

Review Article

Behavior of Reinforced Concrete Columns Strengthened with FRP: A State-of-the-Art Review

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ABSTRACT

Structural columns often require strengthening due to deterioration, increased load requirements, or structural modifications, and their complete replacement prior to the end of their design life is economically impractical. Rehabilitation of Reinforced Concrete (RC) columns using modern materials, such as Externally Bonded (EB) Fiber-Reinforced Polymer (FRP) composites, is widely used. Similarly, Near-Surface Mounted (NSM) FRP is an effective and reliable technique for improving column load-carrying capacity while preserving the architectural profile of the structure after strengthening. The main aim of structural strengthening is to increase the ductility and ultimate strength of RC columns, increase their load-carrying capacity, and minimize the risk of damage or failure under increased service loads while ensuring structural compatibility. This paper reviews the latest research and developments on the performance and behavior of RC columns strengthened with FRP under various loading conditions and key operational parameters, such as cross-sectional geometry, slenderness, and eccentricity. Overall, the review highlights that combining longitudinal NSM strengthening with transverse EB-FRP confinement yields superior structural performance by mitigating premature debonding, enhancing flexural rigidity, and optimizing strain distribution across non-uniform stress gradients. Based on a comprehensive review of experimental and numerical studies, structural strengthening using FRP composites yields distinct quantitative improvements depending on the technique employed, full EB-FRP wrapping increases axial capacity by 25%–110% under concentric load and 35%–90% in damaged short columns, while NSM systems enhance flexural capacity by 38%–72% and energy dissipation up to 120%. Under eccentric loading, axial gains diminish to 8%–33%. Hybrid FRP systems (NSM combined with EB wraps) yield peak capacity gains of 49%–95% and restore up to 100% of original strength in pre-damaged columns, effectively delaying debonding

1. INTRODUCTION

Constructing new structures or demolishing existing ones involves substantial technical challenges and significant financial investments. The aging of structures, along with the detrimental effects of corrosive environments, seismic occurrences, and many natural threats, necessitates structural strengthening [1–3]. Replacing an entire structure entails significant challenges, including high material and labor costs and extended construction timelines. As a result, it is often necessary to strengthen RC columns to regain their load-carrying capability, meet design specifications, and prolong their operational service life. Over the last three decades of the twentieth century, FRP composites emerged as a viable method for infrastructure rehabilitation, especially for strengthening RC columns. The fibrous phase provides structural tensile capacity, whereas the polymeric matrix encapsulates the fibers and distributes loads between them, preserving structural stability. Among the diverse FRP systems, including Aramid (AFRP), Glass (GFRP), and Carbon (CFRP), CFRP has emerged as the most widely employed material in structural engineering for enhancement, restoration, and seismic retrofitting. CFRP composites are produced commercially in many geometric forms designed to meet structural specifications, such as laminates/plates, flexible sheets, bars, and strips, as seen in Fig. 1(a, b, c, and d).

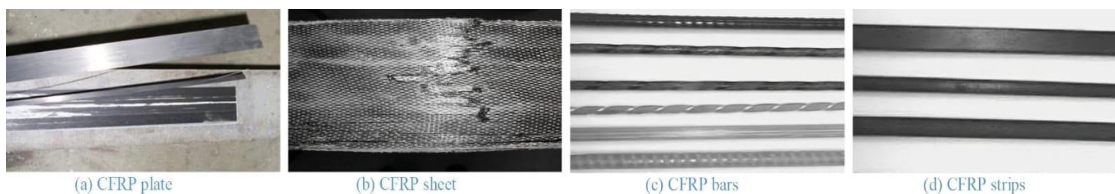


Fig. 1. CFRP products as a) plates, b) sheets, c) bars and d) strips [4, 5 & 6]

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FRP strengthening techniques offer versatile applications, ranging from structural retrofitting to modern column confinement [7 - 13]. FRPs are increasingly favored as strengthening materials due to their exceptional longitudinal tensile strength, ease of installation, resistance to fungal and insect growth, stiffness, chemical durability, corrosion resistance, and high strength-to-weight ratio [14 -19]. The superior strength of FRPs relative to conventional steel is evident in Fig. 2, which illustrates the stress-strain behavior of mild steel alongside various FRP materials. Among these, CFRP is particularly preferred for RC column strengthening owing to its exceptional mechanical properties and favorable life-cycle cost. In CFRP composites, high-tensile-strength fibers are embedded in an epoxy matrix. To achieve effective composite action between CFRP and concrete, proper surface preparation is critical, as stress transfer between the concrete substrate and EB-CFRP relies heavily on bond strength and quality. The material properties of the epoxy matrix and the concrete substrate attributes (including its strength, cleanliness, and surface roughness) directly influence bond quality. Epoxy resins are most commonly utilized due to their superior adhesion to both carbon fibers and concrete surfaces [17].

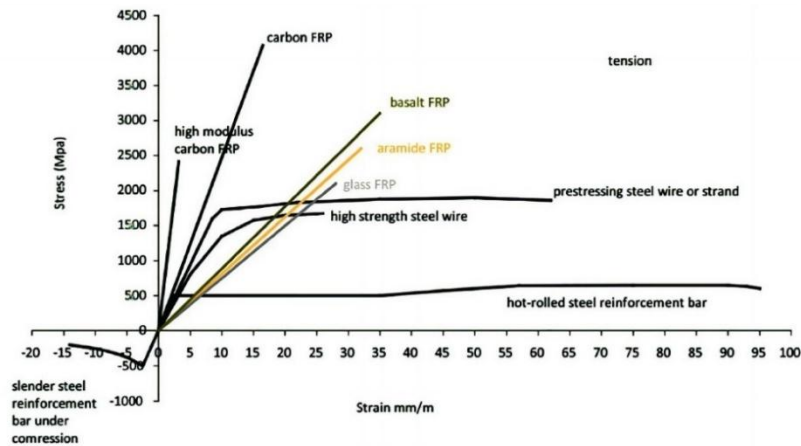


Fig. 2. Comparison between mild steel and common FRP materials [20]

Despite significant advancements in FRP strengthening technologies, concerns remain regarding their long-term durability and structural performance under critical exposure conditions. Consequently, investigating the dynamic response, cyclic performance, and long-term durability of FRP-strengthened RC columns is imperative. The efficacy of structural rehabilitation can be severely compromised if the applied FRP composite systems fail to maintain bond integrity and confinement effectiveness throughout the intended design life of the column. To delineate the scope of this study, this review specifically focuses on EB, NSM, and hybrid FRP strengthening techniques applied to RC column members. As the primary load-carrying members responsible for maintaining global structural stability, columns operate under multi-axial stress states, often subject to high axial compression combined with lateral loads. The review encompasses experimental and theoretical literature published between 2011 and 2025, emphasizing performance parameters such as axial capacity, flexural and shear enhancements, load eccentricity, slenderness, and hybrid retrofitting configurations. Selecting 2011 as the starting point to evaluate developments over the past 15 years is justified by the emergence of comprehensive experimental research during this period that systematically investigated diverse FRP strengthening techniques across various cross-sectional geometries and complex loading conditions.

2. RESEARCH SIGNIFICANCE

One strengthening method that has gained widespread adoption is the application of EB-FRP sheets to RC structures using epoxy resin. Thus, selecting the optimal technique to strengthen cracked concrete members under various loading conditions remains an important engineering challenge, and the availability of extensive experimental databases in the literature provides guidance for this selection, although systematic comparison of different techniques under similar conditions remains limited. Despite the widespread use of FRP composites, specifically EB systems and NSM techniques, in structural rehabilitation, selecting the optimal retrofitting system for RC columns remains a complex design challenge.

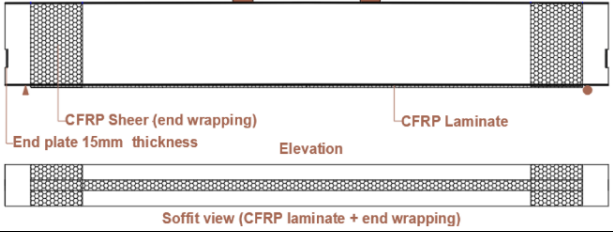
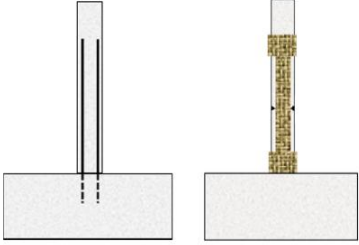
Despite the widespread use of FRP composites in structural rehabilitation, selecting the optimal retrofitting system for RC columns remains a complex design challenge. While existing review papers primarily focus either on EB-FRP confinement in general concrete elements (such as beams and slabs) or address individual strengthening techniques in isolation, a critical research gap remains regarding the integrated performance of RC columns under combined axial, flexural, and eccentric loading regimes. Specifically, a comprehensive, multi-variable comparative evaluation contrasting traditional EB wrapping, longitudinal NSM, and hybrid NSM/EB retrofitting configurations under identical operational parameters such as section geometry, slenderness, and load eccentricity is currently lacking in the literature.

The results of this study will provide researchers with a comprehensive understanding of FRP applications for strengthening RC structures. This research provides practical guidance for structural engineering applications. From a practical perspective, this study provides engineers with a clear decision-making framework for selecting the appropriate FRP strengthening scheme based on column geometry and load eccentricity.

3. STRENGTHENING TECHNIQUES FOR RC MEMBERS

Depending on the predominant structural action (flexure shear, or axial compression), a suitable strengthening method is required to restore the strength and serviceability of affected structures and extend their operational service life. Table I summarizes the various configurations of FRP strengthening systems. Two widely used techniques for rehabilitating and strengthening concrete members using FRP materials are EB and NSM systems. The fundamental mechanism of these technologies involves applying FRP materials to tension-exposed surfaces to improve the stiffness and flexural capacity of the structural components.

TABLE I. STRENGTHENING OF FRP SYSTEMS

Type of strengthening	Strengthening systems	Reference
EB (Shear & Flexural)		[14]
EB (Flexural)		[21]
EB & NSM (Shear & Flexural)		[22]
NSM (Flexural)		[23]

EB-FRP strengthening can be applied in several configurations, including vertical, inclined, side-bonding, and full or partial wrapping. Conversely, the NSM technique involves positioning FRP laminates or rods within grooves cut into the concrete cover and securing them with adhesives [24 & 25]. The NSM technique requires cutting a groove into the concrete cover of the RC column, then bonding the FRP strengthening with epoxy resin. Fig. 3 illustrates the geometric limits and dimensional recommendations specified by the ACI 440.2R-23 guidelines [26].

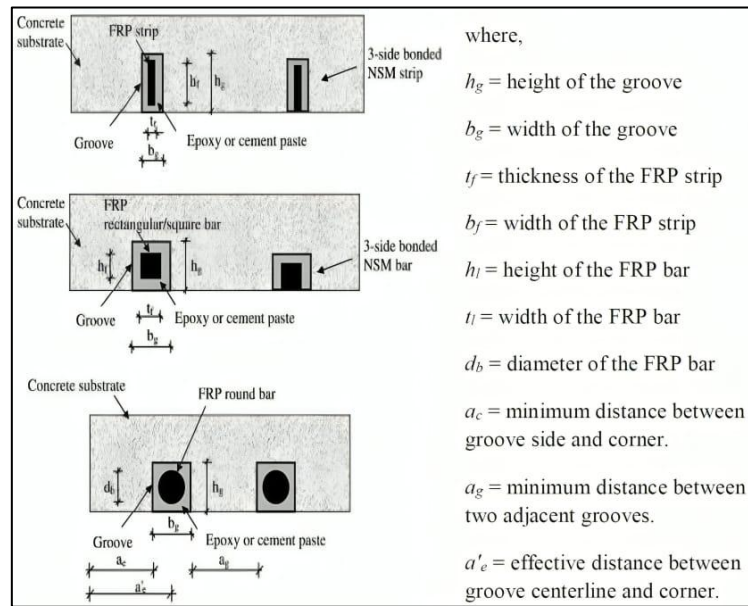


Fig. 3. Groove limits for different NSM systems [6]

Groove preparation in concrete members for NSM installation is typically achieved via two primary methods depending on the application context. In field applications and structural retrofitting of existing RC members, grooves are mechanically saw-cut into the hardened concrete cover using diamond-bladed saws. For experimental testing on newly cast laboratory specimens, pre-formed grooves are efficiently established by securing high-density expanded polystyrene strips matching the specified groove dimensions to the internal mold prior to concrete placement. Following mold removal, the sacrificial polystyrene inserts are stripped, scraped, or dissolved with mild solvents. Owing to the low mechanical resistance of polystyrene relative to the concrete matrix, this technique forms precise, clean indentations without inducing micro-cracking, edge spalling, or localized damage to the surrounding concrete.

Overall, the NSM technique offers distinct structural advantages, as the FRP material is protected by the concrete cover, which offers enhanced resistance to UV radiation and other weather-related concerns. Furthermore, relative to the EB technique, it exhibits higher resistance to debonding because the Interconnection surface between the concrete and the FRP is larger [27 & 28]. A variety of anchoring systems, such as FRP anchors, straps, powder-actuated fasteners, spike anchors, mechanical fasteners, and any other appropriate configurations, can be used for FRP strengthening [29 - 32].

Quality control and structural inspection protocols for FRP-strengthened concrete specimens, utilizing both EB and NSM techniques, rely on meticulous specimen preparation, interfacial bond integrity, and post-installation non-destructive evaluation [26]. In EB-FRP applications, quality verification begins with specimen preparation and surface processing. This requires a roughened concrete surface and rounded corners to prevent stress concentrations. Interfacial bond strength is verified through direct pull-off tensile testing, confirming cohesive failure within the concrete substrate rather than adhesive debonding at the epoxy-concrete interface. Post-curing evaluation includes full-coverage acoustic testing or infrared thermography to detect voids, unbonded zones, and subsurface delamination [33].

While EB and NSM strengthening techniques offer substantial structural advantages, their real-world applicability and long-term durability are significantly governed by environmental conditions during application and throughout service life. The structural bond integrity relies heavily on the full polymerization and curing of epoxy adhesive. Epoxies generally require ambient application temperatures between 15°C and 30°C to cure properly. Applying these adhesives at low ambient temperatures below 10°C severely retards the curing reaction, preventing the resin from reaching its target mechanical strength. Conversely, high temperatures during application accelerate reaction kinetics, drastically reducing the adhesive's working pot-life. Furthermore, during service life, structural performance deteriorates rapidly if exposure temperatures approach or exceed the glass transition temperature of the epoxy matrix, which typically ranges from 55°C to 82°C. Crossing this threshold causes matrix softening, loss of shear modulus, and loss of bond strength at the concrete interface.

Environmental sensitivity and moisture levels during construction also present critical constraints. The presence of excessive moisture or high relative humidity above 85% during surface preparation or adhesive curing adversely affects interfacial adhesion. Moisture on the unconfined concrete substrate inhibits proper penetration and wetting of the resin, leading to plasticization of the matrix, micro-delamination, and premature debonding failure. Consequently, maintaining strict field

quality control, ensuring proper concrete surface drying, and monitoring ambient atmospheric conditions remain vital prerequisites prior to executing EB or NSM strengthening operations.

Conversely, NSM-FRP inspection protocols focus on precise groove preparation and complete epoxy encapsulation. Before cutting the grooves, radar or other measuring devices map the existing internal reinforcement to avoid damaging the reinforcing bars. The cut grooves are inspected for dimensional tolerances and thoroughly cleaned with compressed air to remove mortar, dust, and cracked concrete before resin injection. During installation, verify complete encapsulation of the FRP bar or strip within the structural adhesive to ensure bond transfer from all sides. Finally, post-curing integrity within the grooves is assessed using ultrasonic pulse velocity to ensure bond continuity and overall structural performance [34].

4. FRP-STRENGTHENED STRUCTURES PERFORMANCES

In general, it is possible to enhance the flexural strength, shear resistance, ductility, and strain capacity of pre-existing RC columns, slabs, beams, bridge components, and prestressed structural components under various loading scenarios [14, 32, 35 & 36]. The codes used for developing FRP systems are CECS 146, FIB 14, and ACI 440.2R. Because FRP-strengthened structures may experience diverse loads and exposure circumstances, the behavior of FRP-strengthened structures must be verified under relevant service conditions.

4.1 Flexural Strengthening

Increasing flexural strength is essential for structural members because it improves resistance to repeated bending forces. The effectiveness of a flexural strengthened component depends on the strengthening technique used, the adhesives, the FRP properties, and any additional anchoring. The fundamental idea behind flexural strengthening is to reinforce the tensile surface of concrete to enhance both the stiffness and strength of concrete members subjected to flexure. The fibers in FRP laminates should be distributed along the member. In contrast, the popular EB-FRP sheet is positioned on the tensile surface of a concrete structure and offers exceptional performance under bending [10, 37 - 40]. Although NSM strip strengthening has demonstrated efficacy, it may not significantly improve flexural behavior when the column is wrapped with an EB-FRP sheet [41]. As shown in Fig. 4, debonding is a common failure mechanism in FRP-strengthened RC structures subjected to bending, as it reduces the efficiency of the strengthening [42 & 43].

FRP-strengthened beams exhibit a marked increase in ultimate load-carrying capacity compared to unstrengthened control specimens. The ductility and deflection in the strengthened FRP beams are markedly reduced compared to the unstrengthened beams. The ductility ratio is defined as the ratio of the ultimate deflection to the yield deflection of the member. Furthermore, the potential for early debonding failure due to brittle behavior is even more undesirable in FRP-strengthened beams. Owing to the sudden failure characteristic of low-ductility structural elements, improving ductility in FRP strengthening is essential. Therefore, in FRP-strengthened flexural members, it is important to achieve both increased ductility and improved load-carrying capability. In the context of RC columns, while these flexural mechanisms are derived from beam action, they apply directly to columns subjected to eccentric axial loads or lateral forces, where longitudinal FRP strengthening prevents flexural tension failure, controls cracking, and increases moment-resisting capacity.



Fig. 4. Failure modes of flexural strengthening [17 & 44]

Furthermore, research indicates that NSM-strip-strengthened beams have superior bending performance compared with the commonly used EB laminate method, potentially increasing total strength by more than 200% [38, 45 & 46]. This is often attributed to the stiffness of NSM strips compared with two-dimensional fiber-based FRP laminates [47]. FRP wrapping improves ductility by decreasing the deflection and width of cracks during bending [48].

The structural performance of EB-FRP strengthened concrete bending members depends primarily on the integrity of the interfacial bond, the thermomechanical behavior of the structural adhesive, and compliance with service limit conditions. Debonding failures are classified into several types, the most important being end debonding and intermediate crack-induced

debonding. End debonding initiates near the sheet endpoints where high interfacial shear and normal peeling stresses concentrate, and manifests either as debonding of the concrete cover, which propagates horizontally along the longitudinal reinforcement plane, or as debonding of the plate ends within the adhesive resin layer. Conversely, intermediate crack debonding occurs at locations of flexural cracks or flexural-shear cracks in areas of high moment, where localized tensile strain discontinuities produce shear stress maxima along the FRP-concrete interface, which extend outward toward the supports.

Effective stress transfer across the composite contact surface depends heavily on the mechanical and thermal properties of the polymer adhesive. Ductile adhesives facilitate the redistribution of plastic strain along the bond line, mitigating extreme shear concentrations and delaying brittle detachment, while stiff adhesives lead to premature debonding. The glass transition temperature controls the thermal response; exceeding this temperature causes the polymer matrix to soften rapidly, resulting in a sharp deterioration of the shear modulus and bonding capacity [49]. To ensure structural reliability, the surface must be prepared to remove the weak cement mortar layer and expose the intact coarse aggregate, eliminate air voids during mixing, and maintain a precise, uniform bond line thickness.

In design practice, service limit states often dictate member dimensions before they reach ultimate flexural capacity. EB-FRP sheets increase the moment of inertia after cracking, improving post-cracking flexural stiffness, controlling crack propagation to reduce reinforcement corrosion, and limiting service-load deflections to meet allowable code thresholds. Furthermore, the service design imposes strict stress limits under sustained loading to prevent creep rupture and fatigue failure.

4.2 Shear Strengthening

Various techniques, such as epoxy-bonded steel plates [50 & 51], active external prestressing [52 & 53], and FRP materials [54 - 56], have been used in some studies to mitigate brittle shear failure patterns and strengthen reinforced concrete beams under shear stress [57 - 61]. FRP, made of glass, carbon, and aramid fibers, is frequently applied externally to strengthen RC members (columns, beams) in both flexural and shear directions [59 - 64].

The external bonding technique is used as continuous jacketing or strips for shear strengthening. Fig. 5 shows the three primary forms of FRP strengthening: side bonding, full wrapping, and U-wrapping [65]. Because it is feasible even with certain geometric restrictions, the most efficient shear strengthening technique for FRP is the full wrapping of the components of RC structures [14]. The quantity, quality, direction, and distribution of the FRPs and the internal steel bars affect the quality and functionality of the strengthened structure [57, 58].

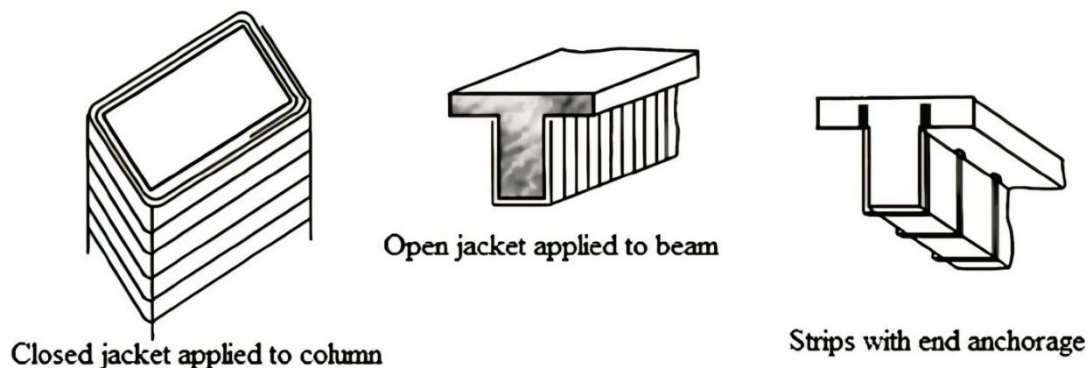


Fig. 5. Shear strengthening techniques [42]

The efficiency of shear strengthening of FRP members is strongly influenced by geometric parameters, especially the ratio of shear span to depth (a/d) and the influence of structure size. In deep beams ($a/d < 2.0$), load transfer is governed by direct arch action, while the FRP mesh mainly limits compressive concrete support and delays crack failure. In contrast, in slender beams ($a/d \geq 2.5$), the load transfer shifts to the beam action, so that the external composite can directly bypass diagonal tensile cracks and maximize the enhance in shear strength up to the flexural limit applicable at higher ratios ($a/d > 3.5$).

Furthermore, FRP-strengthened members exhibit a pronounced size effect, characterized by a decrease in nominal shear strength with increasing effective depth (d). Because deeper members store higher elastic strain energy, wider diagonal crack openings form when fracturing occurs, significantly reducing aggregate overlap and accelerating the debonding of interfacial surfaces at average FRP strains much lower than those recorded in small-scale specimens. Consequently, modern accurate predictive models must incorporate depth-dependent empirical reduction factors or fracture energy scaling parameters to avoid unconservative predictions of shear capacity in full-scale structural members. In the context of RC columns, transverse

shear strengthening is vital to withstand dynamic and seismic lateral loads, where full FRP wrapping intersects diagonal shear cracks, prevents premature brittle shear failure, and shifts the structural response toward a more ductile flexural failure mode.

4.3 Axial Strengthening

Using FRP materials oriented transversely along a column's longitudinal axis can increase or improve its axial compressive strength. When using the FRP sheet for strengthened structural elements, the failure modes can be (rupture of FRP, failure of concrete, or debonding of FRP). One common strengthening technique that effectively improves compressive strength is wrapping an EB-FRP sheet around the column's periphery [66]. The structural response of axially loaded RC columns with FRP composites depends on lateral confinement, the efficiency of the geometric cross-section, and the interaction between the internal and external reinforcement. Unlike unconfined concrete subjected to direct axial stress, FRP composite jackets provide confinement that is activated solely by the lateral expansion of the concrete under axial loading.

Strain compatibility requires that the circumferential (hoop) tensile strain in the FRP jacket at the contact surface between the concrete and the FRP be equal to the lateral expansion strain of the concrete. At low axial stress levels, the lateral expansion of the concrete is minimal, rendering the FRP virtually unstressed. Once micro-cracks begin to form and widen near the peak strength, the ratio of lateral strain to concrete increases rapidly. This lateral expansion leads to peripheral tensile strains in the external jacket, generating reactive lateral confinement pressure. Induced confinement compression transforms the brittle uniaxial stress state into a ductile triaxial compressive stress state, delaying the formation of the shear plane, elevating the ultimate axial compressive strength, and greatly expanding the ultimate axial deformability/strain.

Full wrapping is most effective to constrain the column, thereby improving its compressive strength, enhancing its resistance to lateral deflection and ductility, and increasing its ability to control strain capacity [38]. By contrast, partial wrapping systems using FRP under direct compression are less effective than the above [67]. Increased FRP jacketing thickness enhances ductility and reduces cracking. It also shifts the structural member's failure mode from shear to flexure [68, 69]. P. G. Lignola, et al. [79] studied the effects of strengthening FRP columns through practical experiments, and results from seven prismatic columns indicate that adding more FRP layers increases column ductility and reduces shear cracking. The fiber's thickness, rupture strain, and modulus of elasticity, as well as the size and shape of the column, also influence the degree of confinement and enhance the concrete's confinement resistance. , as illustrated by the typical failure modes of FRP-confined columns under axial compression in Fig. 6.



Fig. 6. Columns confined by FRP under axial compression [70 - 72]

In rectangular and square columns, the confinement of FRP is non-uniform due to the varying flexural stiffness along straight edges compared to the high stiffness at the corners. In unmodified square/rectangular sections, stress concentration peaks develop at the 90° sharp edges, leading to premature localized rupture of the FRP jacket at hoop strains well below its ultimate material capacity. To mitigate stress concentration, rounding the corners to a radius eliminates the sharp contact points. This redistributes the high localized shear and flexural stresses over a wider arc, preventing premature localized tensile splitting in the composite. Rounding the corners also increases the equivalent contact area, thereby increasing the effective confinement area-to-cross-sectional area ratio.

5. LITERATUE SURVEY

Lately, FRP composites, primarily used as EB sheets, wraps, or NSM bars, have gained widespread popularity for strengthening RC columns. Numerous studies have investigated the effectiveness of FRP methods in increasing the axial and flexural responses of columns. Current research on FRP strengthened of RC columns can be categorized based on three main parameters: (a) load system, (b) strengthening techniques, and (c) column configurations.

5.1 load system

The structural performance of FRP-strengthened RC columns varies significantly under different loading regimes.

In 2011, M. Quiertant, and J. L. Clement, [73] examined the structural efficacy of square RC columns strengthened with diverse CFRP composite systems under eccentric compressive loading. To replicate outdated infrastructure and inadequate structural components, the authors constructed ten full-scale square columns utilizing conventional concrete with non-seismic specifications (minimal reinforcement ratios and sparse stirrup distribution). The authors strengthened eight specimens using four distinct composite methodologies, including unidirectional and bidirectional CFRP textiles and prefabricated panels. The experimental findings indicated that CFRP confinement markedly improves ultimate axial load capacity, ductility, and tensile strain distribution along the tension face during eccentric loading. The extent of these mechanical improvements was strongly influenced by the structural arrangement of the composite system (i.e., fiber alignment and panel continuity).

In 2013, X. Song, et al. [74] studied the compressive behavior of RC columns strengthened with FRP composites subjected to both concentric and eccentric axial loads. They developed a non-linear analytical-numerical model based on the constitutive stress-strain relationship of concrete. They adjusted it based on the actual constrained concrete area observed during physical compression testing. Furthermore, the authors proposed of analytical equation to predict the ultimate axial load capacity of FRP-confined reinforced concrete columns. Comparative assessments with unstrengthened baseline specimens revealed that the ultimate compressive strength of FRP-wrapped columns improved linearly with the number of composite layers, decreased progressively with higher load eccentricity, and increased exponentially with unconfined concrete compressive strength. Fig. 7 depicts the experimental load-strain curves. Crucially, the analytical findings show that externally bonded FRP jacketing achieves its highest confinement efficiency when applied to low-strength concrete structures, making it an optimal retrofitting solution for aging or sub-standard infrastructure.

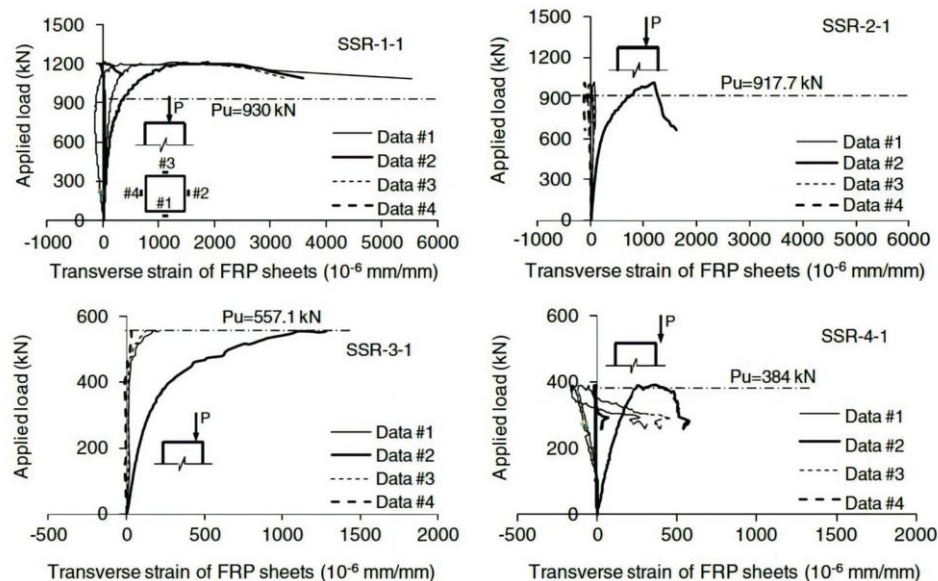


Fig. 7. Load-strain curve of eccentrically loaded FRP sheets [74]

To show the improvement obtained through the application of two established external strengthening methods, namely CFRP laminate and NSM rebar, to partly cracked columns, Q. F. Hasan, et al. [22] in 2016 examined three RC column specimens evaluated under increasing cyclic lateral load. While NSM rebar demonstrated superior improvements in load capacity, ductility ratio, and dissipated energy, CFRP laminate strengthening demonstrated superior improvements in crack development and propagation. Thus, for strengthening and retrofitting of such cracked RC columns that may be exposed to seismic events, NSM rebar might be a superior choice.

In 2018, H. F. Isleem, et al. [72] studied the stress-strain performance of concrete columns with EB-CFRP composites. The first part presents the results of experimental testing. The experimental program involved testing 28 large concrete columns (unreinforced and reinforced) encased in CFRP sheets. The test parameters included the volumetric ratio of steel reinforcement, the number of CFRP layers, the cross-sectional dimensions and aspect ratio, and the type of loading (cyclic and monotonic). Axial strain significantly improved in all of the confined columns, although axial strength only slightly improved. The study's key finding was that longitudinal and transverse reinforcement affected plastic strain values, unloading and reloading pathways, and the forms of the axial stress-strain envelope curves.

In 2018, M. Elsayed, et al. [75] investigated the structural response of slender rectangular RC columns strengthened with CFRP under eccentric loads. Twelve rectangular RC columns were designed and tested, with nine CFRP-strengthened columns and three unstrengthened control columns. The study considered several variables, including CFRP thickness, different strengthening systems, column slenderness, and eccentric load. The experimental results showed a significant improvement in the performance of the CFRP-wrapped columns compared to the unwrapped columns. The load-carrying capacity and ductility of the columns were clearly increased as a result of the CFRP wrapping. Partial and full CFRP wrapping significantly increase the ultimate load-carrying capacity by 55% to 75%, respectively. The effect of CFRP strengthening technology decreases with eccentric loads.

In 2020, J. Yang, et al. [76] conducted a comprehensive experimental and theoretical study into the axial compressive response of square concrete columns partially confined with CFRP composites. An experimental program was implemented involving forty square specimens with a cross-section of (150 X 150) mm and a length of (300 mm) under monotonic axial compression to systematically investigate key structural parameters, including the type of concrete components, the number of CFRP layers, the net spacing ratio of the partial confinement, and the wrapping configurations. Thirty-four CFRP-strengthened columns and six unstrengthened control specimens were tested (Figure 8). The experimental results showed that columns partially wrapped with two CFRP layers, when the spacing between the strips is reduced, increase the average ultimate strength by 13.6% to 36.6% and improve the axial strain by 22.3% to 91.9%. Increasing the thickness of the CFRP sheets increases ultimate strength and axial deformability by up to 57.6% and 108.8%, respectively. Furthermore, the researchers compiled a comprehensive experimental database to critically assess existing axial stress-strain Constitutive models for FRP-confined square concrete. Based on these evaluations, the authors developed a novel stress-strain model specifically calibrated for partially wrapped square columns, which showed superior predictive accuracy compared with established theoretical models in the literature.

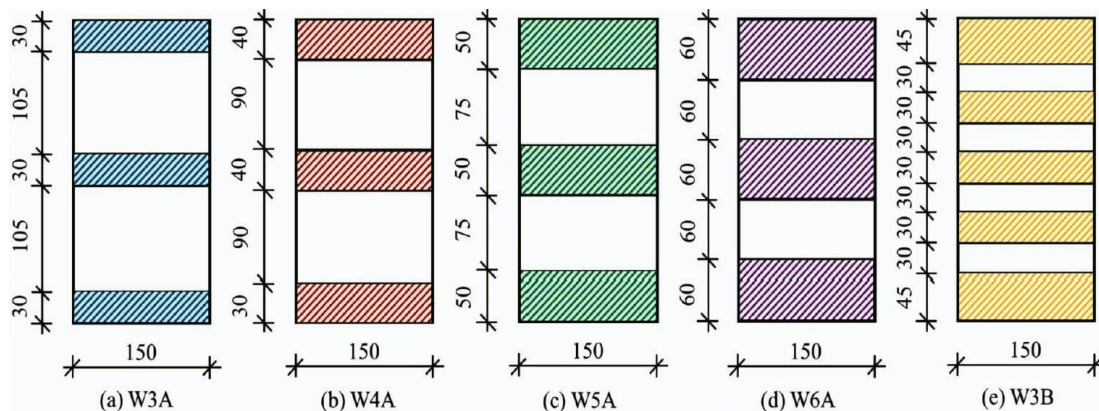


Fig. 8. Columns strengthening schemes with CFRP [76]

In 2021, H. X. Tin, et al. [70] conducted an experimental study to evaluate the behavior of a rectangular RC column with different CFRP wrapping patterns under eccentric loads. Both loading conditions, uniaxial and biaxial eccentric loads, were considered as test parameters for the CFRP-strengthened specimens, which were strengthened with a one-layer of vertical CFRP sheets on all four sides along the axis with the main fibers. The uniaxial eccentric load test showed an increase in ultimate load capacity of 8% and 33% for partial and full CFRP wraps, respectively. Meanwhile, under the influence of biaxial eccentric loading, partial CFRP confinement yielded capacity improvements of 19% and 31%. This indicates that partial CFRP confinement increases the ultimate load capacity under larger biaxial eccentric loads.

In 2021, M. Nematzadeh, et al. [77] studied the unusual compressive performance of steel fiber-reinforced concrete columns strengthened with CFRP wraps. Eighteen columns were fabricated and tested, and the results showed that the CFRP sheets increased the RC columns' load capacity and ductility. At the same time, the steel fibers in the concrete had little impact on the columns' load capacity but increased their ductility. Further, the confinement effect of CFRP sheets on the strength of the reinforced concrete was reduced due to the eccentricity of the applied load. An analytical model was developed to predict

how fibrous RC columns strengthened with CFRP sheets would respond under an eccentric compressive load, given the importance of their performance. In this model, the fiber section analysis method was used to determine the moment-curvature and load-deflection diagrams by accounting for the simultaneous effects of confinement from transverse reinforcement and CFRP sheets. The suggested model may accurately forecast the performance of fibrous concrete columns reinforced and supported by CFRP sheets and transverse reinforcement under eccentric loads, according to an evaluation comparing the analytical results with the experimental results of this study and those from previous research.

5.2 Strengthening Techniques

The choice of strengthening method dictates the load-transfer mechanisms and structural efficacy.

In 2019, M. Chellapandian, et al. [78] examined the bending and axial compression interaction performance of RC columns that had been severely damaged and subsequently strengthened using various FRP methods. A total of eighteen columns were cast and tested under different loading conditions. Initially, the columns deteriorated under varying ratios of bending load to axial compression. The columns were later restored utilizing high-strength cement grout (HSCG) and strengthened further with (i) NSM-CFRP laminates and (ii) a hybrid FRP approach that combines NSM laminates with EB fabrics. The columns were then loaded again until failure. Fig. 9 shows the practical results for the columns. For the severely damaged columns, an experimental axial force-bending moment (P-M) interaction diagram is shown. The experimental results show that the specimens repaired and strengthened using hybrid FRP technology can effectively regain their original strength under various eccentric loading levels. Additionally, by combining strain compatibility with the modified constitutive models, the interaction curves were analytically derived.

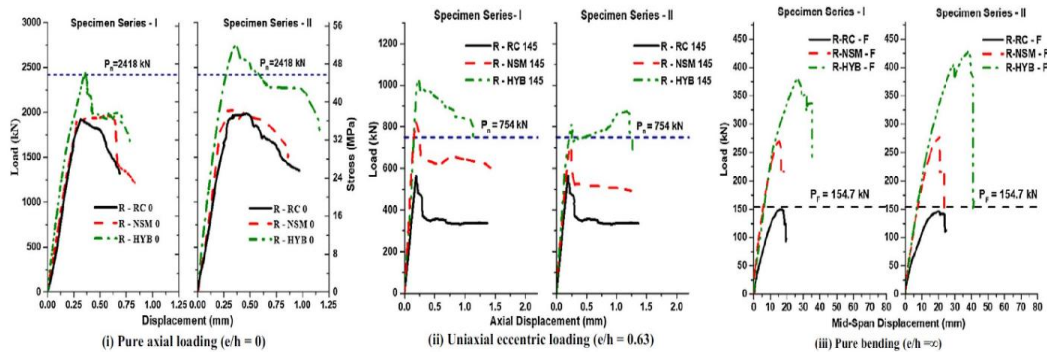


Fig. 9. Behavior of columns under different loading ratios [78]

In 2020, G. Xing, et al. [79] investigated the flexural response of RC columns strengthened with NSM using Shape Memory Alloy (SMA) bars and CFRP bars. The experimental program comprised seven large-scale RC column specimens evaluated under combined constant axial load and quasi-static lateral cyclic loading. The variables included the type of strengthening bar in the NSM method (SMA or CFRP), external CFRP strengthening, and the NSM reinforcement ratio. Fig. 10 shows the hysteresis curves for lateral load and displacement. The test results showed that NSM strengthening with SMA or CFRP bars significantly improved the columns' flexural behavior, with marked improvements in lateral load-carrying capacity. Furthermore, it reduced the deterioration of shear stiffness under cyclic reversals and enhanced the dissipation of cumulative energy before final failure.

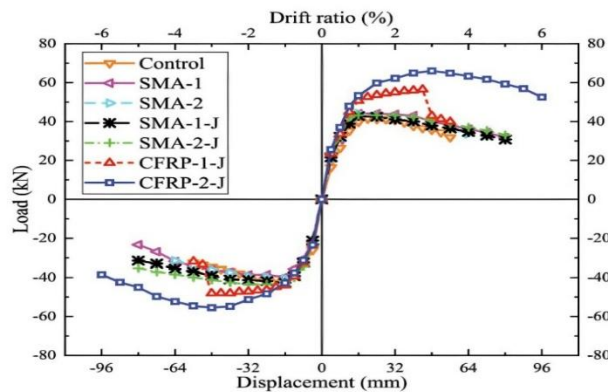


Fig. 10. Load-displacement curves for all columns [79]

In 2021, R. S. Ibraheem, and A. H. Al-Zuhairi, [71] studied the performance of axially loaded RC columns confined with Steel Jackets (SJ) and CFRP sheets. The experimental program included twelve columns that were tested to failure as the basis for the study. The concrete's compressive strength and the proportion of steel reinforcement were the primary variables. Furthermore, the experimental results showed a significant increase in the ultimate load capacity of the strengthened column specimens. By increasing the axial deformation ratio from around 59.2% to 95.7%, the CFRP sheets significantly improved column ductility compared with the control specimens. However, because SJ provides composite action, unlike CFRP sheets, which offer unidirectional lateral confinement, it made a substantial contribution to the specimens' ultimate load capacity, raising the RC load from 75% to 107%. The failure patterns from the two approaches were entirely different. Because the sheet fibers ruptured, columns strengthened with CFRP sheets collapsed. SJ-strengthened columns collapsed because the concrete was crushed and the steel corners buckled due to direct contact with the column head.

In 2021, fifteen RC columns that had been strengthened or repaired using NSM-CFRP were experimentally tested by Y. T. Obaidat, et al. [80] under different loads (concentric, eccentric, and pure bending moment) with an eccentricity of 125 mm (balanced state), taking into account the impact of various configurations on the interaction diagram. Additionally, by altering the direction of CFRP strips used for strengthening, this study examines how effective these novel configurations are in enhancing the capacity of the RC specimens. The specimens' overall response was examined in terms of toughness, axial displacement, failure mechanisms, and axial load-carrying capacity. The experimental results are shown in the load-displacement relationships in Fig. 11. Each group's interaction diagram was developed and examined. For every group, the retrofitted and strengthened columns showed a notable enhancement in the interaction schema and a notable increase in axial capacity. According to the research, specimens that were strengthened longitudinally and transversely exhibited the greatest enhancement in the interaction schema for both the compression- and tension-control regions. Furthermore, the interaction diagrams provided a straightforward solution for the NSM-CFRP ratio. The updated design model predicted the axial load capacity of NSM-CFRP strip columns.

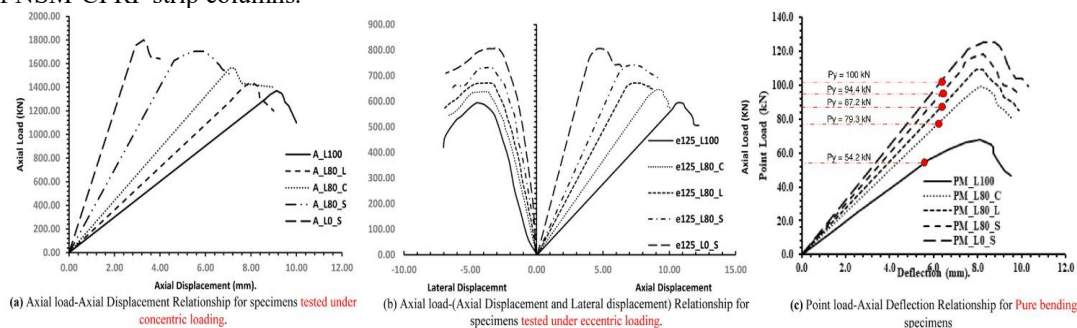


Fig. 11. Load – displacement and deflection curves for all specimens [80]

In 2021, R. Abokwiek, et al. [81] examined the efficacy of strengthening RC columns using NSM-CFRP strips combined with external CFRP wrap confinement. Fifteen RC columns were tested in this study, which examined how the number of CFRP layers, eccentricity ratio, and the presence of NSM-CFRP strips affected specimen capacity. Their findings revealed that the retrofitted columns exhibited substantial improvements in both ductility and load-carrying capacity compared to the unstrengthened control specimens. Specifically, the ultimate load capacity of the confined, strip-strengthened columns improved by up to 49% and 95% under uniaxial bending and axial loading. The study ultimately concluded that incorporating CFRP wraps with NSM-CFRP strips consistently enhances column performance (ductility and capacity) across all applied eccentricity ratios. Additionally, the authors verified and developed an analytical model using the experimental data to predict the strength of RC columns augmented with NSM-CFRP.

In 2023, Z. Al-Khafaji, [82] studied the behavior of short, high-strength concrete columns under concentrated load, confined with CFRP wraps. The study tested nine short square RC specimens. The authors established the confining designs based on prior research on short columns with square cross-sections. The research investigated the influence of different confinement methods on the load-carrying capabilities of columns using concentric uniaxial compression testing. The use of several confinement methods resulted in enhanced load-carrying capabilities of confined concrete columns, illustrating the efficacy of EB-CFRP wraps in improving the behavior of short square concrete columns under concentrated load. The results showed CFRP's effectiveness in restoring damaged columns, with load-carrying capacity increasing of 35% to 90%.

In 2023, T. M. Balla, et al. [83] examined the influence of size on the compressive performance of hybrid FRP-strengthened square RC columns. The confinement effectiveness of FRP diminishes as the cross-sectional size increases. Consequently, an effective FRP-based strengthening technology is needed for large cross-section square columns. Hybrid FRP strengthening integrates the benefits of both EB and NSM techniques to improve the overall behavior of RC members under various load combinations. Comprehensive nonlinear FE models were developed and verified using experimental findings and literature data. The results indicate that the efficacy of hybrid and EB FRP strengthening decreased as the cross-section

ratio of square specimens increased. Hybrid FRP strengthening enhanced both ductility and strength across all size ratios compared with FRP external bonding or near-surface-mounted strengthening alone. A parametric analysis was conducted using the validated finite element models to assess the impact of external bonding and near-surface-mounted strengthening ratios, as well as column dimensions, on the efficacy of hybrid fiber-reinforced polymer strengthening.

In 2024, E. M. Lotfy, et al. [84] systematically evaluated the structural response of slender rectangular RC columns subjected to eccentric axial compression when strengthened with CFRP composites. To investigate the flexural strength of the RC columns, two different strengthening programs were implemented: one using longitudinal near-surface mounted (L-NSM) CFRP strips, and the other a hybrid strengthening combining L-NSM-CFRP strips with external CFRP sheet strengthening for lateral confinement and flexural enhancement. Slender concrete column models were designed and tested under unidirectional loads with a constant eccentricity of 35 mm. A finite element method non-linear numerical modeling program was also implemented, which showed good agreement with experimental load-deflection curves and failure modes. Furthermore, the experimental database supported a comprehensive parametric evaluation across fifteen analytical confinement models to isolate the governing structural parameters influencing CFRP-confined and NSM-strengthened concrete elements. The study established that hybrid CFRP retrofitting substantially augments both axial and flexural rigidity, thereby mitigating secondary moments. Crucially, the authors concluded that the performance enhancement provided by the strengthening scheme is non-linear and heavily governed by the slenderness ratio of the column.

5.3 Column Configurations

The physical geometry and aspect ratios of the host column alter the effectiveness of FRP confinement.

In 2022, K. Samy, et al. [85] investigated an innovative confinement technique to improve the structural efficiency of CFRP-strengthened RC columns, particularly those with rectangular cross-sections. To address the efficiency constraints linked to sharp corners, the authors suggested altering the cross-sectional shape to an optimal near-elliptical configuration, thus increasing the effective contact area between the concrete surface and the CFRP jacket. The experimental study assessed thirteen RC columns subjected to axial compression to determine the effects of cross-sectional shape and corner-radius design. The study thoroughly examined axial stress-strain behavior, lateral strain distributions (at mid-height and quarter-height), crack propagation patterns, cracking loads, and ultimate load capabilities. Additionally, a thorough analysis was performed to develop predictive models for confined columns with differing radii of curvature (R). The results indicated that altering the cross-section significantly reduced the traditional "dead zone" effect commonly associated with square and rectangular columns. At the same time, the suggested cross-sectional alteration resulted in about an 80% increase in axial load capacity relative to unstrengthened control specimens, representing about a 60% efficiency gain over conventional rectangular CFRP jacketing.

In 2023, T. M. Balla, et al. [83] demonstrated via experimental and finite element parametric analyses that the efficacy of confinement in both hybrid and EB-FRP systems declines with an increase in the cross-sectional scale ratio of square columns.

In 2024, E. M. Lotfy, et al. [84] demonstrated through experimental analysis and finite element modeling across fifteen confinement models that the performance improvement from FRP retrofitting is non-linear and strongly influenced by column slenderness ratios.

In 2025, Z. E. A. Benzeguir, et al. [86] conducted an extensive experimental investigation into the axial confinement mechanics of concrete columns possessing non-circular geometry using EB-CFRP wraps. Recognizing elliptical cross-sections as a practical geometric compromise for column rehabilitation, the experimental campaign evaluated 20 full-scale elliptical concrete specimens subjected to monotonic compression. The testing program included an unstrengthened control group and three strengthened series designed to isolate two critical variables: the elliptical cross-sectional aspect ratio and the volumetric confinement ratio (dictated by the number of EB-CFRP layers). Experimental findings showed that EB-CFRP confinement substantially enhanced both peak axial compressive strength, achieving gains of up to 137% over control specimens, and ductility. While strength gains increased strongly and directly with jacket thickness (number of CFRP layers), overall confinement effectiveness and axial ductility systematically degraded as the cross-sectional aspect ratio (A/B) increased away from circular symmetry, highlighting the severe reduction in confinement pressure along the flatter cross-sectional sides.

5.4 Critical Synthesis of Literature

Studies consistently confirm that concentric compression yields maximum FRP confinement efficiency (up to 110% load capacity gain). However, increasing eccentricity (e/h) systematically degrades confinement effectiveness by inducing non-uniform stress gradients that shift the primary failure mechanism from tensile FRP rupture to localized compression concrete crushing.

A notable discrepancy is observed in partial wrapping performance under multi-axial loads: while Elsayed et al. [75] reported continuous capacity loss under eccentric loads, Tin et al. [70] demonstrated that partial CFRP wraps yielded higher relative

capacity gains under biaxial eccentricity 19%–31% compared to uniaxial eccentricity 8%, proving that multi-axial strain gradients alter localized composite energy storage.

EB provides transverse confinement ideal for axial and shear upgrades but negligible flexural resistance [66, 71]. Conversely, NSM strengthened directly resists longitudinal tensile stresses, enhancing flexural capacity by up to 72% [79, 80]. There is strong consensus that hybrid systems (NSM strips + EB wraps) overcome single-system limitations by suppressing premature debonding, restoring up to 100% of original capacity in pre-damaged columns [78, 81, 84].

Sharp 90° corners induce severe stress concentrations that trigger premature FRP rupture. Rounding corners or reshaping rectangular sections to near-elliptical profiles eliminates unconfined "dead zones" and yields up to 80% capacity gains over standard rectangular wraps. Crucially, confinement efficiency degrades non-linearly with increasing slenderness and cross-sectional scale, as moments cause flexural buckling before concrete expansion can fully activate the FRP jacket.

6. RESULTS AND DISCUSSION

Published studies on FRP RC columns cover many design criteria: load system (concentric, uniaxial/biaxial eccentric, and cyclic), strengthening techniques (external confinement/wrapping, NSM systems, and hybrid retrofitting), and column configurations (cross-sectional geometry, slenderness, and scale effects). Table II summarizes previous studies on FRP RC columns and hybrid systems

TABLE II. COMPREHENSIVE COMPARISON of LITERATURE STUDIES

Authors and Year	NO. of Specimens	Section Geometry	f'_c (MPa)	Steel Reinforcement Ratio (%)	Strengthening Technique	load system	Failure Mode	Result
M. Quiertant, and J. Clement, (2011) [73]	10	Square & Circular	30	1.13	CFRP Wrapping	Variable Load Eccentricity	High eccentricity: Compressive concrete crushing; Low eccentricity: FRP rupture.	32% - 85% gain in load capacity; enhanced ductility under eccentric load.
X. Song, et al. (2013) [74]	18	Circular & Rectangular	25 - 40	1.01	FRP External Wrapping	Concentric & Eccentric	FRP tensile rupture at corner / compression crushing	25% - 110% gain in concentric capacity; gains decreased with higher e/d.
Q. Hasan, et al. (2016) [22]	3	Square & Rectangular	22	1.34	NSM-bars & CFRP-Laminates	Cyclic Loading	NSM bar yielding followed by concrete crushing	48% gain in load capacity, 120% increase in energy dissipation.
H. Isleem, et al. (2018) [72]	28	Rectangular	30	0.85 – 1.5	CFRP Confinement	Monotonic & Cyclic Axial Compression	Tensile jacket ruptured along major axis corner	Axial ultimate strain increased by 80% - 160%; axial strength gains 12% - 35%.
M. Elsayed, et al. (2018) [75]	12	Rectangular & Square	30	1.12	CFRP Composites	Eccentric Loading	Concrete crushing on compression face & buckling	55% (partial) and 75% (full wrap) axial load capacity increases.

Authors and Year	NO. of Specimens	Section Geometry	f'_c (MPa)	Steel Reinforcement Ratio (%)	Strengthening Technique	load system	Failure Mode	Result
J.Yang, et al. (2020) [76]	40	Square	40	Unreinforced	Partial CFRP Wrapping	Axial loading	Concrete spalling in clear gaps and CFRP band rupture	Ultimate strength increased by 13.6% - 57.6%; peak strain increased to 108.8%.
H. X. Tin, et al. (2021) [70]	15	Square & Rectangular	30	1.23	FRP Sheet Wrapping	Uniaxial & Biaxial Loads	Concrete compressive crushing under non-uniform stress	Uniaxial gain: 8% (partial), 33% (full); Biaxial gain: 19% (partial), 31% (full).
M. Nematzadeh, et al. (2021) [77]	18	Circular & Square	40	Steel fibers	CFRP Wraps	Eccentric loading	Fiber pull-out combined with CFRP corner rupture	CFRP increased capacity (20% - 65%); steel fibers enhanced ductility.
M. Chellapandian, et al (2019) [78]	18	Square	35	1.23	Hybrid FRP (NSM Strips & CFRP Wraps)	Combined Axial load & Flexure	FRP debonding prevented; ultimate rupture of wrap	Restored 100% original strength; enhanced ultimate bending moment by 65%
G. Xing, et al. (2020) [79]	7	Rectangular	30	1.05	NSM & CFRP Bars	Flexure Loading	Bar yielding, low residual drift (SMA), concrete crushing	38% - 72% gain in lateral load capacity; mitigated stiffness degradation.
Y. Obaidat, et al. (2021) [80]	15	Square & Rectangular	30	1.23	NSM CFRP Rods/Strips	Axial & Uniaxial Loading	Epoxy-concrete interface debonding & concrete splitting	Longitudinal + transverse NSM yielded greatest interaction diagram expansion.
R. Ibraheem, and A. Al-Zuhairi, (2021) [71]	12	Square	25 – 45	1.13	CFRP Jacket & Steel Jacket	Axial loading	CFRP: Tensile fiber rupture; SJ: Concrete crushing & steel buckling	CFRP axial deformation gain: 59.2% - 95.7%; SJ load capacity gain: 75% - 107%.
R. Abokwiek, et al. (2021) [81]	15	Rectangular	30	1.1	NSM-CFRP (Strips & Wraps)	Combined Axial & Bending	Outer wrap fiber rupture; delayed NSM strip debonding	Capacity improvements up to 49% (axial) and 95% (uniaxial bending).

Authors and Year	NO. of Specimens	Section Geometry	f'_c (MPa)	Steel Reinforcement Ratio (%)	Strengthening Technique	load system	Failure Mode	Result
Z. Al-Khafaji, (2023) [82]	9	Square	55	1.45	EB-CFRP	Concentric Axial Load	Concrete crushing following FRP rupture	Load-carrying capacity improved by 35% to 90%.
T. Balla, et al. (2023) [83]	16	Square	30	1.13	Hybrid FRP System	Concentric loading	Size-dependent strain localization & jacket rupture	Relative strength/ductility gains decreased as section cross-section increased.
E. Lotfy, et al. (2024) [84]	15	Rectangular	30	1.01	FRP Wrapping & Strips	Axial loading	Flexural buckling & compression concrete crushing	Substantially increased flexural rigidity; efficiency decreased with slenderness.
K. Samy, et al. (2022) [85]	13	Square & Rectangular	30	1.01	CFRP Sheets	Axial loading	Continuous jacket tensile rupture without localized stress peaks	Reshaped section achieved approx 80% axial capacity gain (60% over square wrap).
Z. Benzeguir, et al. (2025) [86]	20	Square & Rectangular	34	1.15	CFRP Systems	Axial loading	Rupture along flatter sides; anchorage edge failure	Peak strength increased to 137%; performance degraded as aspect ratio A/B increased.

6.1 Axial Strengthening

A. Effect of Load Eccentricity

- Concentric axial compression maximizes the efficiency of FRP wrapping by establishing a uniform lateral pressure as concrete expands transversely [71, 72, 76, 82]. However, under uniaxial or biaxial eccentric loading [70, 73, 74, 75, 77], Non-uniform stress gradients develop across the section, subjecting one face to high compression and the opposite face to tension or reduced compression.
- Reduced Confinement Efficiency:** As eccentricity (e/h) increases, the neutral axis shifts, creating a compression zone and a tension zone. This gradient significantly reduces the effective lateral compression provided by the outer casing, changing the failure mode from rupture of the composite under tension to localized compressive crushing of the concrete [73, 74].

B. Hybrid Strengthening Efficacy (EB & NSM)

- Confinement Performance:** External confinement strengthening alone primarily enhances resistance to axial loads. External jacketing improves axial strength but provides limited flexural strength, while longitudinal strengthening NSM bars improve flexural strength but are susceptible to debonding or buckling [79, 80].
- Combined Effect:** Combining longitudinal strengthening NSM-FRP (strips or bars) with transverse CFRP jackets [22, 78, 81] provides optimal performance. The external sheet prevents the combined Strengthening from

debonding or premature buckling under the influence of cyclic loads, while the NSM Strengthening directly carries the tensile stresses [22, 78, 81].

C. Geometric, Scale, and Slenderness Effects

- **Section Geometry:** In square and rectangular columns [70, 72, 75, 82], lateral confinement stress is concentrated at the corners. Unless the corners are modified with a sufficient corner radius (e.g., radius ≥ 20 mm as recommended in previous literature [85, 86]), sharp 90° edges induce severe stress concentrations that trigger premature localized failure of the FRP jacket at strain levels far below its ultimate material capacity. Circular columns, on the other hand, achieve continuous and uniform confinement.
- **Slenderness Effects :** As column slenderness increases [84], second-order lateral deflections ($P-\delta$) cause initial bending moments. FRP confinement becomes less effective because failure shifts from crushing to buckling. The efficiency of FRP confinement depends strongly on the column's slenderness ratio. Based on the reviewed literature, FRP confinement becomes largely ineffective at suppressing buckling or providing substantial strength gains once the slenderness ratio exceeds a critical threshold (typically $H/D \geq 12$ to 15 , or $\lambda \geq 50$ for non-sway members). Beyond this limit, the overall flexural-buckling behavior dominates the response, causing failure before the core concrete can fully mobilize the lateral confining pressure of the FRP jacket.
- **Scale effect:** Experimental scaling studies [83] show that larger-scale columns show less improvement in relative strength than their smaller counterparts at laboratory scale. Because the FRP jacket applies confinement pressure only at the periphery, this lateral restraint cannot effectively penetrate the deep core of the large cross-section, leaving the central concrete relatively unconfined compared with a smaller specimen. Furthermore, maintaining an equivalent confinement ratio in larger columns requires thicker FRP jackets; with standard wrap thicknesses, the actual lateral stiffness provided to the larger cross-section is significantly reduced.

6.2 Discussion

- FRP confinement performs well under monotonic compression [72]. However, under cyclic or seismic loadings [22 & 72], FRP jackets experience progressive bond deterioration and stiffness degradation. The addition of NSM strengthening [22] significantly improves column behavior and increases cumulative energy dissipation.
- To mitigate tension-side weakness under flexure, NSM CFRP strips [80 & 81] directly resist axial tension and bending moments. The super elasticity of SMA [79] adds self-centering capabilities, reducing residual drifts after yielding.
- Standard design equations that assume uniform confinement may significantly over-predict the capacity of eccentrically loaded, rectangular, or large-scale columns [70, 74 & 83]. Models must explicitly incorporate non-uniform stress distribution factors and scale-reduction coefficients.

7. CONCLUSIONS

This paper reviews existing research on structural concrete members repaired or strengthened using FRP systems. FRP may fulfill the criteria for strengthening RC members under controlled conditions. The selection of FRP materials for strengthening any RC structural member must consider their qualities, long-term performance, and interaction with the environment. Nonetheless, FRP composites have attained significant acclaim globally; therefore, international building organizations have developed design and construction codes specifically for the use of FRP reinforcements as concrete rebar.

This review provides critical insights into enhancing the application and performance of RC members by strengthening and retrofitting them with FRP. Conclusions can be derived from previous studies, and suggestions can be made for future studies on strengthening RC members with FRP:-

1. The mechanical performance of FRP composites, although mostly influenced by the fibers, is also contingent upon the parameters of the concrete, including tensile strength, ultimate strain, modulus of elasticity, and the bond strength between the concrete and fibers.
2. The acceptance and implementation of FRP in strengthening reinforced concrete structures will increase further as technologies develop that utilize the full strength of FRP, reduce brittleness, fire hazards and accidental damage and lower the high initial cost through the development of more cost-effective manufacturing processes and alternative fiber types.
3. The efficiency of FRP confinement degrades substantially under non-uniform stress gradients induced by load eccentricity or non-circular section geometries.

4. Hybrid strengthening (longitudinal NSM bars/strips combined with transverse EB-FRP wraps) effectively resolves premature debonding while simultaneously upgrading flexural and axial capacities.
5. Full EB-FRP Wrapping achieves a 25%–110% increase in axial compressive strength under concentric loads, and 35%–90% for damaged short columns. However, the increase in strength decreases to 8%–33% under uniaxial eccentricity and to 19%–31% under biaxial eccentricity.
6. NSM-FRP technology improves flexural load capacity by 38% to 72% and the ultimate bending moment under lateral loads, while increasing cumulative energy dissipation by up to 120%.
7. Hybrid systems (NSM, EB-FRP) provide peak strength improvements of 49% to 95% under axial compression and flexure, resulting in the restoration of almost 100% of the original structural strength in previously severely pre-damaged columns.
8. EB-FRP Wrapping is preferred when the primary design objective is to increase axial capacity, shear resistance, and concrete ductility in columns subjected to compression. NSM-FRP systems are preferred when increasing flexural capacity and bending stiffness is a priority, or when maintaining architectural form is essential. Conversely, a hybrid strengthening system (NSM, EB-FRP) is recommended for columns with eccentric, slender, or seismic loads, to provide both flexural reinforcement and prevent strip debonding.
9. While the design of concrete buildings with FRP is fundamentally grounded in strength requirements, serviceability needs often take precedence in the design process.
10. Investigations on the fatigue performance of strengthened concrete members are limited.
11. Long-term experimental studies are required to quantify the creep deformation of epoxy adhesives and FRP composites over extended operational lifespans, aimed at formulating predictive models for serviceability and long-term durability under various conditions.
12. Further research is needed to evaluate the confinement effectiveness of FRP-confined columns under axial loads and cyclic loading protocols affect the strengthening of reinforced concrete.

Conflicts of Interest

The authors declare no conflict of interest.

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Author Contributions

Conceptualization, Al-Zuhairi, A.H.; methodology, Al-Zuhairi, A.H.; validation, Younis A.A.; formal analysis, Younis A.A.; investigation, Younis A.A.; resources, Al-Zuhairi, A.H.; data curation, Al-Zuhairi, A.H.; writing—original draft preparation, data curation; writing—review and editing, Younis A.A.; supervision, Al-Zuhairi, A.H.; project administration, Al-Zuhairi, A.H.; funding acquisition, Younis A.A.

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Ethical Approval

This study did not involve human or animal subjects, and ethical approval was not required.

Data Availability Statement

The study relies on publicly accessible existing data.

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