-	1.03	-	0.977	1435
S1N8	950	1153	5.31	0.224	0.01062	1.16	-	1.44	-	1.07	1919
S3E0h	1305	1961.8	3.425	1.166	0.0068	1.977	1.717	0.928	0.882	1.29	4558
S4n2H	917	1146.4	3.067	0.002	0.00613	-	-	0.831	0	1.2	2310
S6E1s	2248	2403	6.114	0.426	0.01222	2.42	2.1	1.65	1.575	1.04	6573
S6E1.5s	2033	2203	6.050	0.794	0.0121	2.22	1.93	1.64	1.56	1.09	5132
S6E2s	1800	2206.8	5.347	0.503	0.01069	2.22	1.93	1.45	1.38	0.96	1887
S6n2s	1568	2090	5.821	0.644	0.01164	2.1	1.83	1.57	1.5	1.04	3588
S6noH	655	946.8	3.514	0.149	0.00702	0.95	-	0.952	-	1.13	1584
S6n2hH	671	1277.4	3.063	0.171	0.00612	1.28	-	0.83	-	1.04	1820
S6n2sH	1265	1408	4.373	0.002	0.00874	1.42	-	1.185	-	1.07	2721
S6E2m	2204	2292.3	4.440	0.45	0.00888	2.31	2.01	1.203	1.14	1.13	4093
S7E2hp3	813	1866	6.120	0.002	0.01224	1.88	1.58	1.658	1.375	0.92	2063
S7E2sp3	1500	1941.4	5.364	1.391	0.01072	1.95	1.65	1.45	1.20	1.01	3518
S7E2hp2	622	1287.5	6.647	0.002	0.01329	1.28	1.44	1.8	1.826	0.96	3470
S7E2sp2	827	1210.4	5.207	0.002	0.01041	1.22	1.35	1.41	1.43	1.06	2514
S11n2sc	2156	2336.7	4.891	0.490	0.00652	2.314	2.027	0.860	0.614	1.06	3927
S11E2sc	1552	2022.4	4.576	0.108	0.00610	2.003	1.754	0.805	0.575	1.01	3593
S11n2hH	1045	1168.9	3.684	0.002	0.00491	1.158	-	0.648	-	1.1	1668

S3E0h; S: square column, 3: third group, E: epoxy, 0: SF ratio, h: hooked fibers.

S6E1s; S: square column, 6: sixth group, E: epoxy, 1: SF ratio, s: straight fibers.

S6n2sH; S: square column, 6: sixth group, n: no epoxy, 2: SF ratio, s: straight fibers, H: hoop strengthening case.

S7E2hp3; S: square column, 7: seventh group, E: epoxy, 2: SF ratio, h: hooked fibers, 3: three sides strengthening.

4.2. Stress-Strain Relationship

The stress-strain relationship in Figures 4 to 18 shows that the jacketed columns behave linearly until it reaches about an average value of 75% of their ultimate strength. Overhead this point, the load increases gradually up and reaches the maximum load capacity as demonstrated in Table 6. The outcomes exhibited that the obtained strengths results ranged between (895 – 2403) kN with vertical deflection ranged between (3.06-6.12) mm as shown in Table 6. Figure 18 shows the general compressive stress-strain curves of stub concrete column confined by FRC jackets that similar mechanism of the behavior by the study of Xie et al. [52]. The stress-strain curve of the tested column exhibited that the curve passes from several stages starting from the linear region and ending in the crushing of concrete. Three stages of the concrete column during the loading which the first one is the elastic stage, the second one is the nonlinear stage, then the recession or softening stage. In the elastic phase, the compressive strength of the tested confined column rises linearly. In the second one, the column starts to enter the nonlinearity zone due to the cracking in the concrete jackets and nonlinear behavior column. At the end of the nonlinear phase, columns reach their ultimate strength capacity. After this point, the column started to lose its stiffness in a rapid process called the softening region which the strength decreases quickly. The softening region considered the index of the ductile behavior, the use of straight fibers and increase the jacket thickness increased the ductility of the column specimen. In general, the obtained results by this study are similar to the obtained ones by Xie et al. [41] concerning the hoop jacket and jacket thickness. The argument of this study is to find the most effective jacket to strengthen concrete columns through these variables.

4.2.1. Effect of Steel Fibers

In this study, one of the main variables that are important and directly affect the performance of the concrete column is the use of steel fibers. Increase of straight steel fiber ratio (1, 1.5 and 2%) in the in presence of epoxy as bond material exposed different stress capacities which showed increments by (22, 12 and 12%) ultimate stress capacity respectively in comparison with column (S3E0h). The obtained ductility in the strengthened column with (1%) steel fibers ratio is better than other ratios which got strain by (0.01222) as revealed in Figure 4. An increase in steel fibers does not mean a permanent increase in ultimate load capacity, Therefore, the unnecessary increase in the number of steel fibers causes more cost without large benefit. The optimum value for straight steel fibers in this study is (1%) as demonstrated in Figure 5. The obtained enhancement in the stress capacity by use of straight fiber was better than those columns which used hooked fibers. Both types of steel fibers (hooked and straight fibers) were used together (column S6E2m) which presented higher load capacity by (4%) with columns with straight steel fibers (S6E2s) as exposed in Figure 6. Enhancement in the stress capacity with using of straight steel fibers is more than hooked for the hoop strengthening case by (10%) as shown in Figure 7. It should be noted that the use of both types of steel fibers was less cost of straight fibers, so it can be considered is the optimum choice of strengthening because it provides higher strength with less cost than presented by other techniques. The presence of epoxy improved the ultimate load-carrying capacity but with less displacement which the column S6E2s was better than S6n2s by 5.6% (about 117 kN).

4.2.2. Effect of Jacket Height and Thickness

The effect of jacket height was evident in the overall behavior of the concrete column, the stress distribution mechanism, and the failure mechanism. Change of the jacket height from composite to hoop case showed better enhancement in the stress capacity but lower than load-carrying capacity. Jacketing the RC column with a hoop jacket with zero steel fiber didn't show any enhancement, but jacketing with FRC jacket improved the ultimate stress of the column. Comparison between columns (S6noH and S6n2hH) showed enhancement in the stress and load capacities by (35%). Also, use straight fibers for a ratio of (2%) in hoop case presented increase in the stress capacity more than happened in the hooked ones by (10%) in comparison with column (S6n0h) as revealed in Figure 7. It should be noted that hoop strengthening with straight fibers increased the stress capacity by (48.7%) in comparison with the reference column (S1N1). Concerning strengthening thickness, jacketing by (25 mm) was better than (35 mm) jacket thickness by (7%) in the ultimate stress capacity with the trivial change in the displacement. The obtained results indicated that the thickness of FRC jacket affects its internal stress distribution and this distinction cannot be ignored which similar to that results of Xie et al. [41].

4.2.3. Effect of Partial Strengthening Jacket

Other techniques used to strengthen the RC columns by retrofitting the column by jacketing into two and three sides and keep the remaining side without strengthening. The stress distribution, failure mode also been changed besides the general behavior due to the variation in the cross-section area. Starting from the columns (S7E2hp2 and S7E2sp2) that strengthened by two sides jacket in adjacent directions with straight and hooked steel fibers (each column has one type) which showed an increase in the ultimate load capacity by (22% and 30%) respectively in comparison with the un strengthen column (S1N1) as revealed in Figure 8. These two sides strengthening improved the maximum ultimate stress capacity by (35 and 44%) for the two columns respectively in comparison with the reference column (S1N6) that have the same cross-section area as shown in Figure 9. While when comparing the two sides strengthening with four sides strengthening, it found that strengthening by four sides had better enhancement in the ultimate load capacity than two sides.

Concerning three sides strengthening, two strengthened columns showed a good increment in the ultimate load capacity for the hooked and straight fibers by (88 and 96%) respectively in comparison with the reference un strengthen column (S1N1) as revealed in Figure 10. When comparing these three sides strengthened column with the reference column that has the cross-section area (S1N5), it is found that ultimate stress capacity enhanced by (58 and 65%) for both hooked and straight fibers as demonstrated in Figure 11. In general, three sides strengthening is better than two sides strengthening in the enhancement of the ultimate load capacity. Also, the three sides provide less enhancement in comparison with the four sides strengthening. The ultimate strength enhancement comes as follows; three sides strengthening is stronger than two strengthening of two sides by (60%). While the four sides strengthening is stronger than three sides by (14%) as demonstrated in Figures 12 and 13.

4.2.4. Effect of Column Length

Increase the length from 500 mm to 750 mm for square columns affected the general behavior of the column. The use of composite jacket increased the load-carrying capacity by (131%) for the jacket with straight fibers in comparison with the un-strengthen reference column (S1N7) as revealed in Figure 14. In comparison with the control column that has the same cross-section area (S1N8), composite jacket enhanced the ultimate stress capacity by 102% as revealed in Figure 15. Effect of epoxy was cleared in the columns (S11n2sc and S11E2sc), which presented enhancement in the stress carrying capacity was a lower value than those in the column with straight fibers without epoxy by less than (14%) as demonstrated in Figure 16. Hoop jacket case was carried out in the long column case which appeared improvement in the stress capacity was (15%) only in comparison with the control column (S1N7) as revealed in Figure 17. To check the effect of the length on the ultimate load carrying capacity, a comparison is carried out with the square columns with a length of (500) mm that have the same parameters. The use of hoop jacket for (500) mm length column (S6n2hH) enhanced the ultimate load capacity by (28.7%) while for 750 mm length column (S11n2hc) enhanced the ultimate stress capacity by (15.7%).

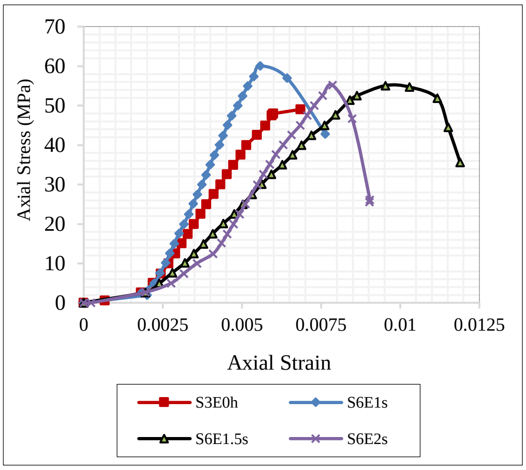


Figure 4. Stress capacity of columns with increment SF ratio

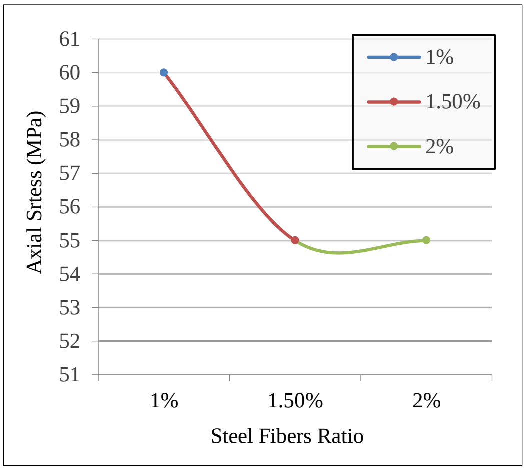


Figure 5. Optimum SF ratio straight fibers

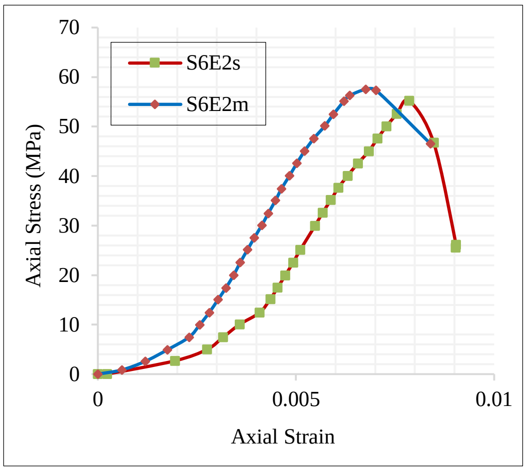


Figure 6. Stress-strain relationship of displayed the effect fibers

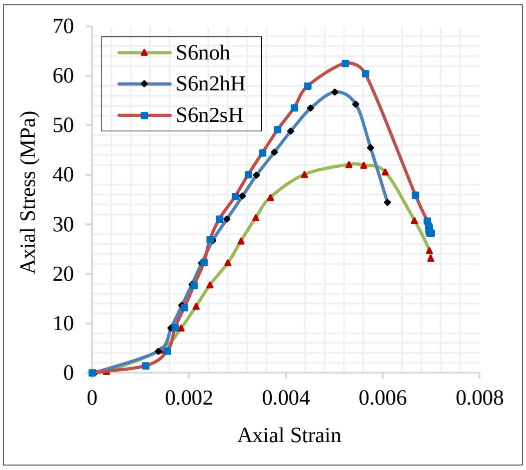


Figure 7. Stress-strain relationship of displayed the effect of jacket height

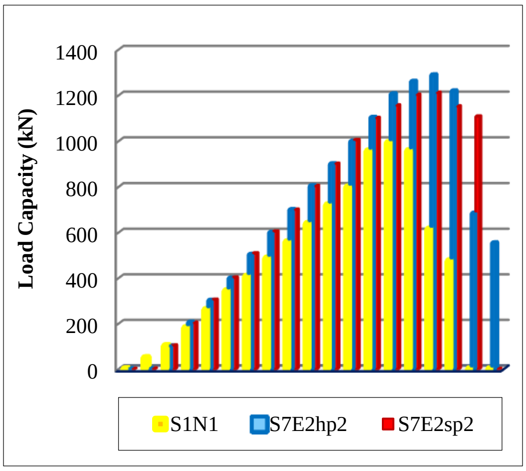
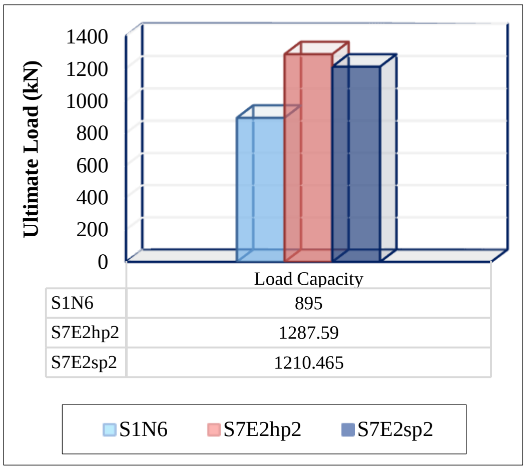


Figure 8. Effect of partial strengthening on the ultimate load



	Load Capacity
S1N6	895
S7E2hp2	1287.59
S7E2sp2	1210.465

Figure 9. Effect of partial strengthening on the ultimate load

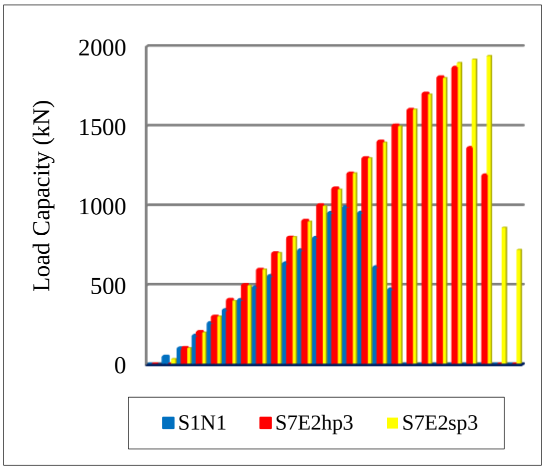


Figure 10. Stress-strain relationship of displayed the effect of partial jacketing

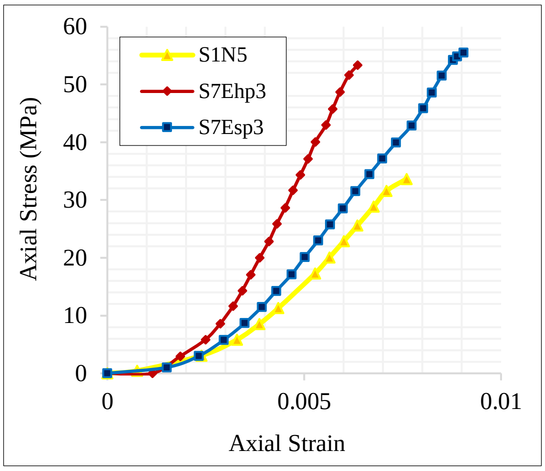


Figure 11. Stress-strain relationship of displayed the effect of partial jacketing

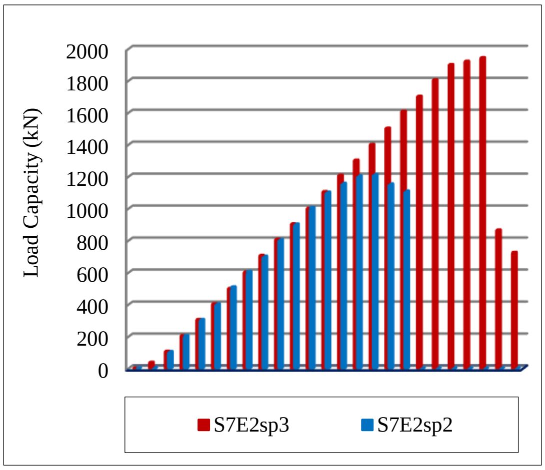


Figure 12. Comparison between two and three sides partial strengthening

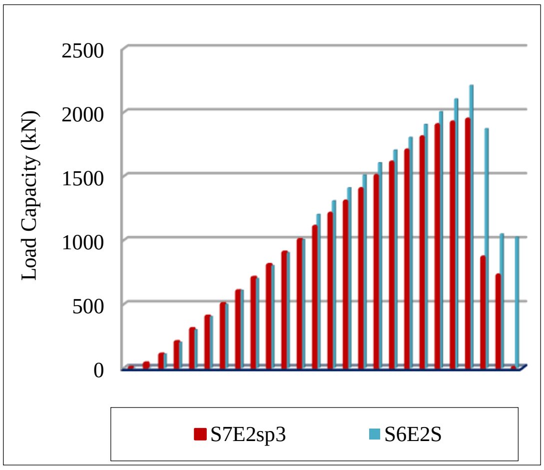


Figure 13. Comparison between four and three sides partial strengthening

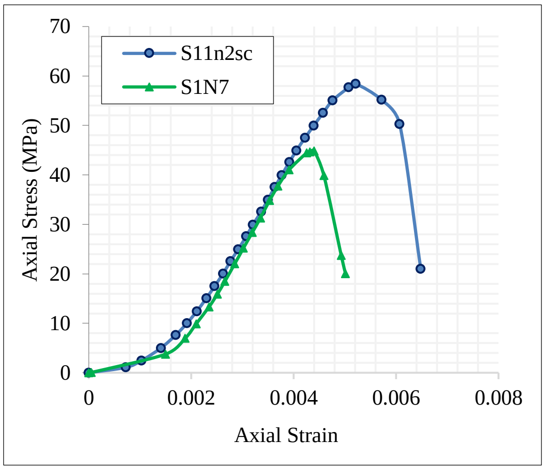


Figure 14. stress-strain curve clarifying the effect of length

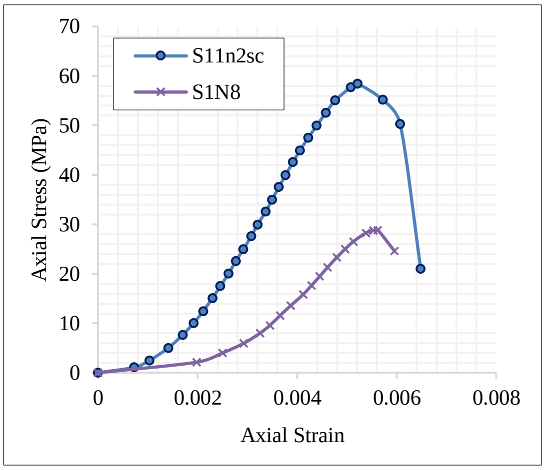
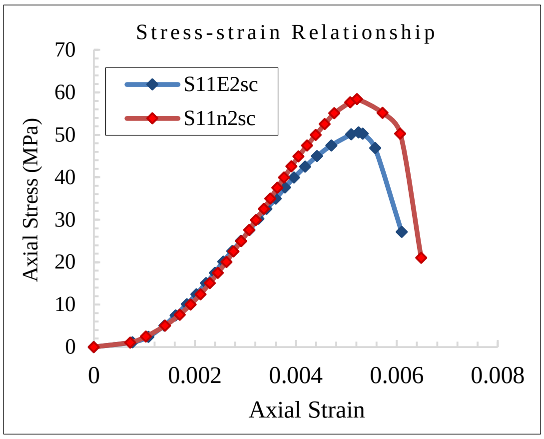


Figure 15. stress-strain curve clarifying the effect of length



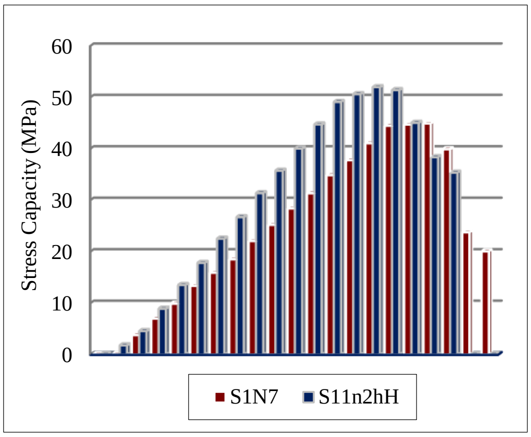


Figure 16. Stress-strain relationships clarifying the effect of epoxy

Figure 17. Stress index figure clarifying the effect of hoop jacket

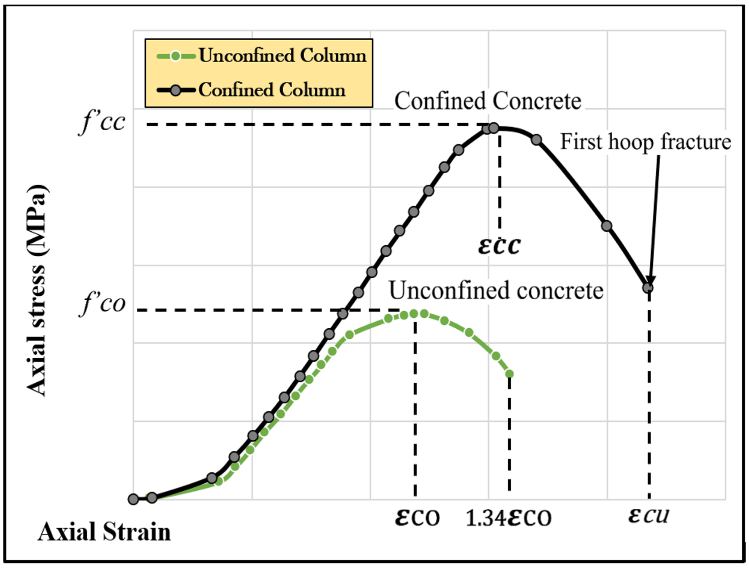


Figure 18. General stress-strain behavior of confined and unconfined column

5. Ductility Index

Ductility index (*DI*) considered the main index to calculate the ductility of the tested member. This index can be measured through load-displacement curves [55]. *DI* is described by Equation 1 by a ratio of displacement at 85% of the maximum load (Δu), to the displacement at the rupture load (Δm). Where Δu is the ultimate displacement when the post-peak remaining capacity of the column has dropped 85% of the peak load.

$$DI = \frac{\Delta u}{\Delta m} \qquad (1)$$

Table 6 lists DI for all columns. Table 6 exhibits the influence of the thickness of the confining FRC jacket and effect of the steel fibers and epoxy on the ductility index, Ductility index enhanced which showed average enhancement by (6.7%) for retrofitted short columns while for the columns with (750 mm) length was (5.6%).

6. Toughness

Toughness or energy absorption can be defined as the ability of the loaded member to absorb the energy that resulted from the loading and can be calculated by the area under the curve of load-deflection Toughness of RC is higher than that of the control concrete mixture. Though, the toughness of RC with steel fibers is higher than that of RC columns by average enhancement (80%). The average improvement in the toughness for the columns with length (500 mm) was (64.5%) while for long columns (750 mm) was (134%). Changes in roughness values with the addition of steel fibers are determined by measuring the areas under the stress-strain diagrams as listed in Table 6.

7. Finite Element Analysis on Stub Concrete Column Confined by FRC Jacket

7.1. Numerical Simulation

Nonlinear analysis by ANSYS is the primary evidence of the accuracy of the results obtained from the experimental study. Confined columns can be modelled by creating and discretizing the model into finite elements. Then assuming the shape functions and develop matrices for these elements and starting to solve the matrices by boundary conditions. FE theory by ANSYS was to analyze the confined columns by use of three-dimensional elements such as, SOLID65 which included eight nodes with three degrees of freedom at each node. ANSYS element must simulate the real behavior of the analyzed material such as SOLID65 simulate the behavior and properties of concrete such as cracking, crushing, and plastic deformation, a Smeared method used to represent the steel fibers with random orientation inside the concrete element. LINK180 considered the main element to represent steel reinforcement (both stirrups and longitudinal rebar) which this element has two nodes with three degrees of freedom at each node. Regarding the secondary requirement to simulate the confined columns is the modeling of steel plates. SOLID185 element is a non-compressible element used to simulate the loading and bearing plate. This element with eight nodes, each node has three degrees of freedom. Concerning the epoxy modeling, the cohesive zone interface element INTER205 can be used. This element simulates the epoxy between the jacket and concrete columns as the interface. Eight nodes with three degrees of freedom to each one [56].

7.2. Material and Modeling

Regarding the Material models used in the ANSYS, the same material properties for the normal and FRC concrete and steel rebar were inputted. Constitutive models of NSC and FRC that presented by Kachlakev [57] and Hsu [58] were used in the software. The stress-strain curves were of the concrete column and jacket according to the obtained experimentally reaching the ultimate strength and crushing of the concrete.

The steel reinforcement was modeled by a discrete model that permits the LINK180 to be embedded in the concrete. The bilinear curve of Von mises theory was used to represent the behavior of the steel material in this research. Tangent modulus was chosen equal to the value of the yield stress due to the convergence purpose.

The perfect bond assumption between the column and steel rebar was utilized to simulate the concrete core. Mesh and modeling of the confined columns are shown in Figure 19. FRC jacket was modeled with SOLID65 and representing the steel fibers in the smeared model (fibers inside the concrete element with different orientation angles). Steel plate modeled with a perfect bond with the top and bottom of the concrete column. Regarding the boundary conditions, the bottom of the plate was fixed support, and the top surface of the top-loading plate subjected to uniform loads distributed on the nodes uniformly. Mesh of the member was selected as semi-fine mesh depending on the capability of the provided computer which the element numbers were 4359. The concrete core is a very sensitive member so the element number was 3924 elements to be fine mesh while the strengthening jacket had elements of 435. Full Newton-Raphson method was used as a solving strategy. Many options were used to get the good results, increase the efficiency of the analysis, and to avoid the convergence problems that increase the mesh of the concrete column, and use of line search option for automatically scaling the incremental force.

7.3. Validations

It should be noted the after the ultimate load capacity the concrete element crushed and considered this point is the failure point. The verification process included simulation of the confined column and get the results in the same way that the load-deflection curves obtained in the experimental work. Figure 20 and Table 8 present the obtained results of the FE work in comparison with the experimental one. These figures showed that the numerical load-displacement curves are in good agreement with those experimental curves. The FEM predicted initial stiffness, ultimate compressive resistance, and corresponding displacements are compared with those experimental values in Table 8. Numerical simulation shows that the developed FEM could predict well the real behavior developed in the FRC jacket. Thus, it can be concluded that FEM could provide reasonable simulations on the compressive behavior of the concrete columns confined by FRC jacket based on the validations on load-displacement curves, elastic stiffness, failure modes, ultimate compressive resistance, and corresponding displacements. Stress distributed over the cross-section and along with the concrete core and strengthening jacket as revealed in Figures 21 and 22. Stresses concentrated at the corner causing cracking and deterioration in this zone. Regarding the stresses along with the column height, stresses concentrated over the cross-section of the concrete core larger and strengthening in different percentages.

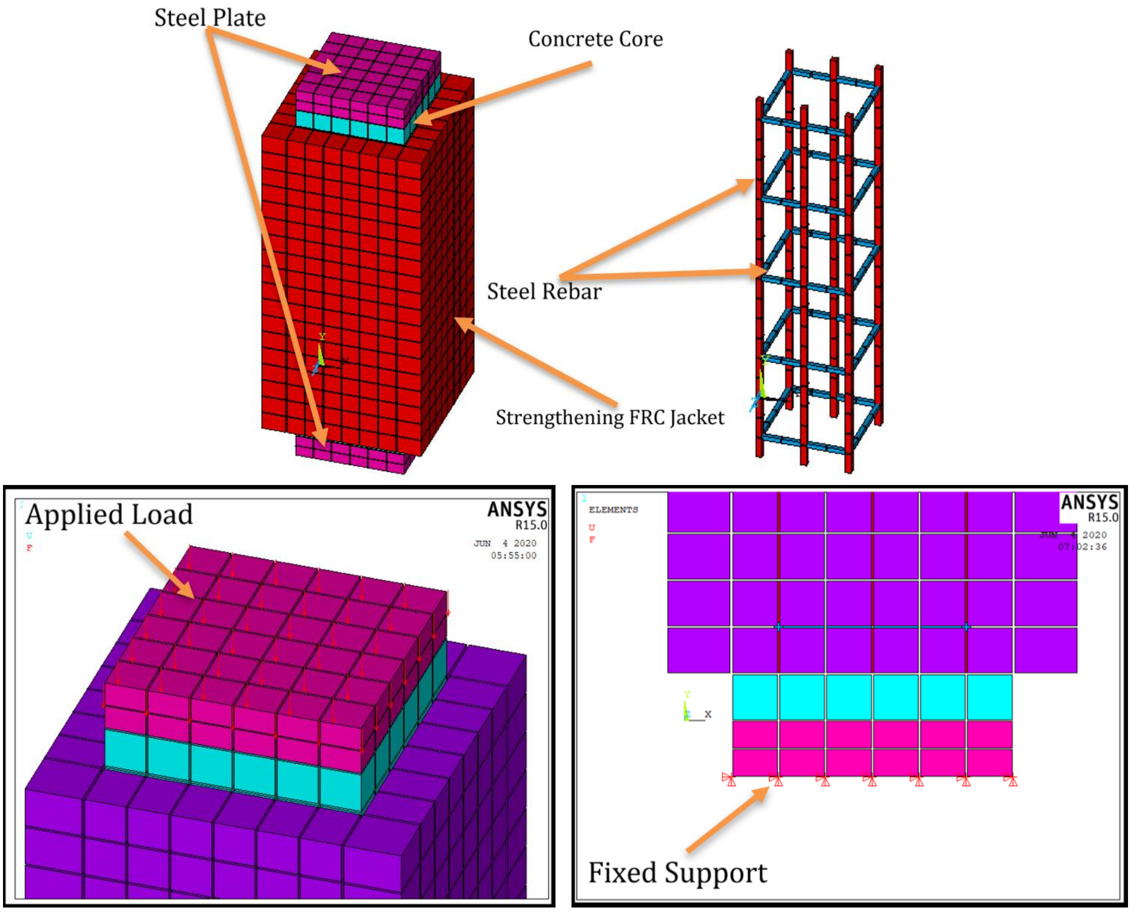


Figure 19. Finite element mesh of concrete core, strengthening jacket, and steel rebar analyzed columns

Table 7. Test results of the numerical simulation and verification with an experimental study

ID	$V_{Ansys(KN)}$	$V_{Exp.(KN)}$	V Agreement %
S1N1	991	992.3	99.8%
S1N2	1180	1142.6	96.8%
S4n2H	1146.4	998	87.1%
S6E1s	2403	2006	83.5%
S6E1.5s	2203	1863	84.6%
S6E2s	2206.8	2322	95%
S6n2hH	1277.4	1184	92.7%
S7E2hp2	1287.5	1345	95.7%
S7E2hp3	1866	1905	98.0%
S11n2sc	2336.7	2279	97.5%

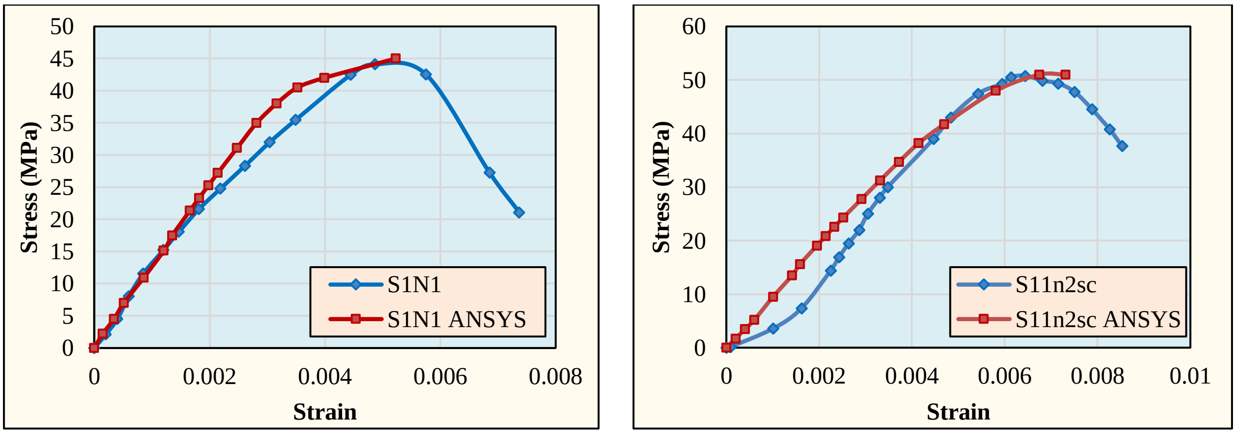
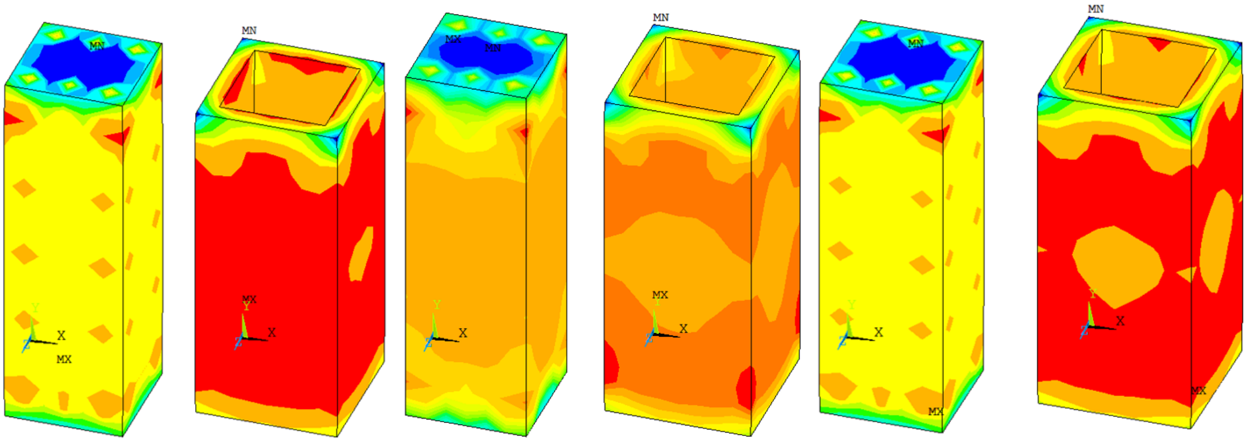
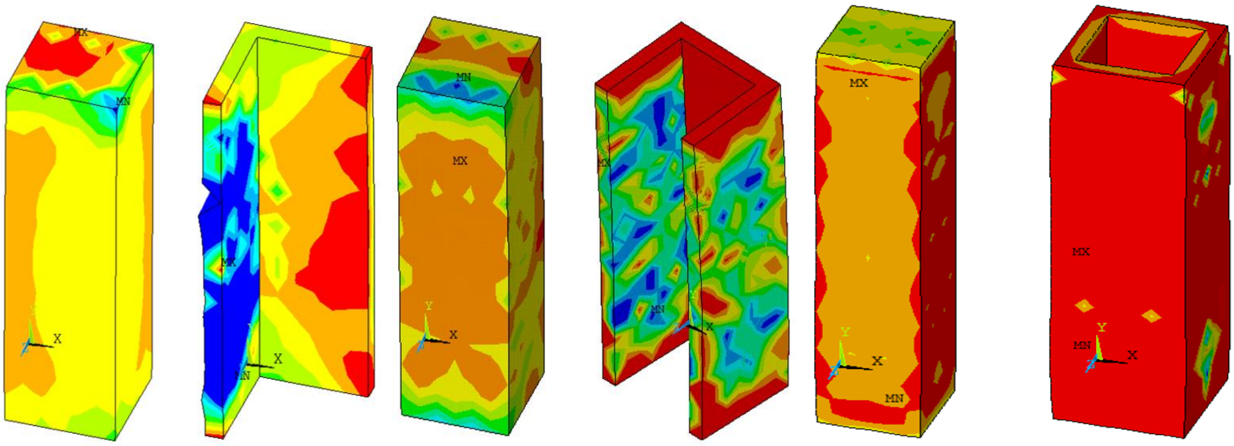


Figure 20. Verification between the experimental and numerical results

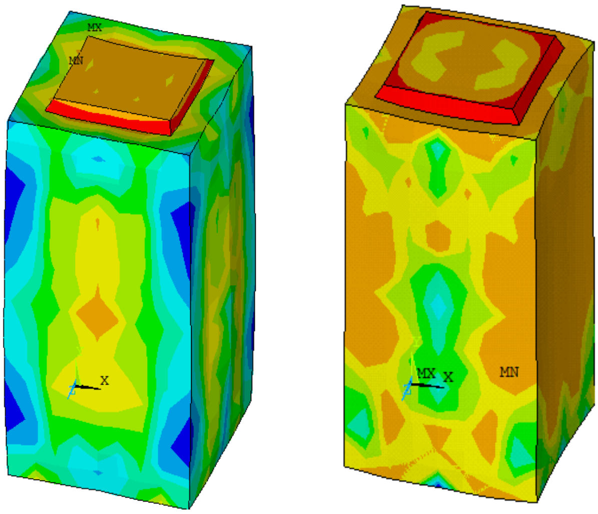


(a) S6E1s **(b) S6E1.5s** **(c) S6E2s**



(a) S7Ehp2 **(b) S7Ehp3** **(c) S11n2sc**

Figure 21. Verification between the experimental and numerical results



(a) S7Ehp2 **(b) S7Ehp3**

Figure 22. Verification between the experimental and numerical results

8. Conclusions

In this manuscript, the compressive tests on 23 stub concrete columns confined by FRC jacket were firstly carried out. Based on these experimental studies, the confinement effect of FRC jacket was discussed and revealed. Then, an analytical model was proposed to predict the compressive strain-stress behaviors of concrete stub columns with FRC jacket. A 3-D nonlinear FEM was also developed to simulate the compressive behavior of concrete columns with external confining FRC jacket. Based on these experimental studies and analytical and numerical analysis, the following conclusions are drawn:

- The addition of FRC jacked redistributed the internal stresses and enhanced the ultimate stress, load-carrying capacity, ductility, and energy absorption of the concrete column.
- Increase of straight steel fiber ratio (1, 1.5 and 2%) in presence of epoxy as bond material exposed different stress capacities showed increments by (22, 12 and 12%) respectively in comparison with column (S3E0h). An increase in steel fibers does not mean a permanent increase in ultimate load capacity, Therefore, the unnecessary increase in the number of steel fibers causes more cost without large benefit. The optimum value for straight steel fibers in this study is (1%).
- The obtained enhancement in the stress capacity by use of straight fiber was better than those columns which used hooked fibers. Enhancement in the stress capacity by using straight steel fibers is more than hooked for the hoop strengthening case by 10%.
- The use of two types of steel fibers (hooked and straight fibers) presented higher load capacity by (4%) with columns with straight steel fibers. It should be noted that the use of both types of steel fibers was less cost of straight fibers, so it can be considered is the optimum choice of strengthening because it provides higher strength with less cost than presented by other techniques.
- The effect of jacket height was evident in the overall behavior of the concrete column, the stress distribution mechanism, and the failure mechanism. Hoop jackets column showed enhancement in the stress capacity higher than composite one.
- Partial strengthening by two and three sides showed an enhancement in the stress capacity but less than strengthening into four sides. The failure mode of partial strengthening jacket was more brittle than full strengthening case.
- A FEM was also developed for stub concrete columns confined by FRC jacket. Experimental compressive/tensile behaviors of FRC were used as the input information. Validations of predictions of the FE and test data indicated that FEM offered reasonable estimations on the compressive behaviors of the concrete stub columns strengthened by jacket.

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10. Conflicts of Interest

The authors declare no conflict of interest.

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