



THE APPLICATION OF CFRP BARS AND SHEETS IN REINFORCED CONCRETE STRUCTURES: A REVIEW

Hajir A Al-Hussainy¹ and Mortada Sabeh Whwah²

¹ College of Engineering, University of Kerbala, Karbala, Iraq,
Email:Hajir.a@uokerbala.edu.iq.

² College of Engineering, University of Kerbala, Karbala, Iraq,
Email:mortada.s@uokerbala.edu.iq.

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ABSTRACT

This review aims to carefully analyze how Carbon Fiber Reinforced Polymer (CFRP) bars and sheets are used in reinforced concrete, focusing on their strength, durability and ability to support a structure. The analysis compiles recent research to look into the positives and negatives of using CFRP rather than steel as a reinforcement for structures. The main parts of this field are bonding ways, extra costs, effects on the environment and how CFRP performs in various situations. The summary points out that CFRP can considerably increase flexural and shear strength in concrete, resist corrosion and create objects that are both durable and light in weight. Despite the expensive cost, limited information about durability and some bonding-related issues, CFRP systems exhibit encouraging effects in applications like flexural strengthening, shear reinforcement and confining concrete columns. Research and new technologies will likely allow CFRP to be more widely used in the future, solving many infrastructure problems.

KEYWORDS

CFRP bars, CFRP sheets, durability, concrete structure, lightweight material.



1. INTRODUCTION

The construction industry now seeks superior materials for concrete structures because they improve durability along with performance. Traditional steel reinforcement displays two main drawbacks in concrete applications because of its corrosion sensitivity as well as its heavy weight compared to its strength capabilities. The construction industry now embraces CFRP (CFRP) bars and sheets as superior building elements for fresh constructions together with the repair of existing structures (Hollaway, 2010). Polymers represent the leading material choice because processing them remains simple and their weight is noticeably lighter than other substances. They have exceptional mechanical properties. High temperature resins serve today as complex structural materials that find use in production of aircraft along with rockets and electronic systems and spacecraft (P.K. Mallick, 2007). The most crucial role is played by reinforcements when the composite uses hand-woven reinforcements positioned in an oblique direction because the fibers bear most of the structural load (such as carbon/epoxy composites) (Gibson, 2016) . The final strength characteristics and stiffness measurements of several composites depend totally on the strength measurements and stiffness measurements of their fiber components. Carbon and graphite maintain their strength and stiffness properties until they reach temperatures of 2500°K because they both serve as excellent high-temperature materials. The aerospace industry along with biomedical applications and security needs employ carbon fiber composites in addition to their usage in industrial and space sectors. The materials were first created to meet high-performance requirements in components subjected to extreme temperatures during rocket operations. Slag composites serve contemporary uses both in industries and maritime sectors (Chowdhury et al., 2021). The construction industry currently substitutes traditional steel reinforcement with fiber-reinforced polymer (FRP) bars for concrete structures. The non-corrosive characteristics combined with non-magnetic properties of these products make them suitable for concrete reinforcement in harsh environments (Bakis et al., 2003) . The shear and flexural strength of concrete structures are reinforced by various types of fiber-reinforced polymer materials. The main FRP categories consist of glass fiber-reinforced polymer (GFRP) and carbon fiber-reinforced polymer (CFRP) with aramid fiber-reinforced polymer (AFRP) as the third key member (Goldston, Remennikov and Sheikh, 2014). The main benefits of these materials surpass traditional reinforcements through their resistance to corrosion and magnetic field compatibility and their lightweight yet strong characteristics (Rolland et al., 2015).

2. CHALLENGES AND LIMITATIONS

2.1. Bonding Issues

The utilization of carbon fiber reinforced polymer (CFRP) in concrete work requires excellent bonding between CFRP material and the concrete surface. The bond strength relies heavily on three elements including surface condition, environmental exposure and adhesive quality. Thermoset CFRP adhesive bonding presents great potential yet failure performance degrades when release agents and excessive top-layer matrix remain inside the joint. The best surface conditions prior to bonding occur when carbon fiber reinforced plastics undergo laser treatments using UV (355 nm) and IR (1064 nm) sources (Schweizer et al., 2017). Lightweight construction methods now require fresh bonding methods. All applications now heavily embrace CFRP bonding since this approach leads to decreased structural weight while cutting down fabrication costs even as it increases design versatility (Liu, Tang and Cong, 2012).

2.2. High Initial Costs

CFRP materials have significantly higher costs than standard steel reinforcement materials thus representing a disadvantage for projects that need financial constraints. The initial expense of installing CFRP is high yet existing for an extended period as well as minimal upkeep needs and extended service duration prove to be cost-effective over time. The application of composite materials proves successful nowadays in market sectors that prioritize both high performance standards and cost-effective approaches and expedited production cycles (Vita et al., 2019). Carbon fiber-reinforced polymers (CFRP) and other carbon composite materials continue to gain the status of cost-effective solutions against traditional materials within the market. These composites have established the automotive sector as one of their main application areas (Nickels, 2018).

3. ENVIRONMENTAL IMPACT AND SUSTAINABILITY

Smooth production of CFRP materials needs vast energy consumption and relies on non-renewable resources which generates concerns regarding environmental impacts. The extended service life together with reduced maintenance requirements for CFRP structures minimizes several limitations within the construction industry. Improved recycling technologies for CFRP materials would enhance their sustainability level by an additional degree (Mezher et al., 2016).

4. APPLICATION OF CFRP BARS IN CONCRETE STRUCTURES

4.1. 4.1 Flexural Strengthening

The all-encompassing adoption of CFRP bonding in all applications happens since this approach both reduces design costs and cutting down structure weight and creating expanded

engineering possibilities. The use of CFRP bars in beams and slabs enables substitution or addition of steel reinforcement to construct lighter structures with matching or better strength capabilities. (Rafi and Nadjai, 2011) designed an experiment to learn how carbon fiber-reinforced polymer (CFRP) bars affected the performance of concrete beams. This research looked at the reinforcement type (CFRP or conventional steel) and the way the beams behaved under bending loads. Beams were tested in a four-point bend to check their strength, the pattern of their failure, maximum moments they could take and how they would function regularly. It was found that both types of beams failed in much the same way, meaning that reinforcing CFRP could provide just as much structural strength as steel. Even so, the moment capacity of CFRP-reinforced beams as calculated by the usual design codes was often underestimated. Even so, the way these beams deflected followed the predictions made by theory for common service loads. The CFRP-reinforced beams showed a ductile behavior, as they were able to bend a lot, they surpassed a deformability index of six which usually means they could handle a lot of energy and keep bending after the yield point. It was found that CFRP bars have similar flexural properties to steel but maintain enough ductility which makes them ideal for reinforced concrete applications.

(Rafi and Nadjai, 2011) performed an experiment to study the behavior of RC beams with CFRP and steel-CFRP reinforcement under increased temperatures to retain their shape and strength as the temperature rose. The study looked at the main factors of the reinforcement type (between CFRP and hybrid steel-CFRP), how high the temperature was and the amount of CFRP bar layers. The testing took place in a fire furnace on the floor, involved continuous load and high temperatures to resemble a fire environment. It became clear about the flexure properties of beams as a result of performing flexural tests following their thermal exposure. It was found that the compressive core of the concrete was only mildly affected by higher temperatures which explained why there was little damage to the concrete and no significant lowering of its mechanical properties. All beams broke due to bending, as was planned for the experiment. Even so, higher temperature was found to promote breakage of the concrete mainly by causing extra slippage of CFRP bars. Hybrid reinforcement, which involved both steel and CFRP, offered the best overall performance, strengthening the structure and providing stiffer support when tested against CFRP-only reinforced beams. Two layers of CFRP bars in the beam gave the strongest performance in flexural strength, yet it did not allow the beam to bend as much. Results prove that hybrid reinforcement better protects RC beams from heat and enables them to function properly under the stress of temperature.

(Dhanraj Pamar et al., 2015) performed an experimental study on the mechanics of CFRP

laminates to see how the direction of the carbon fibers affects their behavior. In the study, the main variable was the angle at which the fiber was aligned which was tested at 30°, 45° and 90°. Laminates were built using hand lay-up and after that were cut according to ASTM guidelines to create the specimens used for strength testing. It was clearly seen from the experiments that fiber orientation strongly influences mechanical behavior. 90° alignment of the fibers led to the strongest specimens, thanks to the load being evenly put on the fibers which prevented them from bending and breaking easily. Studies also found that the elongation at failure was reduced in the specimens. Samples with fibers at angles of 30° and 45° underwent more stretching yet were weaker because the off-center loading pulled out more fibers. Specimens kept at 45° underwent considerable displacement before breaking, which points to their ability to absorb a lot of energy before giving way. The study concluded that the direction of the fibers is very important for the strength and deformation of CFRP laminates. Best resistance to tension and bending was found with the panels oriented at 90°, but off-axis orientations of 30° and 45° allowed greater ductility and strain without offering the same load capacity.

(Aljebory and Kamonna, 2025) performed an experimental study to examine the use of Carbon Fiber Reinforced Polymer (CFRP) composites for repairing two-span continuous one-way reinforced concrete (RC) slabs that suffered from flexural damage. A group of thirteen RC slab specimens was fabricated and these included a control slab and slabs that were preloaded to 40% and 65% of the ultimate load capacity. Externally bonded (EB) CFRP sheets and near-surface mounted (NSM) CFRP bars were the two main tools used and researchers investigated differences based on the CFRP length, spacing between bars, anchorage and the type of damage. It was shown that EB and NSM techniques both made the structure more resistant to damage. These repaired slabs showed improvements in ultimate load capacity which ranged from 42% to 70% and decreases in deflection, from 11% to 25%. EB-CFRP was better at making the parts stronger and stiffer and NSM made them more flexible. Also, the addition of end-anchors was helpful in avoiding debonding and made the system function better.

4.2. Shear Strengthening

Shear failure in concrete structures is critical, especially in seismic regions. CFRP bars, when used as shear reinforcement, can significantly improve the shear capacity of concrete beams and columns, contributing to the structure's overall ductility and seismic resistance. (Rahal et al., 2011). performed an experimental analysis of four reinforced concrete beams through the application of shear strength using near-surface mounted (NSM) carbon fiber reinforced

polymer (CFRP) bars and conventional steel reinforcing bars. The study analyzed three essential variables which involved web element and flange section concrete anchorage as well as reinforcing bar alignment regarding beam axis positioning at vertical versus 45-degree orientations. The research analyzed the reinforcement effect of NSM bars which were either made from CFRP or standard steel materials. The shear test conducted on these beams helped researchers understand the impact of bar orientation and anchorage together with material type during casting. NSM bars functioned to resist shear after cracking based on the research findings. The shear capacity of beams improved by 37%–92% through strengthening while diagonal cracks minimized and enhanced flexural ductility became possible. Extended anchorage into the flange of bars which were positioned at 45° degrees enhanced the overall strengthening efficiency. Shear capacity measurements in CFRP-reinforced areas exceeded steel-reinforced areas by 7 to 10 percent while their measured behaviors matched.

(Kobraei, Jumaat and Shafigh, 2011) studied the impact of using CFRP bars as substitute shear reinforcement in RC beams compared to the standard stirrups. Seven RC beams formed part of their experimental research which split into two separate groups. Both groups of members included steel with CFRP longitudinal reinforcement having 12 mm diameters yet only one group incorporated 14 mm diameter steel bars. Group one contained the experimental control beam with normal stirrups while five more beams had straight combinations of steel bars and CFRP bars as shear reinforcement. All constructed beams received their concrete from high-strength, self-compacting concrete (HSC/SCC). The research investigated laboratory specimens to study multiple failure mechanisms through the evaluation of ultimate moment strength together with load-deflection data and first crack load readings as well as crack width measurements and neutral axis positions. Research indicated that shear reinforcement made from CFRP bars presented a functional substitute for traditional stirrups when used in reinforced concrete beams.

5. APPLICATION OF CFRP SHEETS IN CONCRETE STRUCTURES

5.1. Strengthening and Retrofitting

CFRP sheets are commonly used for strengthening and retrofitting existing concrete structures. These sheets can be externally bonded to concrete surfaces, providing additional tensile strength and improving the load-bearing capacity of the structure. (Esfahani, Kianoush and Tajari, 2007) carried out an experimental study to examine the flexural performance of reinforced concrete beams strengthened with carbon fiber-reinforced polymer (CFRP). This research investigated beam flexural strength modification through changes in reinforcement ratio. The researchers

prepared twelve concrete beam specimens that had 150 mm width and 200 mm height with a total length of 2000 mm. The reinforcements in the longitudinal direction of each beam had varying ratios between each other. CFRP sheets were applied to reinforce nine of these specimens in flexure. The predicted enhancement of flexural strength in beams with low values from CFRP sheets exceeds actual results as per both ACI 440.2R-02 design guidelines and ISIS Canada. The guidelines establish max as the maximum allowed value that exceeds the true influence of CFRP sheets. The elevation of beams leads to increased valuation. Test load ratios increased together with values derived through ACI 440 and ISIS Canada methodology. The published equations within both design methods yielded higher load calculations following the use of guidelines is better suited for beams that have high values. The failure was observed in the reinforced specimens that had a high ratio of reinforcing bars, which approached the maximum allowable value according to the code. However, these specimens exhibited sufficient ductility.

The experimental analysis of carbon fiber reinforced polymer (CFRP) as a rebar corrosion inhibitor was performed by (Tarigan et al., 2020) et al. The experimental research incorporated the production of 300 mm tall and 100 mm diameter concrete cylinders that received CFRP wrap. Anti-corrosive rubber covered the rebars in the procedure. The experimental cylinders were subjected to a combined solution of 0.5M HCl and 3% NaCl for sixty days to trigger corrosion. Research scientists monitored corrosion rates through successive measurements using Half-cell potential and Linear Polarization Resistance methods and Tafel plots. The tests showed robust resistance to corrosion among CFRP in different measurements.

(Shakir, Mo. Yahya and Jasim, 2021) performed experiments to test how well carbon fiber reinforced polymer (CFRP) sheets could improve the strength of T-deep beams made using self-compacting concrete when these beams included big web openings. Thirteen beams which included both untreated and reinforced specimens, were examined in the study. Square or rectangular cutouts were usually placed on the beams either flush with the flange or lower down at the web. It was found that the ability of concrete to carry weight was greatly reduced by openings as much as 70% decrease depending on the size and placement. Yet, reinforcing the structure with CFRP sheets raised its performance abilities. With square openings flush to the flange, the capacity rose by 19%. However, capacity rose by 64% for rectangular openings that were flush. The changes were larger yet in openings found at the bottom of the web which yielded 37% better results and 87% less air loss. Researchers found that strengthening with CFRP led to an increase in ultimate load, having stronger structures, shrinking crack widths and sometimes changing how the system failed. In most cases, full wrapping and CFRP strips at

angles gave the best result, especially when how the beams connected were interrupted by the openings.

(Hibtallah and K. Madlum, 2022) studied how Carbon Fiber Reinforced Polymer (CFRP) sheets and Glass Fiber Reinforced Polymer (GFRP) bars strengthening RC slabs affect their dynamic activity under impact loading. The experiment tested five full-scale RC slabs (1550×1550×150 mm), one without CFRP and the other four with different types and numbers of CFRP sheets (one or two layers, full or partial). The impacts used a 150 kg drop-mass released from a height of 5 meters. Using CFRP strengthening was seen to improve the impact performance of slabs by slowing cracking, lowering the maximum deflection, strain and energy absorbed. Composites with a pair of CFRP layers showed more rigidity and had less deflection. CFRP layers also increased the rate of response and added more support which proves the structure is better protected. The authors noted that GFRP bars and CFRP sheets together stop brittle damage and better protect RC slabs from impact which is a good option to use in areas with corrosive conditions.

5.2. Shear Strengthening

(Bukhari et al., 2010) performed an experimental analysis using seven rectangular two-span continuous concrete beams with dimensions 152 mm x 305 mm that received carbon fibre reinforced polymer (CFRP) sheet reinforcement. Seven two-span continuous concrete beams with 2.85 a/d ratio and 267 mm steel reinforcement effective depth were examined. The beams received three 16 mm steel bars at both the top and bottom section with a yield strength of 494 MPa. The beams demonstrated a failure load at flexure amounting to 500 kN. Only steel stirrup reinforcements were included in the outer shear spans at 130 mm spacing while central spans received no internal stirrups to enable evaluation of different CFRP configurations. The beam received complete carbon fiber reinforcement as researchers measured the influence of CFRP anchorage extent. This experiment employed CFG sheet which had a thickness of 0.34 mm and showed elastic modulus values at 234.5 GPa as well as ultimate tensile strength reaching 3450 MPa.

It was shown through experimental testing that beams receiving CFRP sheets achieved stronger shear strength and reached their optimal improvements by orienting the FRP at 45 degrees relative to the beam axis. The superposition method using the variable angle truss model determined shear strength in FRP-strengthened beams by adding concrete and steel stirrup and FRP resistance contributions to calculate the total value.

(Akroush et al., 2017) performed experimental research on continuous reinforced concrete (RC)

beams which received CFRP sheet strengthening. Eight two-span beams received U-wrap CFRP treatment at the intermediate support to assess the present bond reduction factor which might be conservative for regions subjected to normal and shear forces simultaneously. The analysis demonstrated that CFRP strengthened the shear capacity by 21% to 47% compared to unstrengthen beams through increasing the first shear crack load by 21% to 47%. The strongest strength enhancement under these conditions occurred when CFRP wrapping was applied throughout beam depth. The study determined that CFRP-strengthened beams developed a reserve strength after cracking which reached between 37% to 62% above their first shear cracking load but this strength reduction occurred when increasing the CFRP laminate amounts. The study proved the validity of ACI 440.2-08 bond reduction factors intended for high shear regions of simple beams across shear and normal stress combinations in continuous beams. Laboratory measurements of shear strength from CFRP laminate-strengthened beams showed differences of less than 6% compared to the calculated values.

(Abdulqader, Makki and Mousa, 2021) performed an experiment to study how SCC beams become stronger after being strengthened by carbon fiber reinforced polymer (CFRP) strips. A total of eleven simply supported SCC beams were tested and one of these was an unstrengthen reference beam. After that, the final ten beams were reinforced externally through using CFRP strips that were either vertical, in U-shape or fully wrapped around each beam. How to arrange CFRP, the amount of CFRP, the number of strips and using horizontal straps were all explored. Studies showed that using CFRP adds substantial resistance to shear forces and cracks in SCC beams. The added load for the CFRP beams could be anywhere between 15% and 74%, depending on the way CFRP was used. The greatest benefit came from applying complete CFRP wrapping which caused failure to occur by bending instead of shearing. Also, the use of horizontal CFRP straps lowered the chance of strip debonding and increased the structure's carrying capacity. It proves that using CFRP wrapping increases the shear resistance of SCC beams and that the way the wrapping is applied and the amount of CFRP affect the performance.

5.3. Confinement of Concrete Columns

The application of CFRP sheets works effectively to confine concrete columns thus enhancing their load capacity and ductility measures. The application shows specific merit in seismic retrofitting because it enhances confinement which prevents brittle failures.

(Wu and Wei, 2010) explored the axial properties of short rectangular concrete columns which received external strengthening through CFRP wraps in their experimental research. The specimens had a uniform height of 300 mm and a fixed corner radius of 30 mm, while the cross-sectional aspect ratio h/b (where h and b represent the longer and shorter sides, respectively)

varied among values of 1.0, 1.25, 1.5, 1.75, and 2.0. Additionally, the CFRP jacket thickness was varied across three levels: unconfined, one-ply, and two-ply. For each configuration, three identical specimens were prepared, resulting in a total of 45 specimens.

The results from uniaxial compression tests revealed a clear trend: the strength enhancement provided by CFRP confinement, expressed as the ratio f_{cc}/f_{co} , decreased with increasing aspect ratio and became negligible when the aspect ratio reached 2.0 as shown in Fig. 1. Experimental data proved inconsistent with existing confinement strength models because they failed to match actual column behavior. As a response the authors developed a renewed strength design model specifically for rectangular columns confined with FRP but included an aspect ratio dependent modification factor. The model establishes a single framework that works for circular as well as square and rectangular cross-sections while its parameters stem from testing data within an established experimental database.



Fig. 1. failure modes

(Fitzwilliam and Bisby, 2020) carried out extensive testing to determine how slenderness influenced CFRP-wrapped circular reinforced concrete (RC) columns under eccentric axial loading conditions. A total of eighteen small circular reinforced concrete columns were studied by the researchers who used columns with 152 mm diameter and four D5 deformed steel bars (6.4 mm diameter) as internal reinforcement with D5 closed circular steel ties at 100 mm centers. The columns featured structural designs that reflected deficient conditions especially regarding insufficient longitudinal reinforcement.

The research revealed that covering columns with CFRP increased their axial strength as well

as their capacity to deform effectively. The analysis confirmed that short columns received higher benefits from confinement than their slender column counterparts. Research investigators constructed axial-flexural interaction diagrams based on conventional sectional analysis while establishing an easy stress-strain model for FRP-confined concrete. The diagrams presented by these researchers delivered safety-based estimates for CFRP-wrapped columns that were not slender under eccentric loads.

The research identified that baseline CFRP wraps used along the column height play an essential role in reducing lateral bending movements of slender columns. The intervention provided an effective method for making slender columns match the strength levels of regular columns through increased lateral movement. The study demonstrates the advantages of longitudinal CFRP reinforcement that enhances slender RC columns by making their performance and behavior approach that of short CFRP-confined members subjected to eccentric axial loads.

6. CONCLUSION

It has been shown in this review that Carbon Fiber Reinforced Polymer (CFRP) bars and sheets provide many advantages when used to strengthen concrete structures. Thanks to their excellent abilities, high strength, low weight, good anti-rust performance, and non-magnetism they suit the highly demanding environments and are favored over regular steel wires.

All the experimental and analytical studies analyzed in this paper found that CFRP materials make concrete structures stronger in bending and shear, enhance their ductility, and guard against environmental deterioration. It has been proved through many studies that EB and NSM CFRP applications are effective in strengthening or repairing existing structures. Nevertheless, high starting costs, trouble getting bonds, and a lack of long-term proof of results prevent CFRP from being widely used. There are still major concerns about the environment and the capability of recycling CFRP materials. From the overall point of view, CFRP reinforcement can greatly benefit future infrastructure projects. Further investigations on materials, methods to control costs, and sustainable ways to make them should be carried out to use composite materials more widely in civil engineering.

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