

Research Article

Impact of CFRP Strengthening on the Performance of RC Columns Under Static and Dynamic Loading

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Abstract

This study evaluates the effectiveness of Carbon Fiber Reinforced Polymer (CFRP) jackets in retrofitting reinforced concrete (RC) columns to meet global safety standards. The research addresses the critical need to mitigate brittle failure modes observed in recent seismic events, particularly in existing structures with deficient seismic detailing. The methodology integrates two primary approaches: First, a theoretical framework is developed to propose a design method for CFRP-confined columns, utilizing actual stress-strain relationships and advanced confinement models to generate P-M interaction diagrams. Second, a comprehensive analytical review of major international experimental programs is conducted to assess the seismic behavior of these columns, focusing on critical variables such as cross-sectional geometry and internal reinforcement details. The findings demonstrate that CFRP confinement significantly enhances not only the ultimate load-carrying capacity but also the structural ductility and energy dissipation potential. Furthermore, the study establishes a technical guide based on international design codes, outlining essential parameters to ensure the efficacy of the strengthening process. This work serves as a technical reference for engineers in making informed decisions during the structural rehabilitation of RC members.

Keywords: CFRP; Reinforced Concrete; Columns, Static Loading; Seismic Loading; Design Standards.

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Introduction

Reinforced concrete (RC) columns constitute the foundational elements of contemporary structural systems, playing a pivotal role in the transfer of vertical gravitational loads and the resistance of lateral forces resulting from seismic events and wind pressures. The 2023 Türkiye-Syria earthquakes, which were of a catastrophic magnitude, served as a tragic reminder of the unexpected vulnerability inherent in these structural components when not adequately designed for such extreme events. Post-earthquake forensic investigations revealed a disturbing pattern of sudden column failures that triggered devastating progressive collapse sequences, resulting in unprecedented human casualties and massive economic losses (Işık et al., 2024). These events have reinforced the critical importance of ensuring column safety and have also highlighted the severe consequences of structural deficiencies. Such deficiencies may originate from design miscalculations, construction imperfections, material deterioration, or unanticipated load increases from subsequent structural modifications. Consequently, the development of effective strategies for performance enhancement remains one of the most urgent challenges confronting the structural engineering community worldwide.

Strengthening Imperative and FRP Fundamentals

A substantial proportion of the existing global building inventory was constructed according to now-outdated design codes and specifications, leaving them critically deficient in the necessary structural detailing required to withstand seismic deformation demands (Celik & Ellingwood, 2009). The retrofit and strengthening of these vulnerable structural elements therefore aims to achieve two fundamentally interconnected objectives: significantly enhancing the strength capacity to resist increased load levels, while simultaneously improving the ductility to ensure the element's ability to undergo substantial inelastic deformation and absorb seismic energy without rapid degradation of its load-bearing capacity. This cornerstone principle of modern performance-based seismic design philosophy has gained widespread acceptance in engineering practice (Balázs et al., 2019).

In the realm of contemporary strengthening methodologies, external confinement utilizing reinforced polymer (FRP) composites has emerged as a particularly practical and technically effective solution. Carbon FRP (CFRP) systems have exhibited superior performance characteristics due to their exceptional strength-to-weight ratio, remarkable corrosion resistance, minimal aesthetic impact, and relative ease of application, establishing them as an optimal choice for structural strengthening interventions (Parvin & Brighton, 2014). The fundamental mechanical principle underlying this technique involves the CFRP jacket

providing continuous passive confinement to the concrete core. As the concrete experiences lateral expansion under axial compression—a phenomenon known as the Poisson effect—it progressively activates circumferential tension within the FRP jacket. This, in turn, induces a beneficial triaxial stress state that dramatically enhances both the compressive strength and ultimate deformation capacity of the confined concrete (Lin et al., 2021). The cross-sectional geometry of the column plays a pivotal role in determining the efficacy of this confinement mechanism. Circular columns benefit from uniform hoop stress distribution around their perimeter; however, rectangular and square sections present significant challenges due to stress concentration at the sharp corners and the development of arching action between confinement layers. Pioneering research has demonstrated, through empirical evidence, that implementing adequate corner radius ratios through strategic rounding can elevate the confinement effectiveness to approximately 90% of that achievable in equivalent circular columns. This provides crucial design guidance for retrofitting the predominantly rectangular column shapes found in existing building inventories (Wei et al., 2022). The advantages of CFRP confinement extend far beyond mere strength enhancement to encompass comprehensive improvement in seismic performance metrics. Extensive experimental campaigns have documented significant enhancements in energy dissipation capacity, drift tolerance, and hysteresis loop stability for CFRP-confined columns subjected to reversed cyclic loading simulating seismic (Huang et al., 2024). The confining jacket effectively delays and often prevents buckling of the longitudinal reinforcement, a critical failure mechanism in seismic events. It also provides crucial containment to potential plastic hinge regions. This results in a transformation of the failure mode from a brittle, catastrophic mechanism to a more ductile, gradual, and predictable structural response.

Recent Advances in Computational Modeling

In the past decade, there have been revolutionary advances in computational modeling techniques for predicting the behavior of strengthened columns. These advances have transitioned from traditional analytical models to sophisticated data-driven approaches that leverage artificial intelligence and advanced digital simulation. Machine learning algorithms, including artificial neural networks and support vector machines, have been successfully implemented to develop highly accurate predictive models for the complete stress-strain behavior of FRP-confined concrete. These models have consistently outperformed conventional design-oriented models in terms of accuracy and reliability (Alizamir et al., 2024). Concurrently, advanced three-dimensional finite element modeling

incorporating concrete damage, plasticity, and cohesive zone methods has provided unprecedented insights into complex failure mechanisms, including FRP rupture, delamination, and concrete-FRP interaction under combined stress states (Balázs et al., 2019). These computational innovations have further extended into the realm of probabilistic seismic assessment, where machine learning-generated fragility functions now offer robust analytical tools for evaluating post-retrofit structural performance and quantifying seismic risk reduction (Mangalathu & Jeon, 2019). Notwithstanding these substantial technological advancements, a considerable implementation gap persists between cutting-edge research findings and routine engineering practice. The ongoing challenge of developing simplified yet accurate design methodologies that remain accessible to practicing engineers is a subject of ongoing research. Moreover, the accurate prediction of the complete stress-strain response, particularly for non-circular columns under combined loading conditions, remains an active research frontier due to the highly nonlinear interaction between confinement parameters and concrete material properties. The objective of this research is to address this critical gap by presenting an integrated framework for the assessment and design of CFRP-strengthened RC columns. The investigation is structured around two primary objectives: first, the development of a refined design methodology for static loading conditions through the integration of advanced constitutive modeling and experimental validation; and second, a systematic meta-analysis of seismic performance based on a comprehensive review of experimental studies, with the goal of establishing clear, evidence-based design guidelines. The objective of this research is to develop design solutions for reinforcing concrete columns against various hazards. These

solutions are intended to be balanced, practical, and resilient. To this end, the research synthesizes theoretical principles with empirical validation.

Static Response of CFRP-Confined RC Columns

The stress distribution within the compression zone of unconfined concrete, as defined by design codes, can be represented by an equivalent rectangular stress block. However, this representation is not applicable when the stress-strain curve of CFRP-confined concrete is considered. Therefore, P-M interaction diagrams must be constructed for the design of CFRP-confined RC columns based on the actual stress-strain response. The stress-strain behavior of CFRP-confined concrete has been the focus of several studies (Lam & Teng, 2003; Youssef et al., 2007). The Lam and Teng (2003) model are considered one of the most significant and reliable design-oriented stress-strain models, particularly for normal-strength concrete. A comprehensive understanding of the stress-strain behavior of confined concrete requires a firm grasp of the fundamental concept of confinement pressure. This pressure depends on the number of CFRP layers, their mechanical properties, and the geometry and dimensions of the confined cross-section.

Confinement Pressure Exerted by a CFRP Jacket

Concrete in CFRP-confined circular columns is subjected to uniform confinement pressure (Figure 1) (De Lorenzis & Tepfers, 2003). The value of the material is contingent upon the quantity and strength of CFRP, as well as the diameter of the core.

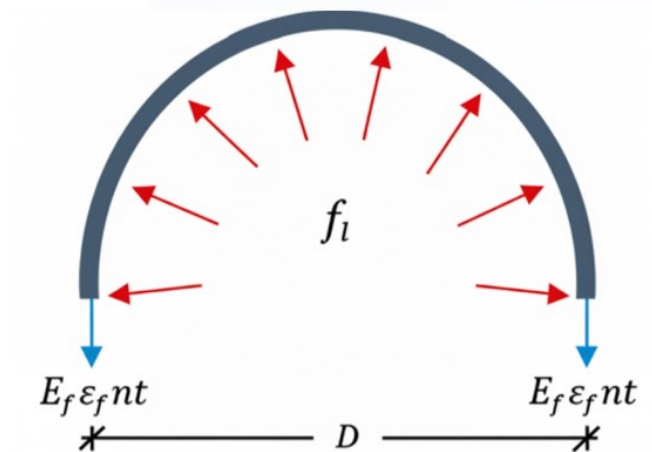


Figure 1. Free-Body Diagram of an FRP-Confined Circular Section (De Lorenzis & Tepfers, 2003).

Where

E_f : tensile modulus of elasticity of FRP,

ϵ_f or ϵ_{frup} : ultimate tensile strain of the FRP,

n : number of FRP plies composing the jacket,

t : FRP nominal ply thickness

f_l : confinement pressure due to FRP jacket.

It is recommended that the corners of a CFRP-confined square section be rounded to improve confinement effectiveness and avoid fiber rupture at

sharp corners caused by stress concentration. However, the corner radius is often limited to small values because of the presence of internal reinforcing steel. Research has shown that confinement in square concrete sections

is typically achieved through arching action (Guadagnuolo et al., 2020; L.-M. Wang & Wu, 2008). This principle is illustrated in Figure 2 (Youssef et al., 2007).

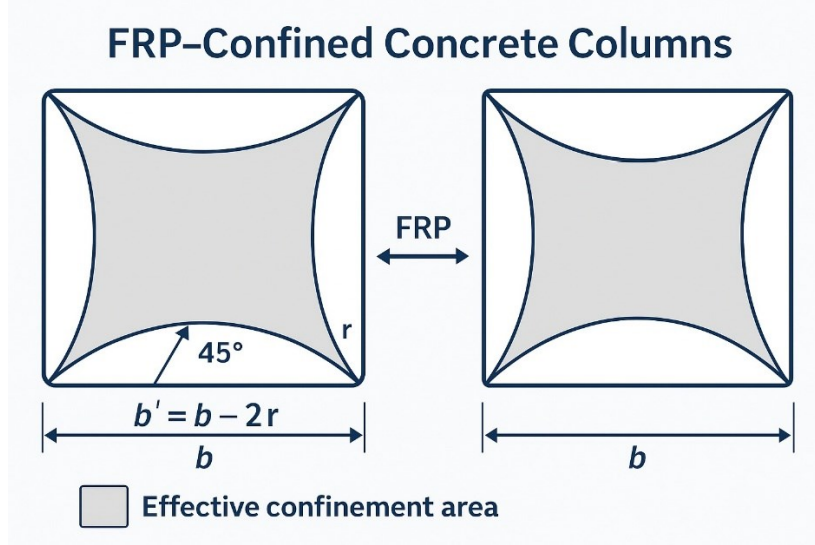


Figure 2. Effective Confinement Area in FRP-Confined Square Sections (Youssef et al., 2007)

Despite the differences between FRP composites and steel in their confinement capabilities, the previously established principle regarding the effectively confined portion remains applicable to FRP. Although confinement is less effective in square sections than in circular sections, experimental findings have indicated that failure of confined square concrete columns also results from rupture of the CFRP jacket (Rochette & Labossière, 2000). As the section becomes more rectangular, the aspect ratio h/b increases. This increase reduces the confinement pressure and, consequently, the effectiveness of confinement. Equations (1) to (9) present a stress-strain model for CFRP-confined concrete and its parameters (Lam & Teng, 2003).

$$f_c = E_c \varepsilon_c - \frac{(E_c - E_2)^2}{4f'_c} (\varepsilon_c)^2 \quad 0 \leq \varepsilon_c < \varepsilon_t \quad (1)$$

$$f_c = f'_c + E_2 \varepsilon_c \quad \varepsilon_t \leq \varepsilon_c \leq \varepsilon_{ccu} \quad (2)$$

$$E_2 = \frac{f'_{cc} - f'_c}{\varepsilon_{ccu}} \quad (3)$$

$$\varepsilon_t = \frac{2f'_c}{E_c - E_2} \quad (4)$$

$$\frac{f'_{cc}}{f'_c} = 1 + 3.3k_e \left(\frac{f_l}{f'_c} \right) \quad (5)$$

$$\frac{\varepsilon_{ccu}}{\varepsilon_{co}} = 1.75 + 12k_e \frac{f_l}{f'_c} \left(\frac{\varepsilon_{f, rup}}{\varepsilon_{co}} \right)^{0.45} \quad (6)$$

$$f_l = \frac{2E_f \varepsilon_{f, rup} \cdot n \cdot t}{D} \quad (7)$$

f'_c : characteristic concrete compressive strength determined from standard cylinder.

E_c : initial modulus of elasticity of concrete.

ε_{co} : axial compressive strain corresponding to f'_c

ε_t : transition strain in $\sigma\varepsilon$ curve of confined concrete, it corresponds to point of change between initial parabola and straight line.

E_2 : the slope of the ascending branch.

ε_{ccu} : ultimate axial compressive strain of confined concrete.

f'_{cc} : maximum compressive strength of confined concrete.

k_e : the effectiveness coefficient.

D is replaced by the equivalent diameter for the case of square section as shown below:

$$D = \sqrt{2}b - 2 \cdot r(\sqrt{2} - 1) \quad (8)$$

$$k_e = \frac{A_e}{A_c} = 1 - \frac{\frac{2(b-2r)^2}{3A_g}}{1 - \rho_g} \quad (9)$$

A_c : cross sectional area of concrete in column

A_e : effectively confined area

A_g : total cross-sectional area

ρ_g : the reinforcement steel ratio

b : short side dimension of a non-circular cross section

r : corner radius of non-circular cross sections

Consequently, to estimate the load-bearing capacity of the confined section after strengthening, an interaction diagram must be created, taking into account

the considerations recommended in this study and in relevant design codes.

Design Requirements for CFRP-Confined Sections According to ACI 440.2R

The design methodology for reinforced polymer (FRP)-strengthened concrete members is governed by the fundamental Bernoulli hypothesis, which posits that plane sections remain plane under flexural deformation. This analytical framework incorporates specified reinforcement distribution, sectional geometry, and material characteristics, while explicitly neglecting the tensile capacity of concrete and limiting the maximum concrete compressive strain to 0.003 at the extreme. The model posits that there is perfect bond integrity between concrete and both conventional steel reinforcement and externally bonded CFRP confinement systems. The constitutive stress-strain (σ - ϵ) relationship for CFRP-confined concrete is adopted from established analytical models referenced in seminal literature (Lam & Teng, 2003; Youssef et al., 2007). In order to guarantee a safe design, it is imperative that the nominal flexural strength (M_n) of a member, calculated in accordance with these principles and reduced by a strength-reduction factor (ϕ), surpass the requisite moment strength (M_u), as delineated in equation 10.

$$\left\{ \begin{array}{ll} \phi M_n \geq M_u, \quad \phi = & \\ \left\{ \begin{array}{ll} 0.90 & \text{for } \epsilon_s \geq 0.005 \\ 0.70 + \frac{0.20(\epsilon_s - \epsilon_{sy})}{0.005 - \epsilon_{sy}} & \text{for } \epsilon_{sy} < \epsilon_s < 0.005 \\ 0.70 & \text{for } \epsilon_s < \epsilon_{sy} \end{array} \right. & \end{array} \right. \quad (10)$$

The structural response is delineated by a sequence of failures, wherein the FRP reinforcement attains its design rupture strain (ϵ_{fu}) prior to the concrete reaching its ultimate compressive strain (ϵ_{cu}). In order to address the characteristically brittle failure mode and consequent lower reliability of FRP composites compared to ductile steel reinforcement, an additional strength reduction factor of 0.85 is applied specifically to the flexural contribution of the FRP. The analytical model makes certain assumptions about the behavior of the adhesive layer, specifically regarding the absence of shear deformation. To account for any potential reduction in flexural strength associated with bond-slip phenomena, a bond-dependent coefficient, designated as "km," is introduced, as detailed in equation 11. In order to avert critical debonding failures, it is imperative to restrict the strain developed in the FRP wrap to a specified allowable value. This value is enumerated in the ensuing expression of equation 11.

$$k_m = \begin{cases} \frac{1}{60\epsilon_{fu}} \left(1 - \frac{nE_f t_f}{2,000,000} \right) \leq 0.90 & \text{for } nE_f t_f \leq 1,000,000 \\ \frac{1}{60\epsilon_{fu}} \left(\frac{500,000}{nE_f t_f} \right) \leq 0.90 & \text{for } nE_f t_f > 1,000,000 \end{cases}$$

$$k_m = \begin{cases} \frac{1}{60\epsilon_{fu}} \left(1 - \frac{nE_f t_f}{360,000} \right) \leq 0.90 & \text{for } nE_f t_f \leq 180,000 \\ \frac{1}{60\epsilon_{fu}} \left(\frac{90,000}{nE_f t_f} \right) \leq 0.90 & \text{for } nE_f t_f > 180,000 \end{cases} \quad (11)$$

Numerical Integration Method for Constructing the P-M Interaction Diagram of CFRP-Confined RC Columns

In light of the recognized propensity of stiffer plates to undergo brittle rupture, a computational approach is warranted. Consequently, a rudimentary computer program can be formulated through the utilization of the numerical integration method (Tinawi, 1983) to generate the P-M interaction diagrams for CFRP-confined columns, meticulously applying the appropriate coefficients derived from the preceding design conditions.

- The following data were entered: the cross-geometric section's specifications b , h , a , d , r , and the properties of concrete f'_{co} , ϵ_{co} , E_c . The properties of reinforcement are as follows: The following variables are to be calculated: E_s , f_y , the area of the reinforcement steel in each layer, and its vertical dimension from the coordinate axis. In addition, the properties of the CFRP jacket, n , t_f , E_f , $\epsilon_{f,rupt}$, are to be determined.

- The following parameters must be calculated: the cross-sectional area A_g , the reinforcement steel ratio ρ_g , the net area of the section A_c , the parameters of the CFRP (stress-strain) model of concrete confined by CFRP (i.e., the confinement pressure f_l , the effectiveness coefficient k_e , the ultimate stress f_{cu} , and the corresponding ultimate strain ϵ_{cu} , the slope of the ascending branch E_2 , and the strain at the beginning of the transition zone ϵ_t . The present study is committed to the most important guidance notes in ACI 440.2R (American Concrete Institute, 2002), Concrete Society Technical Report 55 (Concrete Society, 2004), and the results and recommendations of the experimental research when calculating these parameters (Priestley et al., 1996). As posited by researchers Lam & Teng (2003), the adopted (stress-strain) curve of the confined concrete is derived from the experimental curves, which manifest an ascending segment subsequent to activation. The most conservative estimate of the smallest permissible value of (f_l/f'_{co}) , based on experimental observations on small specimens of ordinary concrete with different confinement ratios of

FRP (Wu et al., 2006), is in the order of 0.08 to ensure the ascending part. However, additional conditions must be met to ensure the ascending shape in the curve. Specifically, it has been demonstrated that $(\frac{f_l}{f'_{co}} > \lambda = 0.13 \sqrt{\frac{250}{E_f}} E_f \text{ MPa})$. In the context of practical design applications, the effective strain, denoted by ε_{fe} , is defined as the product of the effectiveness coefficient, designated as K_ε , and the ultimate strain of the specimen in tension, represented by $\varepsilon_{fe} = K_\varepsilon \varepsilon_{f,rupt}$. The effectiveness parameter, denoted by K_ε , is calculated as the difference between the observed strain at failure in concrete specimens confined by CFRP under axial load and the ultimate strain of the CFRP, as determined through tensile testing. The coefficient K_ε is typically taken as the average value of 0.55, which is consistent with the findings of numerous researchers (Carey & Harries, 2005; Lam & Teng, 2003) in their experimental tests. The effective strain at rupture, denoted by ε_{fe} , is determined in elements subjected to both axial compression and bending moment. The minimum value between $(0.004, K_\varepsilon \varepsilon_{fu})$ is taken as the final value. In order to guarantee the integrity of the confined concrete under shear, as outlined in ACI 440.2R (American Concrete Institute, 2002), it is imperative to consider the findings of the experimental research conducted by Priestley et al. (1996). In accordance with the recommendations outlined in the Concrete Society Technical Report (Concrete Society, 2004), the maximum allowable ultimate axial strain, designated as ε_{cu} , of concrete strengthened with fiber-reinforced polymer (FRP) is constrained to a value of 0.01. This guideline is particularly relevant for components subjected to net compression, where the primary objective is to mitigate the risk of excessive cracking, which can compromise the integrity of the concrete. In the event that ε_{cu} is reduced to 0.01, the $(\sigma - \varepsilon)$ curve is to be utilized for the recalculation of the matching maximum value (f'_{cu}). The equilibrium force equation can be utilized to calculate the confinement pressure that a FRP jacket will impose on a circular cross-section. However, in the case of a non-circular cross-section, the equivalent diameter must be used in place of the diameter D . In the case of a rectangular cross-section, the equation of ultimate strength (5) must be modified by replacing K_e with the efficiency coefficient K_a . Additionally, the coefficient K_b in the ultimate strain equation (6) must be used, as it follows the geometric shape of the cross-section. For a circular section, it is taken equal to 1.0. For a non-circular section, there are two coefficients to consider: the effective confinement area ratio and the ratio of the cross-lateral section's dimensions.

$$k_a = \frac{A_e}{A_c} \left(\frac{b}{h}\right)^2 \quad (12)$$

$$k_b = \frac{A_e}{A_c} \left(\frac{h}{b}\right)^{0.5} \quad (13)$$

- The eccentricity value at which to calculate the carrying capacity, e_o , must be entered.
- The following assumptions were made in order to calculate the height of the compression zone, h_c :
 - A value of strain, ε_c , was assumed to be the maximum compressive strain of the concrete.
 - The height of the neutral axis from the coordinate axis y was assumed to be known.
 - The actual height of the compression zone, h_c , was assumed to be known.
- The following steps were taken to calculate the height of the compression zone, h_c :
 - A number of integral slices were taken in the compression zone, as shown in Figure 3 (Mohamad & Alamoudi, 2021).
 - The Cartesian coordinates of these slices were calculated according to the Gaussian integral (Tinawi, 1983).
 - Subsequently, the strain and stress are calculated according to the $(\sigma - \varepsilon)$ model. Thereafter, the compressive force and moment are determined for each slice. Finally, the total force and the total moment are calculated, as illustrated in Table 1.
- The objective of this study is to determine the strain, stress, tensile or compressive force, and moment corresponding to each reinforcement level. It is important to note that the tensile stresses are given a negative sign in this study. Please refer to Table 2 for more information.
- The calculation of the sum of compressive forces N_{tot} (depending on concrete and reinforcing steel) and tensile forces (depending on reinforcing steel) is necessary. The sum of the moments of compressive and tensile forces about the coordinate axis is also calculated. The results of these calculations are presented in Tables 1 and 2.
- The eccentricity is calculated from the coordinate axis as follows: $(e_s = M_{tot}/N_{tot})$. Therefore, the internal eccentricity is defined as the eccentricity from the section's center ($e_o, inner = e_s - 0.5 h$).
- The difference between the calculated eccentricity and the eccentricity at which the carrying capacity will be calculated is denoted as e_o .
- The value of y is considered true if the value $e_o, inner - e_o$ is equal to zero. When this is achieved by changing the value of y , the strain ε_c is stored. The total strain N_{tot} and total stress M_{tot} corresponding to

ε_c are recorded. Subsequently, the strain is augmented by a specific step, and the loop is repeated until the value of ε_{cu} is accessed, utilizing a straightforward code that has been programmed in Excel.

The maximum force (section bearing capacity) is identified through a series of calculations, including the

calculation of the corresponding moment in the interaction diagram. This process enables the determination of a point corresponding to the assumed eccentricity value, e_o

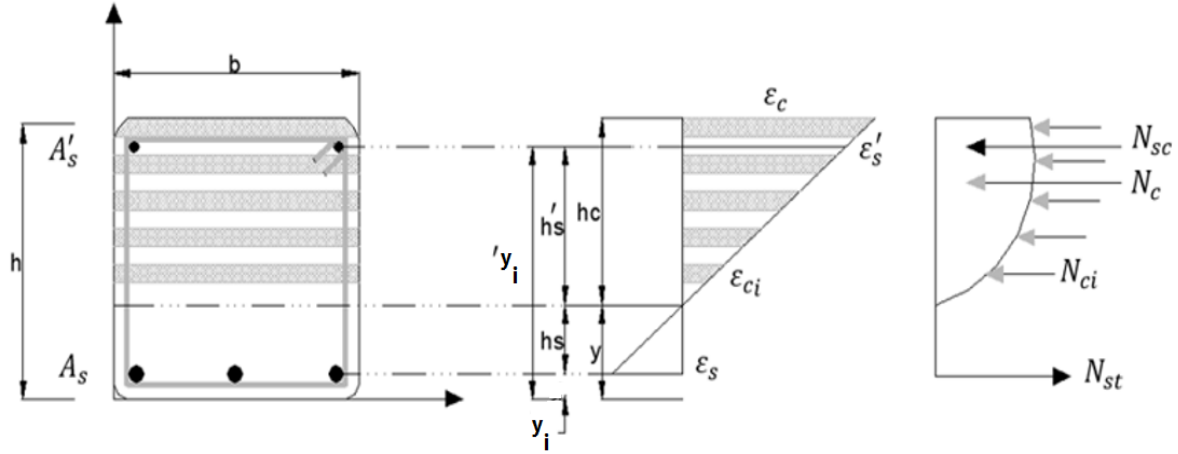


Figure 3. Distribution of Strain and Stress in the Cross Section (Mohamad & Alamoudi, 2021)

Table 1. Calculation of the Compressive Force and Moment about the Coordinate Axis for Each Slice of the Pressure Zone in the Concrete Section.

Point ID	ξ_i	w_i	y_i	ε_{ci}	σ_{ci}	N_{ci}	M_{ci}
$i: 1 \rightarrow ?$ Number of slices relates to degree of (stress-strain) relation	Relative coordinate for integration slices	The integral weight is a constant for each integration slice relates to the number of slices.	$\frac{h+y}{2} \frac{h-y}{2} \xi_i$	$(y_i - y) \times \frac{\varepsilon_c}{h_c}$	From $(\sigma - \varepsilon)$ relation	$\sigma_c \times w_i \times (\frac{h-y}{2}) \times b$	$N_{ci} \times y_i$
						$N_{c\ tot} = \sum N_{ci}$	$M_{c\ tot} = \sum M_{ci}$

Table 2. Calculation of Compressive Force, Tensile Force and Corresponding Moments of Reinforcement Around the Coordinate Axis.

ID Reinforcement Layer	A_s	y_i	H_s	ε_{si}	σ_{si}	σ_{sif}	N_{si}	M_{si}
$i: 1 \rightarrow ?$	Reinforcement area at each reinforcement layer	The vertical distance of reinforcement centroid from the coordinate axis	$ y - y_i $	$\frac{h_s}{2} \times \frac{\varepsilon_c}{h_c}$	$E_s \times \varepsilon_{si} \leq f_y$	$(y_i \leq y) \text{ then } (-N_{si} > 0 \text{ then } N_{si} = N_{sc} \text{ else } N_{st})$	$\sigma_{sif} \times A_{si}$	$N_{si} \times y_i$
							$N_{sc\ tot} = \sum N_{sci}$	$M_{sc\ tot} = \sum M_{sci}$
							$N_{st\ tot} = \sum N_{sti}$	$M_{st\ tot} = \sum M_{sti}$

Response of CFRP-Confined Reinforced Concrete Columns to Dynamic Loads

In light of the recent advancements in the field, which have enabled the prediction of the strength of CFRP-confined columns under static loads, a new set of inquiries has emerged. These inquiries pertain to the efficacy of contemporary CFRP reinforcement systems in enhancing the ductility and energy dissipation capacity of existing reinforced concrete columns. The extant literature on the subject of the seismic behavior of old RC construction with smooth bars has been predominantly developed in recent decades, encompassing a variety of aspects.

- The first point to be considered is the phenomenon of a smooth bar bond to concrete under monotonic or cyclic loading. This phenomenon has been observed by Feldman & Bartlett (2007) , Verderame et al. (2009) , and Yurdakul et al. (2022) .
- Secondly, the subject of subassemblies and portal frames under cyclic loading is addressed (Paolacci & Giannini, 2012) .
- Thirdly, the columns are to be analyzed under monotonic or cyclic loading (Sabbahfar et al., 2025) .

With respect to the columns, which represent the primary subject of this study, extant investigations have indicated lateral deformations resulting from the slippage of reinforcement bars within the foundation or joints. This slippage, observed in both scenarios involving the application of deformed and smooth bars, is typically concentrated at the base crack. It is attributed to strain penetration along the anchored segment of the bar, a consequence of anchorage bond-slip (Zhao & Sritharan, 2007) . Consequently, this type of bar slip can result in increased lateral deflections and reduced lateral stiffness (Wang et al., 2019) . Moreover, as a primary effect, excessive opening of the base crack at the interface due to bar slip may impose substantial rotation demands at the base and modify the main lateral deflection mode of columns with smooth bars from flexure-shear to quasi-rocking mode (Wang et al., 2019).

An experimental program of considerable importance was conducted at the University of Salerno in Italy (Faella et al., 2006) . The objective of this program was to investigate the behavior of unconfined and FRP-confined RC columns under constant axial load and monotonic or cyclically reversed horizontal loads. The study focused on square section columns, which were selected to represent structural elements designed with inadequate seismic details. The columns were cast in concrete with a relatively low compressive strength of 25 megapascals (MPa) and were reinforced with both smooth and deformed steel rebars. The impact of the various bonds between steel rebars and concrete

was examined. The reinforcement features, including anchorages, hoop spacing, and lap splice lengths, were meticulously configured in accordance with the established design guidelines. A subset of the columns that were subjected to testing were not strengthened, while the remainder were strengthened using a fiber-reinforced polymer (FRP) composite, which could be either carbon-fiber-reinforced plastic (CFRP) or glass-fiber-reinforced plastic (GFRP).

Cyclic Response of the FRP-Confined Columns

The experimental findings demonstrated that the FRP-confined columns exhibited a more ductile cyclic behavior in comparison to the non-confined columns. However, it was observed that the confinement system did not enhance the response in terms of increased strength. The observed behavior is consistent across both columns reinforced with smooth rebars and columns reinforced with deformed rebars. In all cases, the hysteretic loops exhibited slight asymmetries and minimal strength degradation, as demonstrated in Figures 4 and 5 (Faella et al., 2006) . According to the findings of other researchers (Fabbrocino et al., 2005) , in the case of a column reinforced with smooth steel rebars, the substantial contribution of the fixed-end rotation to the rotational capacity of the column can be identified.

Expansion and Spread of Cracks of the FRP-Confined Columns

Initially, a flexural crack develops at the column-foundation interface, and its width increases because of inadequate bond between the smooth reinforcing bars and the concrete, as illustrated in Figure 6(a). An additional horizontal crack is then observed at a certain distance from the base, as illustrated in Figure 6(b). In unconfined specimens, compression of the steel bars leads to the formation of diagonal and vertical cracks. Subsequently, the concrete cover undergoes spalling, as illustrated in Figure 6(c) (Faella et al., 2006).

In the case of the strengthened specimens, the presence of the FRP system prevented the spread of these cracks, reducing the damage and avoiding the spalling of the concrete cover, as illustrated in Figure 6(b). A distinct pattern of cracks has been observed in the case of unconfined concrete elements reinforced by deformed steel rebars (Figures 7(a) and 7(b)). (Faella et al., 2006) .

In the case of CFRP confined columns, the presence of a flexural crack at the column-foundation interface was observed. The other cracks were likely obscured by the CFRP system, as depicted in Figure 7(c). However, when compared to a crack that occurred in reinforced columns with smooth rebars, as illustrated in Figure 6(a), the primary crack's width was conspicuously smaller. At the base of the column,

concrete compression failure and compressed steel rebar buckling were observed, thereby supporting the

"conventional collapse." In certain instances, longitudinal rebars failed in tension.

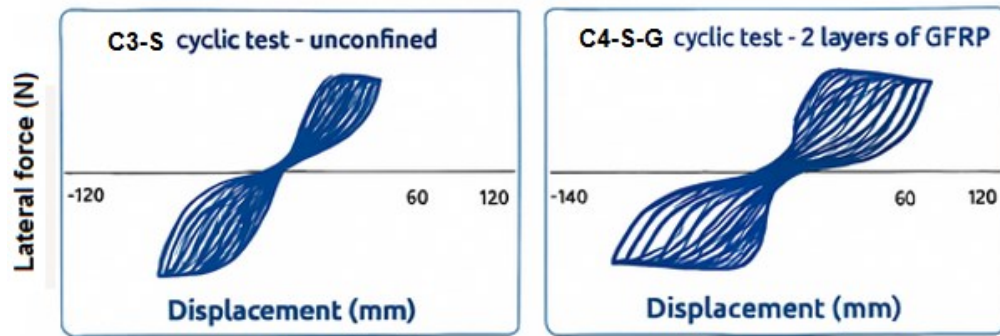


Figure 4. Hysteretic Loops Relative to Columns with Smooth Rebars (Faella et al., 2006).

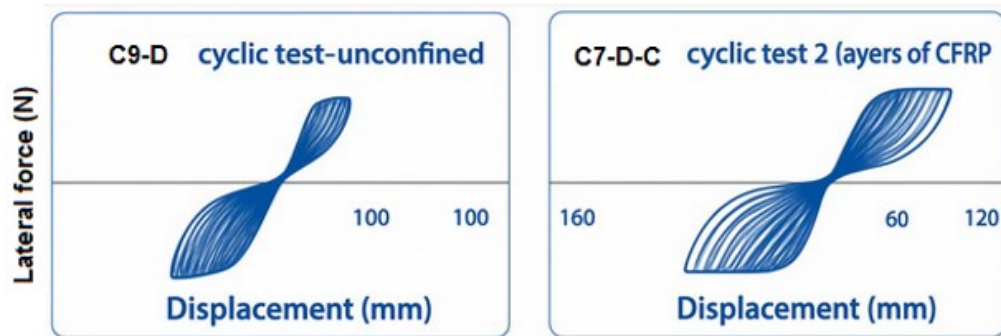


Figure 5. Hysteretic Loops Relative to Columns with Deformed Rebars (Faella et al., 2006).

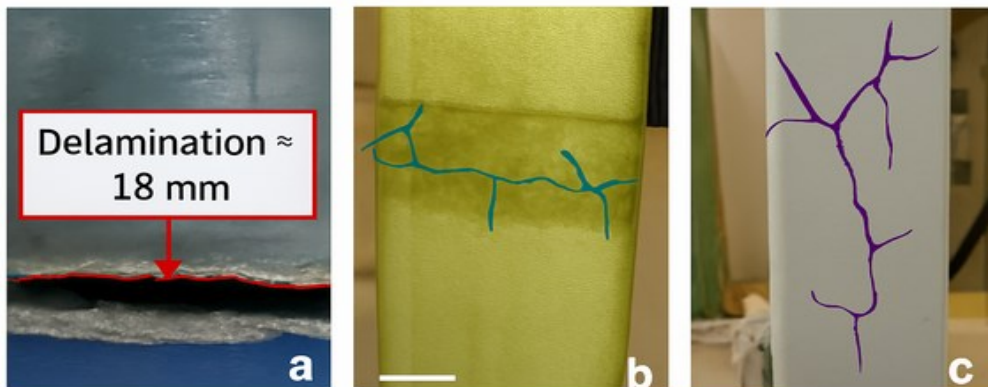


Figure 6. Cracking Patterns in Case of RC Columns with Smooth Rebars (Faella et al., 2006).

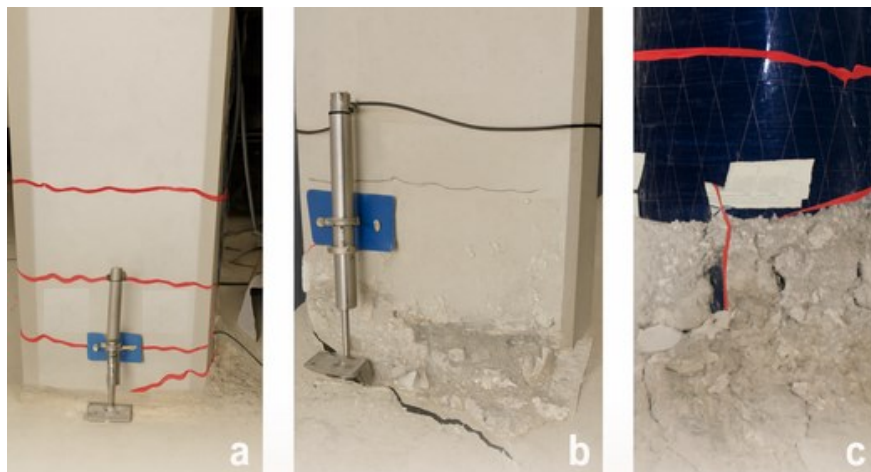


Figure 7. Cracking Patterns in the Case of RC Columns with Deformed Rebars (Faella et al., 2006)

FRP-Confined Short Columns

Concerning short columns, inquiries have been raised regarding the contribution of CFRP to altering the cracking pattern and enhancing mechanical behavior. Short columns experience shear stress during earthquakes due to their inadequate resistance to strongly exerted horizontal displacements. In a substantial experimental program, short columns were subjected to rigorous testing (Concrete Society, 2004). The longitudinal reinforcement of the structure in question exceeded the top limit of Eurocode 8 (*Eurocode 8: Design of Structures for Earthquake Resistance | Eurocodes: Building the Future*, n.d.). However, the transverse reinforcement proved inadequate, resulting in shear failure. Seven of these were GFRP or CFRP reinforced, either continuously or sporadically. The specimens were subjected to a series of tests, including a horizontal quasi-static cyclic load and a continuous compression load. Consequently, the efficacy of the reinforcement could be ascertained through the measurement of the gain in load and ductility.

Failure Mode of Short Columns

The implementation of external FRP confinement (FRPC) introduces a fundamental alteration to the failure mechanism of short reinforced concrete columns, thereby transitioning their structural behavior from a brittle shear-dominated mode to a more ductile flexural response. Colomb et al. (2008)'s experimental investigations demonstrate that partially confined columns (PW) typically exhibit a combined shear-bending failure, whereas fully wrapped specimens (FW) develop a ductile flexural mechanism characterized by plastic hinge formation at the column base.

This transformation is attributed to the effective confinement provided by the continuous FRP jacket, which enhances the concrete's compressive strain capacity and suppresses the development of critical diagonal cracks. The confining action enables the longitudinal reinforcement to yield in tension while maintaining the integrity of the concrete core under compression, thereby promoting stable energy dissipation through cyclic loading.

The strategic implementation of FRP (fiberglass-reinforced plastic) wrapping has been demonstrated to enhance the shear capacity of the structure. More significantly, it has been shown to redirect the failure path towards a more favorable ductile mode. This failure mode transformation is imperative for seismic resistance, as it enables structural elements to undergo controlled inelastic deformations without sudden strength degradation, thereby markedly enhancing the structural safety under extreme seismic events.

Ductility of Short Columns

It is challenging to resist earthquake forces with strengthened short columns. Given the substantial increase in load, despite a modest enhancement in ductility, it is imperative to employ a multifaceted approach that incorporates both ductility and load considerations. The analysis of supplementary indicators, such as stiffness and energy capacity, would also be crucial. By advancing the longitudinal reinforcements' yielding, the ductility of the fully wrapped columns was enhanced, resulting in the formation of a hinge. The FRP reinforcement facilitated rotation in components without inducing buckling of the compressed reinforcements, despite these reinforcements exceeding their elastic limit. In comparison to fully wrapped columns, columns that undergo partial wrapping of strips exhibit enhanced dissipative behavior. This enhancement is attributed to the ductility acquired through the two procedures outlined below: It has been observed that the reinforcements in all column sections have yielded. The phenomenon of concrete cracking has been observed to occur in the area between the FRP strips.

The strength of CFRP-confined columns is difficult to predict because of the influence of seismic loading. Therefore, the desired increase in resistance must be balanced against the required ductility, in accordance with the principal observations reported in experimental research.

Conclusion

A comprehensive review of the behavior of carbon fiber-reinforced polymer (CFRP)-strengthened reinforced concrete (RC) columns under static and seismic loads was conducted. This review led to the establishment of the following key conclusions and practical implications for structural engineers:

- Numerical integration has been demonstrated to be the most reliable and accurate method for predicting the ultimate bearing capacity of CFRP-confined columns under static loads (P-M diagrams).
- The primary benefit of CFRP lies in its ability to remarkably augment the ductility and ultimate deformation capacity of columns.
- The impact of confinement on enhancing shear strength remains constrained; consequently, design should prioritize ductility.
- The confinement system plays a pivotal role in the management of crack propagation and the mitigation of buckling in longitudinal reinforcement.
- In the case of short columns, the process of strengthening effectively converts brittle shear failure into a ductile flexural mechanism.

- It is imperative that engineers optimize corner radii and employ precise confinement effectiveness factors for rectangular sections.
- The utilization of performance-based assessment is strongly advised in order to quantify risk reduction and validate seismic retrofit strategies.
- It has been demonstrated that partial wrapping configurations offer more favorable energy dissipation characteristics in comparison with full wrapping.

Recommendations for Engineering Practice

In order to ensure the reliability and effectiveness of seismic retrofit, engineering practice must adopt advanced modeling techniques, such as numerical integration, for the purpose of accurately predicting the behavior of confined concrete fiber-reinforced polymer (CFRP) columns. Designers must prioritize ductility enhancement, recognizing that the primary benefit of CFRP is the improvement of deformation capacity, rather than pure strength. It is imperative to refine practices by optimizing corner radii and confinement factors. Finally, engineers must implement performance-based evaluation for risk quantification and consider hybrid strengthening approaches for critical structures requiring both strength and ductility. The integration of these evidence-based strategies into routine practice will contribute to more reliable and effective seismic retrofit solutions, ultimately enhancing the resilience of concrete structures in earthquake-prone regions.

Declarations

Authors' Contributions

B.M: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing of the original draft, Visualization.

G.W: Validation, Writing – review & editing, Supervision, Project administration.

F.A.M: Validation, Writing – review & editing, Supervision, Project administration.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration on the Use of Generative AI and AI-Assisted Technologies

No generative AI or AI-assisted technologies were used in the preparation of this manuscript.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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The authors declare that there is no acknowledgement to be made.

Ethics

This study did not involve human participants or animals; hence, no ethical approval was required.

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