Strengthening of RC Circular Short Columns with Fibrous Jacket

Wathiq Jassim Mhuder\textsuperscript{a} and Samir M. Chassib\textsuperscript{b}

Misan University, College of Engineering, Civil Engineering Department, Maysan, Iraq.
\textsuperscript{a} engwathik7780@yahoo.com, \textsuperscript{b} eng_samir@uomisan.edu.iq

Abstract.

This research presented a wide study about the structural behavior and strength of RC circular short columns when strengthened with concrete jackets strengthened with steel fiber. A total of 17 circular columns were designed, fabricated, and tested experimentally under monotonic load. An experimental investigation was carried out to assess the efficiency of the fibrous jacket in the retrofitting of RC column. The parametric study was conducted which included using four columns as control specimens with different cross-section dimensions. The remaining 13 column specimens included strengthening the column by different parameters such as steel fibers ratio and type, jacket thickness, bond by epoxy, and full and limited jacket height. The ultimate stress and strain, crack pattern, failure modes, ductility, and toughness capacity of the specimens were studied. The experimental outcomes exhibited that the fibrous jacket enhanced the ultimate strength capacity, ductility, and changed the failure mode of columns. The increase in the steel fibers ratio (1%, 1.5%, and 2%) enhanced the ultimate load capacity by (194%, 71%, and 126%) respectively. Strengthened columns by FRC jacket with thicknesses (25, 35, and 45) showed enhancement in the stress carrying capacity by (126%, 242%, and 171%) respectively. Using epoxy appeared a different behavior in comparison with square columns. The use of epoxy showed lower stress capacity by (21% and 24%) for (1% and 2%) hooked steel fibers ratio respectively. Use of hoop jacket case enhanced the ultimate stress capacity better than composite case. Straight fibers were better than hooked ones in the improvement of ductility and energy absorption.

Keywords: Circular columns, fibrous jacket, jacket thickness, Ductility, steel fibres, energy absorption.

1. Introduction.

In many cases, the strengthening of the structural members becomes an urgent need as a result of the structure's exposure to damages as a result of the earthquakes, more loads than the structural organ's tolerance, or its exposure to certain environmental conditions that reduce its efficiency. Sometimes the conversion of the structure to another used lead to an urgent need to strengthen this building which requires a high strength of the structure. Columns have special importance for the static system of many buildings [1]. 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 a 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. 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 [2].

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. [3-7]. Existence of steel fibers offer the concrete an increasing in the mechanical properties. Fibrous concrete offers a stiff and ductile block resist the different types of loading.
Naaman [8] presented an experimental study about the fibrous concrete to investigate the effect of fibers in the concrete body. Currently, fiber reinforced concrete (FRC) remains frequently applied in the construction field due to its advantages in improvement the behavior of the structures [9] also this type of concrete was used in tunnel constructions [10]. Presence of fibers as a main part in RC beams and plates instead of reinforcement enhanced the general behavior [11]. Use of fibers in case of Even a complete substitution of conventional steel reinforcements in flat slab construction [12-16].

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 [17] as revealed in Fig.1. The rehabilitation of deteriorated RC columns is becoming increasingly important due to the maintenance purpose. Several rehabilitation systems have been applied in RC columns. Steel plate is one of the traditional retrofit methods and used widely for strengthening RC columns. Johansson and Gylltoft, [18] carried out an experimental and numerical study about the steel-concrete composite column. The outcomes exhibited that the load-carrying capacity and ductility were enhanced. In 2005, Lam and Wong [19] performed a group of tests for short composite concrete-steel columns to inspect the influence of these jackets on the entire behavior. Columns with normal strength concrete (NSC) and high strength concrete (HSC) and then using the steel jackets to enclose these columns were tested. The enhancement occurred in the ultimate stress and strain with a significant change in the deformation capacity which showed more cracks than unconfined columns. Yang and Han [20] investigated the behavior of circular and square columns with normal concrete and recycled aggregate concrete retrofitted by steel jackets. The test outcomes exhibited that both types failed to resist the overall buckling. However, corrosion of steel plates raises another durability problem.

In the past twenty years, fiber-reinforced polymers (FRP) have been extensively applied to rehabilitation for RC structures [21]. The remarkable properties of FRP, such as high tensile strength, light-weight, and ease of installation allow it to be an effective technique for damaged RC columns. Hollaway et al. [22] presented a study about the use of FRP circular tubes filled by concrete. The variables included the usage of two types of the circular tube (carbon and glass tubes). The outcomes referred to that using of glass retrofitting tubes gave gaining in the strength by (51-137) % additional strength capacity while the carbon tube involved increment by (57-177) % additional strength in comparison with reference specimens. In 2008, Chakrabarti et al. [23] performed a theoretical study by using nonlinear FEM to analyze plain and RC columns jacketed by FRP sheets. This theoretical study included using several parameters such as FRP wall thickness and fiber orientation to compute the amount of change and the impact on the overall behavior. According to the gotten analysis outcomes, additional strength, increment in ductility, stress redistributions were occurred due to usage of FRP sheets. However, the durability of the adhesive joint between FRP and concrete can be affected by the severity of the marine and offshore environment [24]. Moreover, the processing of adhesive resin may bring difficulties to the construction site when large surface works need to be performed. Many researchers [25-29] were used the jacketing by ferrocement which showed that the ferrocement 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. Polyvinyl chloride (PVC) pipe is also used for rehabilitation as a pre-installed wrap [30]. In this system, the PVC pipe is incorporated into the new-built bridge column during the casting of concrete, and the durability of the bridge column can be improved due to the protection of the PVC pipe. However, PVC pipes do not apply to the retrofitting of existing damaged columns.

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. [31], 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. [32] examined the influence of jacketing by FRP 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. [33] 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 [34]. 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 [35-39] has 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. 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, including 6 control specimens and 17 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 results are discussed the effect of variables on the ultimate stress, maximum strain, ductility index, and energy absorption.

![Circular short columns](image1.png)

**Figure 1. Circular short columns [31].**

**2. Confinement Analysis**

Fig. 2. Reveals the mechanism of the stress distribution when the column jacketed by FRC. The presence of Jacket around the column representing confinement restricts the column in the hoop direction. The confining jacket reduced the hoop pressure of the strained column due to the continuous loading over the cross-section area of the column. As shown in Fig. 2, assuming that the volume of concrete is unchangeable, then the lateral confining pressure can be calculated by the equilibrium equation: where $f_{FRC}$ and $t_{FRC}$ are the hoop tensile strength and the thickness of the jacket, respectively. $D$ is the diameter of the concrete core. $f_l$ is the lateral confining stress [40].

![Confinement effect on stress distribution](image2.png)

**Figure 2. Confinement effect on stress distribution [40].**
3. Materials properties and Concrete Mixes

The mixed proportions for the matrix of the NSC and HSC that used in this study are summarized in Table 1 & 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 [41], ASTM C109 [42], ASTM C-136 [43], and Iraqi standards No. 45/1984 [44] respectively. For high strength mixture was formed with a maximum size of glassy sand was 1 mm. The Iraqi Standard specification No. 45/1984 [45] 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 [45]. 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/mm² and tensile elasticity 4000 N/mm². 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.

| Material / (kg/m³) | 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   | 0.2   | 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 |

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

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

| Type of steel fiber | Length (mm) | Diameter (mm) | Aspect Ratio (l/d) | Density (kg/m³) | Tensile strength (N/mm²) |
|---------------------|-------------|---------------|-------------------|-----------------|--------------------------|
| hooked              | 30          | 0.55          | 55                | 7860            | 1345                     |
| Straight            | 15          | 0.2           | 75                | 7800            | 2850                     |

4. Experimental Program

4.1 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). Fabrication and testing of experimental specimens is revealed in Fig. 3.

Table 4: Properties of the confined columns.

| Material               | Compressive strength (MPa) | Steel grade (MPa) |
|------------------------|---------------------------|------------------|
| Concrete Core          | 44                        | -                |
| FRC Jacket             | $f_{cu_2}$                | -                |
| Main rebar Ø8          | -                         | 464              |
| Secondary rebar Ø6     | -                         | 432              |
| Hooked Fibers          | -                         | 1340             |
| Straight Fibers        | -                         | 2850             |

Figure 3: Fabricating and casting the cubes, cylinders, and column specimens.

4.2. Columns details and Casting procedure.

These columns included 4 unconfined columns and 13 confined columns with FRC jackets with different variables as revealed in Fig. 4. Unconfined columns with the length of (500) mm, while the diameters were (170, 220, 240, and 260) 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 Ø8 mm for the main reinforcement and Ø6 mm @ 100 mm as transverse reinforcement. 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, 35, and 45), 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). Fabrication of confined columns was as following, an 80 kg mixer was used to mix the concrete for columns. Oil was 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 stock for a cover. Casting the concrete performed by steel forms for the circular forms.
Figure 4: Geometrical details of test columns.

Table 4: Details of circular columns.

| ID     | Dimension (mm) | Jacket thickness (mm) | SF ratio % | Epoxy | SF type | Jacketing   |
|--------|----------------|-----------------------|------------|-------|---------|-------------|
| C2N1   | 170*500        |                       |            | -     | -       | -           |
| C2N2   | 220*500        |                       |            | -     | -       | -           |
| C2N3   | 240*500        |                       |            | -     | -       | -           |
| C2N4   | 260*500        |                       |            | -     | -       | -           |
| C8n2h  | 260*500        | 45                    | 2          | without hooked composite |
| C8n2s  | 260*500        | 45                    | 2          | without straight composite |
| C9n1h  | 220*500        | 25                    | 1          | without hooked composite |
| C9n1.5h| 220*500        | 25                    | 1.5        | without hooked composite |
| C9n2h  | 220*500        | 25                    | 2          | without hooked composite |
| C9E1h  | 220*500        | 25                    | 1          | with hooked composite |
| C9E1.5h| 220*500        | 25                    | 1.5        | with hooked composite |
| C9E2h  | 220*500        | 25                    | 2          | with hooked composite |
| C9E2s  | 220*500        | 25                    | 2          | with straight composite |
| C9n2hH | 220*500        | 25                    | 2          | without hooked Hoop |
| C9n2sH | 220*500        | 25                    | 2          | without straight Hoop |
| C10n2h | 240*500        | 35                    | 2          | without hooked composite |
| C10E2h | 240*500        | 35                    | 2          | with hooked composite |

5. Results and Discussions
5.1. Stress-Strain Relationship

The stress-strain relationship in Fig. 5 shows that the jacketed columns behave linearly until it reaches about 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 (614.8 – 2670) kN with vertical deflection ranged between (2.37-5.786) mm as shown in Table 5. The outcomes 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. [31].

Table 5: Test Results of the confined columns.

| ID     | $P_{cr}$ (kN) | $P_{cc}$ (kN) | $\Delta_L$ (mm) | $\Delta_V$ (mm) | $\varepsilon_{cc}$ | $\frac{P_{cc}}{P_{Ref1}}$ | $\frac{P_{cc}}{P_{Ref2}}$ | $\varepsilon_{Ref1}$ | $\varepsilon_{Ref2}$ | $\varepsilon_{RefX}$ | DI | Tn (kN) |
|--------|---------------|---------------|-----------------|-----------------|-------------------|--------------------------|--------------------------|---------------------|---------------------|----------------------|----|---------|
| C2N1   | 359           | 614.8         | 2.429           | 2.297           | 0.00486           | 1                        | -                        | 1                   | -                   | -                    | 1.08 | 1066    |
| C2N2   | 493           | 902.6         | 2.370           | 1.276           | 0.00474           | 1.46                     | -                        | 0.975               | -                   | -                    | 1.06 | 1153    |
| C2N3   | 725           | 986.2         | 3.718           | 4.83            | 0.00744           | 1.60                     | -                        | 1.53                | -                   | -                    | 1.08 | 2383    |
| C2N4   | 971           | 1313.7        | 3.255           | 0.545           | 0.00651           | 2.136                    | -                        | 1.34                | -                   | -                    | 1.09 | 1936    |
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 a 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.

A. Effect of Steel Fibers

To study the effect of steel fiber ratio in circular columns, three values were used (1%, 1.5%, and 2%) which showed an increase in the stress capacity of the circular columns. The increase in the steel fibers ratio enhanced the ultimate load capacity by (194%, 71%, and 126%) respectively in comparison with the control circular unstrengthen column (C1N1) as demonstrated in Fig. 5 a. When comparing the strengthened column with the control column that has the same cross-section area (C2N2), it is found that the increase in the steel fibers ratio enhanced the ultimate stress capacity by (100%, 16%, and 54%) respectively as revealed in Fig. 5 b. Concerning the effect of epoxy, using epoxy appeared a different behavior in comparison with columns without epoxy. The use of epoxy showed lower stress capacity by (21% and 24%) for (1% and 2%) hooked steel fibers ratio respectively as revealed in Fig. 5 c & d. While the use of epoxy for a column with (steel fiber ratio 1.5%), enhancement occurred in the stress capacity by (76%) approximately (Fig. 5 e). To check the effect of steel fibers type, straight fibers were used in a 2% ratio in column (C9E2s) which exposed a stress capacity was greater than those in hooked fibers by (74%) as demonstrated in Fig. 5 f.

B. Effect of Jacket Height

The effect of jacket height was evident in the overall behavior of the concrete column, the stress distribution mechanism, and the failure mechanism. Use of hoop jacket case in the circular columns enhanced the ultimate stress capacity by (70%) for the jacket with the two ends hooked steel fibers (C9n2hH) and (69%) for the small straight fibers case (C9n2sH) in comparison with the reference column (C2N1). Using two types of steel fibers didn't affect the ultimate stress capacity which showed converged enhancement values. But in terms of general behavior, the initial crack load in straight fiber occurred in an earlier times than those in hooked fibers. Strengthening by hoop jacket with straight fibers cracked in (47%) of the ultimate load. While the hooked case was cracked in (63%) of the ultimate load capacity. The ductility enhanced by using steel fibers in comparison with the reference column. The enhancement in the straight steel fibers is better than hooked fibers which offered maximum strain by (46%) (Fig. 5 f).

C. Effect of Jacket Thickness

The use of variable jacket thicknesses in the circular column affected the general behavior, initial cracking load, stiffness, ductility, ultimate load capacity, and failure mode. Strengthened columns by FRC
jacket with thicknesses (25, 35, and 45) showed enhancement in the stress carrying capacity by (126%, 242%, and 171%) respectively for the jacket with hooked fibers as revealed in Table 5. Initial cracking load doesn’t affect during the transition from the (25 mm) to (35 mm) jacket which showed changing from (71%) to (70%) of the ultimate load capacity. The use of (35 mm) jacket increased the stress capacity in comparison with the column have the same cross-section area (C2N3) by (132%) and initial cracking stress by (102%) as revealed in Fig. 5 g. In the same way, column (C8n2h) is better than the control column with the same cross-section area (C2N4) by higher stress capacity (27%) as revealed in Fig. 5 h. Increasing the thickness of the casing does not mean a permanent increase in the stress capacity, which will be limited to a certain extent. Optimum jacket thickness in this study was (35 mm) which provided higher enhancement. The presence of epoxy offered a slight increment in ultimate stress capacity by (5%) approximately in a comparison between the columns (C10n2h and C10E2h). The initial cracking load also increased from (70% to 77.5%) as demonstrated in Fig. 5 j. Straight fibers were better than hooked fibers by (60%) in the ultimate stress capacity because the straight fibers have higher strength by (110%) almost as shown in Fig. 5 f.

(a) Effect of steel fibers ratio on the circular columns.
(b) Effect of steel fibers ratio on the circular columns.
(c) Effect of Epoxy and steel fiber type on the circular columns stress-strain.
(d) Effect of Epoxy and steel fiber type on the circular columns stress-strain.
(e) Effect of Epoxy and steel fiber type on the circular columns stress-strain.

(f) Effect of Epoxy and steel fiber type on the circular columns stress-strain.

(g) Effect of Epoxy and steel fiber type on the circular columns stress-strain.

(h) Effect of Epoxy and steel fiber type on the circular columns stress-strain.
6. Ductility Index
The ductility of strengthened columns by SFRC jacket can be calculated by the ductility index ($DI$). In this study, the calculation was by using the load-displacement relationship for $DI$ is adopted [46]. $DI$ can be defined as the ratio of the displacement at 85% of the ultimate load ($\Delta u$) during the softening region, to the displacement at the rupture load ($\Delta m$), as shown in Eq. 1. Where $\Delta u$ is the ultimate deflection when the post-peak remaining capacity of the column has dropped 85% of the peak load.

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

Besides, Table 2 lists the calculated $DI$ for all the columns. Ductility index enhanced which showed average enhancement by (9.46%) for retrofitted columns with fibrous jacket.

7. Energy absorption
Energy absorption capacity or toughness ($Tn$) is usually can be defined and calculated by the area under the load-displacement curve which considered an index to the ability of the member to absorb and dissipate the energy. The toughness of the RC strengthened column is higher than that of the control concrete unconfined column. However, the toughness of RC with steel fibers is higher than that of RC columns by average enhancement (130%) while for the increase in the thickness of jacket, the toughness enhancement was by (18.3%) for the thickness (35 mm) and (26.8%) for the thickness (45 mm) in comparison with column with 25 mm jacket thickness (C9n2h). Maximum enhancement in the confined columns occurred in the column (C8n2s) by (251%) due to the role of the straight fibers to enhance the energy aborption. Changes in toughness values with the addition of steel fibers are determined by measuring the areas under the stress-strain diagrams as listed in Table 5.

8. Failure Mode
Regarding the failure mode of circular columns under effect the used parameters, Figs. 5 shows the representative failure modes of circular columns. Increasing steel fiber ratio with and without epoxy caused more deformation capacity in the concrete columns. The failure occurred in the jackets when the process started from small cracks started in the top of the column and then grown and extended along with the RC columns. Increasing thickness of the jacket enhanced the crack propagation along with the columns. Hoop jackets failed in brittle failure which the loads applied directly on the concrete core, so the stains developed directly in the hoop jackets in the mid-length. Dichotomy occurred in the hoop jackets in both columns (C9n2hH and C9n2hH).
9. Conclusion

1) The increase in the steel fibers ratio enhanced the ultimate load capacity by (194%, 71%, and 126%) respectively in comparison with the control circular. When comparing the strengthened column with the control column that has the same cross-section area, it is found that the increase in the steel fibers ratio enhanced the ultimate stress capacity by (100%, 16%, and 54%) respectively.

2) Using epoxy appeared a different behavior. The use of epoxy showed lower stress capacity by (21% and 24%) for (1% and 2%) hooked steel fibers ratio respectively. While the use of epoxy for the column with (steel fiber ratio 1.5%), enhancement occurred in the stress capacity by (76%) approximately.
3) The use of a hoop jacket case in the circular columns enhanced the ultimate stress capacity by (70%) for the jacket with the two ends hooked steel fibers and (69%) for the small straight fibers case. The initial crack load in straight fiber occurred at an earlier time than those in hooked fibers. Strengthening by hoop jacket with straight fibers cracked in (47%) of the ultimate load. While the hooked case was cracked in (63%) of the ultimate load capacity.

4) Strengthened columns by FRC jacket with thicknesses (25, 35, and 45) showed enhancement in the stress carrying capacity by (126%, 242%, and 171%) respectively. Increasing the thickness of the casing does not mean a permanent increase in the stress capacity, which will be limited to a certain extent. Optimum jacket thickness in this study was (35 mm) which provided higher enhancement.

5) Straight fibers were better than hooked fibers by (60%) in the ultimate stress capacity because the straight fibers have higher strength by (110%) almost.

6) Ductility and energy absorption was enhanced for the confined columns.

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