Rehabilitation and strengthening techniques for reinforced concrete columns: review

Alaa Jaleel Naji¹, Haider M. Al-Jelawy², Sura A. Saadoon³, Ahmed Taresh Ejel⁴

¹, ², ³ Roads and Transport Department, University of Al-Qadisiyah, Ad Diwaniyah, Iraq
⁴ Civil Engineering Department, University of Al-Qadisiyah, Ad Diwaniyah, Iraq
*Corresponding author E-mail: alaa.alnsray@qu.edu.iq

Abstract. Reinforced concrete (RC) columns are the primary load-bearing structural components in the building which makes them most likely vulnerable to deterioration. Capacity deterioration of RC columns may result from dynamic loads, impact loads, poor maintenance, creep, non-standard design, corrosion of steel reinforcement and incorrect quality control. Therefore, RC columns should be always monitored for signs of deterioration. Rehabilitation and strengthening of existing reinforced concrete facilities have become an essential part of the construction work. This study aims to review and evaluate methods of strengthening RC columns. Steel jacketing, concrete jacketing, ferrocement jacketing, CFRP jacketing and GFRP jacketing are the most common techniques which have been used for rehabilitation of RC columns. Each method of strengthening is reviewed with emphasis on its performance, advantages, disadvantages, application details, and factors that influence the design and scope of applicability.

Introduction
Collapse of reinforced concrete (RC) structures has become frequent during the past two decades due to increased loads and durability problems. Structural elements may need to be repaired or strengthened due to chemical and physical actions. Cracks due to dynamic loads, impact loads, poor maintenance, creep, non-standard design, corrosion of steel reinforcement and incorrect quality control are examples that lead to deterioration of RC structures.

RC columns are the primary load-bearing structural components in the building which makes them most likely vulnerable to deterioration. Over time, RC columns require strengthening to resist earthquake, increased loads, changing facility types of services or increased traffic volume in bridges. Structure types and loading schemes affect strengthening methods. For instance, structures dominantly subjected to static load, increasing axial and flexural strength should be given priority, and for structures dominantly subjected to dynamic load, increasing shear and flexural strength is more convenient.

This paper presents a review of different strengthening and retrofitting techniques for RC columns which were conducted during the past few years. The authors reviewed each strengthening technique with emphasis on its performance, advantages, disadvantages, application details, and factors that influence the design and scope of applicability.
Techniques for repairing and strengthening RC columns:

1. Steel jacketing

Confining concrete columns with steel jacketing is the oldest method of strengthening concrete columns. Steel jacket technique is extensively used for strengthening of non-ductile columns. Various configurations of steel jackets, plates, external ties, partial jacket, full jacket and different steel shapes have been used to increase the column strength. The basic configuration consists of longitudinal steel angles or channel sections fixed at each corner of the column with which horizontals steel sheets are welded along the column at appropriate intervals. Small space is left between the steel jacket and the column to be filled with a special mortar to improve the system performance. Also, reinforcement can be added to transfer the stress between the mortar layer and the column. Figure 1 shows a control RC column and different steel jacket configurations that include jacketing with angle sections, channel sections, and plates.

Several researchers have focused on the behavior of strengthened RC columns using steel jacketing techniques. Tarabia et al. [1] conducted a study to investigate different parameters that influence the behavior of steel jacketed columns. The testing program consisted of 10 specimens with dimensions (150 * 150 *1000) mm Two columns served as control columns and the other columns were strengthened with steel jackets. The parameters investigated were steel angle dimensions and the use of steel head connections (see Figure 2). Cement and epoxy were used as the grouting material that was injected between the column and the steel cage. The results showed that columns strengthened with steel head connection achieved higher ultimate loads than those without connections, and that was due to the difference in the load transfer mechanism between the two cases.

The behavior of strengthened columns with steel jackets depends heavily on the existence of head connections. When steel jackets are not connected to the steel head, load is transferred to the vertical angles from the column body through adhesion between them. On the other hand, when steel head connection exists, load is transferred from the head to the steel angle in addition to the adhesion between the column and steel jacket. Direct attachment of vertical angles to the steel head enables direct load transfer to the angle, and all angles connected in this manner reaches the yield point before failure of the strengthened column, while indirect attachment causes the load to be transferred by friction and steel angles do not yield.
Ezz-Eiden [3] conducted a study using different details of steel jacketing to strengthen RC columns. Five rectangular control columns with dimensions (120*160) mm and 1000 mm in length were tested with different eccentricities \( e/t = (6.30\%, 12.5\%, 18.75\% \text{ and } 25\%) \). Twelve other columns were divided into three groups: the first group was strengthened with four longitudinal steel angles (20*20*2) mm on both compression and tension sides, the second group was strengthened with four longitudinal steel angles, two angles (40*40*4) mm on compression side and two angles (20*20*2) mm on tension side, while the third group was strengthened with four longitudinal steel angles, two angles (60*40*4) mm on compression side and two angles (60*20*2) mm on tension side. All specimens were strengthened with five horizontal steel plate straps (20*2) mm. The results showed that increasing angle dimensions increased the load carrying capacity of the strengthened columns.

Increasing the covered area of the steel jackets by increasing longitudinal steel dimensions increases the load capacity of the strengthened columns, while increasing number of horizontal straps delays the buckling of steel angles.

Belal et al. [4] performed an experimental study rounded effect types of steel sections for strengthened RC columns. Seven RC columns with dimensions (200*200*1200) were tested. Two columns without strengthening served as control columns, while five strengthened columns were divided into three groups. The First group included two columns strengthened with four longitudinal steel angles (50*50*5) mm; the first column was strengthened with three horizontal steel plate straps (150*100*2) mm, while the second column was strengthened with six horizontal steel plate straps (150*50*2) mm. The second group included two columns strengthened with two longitudinal steel channels (260*50) mm; the first column was strengthened with three horizontal steel plate straps (150*100*2) mm, while the second column was strengthened with six horizontal steel plate straps (150*50*2) mm. The third group included one column strengthened with four longitudinal steel plates at four sides (200*2.4) mm. The results showed that steel jacketing technique generally improved the load capacity and it also showed that using steel angle shape exhibited a higher load capacity than channel shape. Increasing the number of horizontal steel plates with channel shape also improved the load capacity of the columns.

The main longitudinal steel shapes that are used in the steel jacketing system are angles, channel and plates. Steel angles have more improvement effects than channel and plates on strengthening columns. Abdel-Hay et al. [5] investigated the behavior of RC columns partially strengthened using steel jackets. The experimental program (refer to Figure 3) included testing seven columns with dimensions (200*200*1500) mm. One of the tested columns served as a control column, and the other six columns were partially strengthened using different types of steel jackets. First type of steel jacket was designed for two columns, which consisted of four longitudinal steel angles (40*40*4) mm over a partial strengthening length of (500, 750) mm connected with four horizontal steel plates (25*5) mm. The second type designed with a partial length of 500 mm for another two columns included four steel plates

Figure 2: details of steel jacketing with and without head connection [2]
with different thickness (1.5, 3) mm welded together and connected to the columns by bolts. The third type of steel jackets designed with length 500 mm for the last two columns included (3, 4) external steel ties (25*5) mm. The results indicated that the first type of steel jackets improved the ultimate load more than the other types. Also, increasing the number of external ties increased the ultimate load of the strengthened columns. Furthermore, authors did not recommend using plates with small thickness (less than 3 mm) in strengthening columns.

The main function of the steel strips is to delay local buckling of the vertical angles and to reduce the horizontal expansion of the concrete column [6]. Increasing number or size of steel strips delays steel angles buckling. Also increasing the number of steel straps that are used with steel angles does not increase the load capacity, while its use with channel sections increased the column load capacity.

Ferrotto et al. [7] studied the effects of preloading on the compressive behavior of RC columns retrofitted with steel jackets and external ties under sustained loads. Ten RC columns with dimensions (200*200*750) mm were tested. Two columns served as control columns and eight were confined with four angles (50*50*5) mm and seven patterns of steel plates (40*4) mm. Six columns were preloaded with (40, 60, 72, 80) % of column compression strength. Results showed that steel jacketed specimens which were not preloaded exhibited higher ultimate load capacity.

The type of grout material that are used to fill the gap between the steel and the concrete affects the system performance. The higher bond strength of grout material the more delayed the separation between steel and surface of concrete column [6]. Using epoxy grout instead of cement grout slightly enhanced the behavior of the strengthened column. Therefore, it may be economical to use cement grout to fill the gap between the steel jacket and concrete column due to the higher cost of epoxy grout compared with that of cement grout.

**Advantage:** Steel jacketing technique is suitable for strengthening non-ductile columns and non-damaged columns. Also, partial steel jacketing with steel ties is suitable for columns with poor arrangement of straps. Furthermore, using steel jacketing technique causes minimal increase in column dimension, costs less, and reduces construction time.

**Disadvantage:** Steel jackets have the potential to degrade seriously under corrosive environments and fire, a poor appearance in cases where large steel sizes are used. In cases of partial steel jacketing, strengthening improves shear strength only.

**Table 1.** Design & scope of applicability for steel jacketing technique.

| Method          | Factors affecting the design                        | Scope of applicability                            |
|-----------------|-----------------------------------------------------|---------------------------------------------------|
| Steel jacket    | • Area of coverage                                  | • Non-ductile columns                             |
|                 | • Shape of longitudinal steel                       | • Non-damaged columns                             |
|                 | • Horizontal straps                                 | • Columns with poor arrangement of straps         |
|                 | • Column head connection                            | • Columns in non-corrosive environments or non-fire potential areas |
|                 | • Types of gout materials                           |                                                   |
2. Concrete jacketing

Reinforced concrete jacketing has been used widely for rehabilitation of highly damaged or earthquake-prone RC columns. Additional reinforced concrete shell (reinforcing steel cage and a different concrete material) is placed around the damaged column. Adhesive material or anchorage bolts are used to improve bonding between the column and new layers, figure 4 shows details of concrete jacketing types.

Figure 3: details of partial steel jacketing types [5] (a) partial steel jacketing using anchor bolts, (b) & (c) partial steel jacketing using external ties with differently spaced straps, (d) & (e) partial steel jacketing using angles with differently spaced straps.
Several studies investigated strengthening RC columns using concrete jacketing techniques. Sayed et al. [8] carried out a study to investigate the effect of increasing longitudinal reinforcing steel bars on concrete jacketing performance. Fifteen columns were fabricated in three categories: five square columns with dimensions (200*200*1200) mm, five rectangular columns with dimensions (160*250*950) mm and five circular columns with a diameter of 160 mm. First and second groups were strengthened with 50 mm thick reinforced concrete jacket and different reinforcing steel bars (4 Ø 12, 6 Ø 12, 8 Ø 12) while circular columns were strengthened with (4 Ø 10, 6 Ø 10, 8 Ø 10). Anchorage bolts and Kemepoxy adhesive material were used to improve bonding strength between column surface and the concrete jacket. The testing results showed that using reinforced concrete jackets increased column ultimate load capacity. Also, results indicated that ultimate load capacity increases with the increase in the longitudinal steel bars.

The effect of adding longitudinal reinforcing steel bars to the reinforced concrete jackets on the ultimate load capacity is approximately linear. Zakaria H. Helles [9] tested 27 square RC columns with dimensions (100*100*300) mm under axial load. The columns were strengthened with thin concrete jackets with thickness of (25, 30, 35) mm. Ultra-High Performance Self-Compacting Concrete (UHPSCC) without steel reinforcement, Non-Fibrous UHPSCC with steel reinforcement and Fibrous (UHPSCC) with steel reinforcement were used as the concrete jacketing techniques for strengthening. The results showed that Fibrous (UHPSCC) with steel reinforcement exhibited higher ultimate capacity load than the other techniques.

Tayeh et al. [10] investigated the efficiency of concrete cover types that were used for rehabilitation of damaged concrete columns. Forty-five normal strength concrete columns have been tested. Nine columns were considered as reference columns which included three unjacketed columns and six columns with (25, 35) mm thick normal strength concrete jackets. The other thirty-six columns were strengthened with concrete jackets that included additional reinforced steel bars (4 Ø 10), (25,35) mm jacketing thickness, ultra-high-performance fiber-reinforced self-compacting concrete (UHPFRSCC) and normal strength concrete (NSC) as concrete jacketing materials. Surface roughening using mechanical wire brushing and mechanical scarification, and using shear studs were employed as methods to improve bonding between columns and concrete jackets. The results indicated that using (UHPFRSCC) jacket exhibited higher ultimate load capacity than (NSC) jacket. Also, increasing the jacket thickness increased ultimate load capacity. Furthermore, bonding using shear studs increased ultimate load capacity more than other bonding methods.
the ultimate load capacity depends on the material properties used in the cover jacket. Ultra-high performance fibre-reinforced self-compacting concrete (UHPFRSCC), Fibrous concrete reinforced and normal strength concrete (NSC) are the commonly used materials for concrete jacketing. Previous studies showed that (UHPFRSCC) performs better than the other types.

Mahmud et al. [11] performed an experimental study to investigate the effect of interface preparation on the developed bond strength between the column and the added concrete jacket. Twelve columns were fabricated with dimensions (102*102*800) mm and weak concrete (10–14) MPa. The columns were strengthened with four additional longitudinal steel bars and (25–31.5) mm concrete jacket thickness. Eleven columns were prepared with different bonding conditions: untreated and unbonded surface, treated and bonded surface and treated and bonded surface with welded ties. The experimental results showed that RC column jacket increased the column capacity, and the degree of enhancement varied according to the bonding conditions. Treated and bonded surface with welded ties showed higher load capacity than other conditions.

In order to provide good mechanical interlocking between old and new concrete, suitable methods must be used to roughen the column surface. There are many methods used to roughen column surface such as sandblasting, hand chipping, jackhammering, electric hammering, water demolition and iron brushing. Previous studies stated that sandblasting was the most efficient roughening method among those considered [6]. For high-quality bonding condition, cementitious Grouting Solutions (BASF Master Flow), anchorage bolts, welding and different adhesive materials are used.

Wibowo et al. [12] in their sustainability study investigated the use of bamboo bars as an alternative material for steel reinforcement bars in concrete jacketing techniques. Experimental work included 18 specimens retrofitted with (4,8) bamboo bars (10*10, 10*5) mm, and stirrups (bamboo, steel) with different spacing (70, 100, 140) mm. The results showed that using bamboo bars enhanced ultimate load capacity. Also using longitudinal bamboo bars with steel stirrups exhibited the highest ultimate load capacity.

Sustainable materials are one of main topics that attract attention of designers around the world. Using sustainable materials for retrofitting columns is a very good idea to reduce costs, provide alternatives for construction materials and reduce the pollution [13-14].

**Advantage:** Concrete jacketing technique increases stiffness of the structure, improves the seismic performance of the column in terms of axial load carrying capacity, flexural strength and ductility.

**Disadvantage:** Concrete jackets cause enlargement in column sections, add additional weight, require skilled labor and quality control, cost more, and its construction work is time consuming.

**Table 2:** Design & scope of applicability for concrete jacketing technique.

| Method            | Factors affecting the design                        | Scope of applicability                                      |
|-------------------|-----------------------------------------------------|-------------------------------------------------------------|
| Concrete jacket   | • Longitudinal steel bars                            | • Strengthening earthquake-resistant columns                |
|                   | • Types of thin concrete jackets                      | • Highly damaged columns                                     |
|                   | • Surface roughness & bonding                         | • Columns in potential fire zones                           |
|                   | • Connection with slab and footing                    |                                                             |
|                   | • Thickness of concrete jackets                       |                                                             |
|                   | • Stirrups spacing                                   |                                                             |

### 3. Ferrocement jacketing technique

Ferrocement jacketing is an effective retrofitting technique for RC columns. Ferrocement jacketing system consists of thin reinforced mortar (cement-sand mortar) wall with one or more layers of woven wire mesh or welded wire mesh. It provides an alternative solution for retrofitting RC columns compared with highly expensive techniques like steel jacketing and concrete jacketing. Several studies investigated the behavior of ferrocement strengthening method over the past years.
Balamuralikrishnan et al. [15] studied the behavior of full and partial ferrocement jacketing of RC columns. Four control columns with dimensions (150*150*450) mm and twelve columns strengthened with (full and partial) ferrocement jacketing by using (Single, two, three) pre-woven mesh layers and 20 mm ferrocement wall thickness were tested as seen in Figures 5-a and 5-b. The results showed that the confinement with three pre-woven mesh layers exhibited high ultimate load capacity. Also using full ferrocement jacketing enhanced compressive strength more than partial jacketing.

Masud. et al. [16] investigated the efficiency of using ferrocement as wrapping material to confine a circular RC Pedestal. Three control columns with dimensions (150, 260) mm and six other columns...
(same dimensions) strengthened with (one, two) wire mesh layers. The results indicated that confinement with one layer of wire mesh increased load carrying capacity by 23.8%, while using two layers increased load carrying capacity by 55.2%.

The number of wire mesh layers are key factors to consider in the improvement of the ultimate load capacity for repaired columns using ferrocement jacketing technique. Also, the axial deformation increases with the increase of number of wire mesh layers and decreases with the increase of the aspect ratio and preloading condition.

Kaish et al. [17] carried out an experimental study to repair RC columns using semi-automated ferrocement jacketing strengthening system. The jacket was prepared in a controlled laboratory environment with automation technology (Figure 6). Installation process has been done in-place using nut-bolted connections. Tow square RC columns with dimensions (150*150*300) mm were prepared as control columns with 20 MPa in addition to four columns strengthened with semi-automated ferrocement jacketing (L-shape, C-shape). Cement grout and nut-bolted connections were used to improve bond strength between the jacket and concrete stub. The results showed that using C-shape and L-shape semi-automatic ferrocement jacketing increased the ultimate stress by 68.3% and 40%, respectively, compared with unjacketed columns.

![Figure 6: details installation process of semi-automatic ferrocement jacketing system [17]](image)

That new semi-automated ferrocement jacketing technique to retrofit RC columns provided many advantages such as reduced fabrication time, high quality products and reduced labor cost. This technique is expected to see a rapid growth in the construction industry.

Xiong et al. [18] proposed two methods for retrofitting RC columns with ferrocement technique; bar mat-mortar (BM) and ferrocement including steel bars (FS) (see Figure 7). The experimental program included casting 33 circular columns with a diameter of 105 mm and length of 450 mm. All specimens strengthened with BM and FS systems were confined using (one, two, three, four) wire mesh layers. For FS confinement method, using steel bars enhanced the ultimate strength, while for BM confinement method adding wire mesh improved jacketing system by increasing the column ductility.
Kim and Kim [19], studied the seismic performance of bridge rectangle columns (see Figure 8 for column details), in which the lap-spliced region was confined with Stainless Steel Wire Mesh (SSWM) and thin ferrocement jacketing, under cyclic lateral loads. Elliptical and rectangular cross-sections were used to retrofit the rectangle columns (refer Figure 9 for retrofitting details). The results showed that wrapping with elliptical shape for both SSWM and exhibited the highest increase in ultimate load capacity.

Figure 7: (a) BM confined & FS confined [18]

Figure 8: (a) before confinement   & (b) after confinement [19]
Figure 9: shape for mortar casting and (SSWM) wrapping [19]

Table 3. Design & scope of applicability for ferrocement jacketing technique.

| Method            | Factors affecting the design                                      | Scope of applicability                      |
|-------------------|------------------------------------------------------------------|---------------------------------------------|
| Ferrocement jacket| • Number of wire mesh layers                                      | • Ductile columns                           |
|                   | • Thickness of the thin mortar wall                               | • Highly damaged columns                    |
|                   | • Materials of thin mortar wall                                   | • Columns in potential fire zones           |
|                   | • Bonding strength                                                | • Strengthening earthquake-resistant columns|
|                   | • Shape of the thin mortar wall                                   |                                            |

Advantage: Ferrocement jacketing technique is a very easy technique to implement, and it does not require highly skilled workers. Ferrocement confinement improves ultimate load capacity, resistance to impact, resistance to earthquake excitations, resistance to fire and corrosion, and reduces the cost of maintenance.

Disadvantage: Ferrocement jacketing causes enlargement in column section and adds additional weight.

4. CFRP jacketing technique

Using of carbon fiber in strengthening and repairing structural elements has started since the 1960 of the last century as an alternative to the classical methods that often rely on enlarging the cross section of these elements. Carbon Fiber-reinforced polymer (CFRP) is a light-weight composite material that consists of carbon fibers and a polymer matrix. The CFRP is typically installed using an epoxy resin or other resins such as polyurethane [20-22]. The epoxy resin is used to saturate the carbon fibers and attach the composite wrap to the structural member. A lot of investigations have been conducted about the performance on the CFRP jacketing repairing technique.

Jian et al. [23] investigated the shear capacity of reinforced concrete columns strengthened with CFRP sheets. Four columns strengthened with parameters (One & two layers of high strength CFRP sheet, One & two layers of normal strength CFRP sheet) were tested. The tests revealed that the shear capacity of the strengthened RC column is not proportional to the CFRP amount. To some degree, the
shear capacity increased with increasing CFRP amount. However, when the CFRP amount became significant, shear enhancement was negligible.

There are two popular CFRP techniques used for retrofitting RC columns, CFRP confinement form as stirrups or continuous jacketing and near surface mounted (NSM) reinforcement, the confinement increases the concrete compressive strength and ductility as seen in the confined stress-strain models.

Mercimeka et al. [24] investigated the enhancement in strength, ductility, and energy dissipation capacity of RC column by using CFRP strips with width (25, 50) mm and distance (50, 75, 100) and fan type CFRP anchors. Figures 10 and 11) and Table 4 show the strengthening details of specimens. The results indicated that increasing width of CFRP strips and decreasing distance between them exhibited high ultimate axial load capacity. Also, increasing cover area of CFRP and number of anchors improved energy dissipation capacity.

![Specimen images](image-url)

**Figure 10**: show Strengthening details of specimens.[24]

| Specimen No. | Remarks                     | Strengthening Definition                  |
|--------------|-----------------------------|------------------------------------------|
| 1            | References                  | --                                       |
| 2            | CFRP strip wrapping         | CFRP (Sf = 50 mm, Wf = 25 mm)            |
| 3            | CFRP strip wrapping         | CFRP (Sf = 75 mm, Wf = 25 mm)            |
| 4            | CFRP strip wrapping         | CFRP (Sf = 75 mm, Wf = 50 mm)            |
| 5            | CFRP strip wrapping         | CFRP (Sf = 100 mm, Wf = 50 mm)           |
| 6            | CFRP strip by longitudinally| One strip on each side of a column       |
| 7            | CFRP strip wrapping & Anchorage | CFRP (Sf = 50 mm, Wf = 25 mm)        |
| 8            | CFRP strip wrapping & Anchorage | CFRP (Sf = 75 mm, Wf = 25 mm)        |
| 9            | CFRP strip wrapping & Anchorage | CFRP (Sf = 75 mm, Wf = 50 mm)        |
| 10           | CFRP strip wrapping & Anchorage | CFRP (Sf = 100 mm, Wf = 50 mm)       |
| 11           | CFRP strip by longitudinally & Anchorage | One strip on each side of a column |
Gajdosova et al. [25] studied the efficiency of NSM CFRP strips retrofitting method for long columns and compared it with partial jacking of CFRP sheet method (refer to Figure 12). All columns failed in buckling and ultimate compression strength increased by 12.9 % with NSM method compared with 2.4 % increase with CFRP method.

Confinement effect of partial CFRP sheet jacking method is more effective in the case of short columns, while its effects on long columns is negligible. On the other hand, NSM retrofitting method is a good alternative to enhance resistance for both short and long rectangular concrete columns without significant cross section enlargement as well as act more efficiently in tension, which occurs during long column buckling.

Vrettos et al. [26] carried out an experimental study on the behavior of RC columns retrofitted with anchored carbon-fiber sheets with different characteristics (See Figure 13). Strengthening procedure included carbon-fiber sheet 1.4 m long and 200 mm wide that was bonded on two opposite column sides and anchored with fiber spikes. The spikes that were formed from dry carbon fibers, half dry and half coated with epoxy were applied on top of the CFRP sheet with two or three anchors per side. The results indicated that anchored carbon-fiber sheets improved the flexural resistance of RC columns under seismic loading. Also, it was found that the effectiveness of anchors increases almost linearly with their weight.

This method of anchoring was selected based on tensile force transfer from the CFRP sheet, which is terminated at the bottom of each column, into the concrete base. Ozcan, et al. [27] investigates the seismic repair of undamaged and moderately damaged square RC columns with CFRP jacking under a constant axial load of 27% of the column axial capacity and reversed lateral cyclic loading. Repairing
process included rounding column corners to a radius of (30,10) mm and wrapping the columns with one layer of CFRP sheet. FRP strengthening enhanced the column ultimate capacity load and ductility. Corner-rounding radius is an important factor that influence the behavior of square and rectangular columns retrofitted with CFRP jacketing in terms of ultimate load capacity, curvature, ductility, and energy dissipation.

![Figure 13: (a) Control column, (b, c and d) anchored carbon-fiber sheets [26]](image)

**Advantages:** CFRP composites are lightweight materials and they are easy to install on site without disturbing traffic in case of bridge applications. They also do not have corrosion problems like the case of steel jacketing and possess high resistance to chemical attacks. They are protective under fire attack.

**Disadvantage:** CFRP jackets are costly.

**Table 5: Design & scope applicability for CFRP jacketing technique.**

| Method      | Main Factors affecting the design | Scope of applicability                      |
|-------------|----------------------------------|---------------------------------------------|
| CFRP jackets| • Fiber Orientation              | • Ductile columns                           |
|             | • Fiber Volume                   | • Columns in potential fire areas           |
|             | • Type of resin used             | • Strengthening earthquake-resistant columns|
|             | • Corner-rounding radius         |                                             |

5. **GFRP jacketing technique**

In recent years, the use of GFRP has shown considerable interest in the construction industry as a material for strengthening of concrete structures because of its economic cost and high strength characteristics. Glass fibers are available in E-Glass, and S-Glass (high silica), and C-Glass (chemical grade). There has been work done on strengthening RC columns by using GFRP jacketing technique in previous years.

Benzaïd et al. [28] studied the effect of number of layers and corner-rounding radius (see Figure 14) for square RC columns confined using GFRP. Experimental work included seven columns with (8,16) mm corner-rounding radius and wrapped with (1, 2) E-glass fiber composite layers. The results indicated that confinement of RC columns with two layers of GFRP sheets enhanced ultimate load capacity by 5.8 % while the enhancement was 28 % with 16 mm corner-rounding radius.
Figure 14: effect of corner-rounding radius on confined square RC columns [28]

The efficiency of GFRP jacketing is less with a square or rectangular section (R = 0 mm) compared with corner-rounding radius (R > 0 mm). This is due to a high concentration of stresses at the corner of the square section in addition to the smaller effectively wrapped concrete core in this case (R = 0 mm) compared to that with corner-rounding radius (R > 0 mm).

Sudhakar and Partheeban [29] investigated the effect of increasing GFRP layers on the behavior of strengthened RC Columns. Nine columns were tested with (1, 2) layers of GFRP jacketing. The experimental results showed that confinement with one layer enhanced the column axial compressive capacity by 15.31 % while the 2-layer wrapped columns exhibited an increase of 31.35 %.

Ravala and Dave [30] studied the effect of column shape on retrofitted RC columns with GFRP jacketing. Fifteen columns with different shapes (square, rectangular and circular) having the same cross-section area were prepared and wrapped with one-layer of GFRP sheet. Results showed that circular column exhibited the highest increase in ultimate load capacity compared with the square and rectangular columns.

Variations in column shape play an important role in increasing the axial load carrying capacity. In circular cross sections, uniform lateral pressure and uniform stresses are produced. In non-circular sections, the stress distribution is complex and irregular, and the performance of the column is less compared to the case of circular cross sections.

Elsanadedy et al. [31] carried out an investigation focused on the thermal resistance for RC columns confined with GFRP jacketing. Strengthened specimens were subjected to a temperature of 200 °C for 3 hours and tested after cooling down to ambient temperature. The resulted peak axial load was 2047 kN compared with 2332 kN for the control column.

The performance of GFRP strengthened concrete columns is affected by the rate of temperature increase. For a specific target temperature, when the temperature rate rises, the deterioration in concrete strength becomes more noticeable.

Saravanan et al. [32] studied the effect of GFRP sheet thickness on the behavior of confined high strength RC columns subjected to axial load. GFRP sheets with (3, 5) mm thickness have been used to wrap the column specimens. The results indicated that increasing GFRP thickness led to enhanced ultimate load capacity and other characteristics.

Advantages: The cost of glass fibers is more suitable than other fibers, and its tensile strength is high. The chemical resistance of the glass fiber is also high and thus it is suitable for corrosive environments. Also, it has a thermal resistance.

Disadvantage: GFRPs are sensitive to abrasion during transport. The GFRP sheet is relatively fragile and brittle. The fatigue resistance of the GFRP is relatively low.

Table 6: Design & Scope applicability for GFRP jacketing technique.

| Method      | Main Factors affecting the design | Scope of applicability                      |
|-------------|-----------------------------------|---------------------------------------------|
| GFRP jackets| • Fiber Orientation               | • Ductile columns                           |
|             | • Fiber Volume                    | • Columns in potential fire areas           |
|             | • Type of resin used              | • Strengthening earthquake-resistant columns|
|             | • Corner-rounding radius          |                                             |
6. Conclusions:

A number of different rehabilitation and retrofitting techniques for RC columns are presented in this paper. The experimental methods and results of numerous previous investigations were reviewed, and the parameters that influence the techniques design and scope of applicability were evaluated and summarized. Several outcomes can be drawn from the review and can be summarized as follows:

1. Steel jacketing techniques have been widely employed to strengthen deficient RC columns due to readily available design methods for steel-confined concrete. Steel jackets provide a passive lateral pressure, similar to the internal transverse reinforcement, which is activated when the column dilates laterally under the effect of axial load.

2. Concrete jackets incorporate the addition of concrete, longitudinal and transverse reinforcement as a shell that encloses the existing member. This strengthening technique improves the column axial, shear, flexural strength and stiffness. The bond between the old and new concrete should be enhanced beforehand by roughening the surface of the original member.

3. Ferrocement jacketing is an effective retrofitting technique, and it provides an alternative solution for retrofitting RC columns over highly expensive techniques like steel jacketing and concrete jacketing. This technique does not require highly skilled labor. Ferrocement confinement improves ultimate load capacity, resistance to impact, resistance to earthquake, resistance to fire and corrosion, reduces the cost of maintenance.

4. Carbon Fiber Reinforced Polymers (CFRPs) have been used to strengthen and rehabilitate concrete columns, beams, and slabs. The CFRP composite has many advantages compared to other traditional techniques. CFRP sheets have a high strength to weight ratio, very high resistance to corrosion and chemical attacks which makes them, unlike steel plates and concrete jackets, suitable for structures subjected to aggressive environments.

5. Glass Fiber Reinforced Polymers (GFRPs) are great composites for strengthening RC columns. They have shown excellent durability and performance, and they are being widely applied in the construction field because of their light weight and minimal increase in member dimensions. Also, GFRP strengthening technique is time saving.

References:

[1] Tarabia A M, Albakry H F 2014 Strengthening of RC columns by steel angles and strips Alexandria Eng. J. 53(3) 615-626

[2] Campione G, Cannella F, Cavaleri, Ferrotto M F, Papia1M 2018 Assessment of the load carrying capacity of reinforced concrete columns strengthened by steel cages Conf. Italian Concrete Days 2018At: Lecco IT.

[3] Ezz-Eldeen H A 2016 Steel Jacketing Technique used in Strengthening Reinforced Concrete Rectangular Columns under Eccentricity for Practical Design Applications Int. J. Eng. T. T. 35 195-204.

[4] Belal M F, Mohamed H M, Morad Sh A 2015 Behavior of reinforced concrete columns strengthened by steel jacket H. B. R. C. J. 11 201-212.

[5] Abdel-Hay A Sh, Fawzy Y A Gh 2015 Behavior of partially defected R.C columns strengthened using steel jackets H. B. R. C. J. 11 194-200.

[6] Julio E S, Branco F, Silva V D 2003 Structural rehabilitation of columns with reinforced concrete jacketing Prog. Struct. Eng. Mater. 5 29–37.

[7] Ferrotto M F, Cavaleri L, Papia M 2018 Compressive response of substandard steel-jacketed RC columns strengthened under sustained service loads from the local to the global behavior Cons. Build. Mater. 179 500–51.
[8] Sayed A M, Rashwan M M, Helmy M E 2020 Experimental Behavior of Cracked Reinforced Concrete Columns Strengthened with Reinforced Concrete Jacketing *Materials* **13** 2832.

[9] Helles Z. H. 2014 *Strengthening of Square Reinforced concrete columns with fibrous ultra-high performance self-compacting concrete jacketing*. M.Sc Thesis the Islamic University Gaza 1-103.

[10] Tayeh B A, Naja M A, Shihada S, and Arafa, M 2019 Repairing and Strengthening of Damaged RC Columns Using Thin Concrete Jacketing, *Adv. Civ. Eng. J.* **2** 1-16.

[11] Mahmud R, Ahmed KS 2020 Interface dependency of reinforced concrete jacketing for column strengthening *Proc. Institu. Civ. Eng. – Stru. Build.* **173** 31–41.

[12] Wibowo A, Wijatmiko I, Nainggolan Ch R 2019 Axial behavior of RC columns retrofitted using bamboo reinforced concrete jacket, *Int. J. geo.* **17**(60) 6016-23.

[13] Naji A J, Mousa M A, Malik S H 2019 The Production of the Sustainable Concrete by using Different Types of Plastic Waste. *J. Eng. Appl. Sci.* **14** 5557-5560.

[14] Naji A J, Al-Yousefi HA, Mousa MA, Hussein MJ 2019 Optimization of water-cement ratio in concrete contains recycled polypropylene (PP) plastic waste *Periodicals Eng. Natur. Sci.* **7** 1563-1566.

[15] Balamuralikrishnan R, Al Madhani M, Al Madhani R 2019 Study on Retrofitting of RC Column Using Ferrocement Full and Strip Wrapping, *Civil Eng. J.* **5**(11)

[16] Masud Md M, Kumar A 2016 Strengthening of Circular RC Column through External Confinement using Ferrocement *Indian J. Sci. Technol.* **9**(30) 1-5

[17] Kaish A B M A, Nahar L, Jaafar A, Ahmed Y 2018 Prospects of using Prefabricated Ferrocement Jacket for Semi-Automated Strengthening of RC Column Electron. *J. Stru. Eng.* **18**(2) 52-57.

[18] Xiong G J, Wu X Y, Li F F, Yan Z 2011 Load carrying capacity and ductility of circular concrete columns confined by ferrocement including steel bars *Constr. Build. Mate.* **25** 2263–2268.

[19] Kim S H, Kim D K 2011 Seismic retrofit of rectangular RC bridge columns using wire mesh wrap casing *KSCE J. Civ. Eng.* **15** 1227-1236.

[20] Al-Jelawy H M, Mackie K R 2020 Flexural Behavior of Concrete Beams Strengthened with Polyurethane-Matrix Carbon-Fiber Composites *J. Compos. Constr.* **24**(4) P.04020027.

[21] Al-Jelawy H M 2013 *Experimental and Numerical Investigations on Bond Durability of CFRP Strengthened Concrete Members subjected to Environmental Exposure*. M.Sc Thesis University of Central Florida.

[22] Al-Jelawy H M, Mackie K R 2021 Durability and Failure Modes of Concrete Beams Strengthened with Polyurethane or Epoxy CFRP *J. Compos. Constr.* **25**

[23] Jian X, Xue-mei L., Tong Z 2006 Shear capacity of reinforced concrete columns strengthened with CFRP sheet J *Zhejiang Univ SCI* **6A**(8):853-858.

[24] Mercimek Ö, Ghoroubi R, Anil Özg., Çakmak C, Özdemir A, Kopraman Y 2020 Strength ductility and energy dissipation capacity of RC column strengthened with CFRP strip under axial load *Mech. Based Desig. Struc. Machi.* **25** 1-19

[25] Gajdosova K, Bilicik J 2013 Full-Scale Testing of CFRP-Strengthened Slender Reinforced Concrete Columns J. *Compos. Constr.* **17** 239-248.

[26] Vrettos L, Kefala E, Triantafillou Th C 2013 Innovative Flexural Strengthening of Reinforced Concrete Columns Using Carbon-Fiber Anchors *ACI Struc J.* **110**(1) 63-70.
[27] Ozcan O, Binici B, Canbay E, Ozcebe G Repair and strengthening of reinforced concrete columns with CFRPs J. Reinf. Plast. Compos. 29 (22) 3411–3424.

[28] Benzaid R, Chikh, Habib M 2008 Behavior of square concrete columns confined with GFRP composite warp J. Civ. Eng. Manag. 14 115–120.

[29] Sudhakar R, Partheeban P 2017 Strengthening of RCC Column Using Glass Fibre Reinforced Polymer (GFRP) Int. J. Appl. Eng. Res. 12 4478–4483.

[30] Ravala R, Daveb U 2013 Behavior of GFRP wrapped RC Columns of different shapes Proc. Eng. 51 240 – 249.

[31] Elsanadedy H, Almusallam T Al-Salloum, Y, Iqbal R 2017 Effect of high temperature on structural response of reinforced concrete circular columns strengthened with fiber reinforced polymer composites J. Compos. Mate. 51 333–355.

[32] Saravanan J, Suguna K, Raghunath P N R 2012 Strength and Ductility of High Strength Concrete Columns with Glass Fiber Reinforced Polymer Wraps Asian J. Civ. Eng. Build. Hous. 13 585-595.