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*Review*

# FRP Composites Strengthening of Concrete Columns under Various Loading Conditions

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**Abstract:** This paper provides a review of some of the progress in the area of fiber reinforced polymers (FRP)-strengthening of columns for several loading scenarios including impact load. The addition of FRP materials to upgrade deficiencies or to strengthen structural components can save lives by preventing collapse, reduce the damage to infrastructure, and the need for their costly replacement. The retrofit with FRP materials with desirable properties provides an excellent replacement for traditional materials, such as steel jacket, to strengthen the reinforced concrete structural members. Existing studies have shown that the use of FRP materials restore or improve the column original design strength for possible axial, shear, or flexure and in some cases allow the structure to carry more load than it was designed for. The paper further concludes that there is a need for additional research for the columns under impact loading senarios. The compiled information prepares the ground work for further evaluation of FRP-strengthening of columns that are deficient in design or are in serious need for repair due to additional load or deterioration.

**Keywords:** FRP composites; external strengthening; concrete column structure; structural loading; structural rehabilitation; durability; seismic retrofitting

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## 1. Introduction

Natural disasters such as hurricanes, tornadoes, tsunamis, and earthquakes and accidental impacts can damage or destroy deficient structures in a matter of seconds. On the other hand, saltwater, deicing chemicals, and freeze-thaw cycles can cause structural deterioration over a longer period of time. The majority of older buildings and bridges were constructed according to older design codes. These structures are vulnerable during extreme events and need to be retrofitted to meet the current codes and standards.

Traditional retrofit techniques include concrete and steel jacketing. These methods are time consuming and labor intensive. They also increase the cross-sectional area of the structural column member. Another more recent method of repair is the use of fiber reinforced polymers (FRP) because of their excellent mechanical properties, corrosion resistance, durability, light weight, ease of application, reduced construction time, efficiency, and low life cycle cost [1,2].

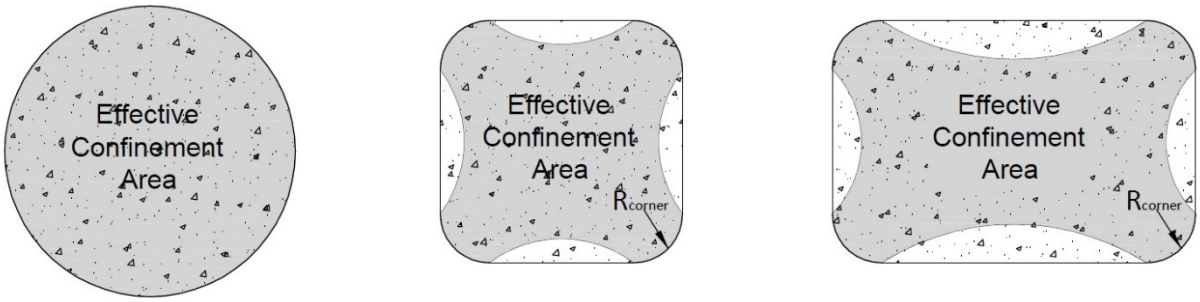
## 2. Strengthening of Columns

The repair and strengthening of reinforced concrete (RC) columns through FRP composites includes external FRP wrapping, FRP encasement, and FRP spraying. Columns can be strengthened to increase the axial, shear, and flexural capacities for a variety of reasons such as lack of confinement, eccentric loading, seismic loading, accidental impacts, and corrosion. In the following sections, these topics are discussed in further detail.

### *2.1. FRP Confinement of Columns*

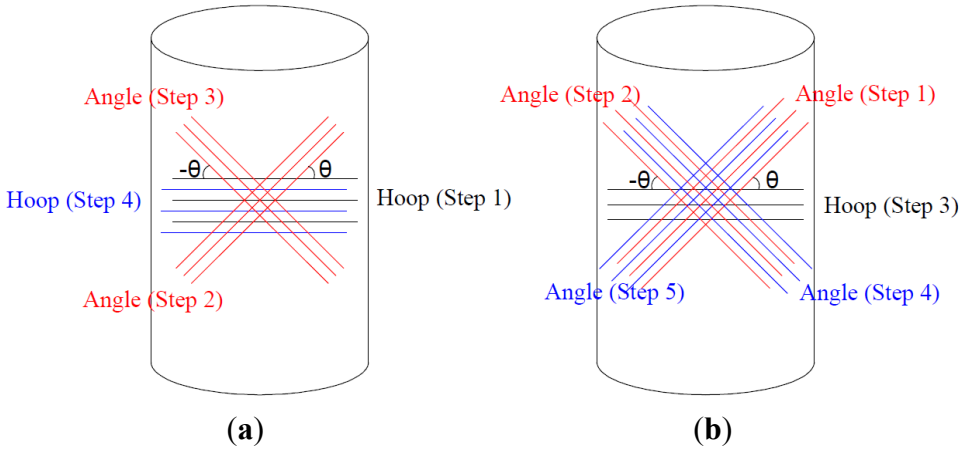
FRP sheets or encasement can be used to increase the axial load carrying capacity of the column with minimal increase in the cross-sectional area. Confinement consists of wrapping the column with FRP sheets, prefabricated jacketing, or *in situ* cured sheets with fiber running in circumferential direction. The use of confinement increases the lateral pressure on the member which results in more ductility and higher load capacity. Confinement is less effective for rectangular and square than circular shape RC columns due to the confining stresses that are transmitted to the concrete at the four corners of the cross-section. This phenomenon is presented in Figure 1, where confinement effectiveness is shown as gray shaded area for various column shapes. Confinement effectiveness improves with the increase in the corner radius [3]. Recent studies show that application of FRP materials in the hoop or lateral direction can effectively increase the load carrying capacity and concrete strain capacity of columns under axial loading [4–17].

**Figure 1.** Effective confinement areas in circular, square and rectangular columns.



The effect of "hoop-angle-hoop" and "angle-hoop-angle" ply configurations (shown in Figure 2) for FRP-wrapped concrete cylinders under uniaxial compressive loading have also been considered. The terms ''hoop'' and ''angle'' indicate that wraps were oriented at an angle of 0° and 45° with respect to circumferential direction for this case. The results showed substantial increase in the axial compressive strength and ductility of the FRP-confined concrete cylinders as compared to the unconfined ones. The cylinders with "hoop-angle-hoop" ply configuration in general exhibited higher axial stress and strain capacities as compared to the cylinders with the "angle-hoop-angle" ply configuration [12]. Likewise, the performance of axially loaded FRP-confined concrete columns with three different wrap thicknesses, wrap ply angle configurations of 0°, ±15°, and 0°/±15°/0° with respect to the circumferential direction, and concrete strength values of 20.7 to 41.4 MPa was investigated. The gain in axial compressive strength in FRP-wrapped columns was observed to be higher for lower strength concrete and the highest in the columns wrapped with the 0° ply angle configuration [13]. Not only the combination of angle and hoop wrap plies configuration, but also their stacking sequence, provide different level of strength and ductility enhancement for the same total wrap thickness. Therefore, based on strength and/or ductility demand, the proper wrap configuration can be selected for design purposes.

**Figure 2.** Ply configurations in fiber reinforced polymers (FRP)-wrapped cylinders. (**a**) Hoop-angle-hoop; and (**b**) Angle-hoop-angle.




The majority of studies on the effect of FRP confinement involve axially loaded concrete cylinders or short columns that are mainly circular shape. Larger-sized square-sectioned RC columns confined with carbon fiber reinforced polymers (CFRP) wrap showed that the CFRP confinement enhanced the axial strain capacity with much higher rate than axial stress capacity [14]. Similarly, experimental study on axially loaded full-scale square and rectangular RC columns confined with glass and basalt-glass FRP laminates showed that the FRP confinement increases concrete axial strength, but it is more effective in enhancing concrete strain capacity [7].

Besides the use of traditional FRP materials, prestressing FRP strips have been tried for confinement of circular and square columns. Motavalli *et al.* [15] reported some researchers revealed no significant effect on ultimate load capacity due to prestressing of FRP confinement, other group of researchers claimed noticable effect in residual strength of the columns after an overload. The residual strength becomes critical in the case of damage to the FRP confinement due to fire, vandalism or damage due to sustained service life.

**Table 1.** Representative experimental data on fiber reinforced polymers (FRP)-retrofitted axially loaded columns. Final mode of failure for all specimens was the FRP rupture.

| Authors | Test ID | Retrofit | Load Increase (%) | FRP Ultimate Stain mm/mm |
|---|---|---|---|---|
| Matthys *et al.* [4] | K2 | CFRP | 59.2 | 0.012 |
| | K3 | CFRP | 59.9 | 0.002 |
| | K4 | GFRP | 61.8 | 0.013 |
| | K5 | GFRP | 13.7 | 0.013 |
| | K8 | CFRP/GFRP | 33.0 | 0.010 |
| Wu *et al.* [5] | L-C-1 | AFRP | 68.6 | Nr [a] |
| | L-C-2 | AFRP | 176.7 | |
| | L-D-2 | AFRP | 30.5 | |
| | L-D-3 | AFRP | 61.2 | |
| | M-C-1 | AFRP | 50.7 | |
| | M-C-2 | AFRP | 112.8 | |
| | M-C-3 | AFRP | 136.7 | |
| | M-D-1 | AFRP | 6.8 | |
| | M-D-2 | AFRP | 19.6 | |
| | M-D-3 | AFRP | 29.4 | |
| | H-C-1 | AFRP | 21.8 | |
| | H-C-2 | AFRP | 52.2 | |
| | H-C-3 | AFRP | 102.1 | |
| | H-D-2 | AFRP | 14. 8 | |
| | H-D-3 | AFRP | 10.0 | |
| Toutanji *et al.* [6] | K9 | CFRP | 14.9 | 0.0131 |
| | K10 | CFRP | 8.5 | 0.0131 |
| | K11 | CFRP | 6.4 | 0.0129 |
| De Luca *et al.* [7] | R-0.5-5GA | GFRP | 13.0 | Nr [a] |
| | R-0.5-5GB | GFRP | 18.0 | |
| Hu *et al.* [8] | F2-202 | FRP and steel tube | 24.0 | −0.0212 |
| | F3-202 | FRP and steel tube | 42.0 | −0.0191 |
| | F4-202 | FRP and steel tube | 64.0 | −0.0192 |
| Herwig and Motavalli [9] | Col. 5 | GFRP | 28.0 | −0.011 |
| | Col. 6 | GFRP | 46.0 | −0.012 |
| | Col. 7 | GFRP | 32.0 | −0.01 |
| Abdelrahman and El-Hacha [10] | NR-CFRP | CFRP | 38.0 | Nr [a] |
| | NR-SFRP | SFRP | 70.0 | |

Notes: [a] Not reported; Carbon fiber reinforced polymers (CFRP); Glass fiber reinforced polymers (GFRP); Aramid fiber reinforced polymers (AFRP); Steel fiber reinforced polymers (SFRP).

Examples of experimental data on the effect of FRP-strengthening of axially loaded columns are shown in Table 1. The range of increase in axial load capacities of the columns in these studies varies from 6% to 177%. The increase depends on several variables including the properties and the amount of FRP reinforcement, concrete strength, column cross-section shape, and axial load level. In most of these experiments CFRP wraps were selected to confine concrete columns. The rupture strain of typical CFRP materials obtained from standard tensile testing of FRP sheets ranges from 1.5% to

2.0%. The actual rupture strains for those column tests that were reported are shown in Table 1. These values are usually less than rupture strain obtained from flat coupon tests.

The effective strain coefficient which is described as the ratio of circumferential ultimate strain to ultimate strain of FRP is in the range of 0.55 to 0.62 for fully-wrapped circular columns [4]. For rectangular or square shape columns, due to stress concentration and inhomogeneous strains at the corners, there is a substantial reduction in effective strain coefficient [6]. In axially loaded columns, external confinement with FRP sheets is much more effective in enhancing concrete capacity or axial deformation. While the FRP amount and tensile strength is responsible for increase in the strength, the enhancement in ductility (ultimate axial strain) is inversely proportional to the stiffness (E-modulus) of the FRP wrap. That means the higher the increase in strength is the lower the increase in ductility is, for a particular FRP wrap [4].

In the case of full-scale square and rectangular reinforced concrete columns, the FRP confinement was able to curtail the buckling of longitudinal bars and crack propagation [7]. The same was true for circular concrete-filled steel tubes used as columns that experienced inelastic local buckling at their end. Once the tubes were confined with FRP sheets, the local buckling of the steel tube was postponed or completely inhibited [8].

In conjunction with experimental investigations, models have been proposed to estimate FRP-confined concrete columns' strength and strain capacities using collective test data of FRP-confined concrete specimens [16]. A comprehensive concrete confinement model entails prediction of stress–strain curves, ultimate strength, and ultimate strains. The main focus has been on stress–strain relationships and ultimate strength; however, prediction of strain has been scattered. In general, the percentage of error in estimating strain is much higher than that for the strength estimation [17]. All studies reported in Table 1 entailed FRP-confined columns subjected to concentric axial load. In the next section, the effect of eccentric axial load on FRP-strengthened columns is examined.

### *2.2. Strengthening of Columns Subjected to Eccentric Axial Load*

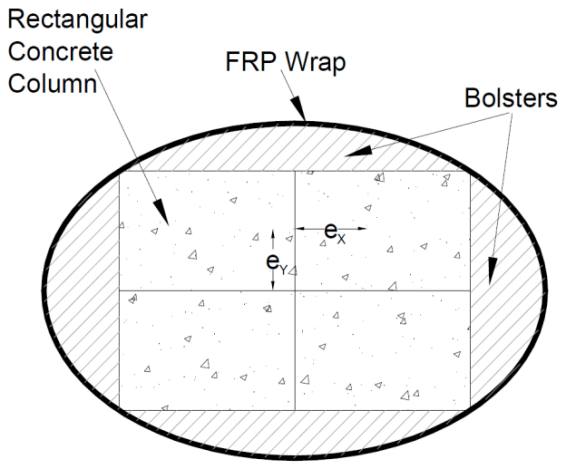
In field applications, most columns are not under perfect concentric loading. This produces a nonuniform confining stress due to the strain gradient which in turn reduces the effectiveness of the column [18]. Recently, research has been conducted on the eccentric axially loaded columns retrofitted with FRP sheets [18–28]. Parvin and Wang [18] studied the effects of the jacket thickness and various eccentricities on the CFRP-retrofitted square concrete columns. Their findings indicated that for both control and FRP-wrapped columns the eccentricity diminished the axial load capacity and corresponding axial deflection. The FRP wrap was also effective in strengthening of eccentrically loaded columns. However, its efficiency is proportional to FRP wrap stiffness and reduces due to strain gradient in the column. Similar observations were also noted for eccentrically loaded circular concrete columns wrapped with CFRP and GFRP sheets. Additionally, CFRP confinement was more effective for normal strength than high strength concrete [19,20].

The effect of wrap orientation on eecentically loaded columns has also been investigated. Experiments on FRP-retrofitted columns with longitudinal and transverse sheets revealed that under large eccentric compression loading, the presence of longitudinal CFRP sheets can enhance the columns' ultimate strength capacity, and ductility factors can improve with the transverse CFRP sheets [21].

Similarly, considerable gain in strength and ductility was achieved when eccentrically loaded concrete columns were reinforced with CFRP (vertical straps and horizontally wrapped) [22].

Columns with rectangular cross-section can be modified to elliptical shape by the addition of bolsters to columns sides to improve confinement effectiveness of FRP sheets. Elliptical concrete columns which were converted from rectangular cross-sections and confined with CFRP are shown in Figure 3. To diminish the adverse effect of eccentric loading, the wrap configuration was properly adjusted [23]. Variables considered were magnitude of eccentricity, number of CFRP layers and their orientation with respect to the transverse axis of column. Again, as compared to columns with concentric load, the efficiency of CFRP wrap diminished in eccentrically loaded columns. However as compared to their control counterparts, compressive strength for elliptical columns with three layers of CFRP in the transverse direction had a gain of 29% for concentric load and 6% to 27% gain for eccentrically loaded columns, depending on the number of layers and their orientation with respect to tranverse direction. On the other hand, for eccentrically loaded columns, axial concrete strain enhancements ranged from 1.7 to 5.4 times the unconfined axial concrete strain. The increase in circumferential concrete strains ranged from 2.3 to 9.7 times unconfined circumferential concrete strain.

**Figure 3.** Shape modification of rectangular column with bolsters to increase FRP confinement effectiveness.




Experiments were also performed on ecccetrically loaded columns with internal steel reinforcement and external FRP wraps [24,25]. El Maaddawy [24] examined the effect of eccentricity to section height ratio ($e/h$) on the confinement of axially loaded RC columns. Similar findings indicated that as the magnitude of eccentricity increased, the gain in strength due to FRP wrap decreased. When the $e/h$ ratio increased from 0.30 to 0.86, the gain in compression strength of fully wrapped columns dropped from 37% to 3%. The gain in ultimate compressive strain ranged from 645% to 124% for FRP-wrapped columns as compared to their control counterparts. In another study, square RC columns (250 mm × 250 mm × 1500 mm) were wrapped with one layer of FRP sheet and were subjected to concentric and eccentric loads. The wrapped columns showed 30.2%, 10.6%, 2.0%, and 1.6% improvement in their load capacity for the eccentricity values of 20, 60, 100, and 150 mm, respectively, as compared to their control counterparts. As the magnitude of eccentricity increased the maximum compression load capacity decreased and the mid-height lateral deflection of the columns

increased. The low-strength concrete columns had higher gain in their load capacity when confined with FRP sheets [25].

A few larger scale tests have also been performed on eccentrically loaded columns [26–28]. Large-scale rectangular RC columns with 0°, 45°, and 90° fiber orientations were tested to obtain their load *versus* displacement, and moment *versus* curvature behavior when subjected to eccentric load. Bending stiffness and moment capacity increased with the addition of longitudinal layers. However, curvature capacity did not increase in this case. For the wrap configuration with angle orientation, in addition to bending stiffness and moment capacity, the curvature capacity also improved [26]. Axial and flexural performance of CFRP-wrapped square RC columns, under various eccentric loadings, was also investigated [27]. Similarly, the addition of CFRP strap in vertical direction combined with CFRP wrapping in transverse direction enhanced the performance of eccentrically loaded columns. Test results on full-scale, eccentrically loaded, rectangular slender RC columns strengthened by CFRP sheets and near surface mounted (NSM) CFRP strips, revealed a significant difference in the effects of strengthening methods for short and slender RC columns. Longitudinal NSM CFRP strips are more effective in improving flexural resistance of slender columns, in which second order effects cause an increase in bending moment at the same value of compressive force. In contrast, transverse FRP sheets showed no significant effect in increasing slender column resistance, but it was effective in confining short columns [28].

Examples of data obtained in research conducted on eccentrically loaded columns are shown in Table 2. Again, the FRP retrofit clearly enhanced the load capacity of eccentrically loaded columns compared to as-built columns. In general, the maximum compression load increases with more FRP layers and decreases as the magnitude of eccentricity increases in the FRP-strengthened concrete columns. With the exception of a few cases, the failure mode was governed by the rupture of FRP sheet.

### *2.3. Strengthening of Columns Subjected to Impact Loads*

With consistently increasing traffic in recent years, vehicular collisions with bridge columns have become more of a prevalent issue [29]. Vehicles often strike columns or piers despite the measures put in place such as guardrails and barriers. Such impacts can lead to concrete spalling or cracking, reinforcement damage or exposure, girder misalignment, connection failure or, in worst case scenarios, structure failure [30]. Most column designs account for static loading only, while an impact load due to a vehicle collision is highly dynamic. There are certainly many existing bridges that could be deficiently designed in the case of vehicular impact. Several studies have been conducted concerning the dynamic effects of a high impact vehicle collision with bridge piers and columns [31–35]. FRP retrofit can offer a quick and economical repair as compared to traditional methods. However, studies looking into the FRP retrofit of columns for impact loads are extremely limited. Ferrier and Hamelin [32] performed experimental investigation on as-built and CFRP-strengthened RC beams and columns. The specimens were subjected to static and dynamic impact loads. For the static load tests that were conducted on three RC beams, the ultimate load of the CFRP-strengthened specimen was 62% higher than that of the as-built specimen. In the dynamic test, it was observed that the CFRP-strengthened RC column load capacity was 88% higher than that of the as-built specimen. Through both static and dynamic tests, it

was found that the use of CFRP material significantly increased the strength of RC columns under impact loading.

**Table 2.** Representative data on FRP-retrofitted eccentrically loaded columns.

| Authors | Test | Retrofit | Eccentricity (mm) | Load Increase (%) | Failure Mode |
|---|---|---|---|---|---|
| Parvin and Wang [18] | C11 | CFRP | 7.6 | 44.4 | FRP rupture |
| | C21 | CFRP | 7.6 | 79.0 | FRP rupture |
| | C12 | CFRP | 15.2 | 47.9 | FRP rupture |
| | C22 | CFRP | 15.2 | 81.0 | FRP rupture |
| Yi *et al.* [21] | C10L-1 | CFRP | 175 | 5.0 | FRP rupture |
| | C01L-1 | CFRP | 175 | 6.7 | FRP rupture |
| | C01S-1 | CFRP | 35 | 7.7 | FRP rupture |
| | C02S-1 | CFRP | 35 | 13.3 | FRP rupture |
| | C10L-3 | CFRP | 175 | 13.4 | FRP rupture |
| | C01L-3 | CFRP | 175 | 4.6 | FRP rupture |
| | C20L-3 | CFRP | 175 | 22.0 | FRP rupture |
| | C11L-3 | CFRP | 175 | 21.0 | FRP rupture |
| Hadi [20] | C2 | CFRP | 42.5 | 7.4 | Nr [a] |
| | C3 | CFRP | 42.5 | 5.0 | |
| | C4 | CFRP | 42.5 | -1.8 | |
| | C6 | CFRP | 42.5 | 22.6 | |
| Hadi [22] | G0 | GFRP | 50 | 11.9 | Nr [a] |
| | G1 | GFRP | 50 | 38.8 | |
| | G3 | GFRP | 50 | 57.8 | |
| | C0 | CFRP | 50 | 55.1 | |
| | C1 | CFRP | 50 | 109.4 | |
| | C3 | CFRP | 50 | 124.6 | |
| Parvin and Schroeder [23] | E01A4 | CFRP | 13.5 | 16.0 | Nr [a] |
| | E02A4 | CFRP | 30 | 14.0 | |
| El Maaddawy [24] | FW-e1 | CFRP | 37.5 | 37.2 | FRP rupture |
| | FW-e2 | CFRP | 54 | 24.2 | FRP rupture |
| | FW-e3 | CFRP | 71 | 8.3 | FRP rupture |
| | FW-e4 | CFRP | 107.5 | 3.3 | FRP rupture |
| | PW-e1 | CFRP | 37.5 | 27.9 | FRP rupture |
| | PW-e2 | CFRP | 54 | 21.2 | FRP rupture |
| | PW-e3 | CFRP | 71 | 3.5 | FRP rupture |
| | PW-e4 | CFRP | 107.5 | 1.1 | FRP rupture |
| Sadeghian *et al.* [26] | S200L2T | CFRP | 200 | 45.6 | FRP rupture |
| | S200L4T | CFRP | 200 | 78.0 | FRP rupture |
| | S300L2T | CFRP | 300 | 82.1 | FRP rupture |
| | S300L4T | CFRP | 300 | 128.2 | FRP rupture |
| Hadi and Widiarsa [27] | 1V2HC25 | CFRP | 25 | 17.8 | FRP rupture |
| | 1V2HC50 | CFRP | 50 | 14.7 | FRP rupture |

**Table 2.** *Cont.*

| Authors | Test | Retrofit | Eccentricity (mm) | Load Increase (%) | Failure Mode |
|---|---|---|---|---|---|
| Gajdosova and Bilcik [28] | C3 | NSM CFRP | 40 | 12.9 | Tensile crack |
| | C5 | CFRP | 40 | 2.4 | Tensile crack |
| | C7 | NSM CFRP | 40 | 15.4 | Tensile crack |
| Song *et al.* [25] | SSR-1 | FRP | 20 | 30.2 | FRP rupture |
| | SSR-2 | FRP | 60 | 10.6 | FRP rupture |
| | SSR-3 | FRP | 100 | 2.0 | FRP rupture |
| | SSR-4 | FRP | 150 | 1.6 | FRP rupture |

Notes: [a] Not reported; Near surface mounted carbon fiber reinforced polymers (NSM CFRP).

Energy performance of columns becomes essential in the case of extreme load such as impact. Few studies explore behavior of concrete columns confined with polypropylene and concrete-filled steel tube for impact load [36,37]. Uddin *et al.* [36] tested the effects of low velocity impact loading on high-strength concrete confined by a prefabricated polypropylene (PP) jacket and compared the results with conterparts CFRP-confined concrete columns. PP-confined specimens were not able to achieve similar compressive strength as CFRP-confined columns. However, PP-confined columns exhibited higher energy absorption capacity and deflection as compared to CFRP-wrapped columns. Therefore, polypropylene jacket might be more suitable for columns subjected to impact load. Yan and Yali [37] reported the impact testing results of the concrete-filled steel tube (CFT) and CFRP-confined CFT stub columns under different impacting energy levels, using a drop-hammer machine. The results indicated that the failure patterns correlated to the impact energy and the increase in the steel tube thickness and additional CFRP trasverse confinement enhanced the impact-resistant behavior. Voyiadjis [38] investigated vessel collisions with over water bridges to identify protective systems. The study revealed that FRP piles arranged in clusters of two provided adequate sideways protection for the low and medium energy performance levels. From sparse studies performed it can be inferred that the FRP materials are good candidates to contribute to concrete columns' impact resistance.

### *2.4. Strengthening of Columns Subjected to Seismic Loads*

Reinforced concrete structures built prior to the modern day design codes may have been insufficiently designed to survive a severe earthquake. Numerous studies involve the FRP retrofit of deficient reinforced concrete columns for seismic loads [39–49]. The effects of the FRP reinforcement length on the plastic hinge region and the drift capacity of FRP-retrofitted columns has been investigated [39]. The plastic hinge length is important, since it correlates to the length of damaged region and is also influential in drift capacity of columns. As the FRP wrap amount of retrofitted columns increases, the sectional curvature capacity can improve. However, the retrofitted columns' drift capacity may be enhanced or impaired with this increase. This is due to the fact that the columns' drift capacity is influenced by plastic hinge length and section curvature together. Parvin and Wang [40] performed nonlinear finite element analysis of control and FRP-wrapped RC large sized columns subjected to axial and cyclic lateral loadings. The FRP fabric in the potential plastic hinge location at the bottom of the column showed significant improvement in both strength and ductility capacities, and the FRP jacket delayed the degradation of the stiffness of reinforced concrete columns.

Lacobucci *et al.* [41] examined the effectiveness of FRP jacketing to retrofit RC columns designed with nonseismic transverse detailing. Substantial increase in the ductility and energy dissipation capacities was observed due to FRP wrapping of deficient RC columns. Similar seismic behavior was noticed for hollow rectangular bridge columns retrofitted with FRP sheets under axial and cyclic lateral loads. FRP sheets effectively improved the ductility factor and shear capacity of hollow rectangular bridge columns [42]. Stay-in-place FRP formwork has also been used as concrete confinement reinforcement for high and normal strength concrete columns under axial compression and lateral deformation reversals. The FRP tubes significantly enhanced the inelastic deformability of columns [43].

A new technique in retrofitting square or rectangular reinforced concrete columns was explored by embedding reinforcement bars into the plastic hinge zone to increase the ductility of the concrete in this region [44]. A design approach for seismic bond strengthening of splice region of reinforced concrete columns was developed. The proposed approach was validated through experiments on gravity load-designed columns that were reinforced with three types of confinement including FRP jacketing. The confinement resulted in the reduction of damage in the splice zone and considerable increases in the lateral load and drift capacities of columns [45].

In an experiemental study, the effectiveness of textile-reinforced mortar (TRM) was compared with equal stiffness and strength FRP jackets used to confine nonseismically designed RC columns with reduced capacity due to bar buckling or bond failure at lap splice regions. The findings reaveled that TRM is as effective as FRP jacketting of deficient columns [46]. FRP material with a large rupture strain (LRS) above 5% made from recycled plastics was used to jacket RC columns for the seismic retrofit. A cyclic stress–strain model was proposed to predict the behavior of LRS FRP-jacketed RC columns under seismic loading [47]. In an analytical investigation, a design method was developed to determine the necessary FRP jacket thickness in upgrading slender RC columns to reach the target displacement ductility [48]. In an experimental study the applicability and anchorage of carbon FRP precured laminates and rods for flexural seismic strengthening of columns with low strength concrete were examined. Despite the increase in flexural capacity and drift, the retrofitted columns did not exibit typical ductile behavior [49]. These studies show that the FRP composites prove to be efficient as retrofit materials in increasing the lateral load and drift capacity and reducing the damage in nonseismically designed RC columns.

### *2.5. Strengthening of Columns Subjected to Corrosion*

Reinforced concrete columns are susceptible to corrosion from marine environments, fire, and deicing agents. The behavior of FRP-wrapped columns has been investigated for freeze thaw exposure, repair of corroding reinforced concrete columns, and fire resistance. The FRP-wrapped columns demonstrated adequate performance under these severe conditions [50]. The FRP jacketing provides an alternative to conventional repair methods for corrosion-damaged reinforced concrete columns.

The FRP jacket characteristics and the repair method of columns upgraded by FRP confinement after being conditioned to accelerated electrochemical corrosion have been examined [51,52]. Bae and Belarbi [53] studied the effectiveness of CFRP sheet in protecting the RC columns from corrosion of the steel reinforcement. The research has shown that FRP retrofit was a practical alternative to

conventional methods due to its superior performance in enhancing the strength and ductility of RC columns. Performance was markedly improved by increasing the number of FRP layers and by providing sufficient anchorage for each layer [51,52]. FRP composites are very efficient as repair materials which can also decrease the rate of corrosion [52,53]. Shield *et al.* [54] performed prelimiary field study on control and FRP-wrapped bridge columns. The columns were subjected to electrochemical chloride extraction (ECE) prior to being wrapped or sealed. The ECE process was effective in removing some chloride ions from the concrete structures. Suh *et al.* [55] performed experiment on one-third scale prestressed piles that were corroded to 20% metal loss and then were wrapped with CFRP. They revealed that epoxy sealing of cracks followed by FRP-wrapping is effective even when corrosion damage is severe. Gadve *et al.* [56] applied CFRP sheets to reinforced concrete cylinders and exposed them to a highly corrosive environment. They also concluded the application of the CFRP sheet on concrete surface was very effective in retarding the corrosion of steel. The effectiveness of fiberglass wrapping in controlling the rate of corrosion in bridge concrete columns has also been evaluated. The findings revealed that fiberglass wrapping stopped the chloride ion ingress to the columns [57]. In general, the FRP repair of corrosion damaged RC columns not only provides strength and ductility, but also could slow down the rate of the corrosion reaction.

### *2.6. Field Application Projects Related to FRP Repaired Columns*

In this section, examples of field application projects in United States of America for strengthening of structure and bridge columns with FRP are presented in Tables 3–5 [58–61]. The types of repairs include: corrosion, confinement, axial, flexural, shear, and seismic strengthening. In the state of California external FRP retrofit is commonly done due to the need for seismic strengthening.

**Table 3.** Selected field application projects: columns retrofitted for axial loads or confinement.

| Agency | Structure | Date | Location | Type of Repair | Material |
|---|---|---|---|---|---|
| Quakewrap | Port Clinton Garage | 2009 | Port Clinton, OH | Axial | GFRP |
| FYFE Co. LLC | Corona Del Mar | 2009 | Orange County, CA | Confinement | GFRP |
| D.S. BROWN | Medford Fire Station | 2007 | Medford, OR | Axial | CFRP |
| D.S. BROWN | Los Gatos Creek Bridge | 2007 | Santa Clara, CA | Axial | CFRP |
| Quakewrap | Cabana Hotel | 2007 | Miami Beach, FL | Axial | CFRP |
| Quakewrap | Rocky Mountain Hardware | 2007 | Hailey, ID | Axial | CFRP |
| D.S. BROWN | House Seismic | 2005 | Puako, HI | Axial | CFRP |
| D.S. BROWN | Childrens Hospital | 2005 | Seattle, WA | Axial | CFRP |
| D.S. BROWN | PNC Bank | 2004 | Lexington, KY | Axial | CFRP |
| D.S. BROWN | I-10 Overcrossing | 2003 | Los Angeles, CA | Axial | CFRP |
| Quakewrap | Plaza In Clayton | 2003 | St. Louis, MO | Axial | CFRP |
| D.S. BROWN | Dolphin Condos | 2002 | Malibu, CA | Axial | CFRP |
| D.S. BROWN | First Union Bldg | 2002 | Charlotte, NC | Axial | CFRP |
| D.S. BROWN | Precast Concrete Plant | 2001 | Boise, ID | Axial | CFRP |
| FHWA 2007 | US 64 WB over Haw River | 2000 | Chatham County, NC | Confinement | GFRP |

**Table 3.** *Cont.*

| Agency | Structure | Date | Location | Type of Repair | Material |
|---|---|---|---|---|---|
| FHWA 2007 | Androscoggin River Bridge | 1999 | Brunswick, ME | Confinement | FRP |
| FHWA 2007 | East Street Viaduct over WV | 1999 | Parkersburg, WV | Confinement | CFRP |
| FHWA 2007 | I-96 over US 27 | 1999 | Lansing, MI | Confinement | CFRP/GFRP |
| FHWA 2007 | I-80 at State Street | 1999 | Salt Lake City, UT | Confinement | FRP |
| Quakewrap | Phoenician Resort | 1999 | Scottsdale, AZ | Confinement | CFRP |
| FYFE Co. LLC | Harris Hospital Parking | 1994 | Fort Worth, TX | Axial | GFRP |

**Table 4.** Selected field application projects: columns retrofitted for corrosion.

| Agency | Structure | Date | Location | Type of Repair | Material |
|---|---|---|---|---|---|
| FYFE Co. LLC | Chula Vista Bayside Park Pier | 2009 | San Diego, CA | Corrosion | CFRP & GFRP |
| Quakewrap | Bay View Bridge | 2007 | Ft. Lauderdale, FL | Corrosion | CFRP |
| Quakewrap | I-90 Bridge at Cline Ave. | 2006 | Gary, IN | Corrosion | GFRP |
| Quakewrap | I-94 Bridge at S.R. 49 | 2006 | Chesterton, IN | Corrosion | GFRP |
| Quakewrap | Tucson Main Library | 2005 | Tucson, AZ | Corrosion | GFRP |
| D.S. BROWN | Bahia Honda Bridge | 2003 | Florida Keys, FL | Corrosion | CFRP |
| FYFE Co. LLC | Miramar Water Treatment Plant | 2003 | San Diego, CA | Corrosion | FRP |
| FYFE Co. LLC | Malibu Residence | 2001 | Malibu, CA | Corrosion | FRP |
| Quakewrap | I-40 Bridge | 1997 | Oklahoma City, OK | Corrosion | GFRP |

**Table 5.** Selected field application projects: columns retrofitted for seismic loads.

| Agency | Structure | Date | Location | Type of Repair | Material |
|---|---|---|---|---|---|
| D.S. BROWN | Day's Inn | 2008 | Portland, OR | Seismic | CFRP |
| Quakewrap | Ted Stevens International Airport | 2008 | Anchorage, AK | Seismic | CFRP |
| FYFE Co. LLC | Pasadena City Hall | 2007 | Pasadena, CA | Seismic | FRP |
| FYFE Co. LLC | 2025 South Figueroa | 2007 | Los Angeles, CA | Seismic | GFRP |
| D.S. BROWN | Vista House | 2005 | Portland, OR | Seismic | GFRP |
| Quakewrap | McKinley Tower | 2005 | Anchorage, AK | Seismic | FRP |
| D.S. BROWN | Mountainview Overcrossing | 2004 | Reno, NV | Seismic/Flex./Shear | CFRP |
| D.S. BROWN | Mogul East & Mogul West | 2004 | Mogul, NV | Seismic/Shear | CFRP |
| D.S. BROWN | Glendale Parking | 2002 | Glendale, CA | Seismic | CFRP |
| FYFE Co. LLC | Sobrante WTP Clearwell Roof | 2002 | El Sobrante, CA | Seismic | GFRP |
| FYFE Co. LLC | L.A. Sports Arena | 2002 | Los Angeles, CA | Seismic | GFRP |
| D.S. BROWN | Richmond Police HQ | 2001 | Richmond, CA | Seismic | CFRP |
| FYFE Co. LLC | Big Tujunga Canyon Bridge | 2001 | Los Angeles, CA | Seismic | FRP |
| FYFE Co. LLC | Arroyo Quemado Bridge | 1999 | Santa Barbara, CA | Seismic | FRP |

## 3. Conclusions

This paper has provided a review of recent research and field application projects on the FRP retrofit of reinforced concrete columns. The existing investigations have revealed that the use of FRP materials restores or improves the column original design strength for possible axial, shear, or flexure and, in some cases, allows the structure to carry more load than it was designed for. In most cases,

the ductility of the columns have improved. With development of additional design standards and increased demand in the field applications, FRP will continue to grow in popularity as a retrofit material. The following conclusions and recommendations are drawn based on the review.

- Preliminary findings suggest that the angle and hoop plies and stacking sequence in wrap configuration provided different level of ductility and strength for the columns with identical FRP wrap thichness.
- Application of hoop and ply combination for wrap configarations on prismatic columns should be pursued, since they may delay premature fracture at the corners.
- Most stress–strain behaviors and related formulation rely heavily on FRP-confined axially loaded cylinders or short columns. However, the scale effect might play a vital role in the design of full size columns. More comprehensive studies incorporating the specimens size effect in analytical models should be followed.
- Modifying the shape of square-to-circular and rectangular-to-elliptical columns will eliminate the corner stress concentration in prisms and improve confinement effectiveness. Subsequent FRP-wrapping of shape-modified columns will substentially improve axial load and pseudo ductility. Shape modification is one of the less explored topics.
- More accurate and reliable models of confined concrete should be investigated through comprehensive set of data for all column shapes to not only predict the strength but axial and lateral strains as well.
- Lower strength concrete columns benefit the most in terms of compression load capacity increase once confined with FRP sheets.
- The FRP wrap stiffness plays a major role in the column jacket design. In order to develop appropriate confinement forces, the jacket must be stiff enough at a relatively low axial strain in the column.
- For eccentrically loaded columns, smaller enhancement factor should be considered in design of FRP-wrapped concrete columns.
- Seiemic damage to deficient RC columns can be reduced or completely prevented by applying unidirectional fiber composite sheet along the longitudinal direction to increase flexural capacity, and by wrapping the columns in the lateral direction to improve their ductility and energy absorption capacity.
- To withstand impact loadings, concrete columns should be properly strengthened to achieve adequate level of energy absorption capacity and ductility.
- The FRP repair of corrosion damaged RC columns not only provides strength and ductility, but also could slow down the rate of the corrosion reaction.

From the review of the literature, it was also concluded there is a need to perform additional research on the FRP retrofit of columns subjected to impact loadings. With further investigations including ways to improve energy absorption capacity and ductility of the structural systems and composite materials, reduction in life cycle costs will outweigh the higher upfront cost of FRP retrofit over conventional retrofit techniques.

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**Conflicts of Interest**

The authors declare no conflict of interest.

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