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Review

Strengthening and Repair of Reinforced Concrete Columns by Jacketing: State-of-the-Art Review

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Abstract: Sustainability necessitates the protection of infrastructure from any kind of deterioration over the life cycle of the asset. Deterioration in the capacity of reinforced concrete (RC) infrastructure (e.g., bridges, buildings, etc.) may result from localised damage sustained during extreme loading scenarios, such as earthquakes, hurricanes or tsunamis. In addition, factors such as the corrosion of rebars or ageing may also deteriorate or degrade the capacity of an RC column, thereby necessitating immediate strengthening to either extend or ensure its design life is not limited. The aim of this paper is to provide a state-of-the-art review of various strengthening and repair methods for RC columns proposed by different researchers in the last two decades. The scope of this review paper is limited to jacketing techniques for strengthening and/or repairing both normal- and high-strength RC columns. The paper also identifies potential research gaps and outlines the future direction of research into the strengthening and repair of RC columns.

Keywords: RC columns; strengthening; repair; jacketing

1. Introduction

There is an increasing focus and emphasis on the sustainability of existing infrastructure. The rehabilitation and strengthening of damaged or deficient reinforced concrete (RC) structures has the potential to restore and/or enhance the structural performance to a level required by current design codes. Rehabilitation and/or strengthening is a more sustainable solution compared to simply just demolishing and reconstructing the entire facility, from both the point of view of the conservation of resources (e.g., time, cost, materials, etc.) and the reducing the overall carbon footprint of the construction industry.

Seismic retrofitting and/or the strengthening of RC columns has been a popular area of research for decades. This is primarily because, in a building frame system or a bridge, the imposed seismic energy demand is dissipated by the displacement of the columns, thereby resulting in slight to severe damage depending on the severity of the earthquake, and hence the need for repair emerges to ensure the smooth post-earthquake recovery of the facility. Secondly, RC building structures that were designed prior to the incorporation of seismic detailing guidelines of the 1970s generally possess non-ductile RC columns, which make them inherently vulnerable during an earthquake. Strengthening techniques can be used to upgrade columns of this nature and allow them to conform to the latest code requirements. The need for strengthening and repair may also arise because of a number of other factors such as the ageing of structure, deterioration of concrete, change in building use and loading requirements, design errors, corrosion of reinforcement and construction mistakes during erection.

Researchers over the past two to three decades have been endeavoring to develop appropriate strengthening and repair techniques for RC columns that balances the structural requirement to enhance the strength, ductility and drift with various non-structural requirements, such as minimising implementation/construction costs, limiting any disruption to building occupants during construction, maintaining the aesthetics of the structure, maintaining or increasing durability and ensuring work safety. Time of repair is another crucial factor, particularly for post-disaster facilities, such as hospitals or emergency services facilities, and shelters that house a significant number of people. Similarly, the functionality of bridges also needs to be maintained or quickly restored immediately after an earthquake, which underscores the importance of rapid strengthening and repair techniques. There are also other challenges and complexities associated with strengthening and repair that need to be dealt with, such as localised changes to the member stiffness, which can possibly change the dynamic properties of the structure and, consequently, change the seismic demands on individual elements or the building as a whole

The earliest proposed strengthening techniques such as steel jacketing or concrete incasing enhanced the seismic performance of the structure by enlarging the cross-section of the column. Since then, researchers have been proposing and evaluating techniques that result in a minimum modification to the structural geometry, while simultaneously enhancing the structural capacity. Fiber-reinforced polymers (FRPs) have widely been seen as an attractive alternative to traditional retrofitting techniques and significant research efforts internationally have been undertaken to investigate various aspects of FRP strengthening. More recently, however, hybrid jacketing, which essentially combines the advantages of different retrofitting methods/materials, has become increasingly popular and the primary focus of most recent research efforts.

This paper provides a state-of-the-art review of different strengthening and repair techniques for RC columns over the last two decades. The authors have reviewed the effectiveness of each of the techniques and also identified potential future research areas to address research gaps.

It is noted that the term 'repair' in the context of this paper generally refers to any methods used to restore the capacity of a damaged RC column; whereas the terms 'strengthening' and 'retrofitting' are generally used interchangeably to refer to any methods used to enhance the capacity of existing RC column. The scope of the paper has generally been limited to 'jacketing' techniques for strengthening and/or repairing RC columns only. Other retrofitting techniques relating more directly to beam–column joints, such as the use of a haunch or knee brace [1,2], are outside the scope of this paper.

The strengthening and repair techniques for RC columns presented in this paper have been broadly categorized into six types, reinforced concrete/mortar jacketing; steel jacketing; externally bonded fiber-reinforced polymer jacketing; near-surface mounted fiber-reinforced polymer jacketing; shape memory alloy (SMA) jacketing; and hybrid jacketing. This state-of-the-art review included 99 studies that have been conducted on the strengthening of RC columns in the last two decades. Of these studies, externally bonded FRP strengthening has been the most popular method in literature, with approximately 59 studies, as shown in Figure 1.

Summaries of the experimental studies employing each of these six broad categories of strengthening and repair techniques is presented in Sections 2–7 respectively. A summary of all the experimental studies for strengthening and repair techniques, respectively, is presented later in Tables 1 and 2. The experimental studies were conducted under three types of loading conditions, namely, unidirectional cyclic lateral loading with constant axial load, bi-directional cyclic lateral loading with constant axial load and hybrid simulation. This is followed by Section 8, which provides a comparison and discussion of the different techniques, and Section 9, which presents research gaps and future potential research directions.

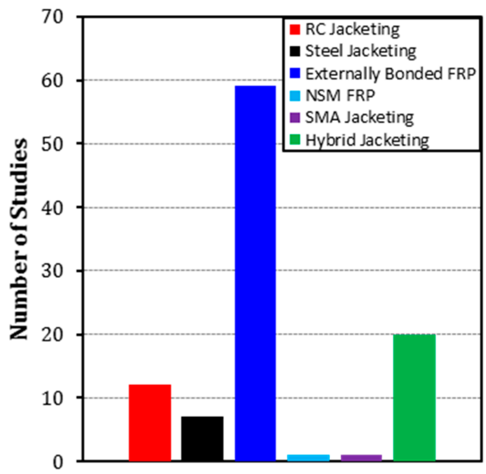


Figure 1. An overview of the experimental studies on the strengthening and repair of reinforced concrete (RC) columns published in the last two decades.

2. Reinforced Concrete/Mortar Jacketing

RC jacketing has been used extensively for strengthening and repairing deficient and damaged RC columns, respectively. In traditional reinforced concrete jacketing, the section of the column is enlarged by casting a new reinforced concrete/mortar section over a part or the entire length of the column. The new section is bonded to the original section through anchor rebars or high-strength bolts. Although this technique improves the seismic performance of the column in terms of axial load carrying capacity, flexural strength and ductility, it is costly and time consuming due to the installation of the formwork. Moreover, the improvement in ductility is relatively small because the jacketing material (i.e., concrete) is brittle. Furthermore, it results in a change in the cross-sectional area of the column, thereby changing the mass and stiffness of the structure, and hence reducing the natural period of the structure, which consequently results in higher seismic demands on the structure. Therefore, high-performance RC materials have been used more recently for jacketing purposes, so that the specimen is strengthened/repaired without a change in the cross-sectional size. The summary of the developments and improvements in the RC/mortar jacketing techniques is provided below.

Lehman et al. [3] repaired moderately to severely damaged circular RC columns with freshly cast concrete along with headed reinforcement and mechanical couplers and reported that although the strength and ductility were restored, the stiffness was not fully restored for moderately damaged columns. The repair technique also proved to be ineffective in restoring the behavior of severely damaged specimens.

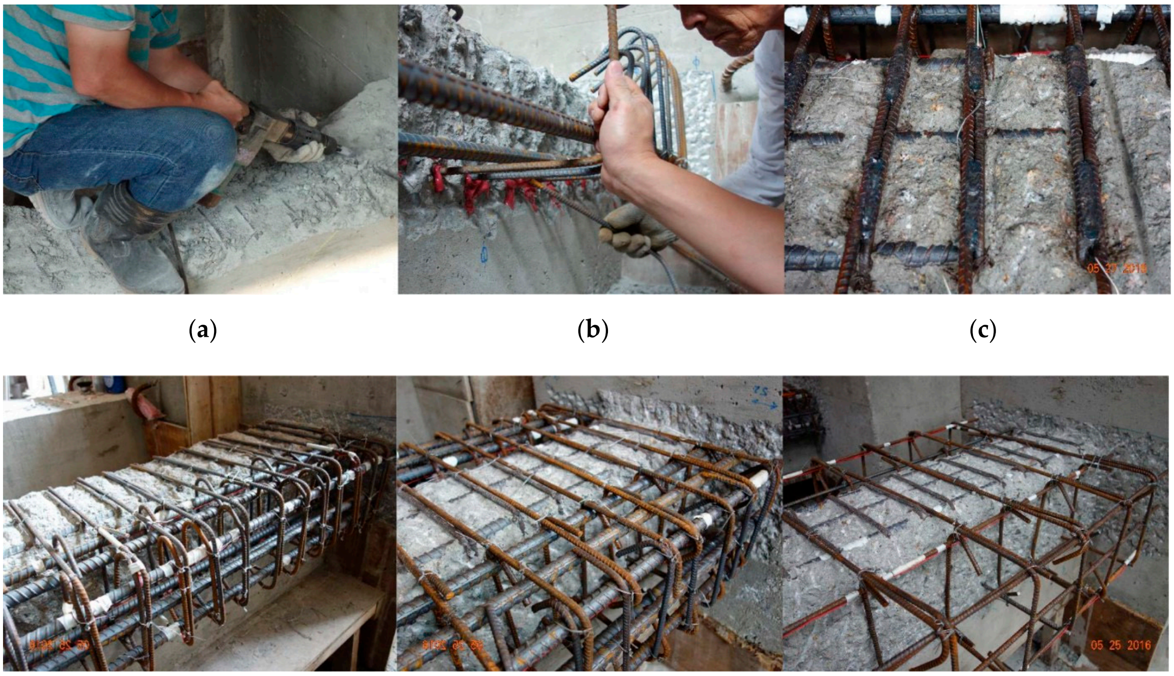
Vandoros and Dristos [4] also used RC jackets with welded stirrup ends, which resulted in the enhancement of the strength and ductility of the RC columns; however, it was reported that the jacket separated from the original column due to a lack of surface/bonding treatment at the interface. The welding of stirrup ends proved to be effective in preventing the buckling of longitudinal reinforcement.

In another study, Chang et al. [5] compared the performance of RC jacketing and wing wall (small concrete panels installed at both sides of the column) installation and found that RC jacketing results in a larger enhancement of energy dissipation and ductility of the deficient RC columns.

In order to reduce the disruption of occupancy, Liu et al. [6] proposed the use of a single asymmetric concrete section for strengthening RC columns. The section was bonded to the original section with anchor rebars or high-strength bolts. The results exhibited a significant increase in the ultimate strength and ductility of the retrofitted specimen. It was also reported that this method reduces the initial stress difference between the original and the retrofitted part. Moreover, the usability of the structure is also not affected as most of the strengthening work can be done outdoors without relocating the furniture/other equipment. In a similar study, Ou and Troung [7] proposed the addition of flanges in the weak axis of the RC column for strengthening RC columns in the first weak story of the existing buildings. The rectangular column would consequently change to L- and T- shaped configurations as shown in Figure 2. The results of the study demonstrated a ductile failure mode and enhanced lateral strength of the retrofitted specimens compared to the original rectangular columns; however, the strength of the retrofitted specimens was lower than the monolithic specimens with L- and T-configurations primarily due to the discontinuity of the longitudinal reinforcement in the retrofitted specimens.

Recently, the durability of high-performance materials has led to the increased use of such materials for the strengthening and repair purposes of RC columns. Cho et al. [8] used high-performance fiber-reinforced cementitious composite (HPFRCC) mortar in the plastic hinge region of the column and found that strengthening with HPFRCC mortar not only reduces bending and shear cracks but also improves the overall force–displacement, energy dissipation and stiffness degradation behavior of the column. Similarly, Meda et al. [9] proposed the use of high-performance fiber-reinforced concrete (HPFRC) to repair corrosion-damaged RC columns and reported reasonable enhancement in the strength of the repaired column.

Dagenais et al. [10] reported that jacketing columns with deficient lap splices in RC bridges with self-compacting ultra-high performance fiber-reinforced concrete (UHPFRC) resulted in the elimination of bond failure and concrete damage in the plastic hinge regions.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 2. Repair with RC Jacketing: (**a**) Removing the cover concrete and roughening the surface; (**b**) Post-installation of transverse reinforcement; (**c**) Welding of transverse reinforcement; Reinforcement cage for an (**d**) L-shaped column; (**e**) T-shaped column; (**f**) T-shaped column with wall-type reinforcement [7-Elsevier Copyrights].

Other high-performance materials such as engineered cementitious composites (ECCs) and ferro-cement jackets were also used to strengthen short RC columns [11]. ECC is a mortar based composite reinforced with fibers, whereas ferro-cement is essentially reinforced mortar applied over closely spaced rebars. It was reported that compared to ferro-cement jacketing, ECC-jacketed specimens exhibited enhanced ductility, energy dissipation and inelastic deformation; however, shear strengths were comparable. ECC-jacketed specimens also showed improved seismic performance even at high axial load ratios. Previously, Abdullah and Takiguchi [12] reported that with ferro-cement jackets, columns exhibited stable cyclic response and improved ductility; however, no improvement was observed in the flexural strength.

More recently, Rodrigues et al. [13] repaired severely damaged RC columns by replacing the damaged concrete in the plastic hinge region with high-strength micro-concrete and welding of ruptured longitudinal bars. The subsequent testing of the repaired columns under bi-directional lateral loading with constant axial compression showed that the repair technique fully restored the strength and ductility of the columns; however, the stiffness was still lower than in the original specimen.

Wrapping with textile-reinforced concrete, which comprises carbon and glass fiber bundles has been proposed very recently by Yao et al. [14] for the repair of corrosion-damaged RC columns. The repair resulted in improved seismic performance in terms of yield load, ultimate bearing capacity, ductility and accumulated energy dissipation; however, the degree of improvement was found to be a function of the initial corrosion ratio, i.e., the higher the initial corrosion ratio, the lower the improvement in behavior.

3. Steel Jacketing

In steel jacketing, the RC section is enlarged by welding or bolting it with a steel section [15], where the gap between the concrete and steel is filled with grout. The method is effective in enhancing the seismic performance of the column but is generally costly, labor intensive and involves antirust work. Moreover, just like RC jacketing, due to the change in the cross-sectional size of the section, this method also changes the stiffness of the structure.

In a study, Daudey and Filiatrault [16] retrofitted RC rectangular columns with the steel jacket and reported that the as-built column failed at lower (1~2) ductility ratios due to the bond slip of the dowel bars, whereas all the retrofitted specimens showed stable cyclic response up to the ductility ratio of 6. No effect of the geometry of the steel jacket, i.e., circular or elliptical, was observed on the performance of the strengthened columns. Wu et al. [17], in a separate study, reported that attaching a steel plate to the flexure faces of the RC column effectively delayed the concrete crushing in the plastic hinge zone.

Steel tube-jacketed square RC columns (STRC) and circular RC columns (CTRC) were tested by Zhou and Liu [18] to evaluate the effectiveness of strengthening RC columns with steel tubes nearly a decade ago. It was reported that tubed RC short columns performed better than conventional RC columns in terms of the displacement ductility, flexural strength, energy dissipation capacity and stable hysteretic behavior due to the effective confinement of concrete provided by the steel tube. For CTRC, it was reported that the brittle shear failure was effectively prevented and increasing the axial load ratio increased the lateral strength and decreased the ductility index; however, very little effect was observed on plastic deformation capacity. On the other hand, STRC was reported to exhibit shear failure at high axial load and an increase in axial load ratio increased the shear strength and decreased the ductility index and the deformation capacity. Overall, the lateral load strength of STRC was reported to be greater than that of CTRC, whereas the deformation capacity of the latter was higher.

Recently, Choi et al. [19] compared the seismic performance of circular RC columns with full and split prefabricated steel wrapping jackets and reported that split jacket results in nearly similar improvement in the seismic performance as that of a full jacket, and hence are more effective from the cost/ease of installation perspective. In this study, the external confining pressure on the steel wrapping jacket was exerted using a cable and a cross device as shown in Figure 3. Similarly, in a study by Pudjisuryadi et al. [20], the behavior of specimens with conventional stirrups was compared with the specimens provided with external steel angle collars at regular spacing over the height of the specimen. It was observed that specimens with steel angle collars showed very ductile behavior and failed at a higher drift compared to the specimens with stirrups for confinement purposes.

In order to minimize the modification to column geometry, mass and stiffness, Fakharifar et al. [21] proposed a rapid strengthening method comprising lightweight prestressed steel jackets for severely damaged RC columns. In this method, several prestressed strands restrain a thin steel sheet, which is then wrapped around the column in the form of a jacket in less than 12 h. The prestressed strands prevent buckling of the steel sheet, whereas steel sheet prevents strands from intruding into the cracked concrete. The results of the experimental study indicated that the strengthening method restored the ultimate strength and ductility of the retrofitted columns to 115 and 140%, respectively, of the original as-built columns. However, the initial stiffness was restored to 80% of the stiffness of the as-built columns.

More recently, Wang et al. [22] proposed an innovative strengthening method in which rectangular RC columns supporting high axial load ratios (i.e., preloaded) were strengthened with post compressed steel plates. The primary purpose of this method was to ensure that the column does not collapse in a severe earthquake and its axial load carrying capacity remains intact even after severe damage. It was reported that the existing axial and seismic shear loads were effectively sustained and shared by the precambered plates. A significant enhancement in the ductility and energy dissipation capacity of the strengthened column was also observed. Moreover, it was found that the improvement in behavior was more pronounced with the increase in the thickness of the steel plates rather than an increase in the precamber of the plates.

(**a**) (**b**) (**c**) (**d**)

Figure 3. Jacketing with prefabricated steel sheets: (**a**) Cutting to shape of steel plates; (**b**,**c**) Installation of steel plates and exertion of external pressure using cable and a cross device; (**d**) Welding to complete the jacketing process [19-ICE Publishing Copyrights].

4. Externally Bonded Fiber-Reinforced Polymer (FRP) Jacketing

FRP jacketing is one of the most popular seismic retrofitting methods all over the world, primarily because of the many advantages FRP composites have to offer over traditional strengthening methods (RC and steel jacketing), such as ease and speed of installation, less labor work, minimum change to the original geometry and aesthetics of the structure, high strength-to-weight ratio, and, most importantly, its occupant-friendly nature. However, it has certain disadvantages as well, such as, the effective utilization of externally bonded FRP is just 30–35%, due to premature debonding [23]. Moreover, FRP is relatively costly and shows poor properties when exposed to high temperatures or wet environment. FRP is generally bonded externally to the column using epoxy resins. Different types of FRP composites have been utilized by different researchers for strengthening purposes, the details of which are provided below.

4.1. Carbon Fiber-Reinforced Polymer (CFRP) Composites

Among all the FRP composites, carbon fiber-reinforced polymers (CFRP) have been the most extensively used for strengthening and repairing RC columns in the last two decades. The majority of studies utilized externally bonded CFRP for strengthening RC columns. This section discusses in detail the various findings of the previous studies related to the general behavior of CFRP-strengthened and repaired columns. Moreover, the comparative effectiveness of CFRP wrapping with respect to other strengthening techniques is also presented. Due to a large number of studies on CFRP strengthening, the studies have been grouped into three categories, namely, CFRP strengthening, CFRP repair and comparative assessment of CFRP with other materials.

4.1.1. CFRP Strengthening

A large number of studies have been conducted to assess the impact of CFRP strengthening on the general behavior and failure modes of the strengthened RC columns. Ma et al. [24] reported that deficient RC columns retrofitted with external CFRP jacketing exhibited stable flexural response with improved ductility and energy dissipation capacity by preventing brittle shear failure. Similarly, Ye et al. [25] found that shear strength of the RC column with inadequate transverse reinforcement can be improved with the CFRP sheets. Moreover, the shear resistance mechanism of CFRP sheets was observed to be similar to reinforcement hoops where it became effective after the diagonal shear cracking of concrete. In another study, Ye et al. [26] reported that ductility of RC columns can be improved by CFRP sheet wrapping due to the confinement effect by CFRP when the strong shear and weak flexure factor is over 1.

Table 1. Summary of studies on the strengthening of RC columns.

Study	Strengthening Method	Strength and Ductility	Initial Stiffness
RC/Mortar Jacketing			
Vandoros and Dristos [4]	Concrete jacketing with end-welded stirrups and dowel placement. Shotcrete jacket with bent-down bars	Enhanced	Enhanced
Chang et al. [5]	RC jacketing and wing wall installation.	Enhanced	Enhanced
Liu et al. [6]	Addition of a single asymmetric concrete section using anchor rebars or high-strength bolts	Enhanced	Enhanced
Ou and Truong [7]	Addition of a RC flange in the weak axis of the column	Enhanced	Enhanced
Cho et al. [8]	High-performance fiber-reinforced cementitious composite (HPFRCC) mortar	Enhanced	Not reported
Dagenais et al. [10]	Self-compacting ultra-high performance fiber-reinforced concrete	Enhanced	Same
Deng et al. [11]	Comparison of engineered cementitious composites (ECCs) and ferro-cement jacket	Same strength for both but more ductility with ECCs	Enhanced
Abdullah and Takiguchi [12]	Circular or square ferro-cement jackets with steel wire mesh	Improved ductility but no flexural strength improvement	Similar
Steel Jacketing			
Daudey and Filiatrault [16]	Steel tube jacketing with concrete or grout fill	Enhanced	Not reported
Wu et al. [17]	Steel plate to flexural faces	Enhanced	Enhanced
Zhou and Liu [18]	Jacketing with steel tube	Enhanced	Not reported
Choi et al. [19]	Wrapping with steel jacket	Strength the same, ductility enhanced	Lower
Pudjisuryadi et al. [20]	Jacketing with steel angle collars	Enhanced	Not reported
Wang et al. [22]	Jacketing with post-compressed steel plates	Enhanced	Enhanced
Externally-bonded Fiber-reinforced polymer (FRP) Jacketing			
Ma et al. [24]	Carbon fiber-reinforced polymer (CFRP) wrapping in plastic hinge region	Enhanced	Not reported
Ye et al. [25]	Discontinuous CFRP wrapping in strips	Enhanced	Not reported
Sause et al. [27]	CFRP jacket confinement in inelastic hinge region	Insignificant increase in strength and considerable increase in ductility	Insignificant increase
Ghobarah and Galal [28]	CFRP wrapping with fiber anchors	Slight enhancement in strength, whereas significant enhancement in ductility	Not reported

Table 1. *Cont.*

Study	Strengthening Method	Strength and Ductility	Initial Stiffness
Haroun and Elsanadedy [29]	CFRP and E-Glass wrapping	Enhanced	Same
Harries et al. [30]	CFRP wrapping in the plastic hinge region	Enhanced	Not reported
Harajli and Dagher [31]	FRP wrapping in the plastic hinge zone	Enhanced	Not reported
Harajli [32]	FRP jacketing in spliced zone	Enhanced	Not reported
Abdel-Mooty et al. [33]	Glass or carbon FRP wrapping in potential hinge zone	Enhanced	Not reported
Ozcan et al. [34]	CFRP retrofitting	Negligible increase in strength but ductility significantly enhanced	Not reported
Harajli and Khalil [35]	FRP Jacketing in spliced zone	Enhanced	Not reported
Colomb et al. [36]	Glass or carbon FRP wraps	Enhanced	Not reported
Yalcin et al. [37]	CFRP wrapping in the plastic hinge region	More enhancement for specimens without lap splice as opposed to the ones with lap splice	Slightly increased
ElGawady et al. [38]	CFRP retrofitting and Steel jacketing	Enhanced	Same
Ozcan et al. [39]	CFRP wrapping with CFRP anchor dowels	Enhancement in ductility only	Not reported
Vrettos et al. [40]	CFRP wrapping in plastic hinge regions with and without CFRP anchors	Enhanced	Enhanced with the use of CFRP anchors
Liu and Sheikh [41]	FRP wrapping	Enhanced	Not reported
Paultre et al. [42]	Full CFRP wrapping	More enhancement in ductility than strength	Not reported
Juntanalikit et al. [43]	CFRP wrapping in the plastic hinge region	Enhanced	Not reported
Lee et al. [44]	Sprayed FRP composed of a mixture of chopped glass and carbon fibers	Enhanced	Not reported
Wang et al. [45]	CFRP wrapping in the plastic hinge region	Enhanced	Enhanced
Zoppo et al. [46]	Discontinuous CFRP strips along the shear span	Enhanced	Enhanced
Castillo et al. [47]	FRP installation in longitudinal and transverse directions using FRP anchors	Enhanced	Not reported
Wang et al. [48]	CFRP wrapping in the plastic hinge region	Strength the same, ductility enhanced	Same
Wang et al. [49]	Externally bonded Strap and full CFRP wrapping	Little enhancement in strength, more in ductility	Not reported
Ghatte et al. [50]	Externally bonded CFRP	Same strength, ductility enhanced	Not reported
Harajli and Rteil [51]	CFRP and steel fiber-reinforced concrete (FRC) confinement	Enhanced strength and ductility	Not reported
Galal et al. [52]	Comparison of CFRP and glass fiber-reinforced polymer (GFRP) wrapping	More enhancement with CFRP wrapping	Not reported
Bousias et al. [53]	Comparison of RC jacketing and CFRP wrapping	More increase in strength with RC jacketing, whereas more increase in ductility with CFRP wrapping	Not reported
Bournas et al. [54]	Textile-reinforced mortar versus FRP confinement	Similar strength but enhanced ductility	Not reported
Zoppo et al. [55]	CFRP wrapping in the plastic hinge region	Strength same, ductility enhanced	Slightly increased
Youm et al. [56]	Glass FRP retrofitting	Enhanced	Not reported
Eshghi and Zanjanizadeh [57]	GFRP wraps in splices/critical hinge zone	Enhanced	Not reported
Choi et al. [58]	GFRP winding wires	Enhanced	Lower
Ouyang et al. [59]	Basalt fiber-reinforced polymer (BFRP) wrapping	Enhanced	Not reported
Chang et al. [60]	Polyester fiber-reinforced polymer wrapping	Enhanced	Not reported
Dai et al. [61]	Comparison of aramid fiber-reinforced polymer (AFRP) and polyethylene terephthalate (PET) wrapping	Similar enhancement for both methods	Not reported

Table 1. *Cont.*

Study	Strengthening Method	Strength and Ductility	Initial Stiffness
Shape memory alloy (SMA) Wire Jacketing			
Choi et al. [62]	SMA wire jackets	Enhanced	Lower
Hybrid Jacketing			
Wu et al. [63]	GFRP bars embedded in grooves and CFRP sheets in plastic hinge zone	Similar strength but enhanced ductility	Same
Bournas and Triantafillou [64]	Near-surface mounted (NSM) FRP bars (CFRP or GFRP) and CFRP wrapping	Both enhanced but more enhancement in ductility with NSM CFRP bars	Enhanced
Sarafraz and Danesh [65]	NSM FRP bars and CFRP wrapping	Enhanced	Not reported
Li et al. [66]	NSM GFRP bars and CFRP jackets	Enhanced	Not reported
Napoli and Realfonzo [67]	Layout 1: NSM rebars with CFRP wrapping in plastic region Layout 2: NSM rebars with CFRP wrapping and steel angles over the length	More enhancement in strength and ductility for layout 2	Lower stiffness for layout 1, higher for layout 2
Seyhan et al. [68]	NSM AFRP bars and CFRP sheets	Enhanced	Not reported
Fahmy and Wu [69]	NSM BFRP bars and externally bonded BFRP sheet	Enhanced	Not reported
Seifi et al. [70]	NSM GFRP bars with CFRP wrapping and NSM steel bars with CFRP wrapping	More enhancement with NSM steel bars	Enhanced
Lu et al. [71]	Concrete-filled steel tube (CFST)/Concrete-filled CFRP-steel tubes (CFCSTS) with CFRP wrapping	Enhanced	Not reported
Realfonzo and Napoli [72]	CFRP wrapping and steel angles	Enhanced	Not reported
Chou et al. [73]	FRP wrapped spiral corrugated tube and GFRP wrapping	Enhanced	Not reported
Cho et al. [74]	HPFRC sprayed mortar combined with steel rebars	Enhanced	Not reported

Similarly, Sause et al. [27] noted that higher deformation capacity and delay in the column failure due to compression zone deterioration and longitudinal reinforcement buckling can be achieved by using FRP jackets with higher stiffness, i.e., greater thickness. The authors also reported that CFRP confinement in the plastic hinge zone significantly improved the deformation capacity, whereas lateral strength or stiffness did not increase significantly. Ghobarah and Galal [28] and Haroun and Elsanadedy [29] also reported that CFRP strengthening prevented the brittle shear failure and improved the ductility from limited to moderate. Another study by Haroun and Elsanadedy [75] concluded that square or rectangular jackets could not develop enough strength required to prevent the slippage or splitting of lap-spliced bars. Thus, circular or elliptical FRP jackets were assumed to be more effective.

While investigating the behavior of columns with lap splices, Harries et al. [30] found that with CFRP retrofitting, the nominal flexural capacity of the column can be achieved; however, after the occurrence of slip and splitting, CFRP jackets had no apparent effect on the residual splice capacity. The ductility of the columns was also reported to be limited by the slip of the lap-spliced bars and resulted in splitting failure in the spliced region. Harajli and Dagher [31] and Harajli [32] also observed that FRP wraps improved the bond strength of the spliced bar, increased the lateral load capacity and resistance and ductility of columns and reduced the bond deterioration and pinching of columns with lap splices.

A few studies were also conducted to study the influence of the geometry of column on the effectiveness of CFRP strengthening. In this regard, Abdel-Mooty et al. [33] reported that the influence of wrapping was more effective in square columns than rectangular columns. In a separate study, Ghosh and Sheikh [76] observed that FRP confinement was more prominent in circular columns as compared to the square ones. It was also stated that for previously damaged columns, the effectiveness of FRP improvement depends on the level of damage experienced.

While studying the behavior of the strengthened columns, Ozcan et al. [34] found that CFRP strengthening increased the rotation capacity of the non-ductile RC columns up to two times. Similarly, Harajli and Khalil [35] observed much more stable hysteretic behavior with increased energy dissipation capacity and reduced strength and stiffness degradation for FRP strengthened columns. The stresses in the FRP were reported to decrease with more layers. Moreover, it was also observed that improvement in bond strength with external FRP confinement is insensitive to the column section shape.

In a study related to the performance of continuous wraps with discontinuous ones, Colomb et al. [36] observed that for specimens fully wrapped with FRP along the length, failure mode was changed from brittle shear to ductile flexural while columns with discontinuous wraps observed mixed shear-flexure failure. Similarly, Yalcin et al. [37] found that with plain rebar dowels, an externally applied passive CFRP strengthening scheme is not effective unless plain rebars are sufficiently developed. ElGawady et al. [38], on the other hand, found that increasing the amount of FRP improves the performance of seismically deficient columns by limiting the budging of the jacket. In a separate study, Ozcan et al. [39] observed that FRP retrofitted columns sustained up to three times higher ultimate drift ratios as compared to unstrengthened deficient columns. It was also reported that using a 16-pinned CFRP anchor dowel configuration can increase the confinement efficiency and ultimate drift ratios.

Interestingly, Liu and Sheikh [41] found that lateral confinement by FRP increases energy dissipation and curvature ductility dramatically, but displacement ductility and drift capacity do not increase significantly beyond a certain limit. Moreover, it was also reported that lateral confinement by FRP at high axial load ratios leads to a remarkable increase in the flexural strength of the column, which is neglected by most design codes.

To address the debonding behavior of FRP wraps, Vrettos et al. [40] proposed an innovative method, which comprised CFRP sheets anchored to the column via carbon-fiber anchors as shown in Figure 4 and concluded that the use of carbon-fiber anchors is effective in the flexural strengthening of the columns if anchors have a significant amount of fibers. It was also reported that the effectiveness of anchors increases almost nearly with the increase in their weight.

In order to overcome the significant stress hysteresis problem of the FRP sheets relative to the concrete core, which essentially weakens the effectiveness of the strengthening method, Zhou et al. [77] used prestressed FRP strips with epoxy bonding. The FRP sheets were prestressed using a self-locking anchor, which was composed of anchors heads, nuts, screws and FRP strips. The results indicated the beneficial effects of prestressing FRP strips such as inhibiting the development of diagonal shear cracks and a change of mode of failure from brittle to ductile, consequently leading to an overall improvement in the seismic performance of the specimens in terms of energy dissipation, load capacity and ductility.

(**a**) (**b**) (**c**) (**d**)

Figure 4. (**a**) Filling holes in the anchorage region with epoxy resin; (**b**) Placement of carbon-fiber anchor; (**c**) Fanning out of fiber anchors over a CFRP sheet; (**d**) Local jacketing with CFRP [40-Authorized Reprint from American Concrete Institute].

In a recent study by Paultre et al. [42], it was found that the enhancement in energy dissipation with CFRP strengthening is more pronounced for specimens with a relatively higher amount of transverse reinforcement and lower axial load ratio.

Juntanalikit et al. [43] reported that after CFRP jacketing, lap-splice deficient specimens do not experience gravity load collapse, as the core, which mainly bears the gravity load, is effectively confined against concrete crushing and spalling by the CFRP jackets.

Recently, Lee et al. [44] proposed an innovative technique in which FRPs, composed of an open-air mixture of chopped glass and carbon fibers with epoxy and vinyl ester resin, are sprayed on the uneven surface of the RC columns. The results indicated a significant improvement in the strength and deformation behavior of the strengthened specimens in comparison to the control specimen. The authors recommended the technique for the strengthening of low- to mid-rise RC buildings.

Wang et al. [45] have recently concluded that the axial load ratio and the number of CFRP wraps do not influence the degradation of effective and reloading stiffness of the columns much.

In another separate study, Zoppo et al. [46] investigated the effectiveness of CFRP strengthening in improving the seismic behavior of short RC columns with poor and medium quality concrete. The specimens characterised by low concrete strength were strengthened with low axial rigidity CFRP sheets, which resulted in an enhancement of the shear capacity but were not sufficient to avoid the brittle failure. It was reported that CFRP sheets with an axial rigidity of 0.34 GPa were able to produce ductile failure in the specimens with low-quality concrete. On the other hand, specimens with medium quality concrete were strengthened with CFRP sheets of relatively high axial rigidity and resulted in a ductile failure mode.

Castillo et al. [47], on the other hand, used FRP anchors and a bond breaking layer with FRP sheets in order to overcome the debonding disadvantage of the FRP sheets in strengthening RC columns. It was observed that due to the inclusion of a novel bond breaking layer, the premature debonding of FRP sheet was prevented and the ductility of the column was enhanced.

More recently, the effect of loading direction on the seismic performance of CFRP-retrofitted RC columns was investigated by Wang et al. [48]. It was found that with the increase in the angle of lateral loading from the strong axis, the energy dissipation and drift capacity of the column generally reduced. Moreover, although CFRP-retrofitted columns performed better than the corresponding unretrofitted columns, the improvement declined with the increase in lateral loading direction angle. Furthermore, worse seismic performance in terms of ultimate and plastic deformation capacity was noted when the loading angle was 60 degrees.

The comparative effectiveness of full CFRP wrapping with strap CFRP wrapping has also been assessed by different researchers. Yang and Wang [78] evaluated the seismic performance of shear controlled columns strengthened with CFRP straps and full CFRP sheet. It was observed that irrespective of the pre-damage condition of the columns, the CFRP wrapping enhanced the shear capacity and ductility of the deficient columns. However, the improvement in behavior reduced with the increasing axial load ratio. CFRP retrofitting also led to gradual post-peak strength degradation and a reduction in the pinching effect in hysteretic behavior. The authors concluded that at the same volumetric ratio, retrofitting with CFRP straps is a superior strategy compared to the wrapping of columns with full CFRP sheets. In a similar study, Wang et al. [49] studied the effectiveness of CFRP strap strengthening and full CFRP wrapping in improving the seismic performance of high-strength RC columns. However, in contrast to the previous study, it was found that full CFRP wrapping over the length of the column produces better results in terms of strength and ductility compared to wrapping in straps over the length. It was also reported that the strength and stiffness degradation, and pinching effect reduced with the increase in the number of CFRP layers.

It is generally believed that columns with extended cross-sections do not perform very well with CFRP strengthening. To investigate this issue, Ghatte et al. [50] conducted a study very recently, in which deficient RC columns with extended cross-sectional dimensions corresponding to the lateral loading direction (h/b = 2) were retrofitted with externally bonded CFRP Jackets, and an increase in the column drift capacity from 3 to 4% for specimens retrofitted with one layer of CFRP and from 3 to 7.5% for specimens retrofitted with two layers of CFRP at an axial load ratio of 0.2 was reported. On the other hand, the drift capacity at an axial load ratio of 0.35 increased from 1.5 to 3 and 5%, respectively, for specimens retrofitted with one and two layers of CFRP.

4.1.2. CFRP Repair

Some of the studies have also investigated the efficacy of CFRP wrapping in the repair of damaged RC columns. The type of damage included the corrosion of rebars, yielding of rebars, concrete spalling and severe damage until failure. Lee et al. [79] repaired RC columns damaged with different levels of rebar corrosion with CFRP sheets and observed that the confinement and shear strengthening by CFRP sheets prevented the growth of shear and bond-splitting cracks and improved the ductility of the repaired RC columns. The ductility and strength capacity of the corrosion-damaged CFRP-strengthened columns with inadequate lap-splice length was found to be higher than the original un-corroded column [80].

Kalyoncuoglu et al. [81] compared the effectiveness of repair with mortar and CFRP jacketing for corrosion-damaged RC columns made of substandard concrete and observed that in contrast to mortar rehabilitated column which considerably increased the strength, CFRP retrofitting improved both the strength as well as ductility of repaired columns.

Recently, Faustino and Chastre [82] tested five columns strengthened with CFRP combined with different strengthening mechanisms such as anchor dowels, external longitudinal bars and high-strength repair mortar. The columns were pre-damaged until yielding of longitudinal bars. The results of the experimental study showed an increase of 7% in the lateral load carrying capacity of the columns, when retrofitted with CFRP sheets only. However, CFRP sheets combined with high-strength mortar in the plastic hinge region resulted in an increase in the column lateral strength by 20%. Similarly, the use of CFRP sheets with external longitudinal steel also increased the lateral strength of the column by 20%.

To investigate the effect of multi-directional loading, Hashemi et al. [83] repaired a fully damaged RC column with CFRP wrapping and mortar and evaluated the effectiveness of the CFRP wrapping in restoring the strength and deformation capacity of the column via hybrid simulation, i.e., dynamic loading conditions in all the three directions (bi-directional loading with a variation of axial load). The results of the experimental testing exhibited a substantial enhancement in the ductility of the column; however, strength was not fully restored, primarily because damaged rebars were not repaired.

In the repair method by Parks et al. [84], the cross-section of the specimens was changed from original octagonal to a circular cross-section using epoxy-anchored headed bars and by filling a CFRP shell with concrete, thereby shifting the plastic hinge region to a less damaged region as shown in Figure 5. It was reported that the repair methodology successfully restored the force–displacement capacity of the damaged columns.

(a) (b) (c) (d)

Figure 5. Repair procedure with CFRP shell and concrete: (**a**) Post-installed headed bars; (**b**) Split CFRP shell; (**c**) CFRP shell around column; (**d**) CFRP shell filled with non-shrink or expansive concrete [84-Authorized Reprint from American Concrete Institute].

More recently, the results of the experimental study with bi-directional lateral loading conducted by Rodrigues et al. [85] demonstrated that the energy dissipation capacity of the severely damaged specimens was restored after CFRP jacketing. It was also reported that the viscous damping of the repaired specimens was higher than the original specimens.

4.1.3. Comparative Assessment of CFRP Effectiveness with Other Materials

Some researchers have compared the relative improvement in the column's behavior after strengthening with CFRP with that of other retrofitting materials. In this regard, Harajli and Rteil [51] compared the effectiveness of CFRP and steel FRC strengthening for RC columns with lap splices. It was reported that the external CFRP confinement significantly improved the seismic performance of columns by decreasing the spliced bars' bond deterioration and improving the energy dissipation capacity of the columns. Similar improvements were reported for internally confined columns with steel FRC.

In another study, Bousias et al. [86] repaired RC columns with or without corrosion-damaged reinforcement with CFRP or GFRP wrapping. The effectiveness of FRP wrapping (G or C) was reported to be the same if the extensional stiffness was kept similar in the circumferential direction. Moreover, the effectiveness of FRP strengthening was found to be more beneficial in the column's strong direction (smaller face) as compared to the weak direction. It was also reported that the effectiveness of FRP wraps as strengthening material is reduced in RC columns with corroded bars because they become the weak link instead of the confined compression zone. Interestingly, in a separate study by Galal et al. [52], CFRP was found to be more effective than GFRP in strengthening the short square RC columns as it increased the shear force and energy dissipation capacity while decreased the FRP and steel tie strains along the column height.

Similarly, Bousias et al. [53] compared the efficacy of RC and CFRP jacketing on RC columns with lap splices and reported that FRP jacketing in the hinge zones and splice regions was found to be more effective than the RC jacketing.

On the other hand, Bournas et al. [54] evaluated the effectiveness of CFRP and textile-reinforced mortar (TRM) strengthening and found that the performance of TRM was equally effective as CFRP of equal stiffness.

Thermou and Pantazopoulou [87] reported an interesting finding that the axial stiffness of the jacket rather than the strength was the defining factor in determining the performance of FRP retrofitting, as both GFRP and CFRP with equal axial stiffness had equivalent effects on the strength and deformation capacity improvements.

More recently, a comparative analysis of the effectiveness of carbon fiber-reinforced polymer (CFRP) wrapping and fiber-reinforced cementitious composite (FRCC) in improving the seismic performance of RC columns with poor and medium quality concrete was conducted by Zoppo et al. [55]. The results of the experimental study showed that CFRP wrapping is more effective in strengthening columns with poor quality concrete. However, the authors concluded that FRCC jacketing can also serve as a reasonable alternative to CFRP jacketing as it not only reduced the concrete deterioration, but also prevented bar buckling and enhanced lateral strength and energy dissipation of the specimens.

4.2. Glass Fiber-Reinforced Polymer (GFRP)

Over the last two decades, few studies have used glass fiber-reinforced polymer for strengthening purposes and reported its benefits. Sheikh and Yau [88] repaired pre-damaged columns having yielded longitudinal bars with GFRP wrapping and reported that the energy dissipation capacity of strengthened columns increased by over a hundred times. Similarly, Memon and Sheikh [89] evaluated the efficacy of GFRP wraps in strengthening deficient or damaged square RC columns. It was found that the strengthening technique enhanced the ductility, energy dissipation and strength capacity of the deficient and damaged columns; however, the extent of enhancement was a function of the existing damage of the column. A reduction in the rate of stiffness and strength degradation with the increase in the number of GFRP layers was also observed. Moreover, for columns supporting high axial loads, a greater number of GFRP layers was needed to produce a similar improvement in the behavior as that of the columns with low axial load ratios. Youm et al. [56] also reported that GFRP retrofitting significantly improved the seismic performance of lap-spliced columns by stabilising the hysteresis response and increasing the displacement ductility factor to 8.3 as compared to un-retrofitted columns of 2.6, which failed prematurely due to lap splice bond failure. It was observed that regardless of GFRP layer thickness, which delayed bond slip failure to a great extent, the yielding of spliced bars was not achieved. In a similar study, Eshghi and Zanjanizadeh [57] also observed that GFRP retrofit was effective in improving the splice bond strength, flexural strength, and displacement ductility and rotation capacity of as-built columns which failed in a brittle manner due to bond deterioration of spliced rebars. It was also argued that GFRP retrofitting can present a practical solution to avoid the soft-storey mechanism in RC structures with deficient detailing.

Recently, Choi et al. [58] reported the effectiveness of strengthening with tensioned GFRP winding wires in improving the seismic performance of RC columns with and without lap splices. The study consisted of two columns with lap splices and two with continuous longitudinal reinforcement. One column of each of the two categories was strengthened with tensioned GFRP wires as shown in Figure 6. The results of the experimental testing showed that GFRP wire winding increased the flexural strength and failure drift of the strengthened columns of both categories compared with the control specimens. Moreover, it was observed that GFRP wire winding prevents buckling of the longitudinal reinforcement, vertical splitting of the lap splices and concrete spalling. Seo et al. [90] also proposed another quick and easy-to-install method comprising a GFRP strip device which is composed of a strip of GFRP composite with a aluminium clip connector and proposed to attach it in the plastic hinge region of the column. The experimental results showed a significant improvement in the seismic performance of the strengthened columns in terms of strength, displacement ductility and energy dissipation capacity. Moreover, the failure mode of the column was changed from a brittle shear to a ductile flexural mode.

(**a**) (**b**)

Figure 6. GFRP wire jacketing: (**a**) Winding of the GFRP wire; (**b**) completed GFRP winding [58-Elsevier Copyrights].

4.3. Basalt Fiber-Reinforced Polymer (BFRP)

Due to its low price as compared to CFRP and other excellent properties such as resistance to fire and chemical corrosion, basalt fiber-reinforced polymer is recently being used for strengthening purposes. In this regard, Ouyang et al. [59] performed a comparative assessment of the effectiveness of externally bonded CFRP and BFRP wrapping and reported that columns strengthened with BFRP sheets exhibited equivalent and even superior performance to their counter parts with the same number of CFRP sheets. Moreover, the price of BFRP sheets was just 20% of the CFRP. In view of this, the authors recommended strengthening with BFRP as a viable alternative.

4.4. Polyester Fiber-Reinforced Polymer (PFRP)

Polyester fiber-reinforced polymer is known for its toughness, flexibility, heat resistance and durability, and hence has been used for strengthening purposes. In a study, Chang et al. [60] utilized polyester fiber-reinforced polymer for strengthening deficient RC columns. The sheet was bonded to the column using urethane adhesive. The study comprised one control specimen and two strengthened specimens with one and two layers of polyester belts, respectively. It was reported that the control specimen exhibited brittle behavior, whereas strengthened specimens experienced ductile behavior. Moreover, a significant improvement in the overall force–displacement behavior of the column was observed after strengthening. Furthermore, the energy dissipation of the polyester fiber-reinforced polymer strengthened specimen was 184% of that of the control specimen.

4.5. Polyethylene Terephthalate (PET) Fiber-Reinforced Polymer Composites

The polyethylene terephthalate FRP composites are made from recyclable materials and have the advantages of high deformability and economy over CFRP composites. Moreover, they possess greater tensile capacity than conventional FRPs. The study by Dai et al. [61] presented the results of PET FRP jacketed specimens and compared the results with a high-strength aramid FRP jacketed specimen. The results of the experimental study demonstrated that PET FRP is a viable alternative to conventional FRPs as it enhances the displacement ductility of RC columns significantly and also does not rupture at the ultimate limit state. More recently, Liu and Li [91] strengthened partially corroded RC columns with CFRP and polyethylene terephthalate (PET) FRP composites, respectively, as shown in Figure 7 and performed a comparative assessment of the relative performance of the two strengthening systems. The results of the experimental study evaluated in terms of energy dissipation, damping ratio, hysteretic performance and stiffness degradation indicated that strengthening using CFRP and PET FRP composites resulted in a nearly similar improvement in the seismic performance of the RC columns.

(**a**) (**b**) (**c**)

Figure 7. (**a**) Corrosion damaged; (**b**) CFRP repaired; (**c**) PET FRP repaired [91-Elsevier Copyrights].

4.6. Hybrid Fiber-Reinforced Polymer (HFRP)

Researchers have been proposing new hybrid FRP composites, which are composed of two different fiber materials. In this way, the resulting hybrid material has the advantages of both individual materials. To study the effectiveness of HFRP strengthening, Peng et al. [92] repaired damaged (up to yielding of rebars) RC columns using sprayed BFRP and sprayed HFRP, which was composed of a mix of BFRP and CFRP. The results of the experiments demonstrated that the proposed strengthening method with HFRP enhances the energy dissipation and ductility of the pre-damaged columns considerably. However, no obvious increase in the peak loads was observed. The authors noted the advantages of this method as low cost and rapid strengthening due to the fast curing of materials. Similarly, Li and Li [93] proposed HFRP wrapping for enhancing the seismic performance of corroded RC columns. A total of six specimens including two control and four strengthened specimens were tested under constant axial load and cyclic lateral loading. The specimens were corroded using accelerated corrosion in the laboratory conditions and the HFRP sheets were wrapped in the plastic hinge region of the column. It was observed that the strengthening technique resulted in 47 and 212% enhancement in the displacement ductility and energy dissipation capacity of the strengthened specimens compared to the unstrengthened control specimens.

5. Near-Surface Mounted (NSM) Fiber-Reinforced Polymer (FRP) Jacketing

In the NSM method, grooves are cut into the cover concrete, and FRP bars are placed in the grooves and bonded using an appropriate filler, such as epoxy paste or cement grout. NSM FRP bars are usually used in the longitudinal direction to enhance the flexural strength of the column. Mostly, the NSM method is used in conjuction with externally bonded FRP jacketing, resulting in a hybrid jacketing as described in Section 7.

In order to investigate the difference between NSM rebar repair and CFRP wrapping, Hasan et al. [94] compared the repair effectiveness of three partially cracked stub RC columns with NSM rebar repair and CFRP laminate strengthening. It was reported that specimens with NSM rebars exhibited higher load capacity and better energy dissipation and ductility. On the other hand, specimens with CFRP wrapping demonstrated better crack formation and propagation behavior. The authors attributed the difference in the behavior of the two repairing techniques to the fact that NSM rebars contribute to the compression and tension behavior of the specimens, whereas CFRP laminates contribute in the tension zone only.

6. Shape Memory Alloy (SMA) Wire Jacketing

Shape memory alloys, that are characterized by their super elasticity, durability and shape memory effect have been considered for the strengthening of structural elements by different researchers. Moreover, SMA alloys are considered a more viable solution to FRP retrofitting due to the advantages such as no need for adhesive, easy installation and no danger of peel off. To investigate this, Choi et al. [62] employed two kinds of shape memory alloy wire jackets, nickel–titanium–niobium and nickel–titanium alloys, for the seismic retrofitting of RC columns. The jackets were attached to the concrete via anchors. The results of the experimental study showed that retrofitting with SMA alloys results in ductile behavior of the columns with lap splices. Moreover, it was observed that the performance of SMA-strengthened columns with lap splices was even better than columns without lap splices. It was reported that nickel–titanium–niobium alloys are more suited for retrofitting civil structures because they offer more appropriate temperature windows compared to nickel–titanium alloys.

7. Hybrid Jacketing

Hybrid jacketing involves a combination of two or more different strengthening methods/materials for enhancing the seismic performance of a column and, thus, benefits from the advantages of both methods. This section summarizes the experimental studies utilizing the hybrid jacketing approach for the strengthening and repair of RC columns.

7.1. NSM Bars with FRP Wrapping

In this hybrid jacketing technique, FRP sheets are used in conjunction with NSM bars, where FRP sheets provide lateral confinement and NSM bars enhance the flexural strength of the column, thereby resulting in enhancement of both the strength and ductility. Wu et al. [63] used this technique by embedding GFRP bars in the plastic hinge zone in addition to the provision of CFRP wraps. It was reported that the retrofitting method effectively delayed the concrete failure and prevented the buckling of longitudinal reinforcement. As a result, the ductility and energy dissipation capacity of retrofitted columns were increased. Similar findings were reported by Bournas and Triantafillou [64] for strengthened columns with different types and configurations of NSM reinforcing materials (steel or FRP). Confinement was also provided by the local jacketing of textile-reinforced mortar (TRM) by FRP sheets. Based on the test results, it was reported that NSM FRP or stainless steel present a feasible solution for the flexural strengthening of RC columns under seismic loading and with proper design and local jacketing at column ends, strength enhancement does not adversely affect the deformation capacity. Local jacketing was reported to be very effective in controlling the buckling of NSM reinforcements, which resulted in the higher strain at failure. In another study, Sarafraz and Danesh [65] also strengthened RC columns with NSM FRP rebars inserted in the grooves cut into the concrete surface combined with CFRP wrapping over the height of the column. It was reported that NSM rebars increase the flexural capacity of the column significantly. Moreover, lateral strength and energy dissipation capacity increase with the increase in the number of NSM rebars. Furthermore, it was observed that the combination of NSM bars with CFRP wrapping improves the overall seismic performance of the column remarkably.

Table 2. Summary of studies on the repair of damaged RC columns.

Study	Pre-Damage Condition	Repair Method	Strength and Ductility	Initial Stiffness
		RC/Mortar Jacketing		
Lehman et al. [3]	Severely damaged until failure	Repair with headed reinforcement, mechanical couplers and freshly cast concrete	Lower	Lower
Meda et al. [9]	Corrosion damaged	HPFRC jacketing	Strength enhanced only	Not reported
Rodrigues et al. [13]	Damaged until failure	Rebar welding and casting of micro-concrete in the plastic hinge region.	Restored	Lower
Yao et al. [14]	Corrosion damaged rebars	Wrapping with layers of textile-reinforced concrete	Enhanced	Lower
		Steel Jacketing		
Fakharifar et al. [21]	Severely damaged until failure	Wrapping with thin prestressed steel sheet	Enhanced	Lower
		Externally-Bonded FRP Jacketing		
Ye et al. [26]	Yielding of reinforcement	Discontinuous CFRP wrapping in strips	Enhancement in ductility only	Lower
Haroun and Elsanadedy [75]	Damaged until failure	Full CFRP wrapping	More enhancement in ductility than strength	Same
Ghosh and Sheikh [76]	Damaged until failure	CFRP jacketing in plastic hinge region and retrofitting of damaged specimens	Enhanced	Not reported
Zhou et al. [77]	Slight to severe damage	Prestressed FRP strips	Enhanced	Same
Yang and Wang [78]	Yielding and concrete spalling	Externally bonded Strap and full CFRP wrapping	Enhanced	Not reported
Lee et al. [79]	Corrosion damaged	CFRP wrapping	Enhancement in ductility reported only	Not reported
Aquino and Hawkins [80]	Corrosion damaged	CFRP wrapping with different layouts	Enhanced	Not reported
Kalyoncuoglu et al. [81]	Corrosion damaged	Layout 1: Mortar Layout 2: Mortar and CFRP sheet	Layout 1: Increase in strength only Layout 2: Increase in both strength and ductility	Not reported
Faustino and Chastre [82]	Yielding of reinforcement	Comparison of repair between CFRP only, CFRP with high-strength mortar and CFRP with external longitudinal bars	Enhancement in strength by CFRP with high-strength mortar and CFRP with longitudinal bars. CFRP wrapping only increased ductility	Not reported
Hashemi et al. [83]	Damaged until failure	Concrete recasting and CFRP wrapping in the plastic hinge region	Strength not restored, ductility enhanced	Not reported

Table 2. *Cont.*

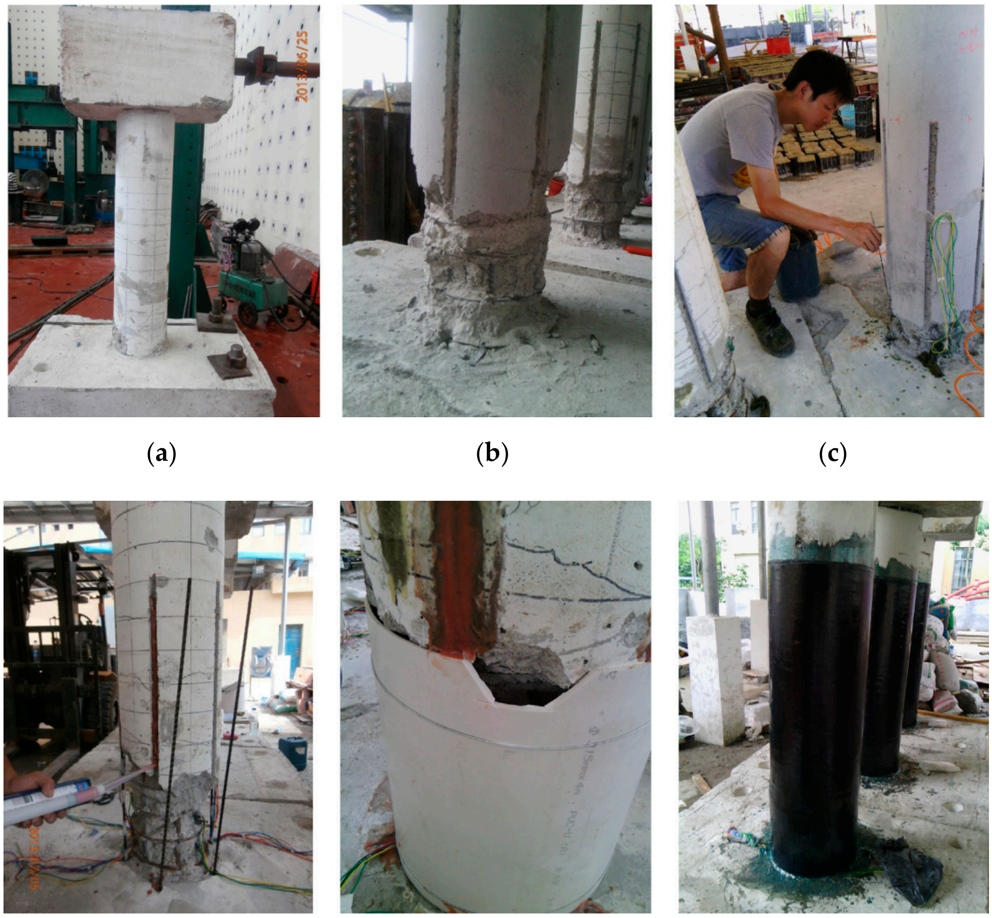
Study	Pre-Damage Condition	Repair Method	Strength and Ductility	Initial Stiffness
Parks et al. [84]	Damaged until failure	Repair with CFRP shell, expansive concrete and epoxy-anchored headed bars	Enhanced	Enhanced
Rodrigues et al. [85]	Damaged until failure	Rebar welding and casting of micro-concrete in the plastic hinge region, followed by wrapping with CFRP	Enhanced	Lower
Bousias et al. [86]	Corrosion damage	Glass or carbon FRP wrapping	Almost similar strength with significantly improved ductility	Same
Thermou and Pantazopoulou [87]	Concrete cracking and reinforcement buckling, yielding and bond deterioration	External glass and carbon FRP jacketing	Slight to no enhancement in strength, while significant enhancement in ductility	Not reported
Sheikh and Yau [88]	Yielding and concrete spalling	CFRP wrapping in the plastic hinge region	Enhanced	Not reported
Memon and Sheikh [89]	Concrete spalling and rebar yielding	GFRP wrapping in the plastic hinge region	Enhanced	Not reported
Seo et al. [90]	Predamaged to a ductility of 2.5	GFRP strip device comprising GFRP composite with aluminum clip connectors	Enhanced	Not reported
Liu and Li [91]	Corrosion damaged	Comparison of CFRP and PET wrapping	Similar enhancement for both methods	Not reported
Peng et al. [92]	Yielding of steel rebars	Comparison of sprayed BFRP and sprayed HFRP	More enhancement in ductility with HFRP than BFRP. No substantial increase in strength	Not reported
Li and Li [93]	Corrosion damaged	HFRP wrapping in plastic hinge region	Enhanced	Same
Near-Surface Mounted FRP Jacketing				
Hasan et al. [94]	Partially cracked	Comparison of NSM rebar strengthening with CFRP wrapping	Comparatively more enhancement for NSM rebar strengthening	Same
Hybrid Jacketing				
Jiang et al. [95]	Damaged until failure	NSM BFRP bars and externally bonded BFRP sheet	Strength enhanced, whereas only ductility restored	Restored
Li et al. [96]	Corrosion damaged	CFRP and steel jacketing	Enhanced	Not reported
ElSouri and Harajli [97]	Severely damaged	Internal steel ties and FRP sheets	Enhanced	Not reported
Ma and Li [98]	Moderately and severely damaged	Fast curing early strength cement mortar and BFRP sheet	Ductility enhanced, whereas strength fully restored for moderately damaged and partially restored for fully damaged columns	Lower
Xue et al. [99]	Damaged until failure	Turned steel rebar and HPFRC	Restored	Restored
Rajput et al. [100]	Corrosion damaged	HPFRC and GFRP wrapping	Only strength enhanced	Not reported
Fakharifar et al. [101]	Damaged until failure	Wrapping with thin-cold formed steel sheet and prestressing strands	Enhanced	Lower
Afshin et al. [102]	Corrosion damaged	CFRP sheet with steel profile	Enhanced strength, but no significant improvement in ductility	Enhanced

In another study, Li et al. [66] proposed using NSM GFRP rebars and CFRP jackets and CFRP anchors in the potential plastic hinge region for strengthening RC columns with a large side aspect ratio. Four types of strengthening layouts were used. In the first layout, the specimen was strengthened with CFRP jackets and CFRP anchors, whereas in the second layout NSM GFRP rebars were also provided in addition to CFRP jackets and CFRP anchors. The third layout had CFRP jackets and NSM GFRP bars, while the last layout had NSM GFRP rebars only. The results of the tests indicated that strengthening by NSM GFRP rebars enhances the flexural strength of the strengthened specimens, whereas CFRP jackets and CFRP anchors increase both the strength and ductility of the column.

Recently, in the study by Napoli and Realfonzo [67], longitudinal rebars were embedded in the grooves cut into the concrete and continuous CFRP wrapping was done in the plastic hinge region of the column, whereas discontinuous CFRP strips were provided in the remaining length of the column. Moreover, in the second layout, steel angles were also used in addition to the longitudinal bars and CFRP sheets. The results of the experimental study exhibited an increase of 48 and 60% in the flexural strength for layout 1 and 2, respectively, compared to the control specimen. It was also noticed that the presence of steel angles delayed the collapse of the specimen with the second layout such that the specimen was able to undergo greater displacement excursions.

Researchers have been using different types of FRP composites in hybrid jacketing techniques. Seyhan et al. [68] proposed the strengthening of deficient RC columns with embedded aramid fiber-reinforced polymer (AFRP) reinforcement in the longitudinal direction to increase the flexural strength and CFRP sheets in the transverse direction to enhance the ductility under cyclic lateral actions with constant axial compression. The proposed retrofitting method resulted in the significant enhancement of the flexural strength of the tested columns. Moreover, the specimens failed at a reasonably satisfactory drift of 3.0%. It was also found that the column provided with fully bonded anchorage performed better than the one with partially bonded anchorage. Similarly, Fahmy and Wu [69] utilized NSM basalt fiber-reinforced polymer (BFRP) bars in grooves and a BFRP jacket in the plastic hinge region to retrofit RC columns with lap-splice deficiencies. It was found that the BFRP bar's texture is the most important parameter that affects the seismic performance of the strengthened columns. Rebars with a rough texture helped eliminate residual displacements and resulted in a gradual increase in the column strength after yielding as compared to smooth rebars. Moreover, the drift capacity of the specimen strengthened with rough BFRP rebars was in the order of 4.5%, compared with columns strengthened with smooth rebars where the drift capacity was up to 3.0%. Similarly, Jiang et al. [95] proposed a repair method comprising NSM BFRP rebars and BFRP sheets jacketing for earthquake damaged RC bridge columns as shown in Figure 8. It was reported that the proposed retrofitting method successfully restored the stiffness and flexural and displacement capacity of the column to a level such that the bridge structure could be used for emergency services after an earthquake.

More recently, Seifi et al. [70] strengthened deficient RC columns representative of older construction practices (pre 1970s) with near-surface mounted glass fiber-reinforced polymer (GFRP) composites and NSM steel rebars. After placing the NSM reinforcement bars in the grooves on the column surface, the specimens were wrapped with CFRP. Both strengthening techniques (GFRP bars and steel bars) resulted in a significant improvement in the flexural strength, energy dissipation and hysteretic damping of the columns. However, the improvement in the behavior of the specimens with NSM steel bars was more pronounced.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 8. Hybrid repair procedure with NSM rebars and FRP wrapping: (**a**) Column after straightening; (**b**) Column after loose concrete removal and chiseling grooves; (**c**) Clearing the holes and grooves; (**d**) Injecting epoxy adhesive and placing the NSM BFRP rebars; (**e**) Repair mortar placement; (**f**) BFPR sheet application. [95-Elsevier Copyrights].

7.2. Self-Compacting Concrete-Filled CFRP-Steel Tubes (CFCSTs)

In this hybrid jacketing technique, a concrete-filled steel tube and CFRP wrapping are used for strengthening RC columns. This was proposed by Lu et al. [71] quite recently. In this technique, the gap between the RC column and steel tube is filled by self-compacting concrete and layers of CFRP wraps are also provided around the steel tubes. The test results demonstrated an increase of 7.4–9.7 times and 42–116% in the ultimate lateral load carrying capacity and ductility of the column, respectively. An increase in the thickness of the steel tubes resulted in better overall seismic performance (both ductility and ultimate bearing capacity). The presence of CFRP wraps around steel tubes delayed the buckling of steel tubes in CFCSTs, and hence improved the seismic performance significantly.

7.3. FRP Sheets with Steel Jacketing

Li et al. [96] evaluated the effectiveness of combined CFRP and steel jackets in improving the seismic performance of corrosion-damaged RC columns. It was reported that the repair of damaged columns with combined CFRP and steel was more effective in improving the strength and ductility than strengthening with the individual material. Also, in damaged columns with higher levels of reinforcement corrosion, the improvements of strengthening were more prominent than those with a lower degree of corrosion. A higher axial load was reported to considerably reduce the ductility of the strengthened columns; however, the strengthening effect was higher than those with lower axial load.

Similarly, Realfonzo and Napoli [72] performed tests on some columns strengthened by steel angles and FRP wraps. It was reported that providing the steel angles anchored to foundation on the column corners improved the flexural strength as compared to the use of FRP only.

A study by ElSouri and Harajli [97] compared the seismic performance of lap-spliced RC columns on strengthening with internal steel ties, external fiber-reinforced polymer sheets and a combination of both. It was found that the repair/strengthening of the columns with internal ties, external FRP sheets or a combination of both improved the seismic performance significantly in terms of lateral load, energy dissipation and drift capacity. Moreover repaired/strengthened columns experienced much less damage than the as-built unstrengthened columns.

Recently, Chou et al. [73] proposed an innovative hybrid jacketing method in which a GFRP-wrapped corrugated steel tube, as shown in Figure 9, was used to improve the seismic performance of RC columns. The presence of a corrugated tube allowed for the creation of a ribbed surface between the concrete and FRP. The results of the experimental study showed a significant increase in the drift capacity of the columns with the increase in the number of GFRP layers. Moreover, the failure mode changed from shear to flexure with the increase in GFRP wraps. Furthermore, the proposed strengthening technique also resulted in increased energy dissipation and the high shear strength of the specimens.

More recently, Afshin et al. [102] proposed a novel hybrid jacketing technique comprising CFRP sheets on the outer periphery and a steel profile on the inside of corrosion-damaged RC bridge columns. The results of the experimental testing showed that the proposed retrofitting method improved the energy absorption and strength degradation behavior of the repaired specimens; however, there was not much improvement in the displacement ductility behavior of the columns.

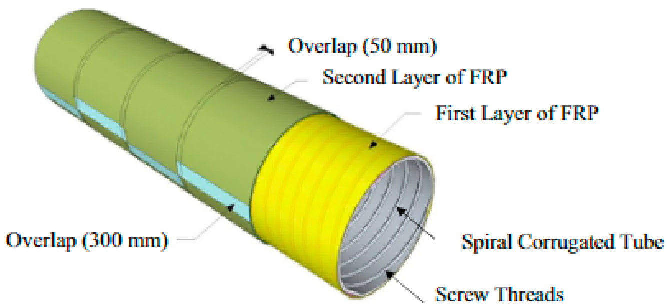


Figure 9. FRP-wrapped spiral corrugated tube configuration [73-Elsevier Copyrights].

7.4. High-Performance Materials with Steel/FRP Rebars or FRP Wrapping

The use of high-performance materials together with steel/FRP rebars or FRP wrapping is also an attractive hybrid repair method. Ma and Li [98] reported the improvement in the seismic performance of moderately to severely damaged RC columns, which were strengthened with fast curing early-strength cement mortar and basalt fiber-reinforced polymer sheets as shown in Figure 10. Significant improvement in the energy dissipation capacity and ductility of the specimens was noticed after strengthening with early-strength cement mortar and basalt fiber-reinforced polymer sheets. Moreover, the flexural capacity of the specimens with moderate pre-damage was fully restored. However, the flexural capacity of severely pre-damaged specimens was only partially restored. Also, the initial stiffness of the strengthened specimens was not fully restored and decreased with the increase in the pre-damage level of high-performance fiber-reinforced cementitious composite (HPFRCC)-sprayed mortar with steel bars to improve the seismic performance of old RC columns.

Another such method comprising turned steel rebars and high-performance fibre reinforced concrete (HPFRC) with steel or polymer fibres was proposed by Xue et al. [99] for repairing severely damaged circular RC bridge columns. In this technique, transverse rebars were first cut and then the damaged longitudinal rebars of the column were removed and replaced with new shaped (turned) rebar segments. This was followed by the construction of a concrete jacket consisting of HPFRC with steel or polymer fibres. The strengthening technique successfully restored the ductility, strength and stiffness of the column and further enhanced the energy dissipation capacity. However, the increase in energy dissipation capacity was less for the HPFRC with polymer fibres as opposed to the column with the steel fibres.

Recently, Cho et al. [74] proposed the use of high-performance fibre-reinforced cementitious composite (HPFRCC) sprayed mortar with steel bars to improve the seismic performance of old RC columns. In the retrofitting method, the surface of the column was grooved first, and then longitudinal and transverse rebars were placed in the groove. Finally, the section of column was enhanced by spraying HPFRC mortar. The results of the cyclic lateral loading tests conducted on the retrofitted columns demonstrated the effectiveness of the technique in improving both the load carrying and deformation capacities of the strengthened columns. The strengthening technique also reduced the bending and diagonal shear cracks in the retrofitted columns in contrast to the un-retrofitted specimens. A significant improvement in the hysteretic damping energy of the strengthened column was also observed.

(**a**) (**b**) (**c**)

Figure 10. Hybrid repair process using high performance materials and FRP wrapping: (**a**) Early-strength cement mortar pouring; (**b**) Epoxy injection; (**c**) BFRP wrapping [98-With Permission from ASCE].

More recently, high performance fiber-reinforced concrete (HPFRC) was used in conjunction with FRP wrapping by Rajput et al. [100] to repair corrosion-damaged RC columns. The columns were strengthened with HPFRC and one or two layers of glass fiber-reinforced polymers (GFRP). It was reported that with the combination of HPFRC and GFRP, the retrofitted columns met the strength requirements of the code for seismically designed column; however, the ductility improvement was reported to be inadequate.

7.5. Thin Cold-Formed Steel Sheet with Prestressing Strands

Prestressing strands with a thin cold-formed steel sheet can be used in rapid and light-weight repair of the earthquake-damaged bridge piers. Fakharifar et al. [101] proposed this hybrid jacketing technique, which involved wrapping the damaged RC column with a thin cold-formed steel sheet on the inside and prestressing strands on the outside, as shown in Figure 11. Moreover, repair grout was used to replace the damaged concrete. The repair method was applied on one large-scale substandard RC column representative of pre-1970s construction practice. The original column was first damaged until 25% strength degradation under constant axial load and cyclic lateral actions and was then repaired using the proposed retrofitting technique. The results of the experimental study demonstrated that the hybrid confinement technique is very effective in enhancing the flexural strength and ductility of the damaged column.

(**a**) (**b**) (**c**) (**d**)

Figure 11. Repair procedure with the hybrid confining jacket: (**a**) Damaged column; (**b**) Patched column with repair grout; (**c**) Sheet metal wrapping; (**d**) Prestressing strands application [101-SAGE Copyrights].

8. Comparison and Discussion of Different Techniques

Numerous different strengthening and repair techniques for RC columns have been presented in the previous sections that included over 90 different experimental studies, including over 500 column specimens. The various techniques have been broadly categorized into six different categories, RC jacketing; steel jacketing; externally bonded FRP jacketing; near-surface mounted FRP or steel reinforcement; shape memory alloy (SMA) wire jacketing; and hybrid jacketing, as discussed in the previous sections. A summary of the benefits and drawbacks for each category of techniques has been summarized in Table 3.

The six broad retrofitting and strengthening categories have been compared using six generic criteria, as follows: effect on strength; effect on ductility; effective on stiffness; cost of strengthening; aesthetics; and impact to occupants, which specifically, is the impact to the building occupants while the strengthening and repairing techniques are being undertaken. This last category would generally be of less concern to infrastructure (i.e., RC bridge columns). A matrix summarizing the performance of each technique for each category is presented in Table 4. It should be noted that the performance levels in Table 4 are broad characterizations only, which have generally been developed from the results and observations of the individual studies presented in the previous section. The actual performance/effectiveness of each strengthening or retrofitting technique will vary on a case-by-case basis and be dependent on the individual circumstances at the time.

Each of the retrofitting and strengthening techniques was generally able to increase the strength of the column. However, the steel jacketing, near-surface mounted FRP/steel reinforcement and hybrid jacketing methods resulted in the largest strength increase. Similarly, each technique was capable of generally increasing the amount of ductility. However, the steel, externally bonded FRP and hybrid jacketing were typically more effective and resulted in higher levels of ductility. However, it is noted that debonding limits the effective confinement of externally bonded FRP columns. A comparative analysis of different material stress-strain models for FRP-confined concrete and their influence on the ultimate behavior of FRP-confined RC columns is presented in Montuori et al. [103,104].

The stiffness generally remained unchanged, except for the RC and steel jacketing, which often increased the stiffness (due to the fact that the overall column cross-section was typically increased), and the SMA wire jacketing, where the stiffness was decreased. Changing the stiffness of the column was generally considered a poor outcome, since that would affect the dynamic properties of the structure. However, it is noted in some situations that changing the dynamic properties of the structure can be a positive outcome.

Table 3. Summary of benefits/drawbacks of the different repair and strengthening techniques.

Strengthening Method	Benefits	Drawbacks
RC/Mortar Jacketing	• Commonly used/available material • Familiarity of practicing engineers with the material • Ability of RC to take any shape • Increases both strength and ductility	• Expensive, labor intensive and time consuming due to formwork installation • Change in cross-sectional size leading to change in stiffness and seismic demands • Increase in ductility is small due to brittle nature of concrete • Disruption of occupancy
Steel Jacketing	• Ductile and commonly used/available material • Excellent confinement leading to considerable increase in both strength and ductility	• Expensive and labor intensive. • Rusting and corrosion • Change in cross-sectional size leading to change in stiffness and seismic demands • Heavy weight
Externally Bonded FRP Jacketing	• Ease and speed of installation • Corrosion resistance • Minimum modification to geometry and aesthetics of structure • Minimum disruption of occupancy • High durability, high strength-to-weight ratio • Better work safety and minimum risk hazard • Enhancement in both strength/ductility	• Costly material (but overall cost is low due to small cost of transportation and installation) • Low efficiency (30–35%) due to debonding • Poor properties on exposure to high temperature and wet environment • Increase in strength is relatively small
Near-Surface Mounted FRP or Steel Reinforcement	• Less prone to debonding • Minimum modification to geometry and aesthetics of structure • Less prone to mechanical impact and accidental damage due to protection by concrete cover • Aesthetics of the structure remain unchanged • Enhances strength considerably	• Costly material (but overall cost is low due to small cost of transportation and installation) • Comparatively more labor intensive in comparison to externally bonded FRP, but lesser than RC or steel jacketing • Not much increase in ductility
Shape Memory Alloy (SMA) Wire Jacketing	• Fast installation • No need for adhesive • No danger of peel off • Super elastic and durable • Increases both the strength and ductility	• Costly material • Ineffective composite action with concrete • Enhancement in strength is relatively small
Hybrid Jacketing	• Fast installation • Minimum modification to geometry and aesthetics of structure • High durability • Significant enhancement in both strength and ductility	• Costly material • Comparatively labor intensive as it combines two different retrofitting techniques

The RC jacketing and steel jacketing generally involve lower cost construction materials with a simple and direct load transmission mechanism [105]. However, they are typically very labor intensive and time consuming. As such, they were considered the most ineffective from a cost perspective. While the cost of materials for externally bonded FRP and near-surface mounted FRP is considerably higher than the former two techniques, the cost of the transportation of materials and installation is much cheaper, which allows for the overall technique to be typically more cost effective. The externally bonded FRP and near-surface mounted FRP/steel reinforcement were also considered to be the best technique from an aesthetics/impact to floorplan perspective, since they result in the least/smallest changes to the column cross section. In contrast, the RC jacketing technique typically increases the column dimensions significantly and, hence, is considered to have the biggest impact on aesthetics and the overall floorplan of a building.

The impact to the occupants category was generally based on two criteria: the first was how long the technique would take to be installed/constructed; and the second was in relation to the construction activities that would need to be performed. RC jacketing and hybrid jacketing typically require a considerable amount for cutting or drilling into the existing concrete, which causes a significant impact due to noise, duration and dust or general construction debris, therefore giving them a lower ranking, whereas, externally bonded FRP jacketing, which is typically quite quick to install and does not require any loud/dirty drilling and cutting of the existing concrete, has therefore been assigned a high ranking.

Table 4. Comparison matrix of different strengthening and repairing techniques for RC columns.

Strengthening Method	Effect on Strength	Effect on Ductility	Effect on Stiffness	Cost of Strengthening	Aesthetics/Impact to Floorplan	Impact to Occupants
RC Jacketing	Increase	Increase	Unchanged/ increased	Very high	Poor	Very high
Steel Jacketing	Significant increase	Significant increase	Unchanged/ increased	Very high	Moderate	High
Externally Bonded FRP Jacketing	Increase	Significant increase	Unchanged	Moderate	Good	Moderate
Near-Surface Mounted FRP or Steel Reinforcement	Significant increase	Increase	Unchanged	Moderate	Good	High
Shape Memory Alloy (SMA) Wire Jackets	Increase	Increase	Decrease	High	Moderate	Moderate to high
Hybrid Jacketing	Significant increase	Significant increase	Unchanged/ increased	High	Moderate	High to very high

9. Research Gaps and Future Research Directions

A review of the experimental studies conducted to investigate the effectiveness of different seismic strengthening and repair techniques indicates that the primary focus of the research in the past was on the repair of normal-strength ($f'_c \leq 50$ MPa) RC columns. Figure 12a shows that in the past two decades, approximately 523 normal-strength RC columns with different strengthening techniques have been tested under simulated earthquake loading, whereas, in comparison, the seismic behavior of only 22 strengthened high-strength RC columns has been investigated so far. On the other hand, the dynamic characterization of concrete performed by Khosravani and Weinberg [106] showed that high-strength and ultra-high strength concrete are more brittle than normal-strength concrete and, therefore, RC columns with high-strength concrete collapse at a lesser drift than the latter [107–110]. Hence, it is expected that the efficiency of the strengthening and repair methods would reduce with the increase in the concrete compressive strength. In future research, this aspect needs to be studied with reference to different strengthening and repair techniques, as high-strength RC columns are being widely used in high-rise constructions all over the world, and such columns may need to be repaired after being damaged in a rare or very rare earthquake event.

Another important aspect that requires attention is the type of lateral loading path. A vast majority of the experimental studies involving strengthening and repair have been carried out under uni-directional cyclic lateral loading, and only a handful of tests have been conducted under bi-directional loading. It is shown in Figure 12b that in the last two decades, only 12 specimens were tested under bi-directional loading as opposed to 533 specimens tested under uni-directional loading. Recent experimental research conducted by the authors [108] has shown that the collapse drift capacity of the column reduces by approximately 50% under bi-directional loading scenarios. In view of this, it is essential to evaluate the comparative effectiveness of different retrofitting techniques under realistic multi-directional loading protocols.

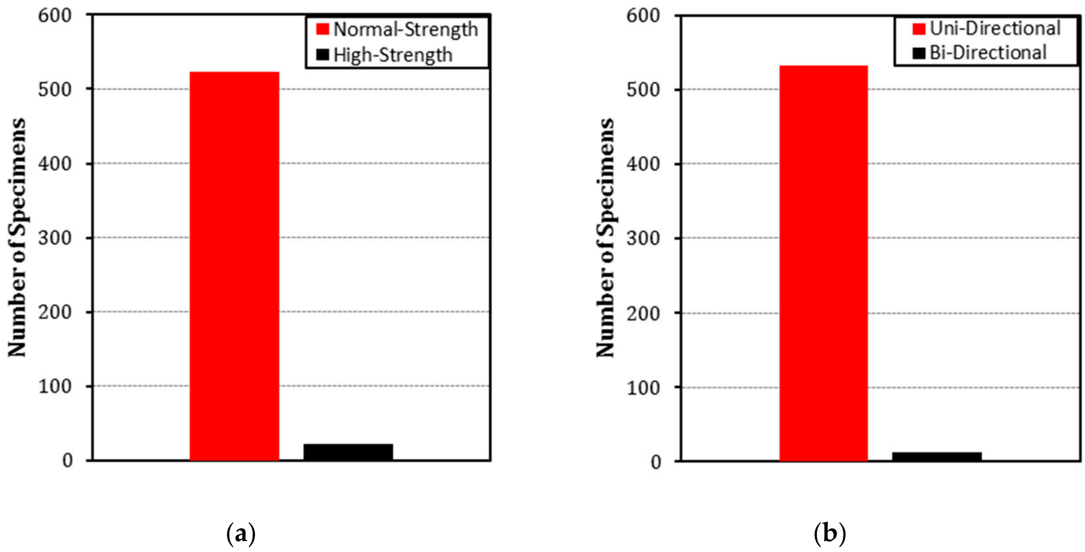


Figure 12. Overview of the experimental tests on strengthened and repaired RC columns: (**a**) Normal-strength vs. high-strength concrete; (**b**) Uni-directional vs. bi-directional lateral loading.

10. Concluding Remarks

This paper presented a detailed overview of various strengthening and repair methods for reinforced concrete columns. These techniques can contribute to the sustainability of existing reinforced concrete infrastructure by ensuring the enhancement of their existing capacity without the need for rebuilding or replacement. Each technique is discussed extensively noting the advantages and disadvantages. The review of the findings of different researchers leads to the conclusion that although the strength, ductility and drift capacity of the damaged columns can be recovered and even enhanced by repair, it is very difficult to fully restore the initial stiffness of the damaged column.

Further, based on the review of the different strengthening and repair techniques, the authors are of the view that hybrid jacketing techniques, which combine the benefits of different materials/strengthening methods can often be the most effective since they have a relatively fast installation, can significantly improve the strength, ductility and drift and can maintain the aesthetics and original geometry/configuration of the structure.

This review also highlights potential research gaps for future research such as the investigation of the effectiveness of the strengthening and repair methods for high-strength RC columns, and also the evaluation of the efficacy of these techniques under realistic bi-directional loading protocols, as most of the studies are currently focussed on the seismic performance of strengthened columns under uni-directional lateral loading scenarios. Whilst older studies focussed on ductility levels that could be used in force based design procedures, contemporary testing has a much greater emphasis on drift behaviour of retrofitted columns that can be directly used in displacement based design methods.

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