

# Strength Enhancement of Reinforced Concrete Columns by Carbon Fiber 600 GSM Wrapping Retrofit Technique: A State-of-the-Art Review

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**Abstract:** Reinforced concrete (RC) columns are the primary load-bearing members of buildings and bridges. Many existing RC columns require strengthening because of aging, corrosion, increased service loads, seismic deficiencies, design errors, or environmental deterioration. Carbon Fiber Reinforced Polymer (CFRP) wrapping has emerged as one of the most efficient retrofitting techniques owing to its high tensile strength, corrosion resistance, low self-weight, and ease of installation. This review critically examines the available research on CFRP confinement of reinforced concrete columns with particular emphasis on externally bonded 600 GSM carbon fiber wrapping systems. The paper discusses confinement mechanisms, material characteristics, strengthening procedures, experimental investigations, analytical models, design guidelines, and recent developments. Factors affecting strengthening efficiency, including the number of CFRP layers, wrapping configuration, fiber orientation, epoxy properties, concrete strength, column geometry, and loading conditions, are comprehensively reviewed. The review indicates that CFRP wrapping substantially improves axial load capacity, ductility, stiffness, energy absorption, and seismic performance while delaying crack propagation and preventing premature failure. Existing research gaps regarding optimization of 600 GSM CFRP layers, long-term durability, fire resistance, and predictive analytical models are also identified. The findings provide useful guidance for researchers and practicing engineers involved in structural rehabilitation and retrofitting.

**Keywords:** CFRP, Carbon Fiber, RC Columns, Retrofitting, Confinement, Strengthening, 600 GSM, Axial Load Capacity

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## I. Introduction

Reinforced concrete (RC) structures are among the most widely used construction systems for residential, commercial, industrial, and infrastructure projects due to their high compressive strength, durability, versatility, and cost-effectiveness. Among all structural components, reinforced concrete columns serve as the primary load-bearing members, transferring loads from slabs and beams to the foundation while ensuring the overall stability and safety of the structure. Since columns play a critical role in maintaining structural integrity, any reduction in their strength or stiffness can significantly increase the risk of partial or complete structural failure.

A large proportion of existing RC buildings and bridges worldwide were designed several decades ago according to earlier design codes that did not account for current seismic requirements, increased service loads, or long-term durability issues. Moreover, rapid urbanization, changes in occupancy, increased traffic loading, environmental degradation, reinforcement corrosion, poor construction practices, accidental impacts, and natural disasters have accelerated the deterioration of many reinforced concrete structures. These factors reduce the load-carrying capacity of columns, resulting in excessive cracking, concrete spalling, reinforcement corrosion, reduced stiffness, and inadequate ductility. Consequently, strengthening and rehabilitation of existing reinforced concrete

columns have become essential for extending the service life of aging infrastructure and ensuring public safety.

Conventional strengthening methods, such as reinforced concrete jacketing, steel jacketing, and external post-tensioning, have been successfully used to improve structural performance. However, these techniques often increase the cross-sectional dimensions of structural members, add significant dead load, require extensive construction time, and are susceptible to corrosion and maintenance issues. To overcome these limitations, Fiber Reinforced Polymer (FRP) composite materials have emerged as an effective alternative for structural retrofitting. Among various FRP systems, Carbon Fiber Reinforced Polymer (CFRP) has gained widespread acceptance because of its high tensile strength, excellent stiffness, corrosion resistance, low density, fatigue resistance, and ease of installation.

The strengthening mechanism of CFRP is primarily based on external confinement. When RC columns are wrapped with CFRP sheets, the lateral expansion of concrete under compression is restrained, creating a triaxial compressive stress state within the concrete core. This confinement enhances the compressive strength, ductility, energy absorption capacity, and post-peak behavior of the column while reducing crack propagation and delaying concrete crushing. Numerous experimental investigations have demonstrated that CFRP-confined columns exhibit significantly higher axial load capacity and improved seismic performance compared with unconfined columns.

In recent years, researchers have shown increasing interest in 600 GSM carbon fiber fabrics, which possess a higher fiber content than conventional lightweight fabrics. The greater fiber density provides enhanced confinement stiffness and allows higher strengthening efficiency with fewer wrapping layers. Consequently, 600 GSM CFRP wrapping has become an attractive retrofit solution for strengthening deteriorated reinforced concrete columns while minimizing installation time and material consumption. Nevertheless, limited research is available on the long-term performance, optimization of wrapping configurations, and analytical modelling of RC columns strengthened specifically with 600 GSM CFRP systems. Therefore, a comprehensive review of recent developments is required to summarize current

knowledge, identify research gaps, and provide guidance for future investigations.

## II. Review of Literature

Amir Mirmiran<sup>1</sup> and Mohsen Shahawy (1997) In this study, it was found that the External confinement of concrete by the high-strength fiber composites can significantly upgrade its strength and ductility as well as it result in large energy absorption capacity. The mechanism of confinement may include wrapping of fibre on existing columns as a retrofitting measure or encasement of concrete in the fiber reinforced plastic tube for new construction. The proper design of such hybrid columns, however, needs an accurate estimate of the performance enhancement. The current design methods use simple extension of the models developed for conventional reinforced concrete columns. Results from a series of uniaxial compression tests on concrete-filled FRP tubes are compared with the available confinement models in the literature. This study indicates that these models generally result in overestimating the strength and unsafe design. The study also shows a unique characteristic of confinement with fiber composites in that, unlike steel, FRP curtails the dilation tendency of concrete, as it reverses the direction of volumetric strains. This study provides a framework for the better understanding of the behavior of fiber-wrapped or FRP-encased concrete columns.

M. Shahawy et al. (2000) this study was done for an urgent need for models that can accurately predict the performance of fiber wrapped concrete columns. In this, it was reported that, the axial compression tests on a total of 45 carbon-wrapped concrete stubs of two batches of normal and high-strength concrete and five different number of wraps were used to verify a confinement model, which was originally developed for concrete-filled glass FRP tubes. Also, a nonlinear finite element model with a non-associative Drucker  $\pm$  Prager plasticity was developed. Both models compared favorably with test results. It was concluded that the adhesive bond between concrete and the wrap would not significantly affect the confinement behavior. Moreover, the same confinement model can be applied to carbon and glass fibers, as long as the model has incorporated the dilation tendency of concrete as a function of the stiffness of the jacket. However, it is of utmost importance to establish the effective hoop rupture strain of the wrap through a

reliability analysis by setting proper confidence level for design purposes.

Hamid Rahimi and Allan Hutchinson (2001) the structural behavior of reinforced concrete beams strengthened with adhesively bonded fiber reinforced plastics (FRP) is presented. The experimental work included flexural testing of 2.3-m-long concrete beams with bonded external reinforcements. The test variables included the amount of conventional (internal) reinforcement and also the type and amount of external reinforcement. For comparison, some of the beams were strengthened with bonded steel plates. Theoretical analyses included 2D nonlinear finite-element modeling incorporating a "damage" material model for concrete. In general, there were reasonably good correlations between the experimental results and nonlinear finite-element models. It is suggested that the detachment of bonded external plates from the concrete, at ultimate loads, is governed by a limiting principal stress value at the concrete/external plate interface.

R. Santhakumar et al. (2004) Presented the numerical study to simulate the behavior of retrofitted reinforced concrete (RC) shear beams. The study was carried out on the retrofitted RC beam designated as control beam and RC beams retrofitted using carbon fibre reinforced plastic (CFRP) composites with  $\pm 45^\circ$  and  $90^\circ$  fibre orientations. The effect of retrofitting on uncracked and pre-cracked beams was studied too. The finite elements adopted by ANSYS were used in this study. A quarter of the full beam was used for modeling by taking advantage of the symmetry of the beam and loadings. The load deflection plots obtained from numerical study show good agreement with the experimental plots reported by Tom Norris, et al (1997). There is a difference in behavior between the uncracked and pre-cracked retrofitted beams though not significant. The crack patterns in the beams are also presented.

V. Valdmantis et al. (2007) the mechanical behavior of concrete confined by carbon fibre-reinforced polymer (CFRP) sheets was investigated in this study. Two series of tests were conducted on standard concrete cylinders with cube compressive strength ranging from 34.2 to 104.1 MPa, confined by CFRP sheets with 234 GPa elastic modulus and volumetric ratio ranging between 0.45 and 1.35%. Split-disc tests were performed to estimate the tensile properties of the CFRP sheet in the hoop direction. The concrete cylinders were subjected to monotonic and cyclic axial

compressive loading with Teflon sheets inserted between concrete and steel bearing platens to reduce friction. The confined cylinder strength, strains and tangent moduli are compared with the values predicted by the recommendations of *fe' de' ration international du be' ton* task group 9.3, fib Bulletin 14. It is concluded that, at least for the investigated range of variables, the CFRP tensile strength has to be reduced with a factor 0.50 in the ultimate strength approach in order to obtain accurate strength predictions. For stability control the tangent modulus  $E_2$  of the confined concrete in the second pseudo-linear branch of the stress-strain curve (above the unconfined concrete strength) must be estimated and in the tests ranged from about 8 to 20% of the tangent modulus of elasticity  $E_1$  of the first branch of the curve.

Jason Fitzwilliam and Luke A. Bisby (2010) In this study, it showed that the external bonding of circumferential fiber-reinforced polymer (FRP) wraps is a widely accepted technique to strengthen circular RC columns, till date, most of the tests performed on FRP strengthened columns have considered short, unreinforced, small-scale concrete cylinders, with height-to-diameter ratios of less than three, tested under concentric, monotonic, and axial load. In practice, most RC columns have height-to-diameter ratios considerably larger than three and were subjected to loads with at least minimal eccentricity. Results of an experimental program performed to study the effects of slenderness on carbon FRP (CFRP) wrapped circular RC columns under eccentric axial loads are presented. It was showed that CFRP wraps increase the strength and deformation capacity of slender columns, although the beneficial confining effects are proportionally greater for short columns, and that theoretical axial-flexural interaction diagrams developed using conventional sectional analysis (but incorporating a simple FRP confined concrete stress-strain model) provide conservative predictions for non-slender CFRP wrapped columns under eccentric loads. The use of longitudinal CFRP wraps to reduce lateral deflections and allow slender columns to achieve higher strengths, similar to otherwise identical non-slender columns, is also demonstrated.

H.R. Ronagh and A. Eslami (2013) He examined that the effectiveness of fibre reinforced polymers (FRPs) in retrofitting/repairing of the reinforced concrete (RC) components has been studied in the past to great detail. However, the seismic performance of RC structures retrofitted using FRP composites is yet to be

scrutinized in terms of lateral resistance, ductility, and failure mechanism. This is of high importance if the retrofitted structures are to withstand higher seismic ground motions than they were designed for and/or pulse-type ground motions. In a comparative study, this paper reports on the results of an investigation into the flexural strengthening of RC buildings using glass/carbon fibre reinforced polymers (GFRP/CFRP). An 8-storey code-compliant RC building was considered as the case study to represent the medium-rise structures. With a slight intervention in the lateral displacement ductility and provision of the weak-beam strong-column design philosophy, the strengthening design strategy is aimed at increasing the lateral resistance. For this purpose, composite sheets were designed to be applied at the two end regions of all beams and columns on a practical flange-bonded scheme. The nonlinear pushover analysis with lumped plasticity approach was implemented in order to compare the seismic response of the original structure with the GFRP/CFRP retrofitted structures. Following validation of the adopted models, the force-deformation curves of the nonlinear plastic hinges are determined in a rigorous approach considering the material inelastic behavior, reinforcement details, and dimensions of the members. While the nonlinear results confirm a significant increase in the lateral load carrying capacity using both composite materials, the CFRP improvement was as much as twice of the GFRP. However, the latter provides higher ductility.

Katarina Gajdosova and Juraj Bilcik (2013) The paper presents an investigation into the performance of slender rectangular reinforced concrete columns strengthened with carbon fiber-reinforced polymers (CFRPs) in two manners. The first approach is a well-known form of CFRP sheet jacketing with the effect demonstrated in many studies, and a second one is a relatively new retrofit method of near surface mounted (NSM) CFRP strips. A total of eight full-scale specimens with rectangular cross sections ( $210 \times 150$  mm) were tested to failure under eccentric compressive loading. The total length of the specimens was 4,100 mm. The results of this study demonstrate a significant difference in slender and short column strengthening in accordance with the predominant stress manner. It was confirmed that the effect of CFRP wraps on the increase in column strength is proportionally greater for short RC columns subjected to predominant compression. The longitudinal fibers in CFRP strips bonded into grooves in concrete cover are more effective in enhancing the flexural load-carrying

capacity of slender reinforced concrete columns subjected to eccentric loading. The most effective approach to flexural capacity enhancement was demonstrated by a synergistic effect of NSM CFRP reinforcement ensured by CFRP sheet wrapping.

Fernández-Cánovas et al. (2016) The study experimentally investigated the compressive behavior of concrete specimens confined with externally bonded Carbon Fiber Reinforced Polymer sheets. Concrete cylinders with different compressive strengths were tested under axial loading to evaluate the influence of CFRP confinement. The results demonstrated that CFRP wrapping significantly increased the compressive strength, ultimate strain, and post-peak ductility of confined concrete. The study further indicated that proper surface preparation and high-quality epoxy bonding are essential to achieve effective stress transfer between concrete and CFRP sheets.

P.N Saira et al. (2017) This study investigates the improvements in the structural behavior of the RC beams retrofitted with various types of FRP such as glass fibres, coir fibres, banana fibers, jute fibers and cotton fibres. The experimental programme includes strengthening and flexural strength test of 18 simply supported RC beams of  $500 \times 100 \times 100$  mm. The test results showed an increase in ultimate load for the retrofitted beam when compared to normal control beam and corresponding increase in the value of modulus of rupture. The retrofitted beams with glass fibre using epoxy as binder having 47.32% more strength than the control beams. Area under load-deflection curve gives toughness. Toughness value is found to be more in RC beams retrofitted with banana fibre.

Ankit Dasgupta (2018) in this paper, the application of FRP in concrete structures is being investigated for its effectiveness in enhancing structural performance both in terms of strength and ductility. The structural components tested so far include slabs, beams, columns and bridge culverts. So far indicate that retrofitting with FRP offers an attractive alternative to the traditional techniques. In many circumstances, it can provide the most economical (and superior) solution for a structural rehabilitation problem. The manufacturing process of FRP and the field application of FRP is very easy and selected results from experimental and analytical. Seismic retrofit with FRP materials has gained notable acceptance from the civil engineering community in recent years.

Gora and Jaganathan (2019) The authors reviewed the application of Fiber Reinforced Polymer composites for strengthening reinforced concrete columns subjected to axial and seismic loading. The study summarized experimental investigations on CFRP, GFRP, AFRP, and hybrid composite systems. It was observed that the confinement effectiveness depends primarily on the number of composite layers, concrete compressive strength, corner radius, fiber orientation, and bond quality between the composite and concrete surface. The review concluded that CFRP provides the highest improvement in strength and stiffness among commercially available FRP systems, whereas GFRP offers a more economical strengthening solution.

Salesa, Esteban and Barris (2022) The researchers carried out a comparative evaluation of international design guidelines for FRP-confined reinforced concrete columns. Experimental results reported by various researchers were compared with analytical predictions from ACI 440, CNR-DT 200, fib recommendations, and other international standards. The investigation showed that the available design models accurately predict the compressive strength of circular CFRP-confined columns but exhibit significant variations when applied to square and rectangular columns. The study concluded that additional experimental research is required to improve confinement models for non-circular sections and develop more reliable design recommendations.

Wahab et al. (2024) The authors developed machine-learning-based prediction models for estimating the compressive strength of CFRP-confined reinforced concrete using extensive experimental databases. Artificial Neural Network (ANN) and other intelligent algorithms were trained using variables such as concrete compressive strength, column dimensions, CFRP thickness, elastic modulus, and number of wrapping layers. The developed prediction models demonstrated excellent agreement with experimental observations and significantly reduced prediction errors compared with conventional empirical

equations. The study concluded that artificial intelligence can effectively support the design of CFRP strengthening systems.

Ahmed A. Elnassar et al. (2025) The authors presented a comprehensive review on the confinement of reinforced concrete columns using Fabric-Reinforced Cementitious Matrix (FRCM) composites and compared their performance with conventional FRP systems. The review discussed the mechanical properties, strengthening mechanisms, durability characteristics, and failure modes of externally confined concrete columns. It was observed that composite confinement significantly improved the compressive strength, ductility, and energy absorption capacity of reinforced concrete columns while enhancing resistance against environmental deterioration. The study also highlighted that the effectiveness of confinement depends on the type of reinforcing fabric, mortar properties, number of layers, and column geometry. The authors concluded that although FRCM systems offer better fire resistance and compatibility with concrete than epoxy-based FRP systems, further experimental studies are required to develop unified design guidelines and improve long-term durability.

Recent Composite Structures Investigation (2026) The researchers experimentally evaluated reinforced concrete columns confined using both internal and external CFRP tube systems under axial compression. The hybrid confinement configuration was compared with conventional external CFRP wrapping to investigate improvements in structural performance. Experimental observations indicated considerable enhancement in compressive strength, ductility, stiffness, and energy absorption capacity due to the combined confinement mechanism. The study concluded that hybrid CFRP confinement systems have significant potential for strengthening heavily loaded reinforced concrete columns and recommended further investigations under cyclic and seismic loading conditions.

Table 1: Comparison Table

SN	Author(s)	Year	Study Focus	Methodology	Major Findings
1	Amir Mirmiran & Mohsen Shahawy	1997	FRP confinement of concrete columns	Experimental	FRP confinement significantly enhanced compressive strength, ductility, and energy absorption. Existing confinement models overestimated the strength of FRP-confined concrete.

2	M. Shahawy et al.	2000	Carbon-wrapped concrete columns	Experimental & Finite Element Analysis	Developed a reliable confinement model and concluded that adhesive bonding has little influence on confinement behavior.
3	Hamid Rahimi & Allan Hutchinson	2001	FRP strengthening of RC beams	Experimental & Numerical	FRP plates significantly improved flexural capacity. Debonding at the concrete-FRP interface governed failure.
4	R. Santhakumar et al.	2004	CFRP retrofitted RC shear beams	Finite Element Analysis	CFRP retrofitting enhanced shear strength and crack resistance. Numerical predictions agreed well with experiments.
5	V. Valdmanis et al.	2007	CFRP-confined concrete cylinders	Experimental	CFRP confinement improved compressive strength and ductility. Existing design recommendations required modification for accurate prediction.
6	Jason Fitzwilliam & Luke A. Bisby	2010	CFRP strengthening of slender columns	Experimental	CFRP wraps increased strength and deformation capacity. Short columns benefited more than slender columns.
7	H.R. Ronagh & A. Eslami	2013	Seismic strengthening using GFRP/CFRP	Nonlinear Pushover Analysis	CFRP almost doubled the increase in lateral load capacity compared with GFRP, whereas GFRP provided higher ductility.
8	Katarina Gajdosova & Juraj Bilcik	2013	Strengthening slender RC columns	Experimental	Combined NSM CFRP strips and CFRP wrapping provided the highest flexural strength enhancement.
9	Fernández-Cánovas et al.	2016	CFRP confinement of concrete	Experimental	CFRP wrapping considerably increased compressive strength and ductility. Proper surface preparation was essential for effective bonding.
10	P.N. Saira et al.	2017	FRP-retrofitted RC beams	Experimental	Glass fiber retrofit increased flexural strength by about 47%. Banana fiber showed higher toughness.
11	Ankit Dasgupta	2018	Review of FRP strengthening	Review	FRP retrofitting is an economical and efficient rehabilitation technique for beams, slabs, columns, and bridges.
12	Gora & Jaganathan	2019	Review on FRP-confined RC columns	Review	CFRP exhibited superior strength enhancement compared to other FRP materials. Performance depended on confinement ratio, fiber orientation, and corner radius.
13	Pham et al.	2020	High-strength concrete confined with CFRP	Experimental	CFRP confinement significantly improved ultimate strain and compressive strength, particularly for high-strength concrete columns.
14	Ozbakkaloglu et al.	2021	Behavior of FRP-confined concrete	Experimental & Analytical	Proposed improved stress-strain models and highlighted the influence of confinement stiffness on column performance.
15	Salesa, Esteban & Barris	2022	Comparison of FRP design codes	Analytical Review	ACI 440 and fib models accurately predicted circular columns but overestimated the strength of square columns.

16	Wang et al.	2023	CFRP-strengthened RC columns under eccentric loading	Experimental	CFRP wrapping effectively enhanced axial load capacity and delayed buckling under eccentric compression.
17	Wahab et al.	2024	Machine learning prediction of CFRP-confined concrete	Artificial Intelligence	ANN models predicted confined concrete strength with high accuracy and lower prediction error than empirical equations.
18	Ahmed A. Elnassar et al.	2025	Review of FRCM confinement systems	Review	FRCM systems improved strength and durability while offering better fire resistance than epoxy-based FRP systems.
19	Recent Composite Structures Investigation	2026	Internal and external CFRP tube confinement	Experimental	Hybrid CFRP confinement significantly enhanced compressive strength, stiffness, ductility, and energy absorption capacity.

### III. Need for Strengthening Reinforced Concrete Columns

The rehabilitation and strengthening of reinforced concrete columns have become increasingly important due to the growing number of aging structures and the rising demand for safe and sustainable infrastructure. Many reinforced concrete buildings constructed several decades ago are currently operating beyond their intended design life and are subjected to loading conditions much greater than those considered during their original design. Instead of demolishing and reconstructing these structures, retrofitting provides a technically feasible, economically viable, and environmentally sustainable solution.

One of the primary causes of column deterioration is the corrosion of reinforcing steel resulting from carbonation, chloride penetration, moisture ingress, and aggressive environmental exposure. Corrosion products occupy a larger volume than the original steel, generating internal tensile stresses that lead to cracking and spalling of the concrete cover. As deterioration progresses, the bond between concrete and reinforcement weakens, ultimately reducing the structural capacity of the column.

Another major reason for strengthening is the revision of structural design codes and seismic provisions. Many older buildings were designed without

considering modern earthquake-resistant requirements. During seismic events, these inadequately detailed columns may experience brittle failure due to insufficient confinement reinforcement and poor ductility. Strengthening with CFRP wrapping significantly improves confinement, allowing the columns to sustain larger deformations without sudden failure.

Increased service loads also necessitate structural strengthening. Renovation projects often involve the addition of extra floors, installation of heavy machinery, changes in building occupancy, or increased traffic loads in bridges and parking structures. These modifications increase axial loads beyond the original design capacity, making retrofitting essential for maintaining structural safety.

Construction defects such as inadequate reinforcement detailing, poor-quality concrete, improper curing, honeycombing, dimensional inaccuracies, and insufficient cover further reduce the strength and durability of reinforced concrete columns. Similarly, accidental events including vehicle impacts, explosions, fire exposure, floods, and earthquakes can significantly impair structural performance. Retrofitting using CFRP wrapping offers an efficient means of restoring lost capacity while minimizing interruption to building operations.

Compared with demolition and reconstruction, strengthening existing structures conserves construction materials, reduces carbon emissions, lowers project costs, minimizes construction waste, and extends the service life of valuable infrastructure. Therefore, structural retrofitting has become an integral component of sustainable infrastructure management.

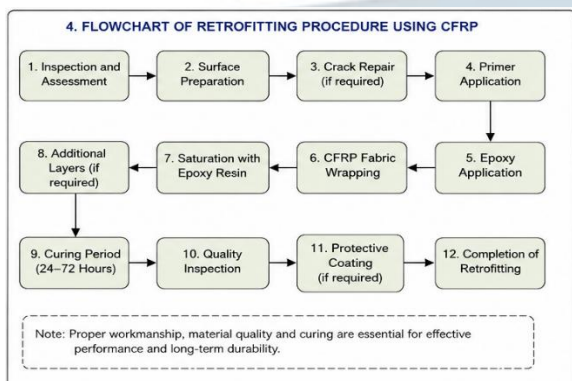


Figure 1: Carbon Fiber Reinforced Polymer (CFRP) and 600 GSM Wrapping

Carbon Fiber Reinforced Polymer (CFRP) is a high-performance composite material consisting of continuous carbon fibers embedded within a polymer resin matrix, typically epoxy. The carbon fibers provide exceptionally high tensile strength and stiffness, while the resin matrix transfers stresses between fibers, protects them from environmental damage, and ensures effective bonding with the concrete substrate. Due to its superior mechanical properties and durability, CFRP has become one of the most widely used materials for strengthening reinforced concrete structures.

Compared with traditional strengthening materials such as steel plates and reinforced concrete jacketing, CFRP offers several significant advantages. It possesses a high strength-to-weight ratio, making it capable of providing substantial structural enhancement without adding considerable dead load. CFRP is highly resistant to corrosion, fatigue, moisture, and chemical attack, making it suitable for aggressive environmental conditions. Furthermore, externally bonded CFRP systems require minimal construction time, do not significantly alter the geometry of structural members, and can be installed with relatively little disruption to building operations.

The performance of CFRP strengthening depends on several parameters, including fiber type, fabric weight (GSM), fiber orientation, number of layers, resin properties, bonding quality, and wrapping configuration. Among these parameters, the fabric weight has a direct influence on confinement stiffness and strengthening effectiveness.

The term 600 GSM refers to a carbon fiber fabric with a mass of 600 grams per square metre. Compared with lighter fabrics such as 200 GSM or 300 GSM, 600 GSM CFRP contains a greater quantity of carbon fibers within the same surface area. This increased fiber content enhances the tensile capacity and confinement pressure applied to the concrete core, allowing significant improvements in axial strength and ductility with fewer wrapping layers. Consequently, the use of 600 GSM CFRP reduces installation time, epoxy consumption, and labour requirements while maintaining high structural efficiency. Based on the synthesis, conclusions were drawn regarding the influence of infrastructure and traffic factors on road regulation and safety, along with recommendations for future research and policy interventions. Typical mechanical properties of CFRP used for structural retrofitting are presented below.

Table 2: mechanical properties of CFRP used for structural retrofitting

Property	Typical Value
Density	1.75–1.95 g/cm <sup>3</sup>
Tensile Strength	3500–5000 MPa
Elastic Modulus	220–250 GPa
Ultimate Strain	1.5–2.0%
Fabric Weight	600 g/m <sup>2</sup>
Corrosion Resistance	Excellent
Fatigue Resistance	Excellent

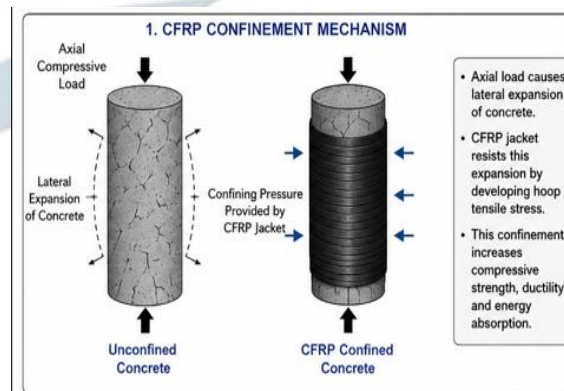


Figure 2: CFRP Confinement Mechanism

The selection of an appropriate CFRP system depends on the required strengthening level, column dimensions, expected loading conditions, environmental exposure, and economic considerations.

#### IV. Factors Affecting Strength Enhancement

The effectiveness of Carbon Fiber Reinforced Polymer (CFRP) wrapping in strengthening reinforced concrete (RC) columns is influenced by several material, geometric, and loading parameters. Although CFRP confinement has been proven to enhance the axial load-carrying capacity, ductility, stiffness, and energy absorption of RC columns, the degree of improvement depends on proper selection of the strengthening system and quality of installation. The major factors affecting the strengthening performance are discussed below.

##### *Concrete Compressive Strength*

The compressive strength of the existing concrete significantly influences the effectiveness of CFRP confinement. Columns constructed with normal-strength concrete generally exhibit greater improvement in ductility and compressive strength because the CFRP wrap effectively restrains the lateral expansion of concrete. In contrast, high-strength concrete possesses lower lateral dilation before failure; therefore, although CFRP still increases its strength, the percentage improvement in ductility is relatively lower. Consequently, the confinement efficiency decreases as the compressive strength of concrete increases.

##### *Number of CFRP Layers*

The number of CFRP layers directly affects the confinement pressure developed around the concrete core. Increasing the number of wrapping layers increases the lateral confining stress, resulting in higher axial load capacity, stiffness, and deformation capacity. However, beyond an optimum number of layers, the increase in strength becomes marginal while the material cost increases considerably. The use of 600 GSM CFRP fabric provides higher confinement stiffness than lighter fabrics, enabling significant strengthening with fewer wrapping layers.

##### *CFRP Fabric Weight (GSM)*

The areal density of carbon fiber fabric is another important parameter influencing strengthening performance. Higher GSM fabrics contain more carbon fibers per unit area and therefore possess greater tensile capacity. Compared with 200 GSM and 300 GSM fabrics, 600 GSM CFRP wrapping can provide greater confinement pressure with fewer layers, reducing installation time and epoxy consumption. However, thicker fabrics require careful resin impregnation to ensure complete bonding and avoid internal voids.

##### *Column Geometry*

The cross-sectional shape of the column greatly affects confinement efficiency. Circular columns provide uniform lateral confinement because the CFRP sheet experiences equal tensile stress around the circumference. In contrast, square and rectangular columns develop stress concentrations at sharp corners, causing premature rupture of CFRP sheets and reducing confinement effectiveness. To improve the performance of non-circular columns, corner rounding is commonly adopted before CFRP application.

##### *Corner Radius*

For square and rectangular columns, increasing the corner radius significantly improves stress distribution within the CFRP wrap. Rounded corners reduce stress concentrations, delay fiber rupture, and enhance the effectiveness of confinement. Most design recommendations specify a minimum corner radius to achieve satisfactory performance.

##### *Fiber Orientation*

The orientation of carbon fibers determines the type of structural enhancement obtained. Fibers oriented perpendicular to the longitudinal axis (hoop direction) provide effective confinement by resisting lateral expansion of concrete. Fibers placed in the longitudinal direction mainly contribute to increasing flexural strength and stiffness. In practical applications, bidirectional wrapping may be adopted when both axial and flexural strengthening are required.

##### *Bond Quality Between CFRP and Concrete*

The strengthening performance of CFRP systems depends on effective stress transfer between the concrete surface and the composite material. Proper surface preparation, crack repair, cleaning, and epoxy

application are essential for achieving strong adhesion. Poor bonding may result in premature debonding, reducing the effectiveness of confinement and leading to early structural failure.

### Type and Properties of Epoxy Resin

The epoxy resin acts as the bonding medium between carbon fibers and concrete. High-quality epoxy with adequate tensile strength, stiffness, and environmental resistance ensures effective load transfer and long-term durability. Improper mixing, inadequate curing, or environmental exposure during installation may reduce bond strength and adversely affect structural performance.

### Loading Conditions

The strengthening efficiency of CFRP wrapping varies according to the applied loading condition. Under pure axial compression, confinement is highly effective because lateral expansion occurs uniformly. Under eccentric loading, bending stresses reduce the confinement efficiency, while cyclic and seismic loading require sufficient ductility and energy absorption. Experimental studies have shown that CFRP wrapping significantly improves the seismic performance of reinforced concrete columns by delaying brittle failure and enhancing deformation capacity.

### Environmental Conditions

Long-term exposure to moisture, ultraviolet radiation, elevated temperatures, freeze-thaw cycles, and chemical environments may affect the durability of CFRP systems. Although carbon fibers themselves are highly resistant to corrosion, the epoxy matrix may deteriorate under adverse environmental conditions. Protective coatings and proper maintenance are therefore recommended for structures exposed to aggressive environments.

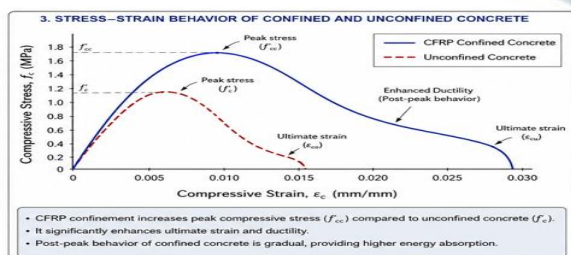


Figure 3: Stress-Strain Behavior

The strengthening efficiency of CFRP-wrapped reinforced concrete columns is governed by the combined influence of concrete properties, wrapping configuration, fiber characteristics, geometric parameters, bond quality, and loading conditions. Proper consideration of these factors ensures optimum utilization of CFRP materials and reliable long-term structural performance.

### V. Comparison of CFRP with Conventional Retrofitting Techniques

Several techniques have been developed to strengthen deteriorated reinforced concrete columns, including reinforced concrete jacketing, steel jacketing, ferrocement jacketing, external post-tensioning, and Fiber Reinforced Polymer (FRP) wrapping. Each method has its own advantages and limitations depending on structural requirements, construction conditions, and economic considerations. Among these techniques, Carbon Fiber Reinforced Polymer (CFRP) wrapping has emerged as one of the most efficient and widely accepted retrofit solutions because of its excellent mechanical properties, ease of installation, and long-term durability.

#### Reinforced Concrete Jacketing

Reinforced concrete jacketing is one of the oldest strengthening methods in which an additional reinforced concrete layer is cast around the existing column. This technique substantially increases the load-carrying capacity and stiffness of the column while improving its seismic resistance. However, it significantly increases the cross-sectional dimensions and dead weight of the structure, requires extensive formwork, and causes considerable disruption during construction. Furthermore, the increased member size may reduce usable floor space and increase foundation loads.

#### Steel Jacketing

Steel jacketing involves enclosing the existing column with steel plates or steel sections connected by welding or bolting. The method provides excellent confinement, improves ductility, and enhances both axial and shear capacity. Nevertheless, steel jackets are susceptible to corrosion, require periodic maintenance, increase the self-weight of the structure, and involve complicated fabrication and installation procedures.

Transportation and handling of steel members also increase construction costs.

#### *Ferrocement Jacketing*

Ferrocement jacketing consists of wire mesh embedded within a cement mortar matrix applied around the existing column. The technique is economical and relatively easy to construct while providing moderate improvements in strength and crack resistance. However, ferrocement offers lower confinement efficiency than CFRP and may experience cracking and durability issues under severe environmental exposure.

#### *External post-tensioning*

External post-tensioning enhances structural capacity by introducing compressive forces through prestressing tendons. The technique effectively controls deflections and increases flexural capacity but requires specialized equipment, careful tensioning procedures, and regular maintenance of anchorage systems. It is generally more suitable for beams and bridge girders than for individual reinforced concrete columns.

#### ***Carbon Fiber Reinforced Polymer (CFRP) Wrapping***

CFRP wrapping has become increasingly popular because it combines high structural efficiency with minimal construction inconvenience. Carbon fibers possess extremely high tensile strength while having a very low density, allowing substantial strengthening without significantly increasing the weight or dimensions of structural members. CFRP is highly resistant to corrosion, fatigue, moisture, and chemical attack, making it suitable for aggressive environmental conditions. Installation is comparatively simple, requires minimal equipment, and can often be completed without interrupting the normal operation of buildings or bridges.

The primary limitation of CFRP systems is the relatively high initial material cost compared with conventional techniques. Additionally, the effectiveness of CFRP depends heavily on proper surface preparation, epoxy bonding, and skilled workmanship. The epoxy resin is also sensitive to elevated temperatures, requiring fire-protective measures in certain applications.

Table 3: Comparison of Conventional Retrofitting Techniques

Strengthening Technique	Strength Enhancement	Increase in Member Size	Added Dead Load	Corrosion Resistance	Construction Time	Durability	Cost
Reinforced Concrete Jacketing	Very High	High	High	Good	Long	High	Moderate
Steel Jacketing	Very High	Moderate	High	Poor	Moderate	Moderate	High
Ferrocement Jacketing	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Low
External post-tensioning	High	Low	Low	Moderate	High	High	High
CFRP Wrapping	Very High	Negligible	Very Low	Excellent	Short	Excellent	Moderate to High



Figure 4: RC Column before and after wrapping

## V. Discussion

Among the available strengthening methods, CFRP wrapping offers the most balanced combination of strength enhancement, durability, lightweight construction, and ease of application. Unlike reinforced concrete and steel jacketing, CFRP does not significantly increase the dimensions or self-weight of the column. The high strength-to-weight ratio, excellent corrosion resistance, and rapid installation make CFRP particularly suitable for retrofitting existing buildings, bridges, industrial structures, and earthquake-prone infrastructure. Although the initial material cost of CFRP is relatively high, the reduced labor requirements, minimal maintenance, and extended service life often make it a cost-effective solution over the entire life cycle of the structure.

## VI. Conclusion

The present review paper critically examined the application of Carbon Fiber Reinforced Polymer (CFRP) 600 GSM wrapping as a strengthening technique for reinforced concrete columns. Based on the comprehensive review of published literature, the following conclusions can be drawn:

- CFRP wrapping is one of the most effective retrofit techniques for enhancing the structural performance of reinforced concrete

columns without significantly increasing their dimensions or self-weight.

- The confinement provided by CFRP converts the concrete stress state from uniaxial to triaxial compression, thereby increasing compressive strength, stiffness, ductility, and energy absorption capacity.
- CFRP-retrofitted columns exhibit improved crack resistance, delayed concrete crushing, reduced spalling, and enhanced post-peak behaviour compared with unconfined columns.
- The effectiveness of CFRP confinement depends on several factors, including concrete compressive strength, number of CFRP layers, fiber orientation, column geometry, corner radius, bond quality, epoxy properties, and loading conditions.
- Circular columns generally demonstrate higher confinement efficiency than square and rectangular columns because the lateral confining pressure is distributed more uniformly.
- The use of 600 GSM CFRP fabric provides higher confinement stiffness and allows significant strength enhancement with fewer

wrapping layers, thereby reducing installation time and epoxy consumption.

- Compared with conventional strengthening techniques such as reinforced concrete jacketing and steel jacketing, CFRP wrapping offers several advantages, including lightweight construction, excellent corrosion resistance, rapid installation, minimal interruption to service, and superior durability.
- Recent developments involving numerical modelling, finite element analysis, and artificial intelligence have improved the prediction of the structural behavior of CFRP-confined reinforced concrete columns.
- Despite the extensive research on CFRP strengthening, limited experimental studies are available specifically on 600 GSM CFRP wrapping, particularly under eccentric loading, cyclic loading, elevated temperatures, and aggressive environmental conditions.

The review indicates that further experimental investigations and improvements in international design guidelines are necessary before the full structural potential of 600 GSM CFRP systems can be realized in engineering practice. Overall, 600 GSM CFRP wrapping represents a promising, efficient, and sustainable strengthening solution for extending the service life of deteriorated reinforced concrete columns. With continued research, improved material technologies, and refined design methodologies, CFRP retrofitting is expected to play an increasingly important role in the rehabilitation of aging infrastructure worldwide.

## VII. Future Scope

Based on the comprehensive review of the available literature, the following future research directions are recommended to enhance the understanding and practical implementation of 600 GSM CFRP wrapping for strengthening reinforced concrete columns:

- Experimental studies on 600 GSM CFRP: Most published studies have focused on 200 GSM and 300 GSM CFRP sheets. Further research is required to evaluate the structural

performance of 600 GSM CFRP under different loading conditions.

- Optimization of wrapping layers: Future investigations should determine the optimum number of 600 GSM CFRP layers required to achieve maximum strength enhancement while maintaining cost-effectiveness. Behavior under eccentric loading: Additional studies are needed to examine the performance of CFRP-wrapped RC columns subjected to combined axial load and bending moments, which are commonly encountered in practical structures.
- Seismic performance evaluation: More experimental and numerical research should be conducted to investigate the behavior of 600 GSM CFRP-confined columns under cyclic and earthquake loading conditions.
- Long-term durability assessment: Future studies should evaluate the influence of environmental factors such as moisture, chloride exposure, ultraviolet radiation, temperature variations, freeze-thaw cycles, and chemical attack on the long-term performance of CFRP-retrofitted columns.
- Fire resistance studies: Since epoxy resin loses strength at elevated temperatures, research is required to improve the fire resistance of CFRP systems through advanced resin formulations and protective coatings.
- High-strength and ultra-high-performance concrete: The effectiveness of 600 GSM CFRP confinement for high-strength concrete (HSC) and ultra-high-performance concrete (UHPC) columns requires further investigation.
- Hybrid strengthening techniques: Future work should explore hybrid retrofit systems combining CFRP with Glass Fiber Reinforced Polymer (GFRP), Basalt Fiber Reinforced Polymer (BFRP), steel jacketing, or Near Surface Mounted (NSM) reinforcement for enhanced structural performance.
- Finite element and numerical modelling: Advanced numerical simulation techniques

should be developed to accurately predict the nonlinear behavior and failure mechanisms of CFRP-confined RC columns.

- Artificial intelligence applications: Machine learning and deep learning models can be employed to predict the compressive strength, ductility, failure mode, and service life of CFRP-strengthened columns using extensive experimental databases.
- Life-cycle cost analysis: Comprehensive economic studies should compare CFRP retrofitting with conventional strengthening techniques by considering installation cost, maintenance requirements, service life, and sustainability.
- Development of design guidelines: Additional experimental evidence is required to improve existing design provisions such as ACI 440, fib Model Code, and other international standards, particularly for rectangular columns strengthened with 600 GSM CFRP.
- Field implementation and monitoring: More full-scale case studies should be conducted on existing buildings and bridges to evaluate the practical performance of CFRP retrofitting under actual service conditions.
- Sustainable composite materials: Future research should focus on environmentally friendly epoxy resins, recyclable carbon fibers, and sustainable composite systems to reduce the environmental impact of structural retrofitting.

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