Carbon Fiber Reinforced Polymer (CFRP) and Their Application

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Abstract:

Carbon Fiber Reinforced Polymer (CFRP) is a high-performance composite material known for its superior strength, lightweight properties, corrosion resistance, and exceptional fatigue resistance.

This report explores the key aspects of CFRP, including its structural characteristics, manufacturing processes, quality control measures, testing standards, and important design considerations. Due to its impressive durability, CFRP is widely applied in industries such as aerospace, wind energy, and automotive. The increasing adoption of CFRP composites is largely driven by their ability to replace conventional materials, offering outstanding strength and low weight, making them highly desirable for engineering applications.

CFRP is used as a structural material across various sectors, with the machining forces required for processing CFRP being lower than those for traditional materials. However, further testing of machining flexibility is necessary to optimize processing time and reduce costs. Existing studies on both conventional and unconventional machining techniques highlight the significant impact of process parameters and cutting forces on the surface quality of CFRP composites.

The material's strength is influenced by several factors, including the fiber-resin ratio, fiber length and orientation, as well as the form (sheet or plate) and the use of anchors. This research emphasizes the wide range of practical applications for CFRP and illustrates its innovative role in enhancing structural design.

Keywords: Carbon Fiber Reinforced Polymer (CFRP)

Goal:

This research aims to explore recent advancements in the use of Carbon Fiber-Reinforced Polymer (CFRP) for reinforcing various types of structures, as well as the modifications made to CFRP composites to further enhance the strength of reinforced elements. CFRPs are widely employed in industries such as automotive, aerospace, and military, owing to their exceptional mechanical properties, including light weight, superior fracture resistance, corrosion resistance, and wear resistance.

The paper presents a literature review on the application of CFRP strips for reinforcing reinforced concrete (RC), steel and wood structures, evaluating their effectiveness as a strengthening solution. While much research has concentrated on the use of Fiber-Reinforced Polymer (FRP) composites for reinforcing rectangular beams, there is an increasing focus on their potential for flexural and shear strengthening of RC members.

Introduction:

Fiber Reinforced Polymer (FRP) is a composite material composed of reinforcing fibers combined with a polymer matrix. Among the various FRP types, Carbon Fiber Reinforced Polymer (CFRP) stands out as a high-performance composite widely recognized for its versatility and adaptability across diverse engineering applications. This is attributed to its exceptional mechanical and physical properties, including high specific strength, high specific stiffness, outstanding thermal stability, and superior corrosion resistance [1-4].

CFRP is particularly valued for its low density, high specific strength, high specific modulus, and the design flexibility it offers [5-7]. However, a key challenge in its application is its susceptibility to sudden failure, particularly under shear stress. This has prompted extensive research aimed at developing effective strengthening techniques to address shear deficiencies in reinforced concrete (RC) beams—whether due to insufficient reinforcement, higher load demands, or when the shear capacity of a beam is lower than its flexural capacity, often following flexural strengthening.

One promising solution to these challenges is the use of composite materials for strengthening and retrofitting concrete elements. Externally bonded (EB) CFRP, in particular, has emerged as one of the most widely used and established techniques for improving the performance of concrete structures [8-14].

While Fiber Reinforced Polymers (FRPs), and CFRP in particular, have seen increased use in steel structures, they have traditionally been applied to the rehabilitation and strengthening of concrete elements. CFRP is composed of carbon fibers, which provide strength, stiffness, and load-bearing capacity, embedded within a polymer matrix [15]. As the name suggests, CFRP consists of carbon fibers embedded in a polymer resin [16], where the fibers serve as reinforcement and the resin functions as the matrix to bind them together.

CFRP is being increasingly utilized across a diverse array of industries, with its range of applications continually growing. It is now commonly found in sectors such as aerospace, automotive, sporting goods, marine, naval, space, machine tools, transportation infrastructure, as well as in the post-strengthening of concrete beams and the reinforcement of shear walls in seismically active regions [17-21].

CFRP is characterized by a broad range of mechanical properties, including static, dynamic, thermal, and chemical traits. Notable for its high strength-to-weight ratio, excellent damping ability, low thermal expansion, and resistance to corrosion and wear, CFRP is a versatile material. However, it cannot be directly used for specific applications without some form of modification. When combined with conventional metallic materials, CFRP requires machining processes such as drilling, milling, slotting, and finishing of keyholes and corners, as well as trimming edges and removing burrs [22].

The main goal of CFRP is to produce a lightweight material with exceptional mechanical properties that are unattainable by the individual components alone. These enhanced properties are largely influenced by the morphological structure and the interactions at the interface between the reinforcing fibers and the matrix, including hydrogen bonding and van der Waals forces [23, 24].

Literature Review:

The mechanical properties of CFRP composites are influenced by several factors, including the fiber content and the type of matrix used. As a result, the mechanical properties of CFRP can vary between manufacturers. However, certain characteristics, such as Young's modulus and tensile strength, are typically several times higher than those of conventional steel.

CFRP exhibits directional strength, meaning its strength depends on the alignment of the carbon fibers and the ratio of fibers to polymer matrix. This unique property makes CFRP an ideal material for reinforcing existing structures, and it is often considered by engineers during the design phase of construction projects.

Carbon fiber, a high-performance material, is composed of long filaments that typically range from 5 to 8 μm in diameter. The manufacturing process involves pyrolysis and crystallization of a precursor material at temperatures exceeding 2000°C. During this process, carbon atoms align along the fiber and are woven into fabric. Polyacrylonitrile (PAN), pitch, and rayon are common precursors used in carbon fiber production. Of these, PAN is the most widely used in commercial production, yielding approximately 50% of the original fiber mass. Rayon, while an alternative precursor, has a lower initial yield (around 25%) and results in less uniform fibers. When compared to aramid and glass fibers, carbon fiber reinforced polymer (CFRP) is known for its longer lifespan and superior performance [25].

CFRP is a heterogeneous composite, made by combining two or more materials that retain their individual properties. It exhibits anisotropic behavior, meaning its properties vary depending on the direction of the fibers. Typically, CFRP consists of carbon fibers that provide strength and stiffness, while the polymer matrix adds rigidity and environmental protection to the composite [25].

Most restoration efforts are focused on rehabilitating structures damaged by seismic activity or natural disasters. Additionally, concrete structures often require strengthening due to degradation resulting from poor design practices or substandard construction quality.

Rehabilitation of existing structural elements is typically more cost-effective, requiring less time and effort compared to traditional construction methods. As a result, it proves to be more economical than other standard rehabilitation approaches in the long term.

Composite materials were first employed to reinforce reinforced concrete (RC) bridges, as well as to strengthen RC columns and brick walls during seismic events [26]. Externally bonded CFRP plates have demonstrated significant effectiveness in strengthening RC beams. However, in some instances, delamination between FRP layers has been observed [27].

To improve stiffness and strength, FRP plates are often applied to components in tension, oriented perpendicular to cracks [28, 29]. Glass Fiber Reinforced Polymer (GFRP) can offer up to a 40% increase in strength for RC beams, while Carbon Fiber Reinforced Polymer Composite (CFRPC) can result in a strength improvement of approximately 200% [30].

The research in [31] investigates the effects of elevated temperatures on the performance of CFRP strips used to reinforce reinforced concrete beams. It was found that high temperatures can cause the adhesive bond between the concrete and CFRP tape to become brittle, resulting in a significant decrease in the load-bearing capacity of the structure. The failure was attributed to delamination within the adhesive layer.

In [32], a novel approach was introduced where the epoxy resin composition was modified by adding different percentages of nanofillers. The results showed an improvement in bending and tensile strength with 2.5% nanofiller content. However, as the nanofiller content increased beyond this point, the strength properties began to decline. Moreover, steel beams reinforced with CFRP tapes are especially vulnerable to the creep effect of the CFRP sheets.

Zhang et al. [33] introduced an elastic method to address the creep effect of CFRP sheets and the influence of temperature on steel beams. They provided computational formulas to model the interface slip between the CFRP sheet and steel beam, as well as the stresses in the CFRP sheet and the deformations in the steel beam resulting from the combined effects of temperature and CFRP creep. The study found that stresses in the steel beam reinforced with CFRP sheets were lowest at the beam's ends and highest at the center of the span.

Banon et al. [34] examined the processing methods for composite materials made by combining CFRP with steel, noting the challenges posed by the differing machinability of these materials. To measure residual stresses in steel–CFRP components, they used the borehole method, applying a formalism to evaluate residual stresses in orthotropic materials, with calibration factors determined through finite element analysis.

Wang et al. [35] carried out orthogonal milling tests on CFRP unidirectional laminate disks to study the impact of varying fiber orientation angles on cutting properties. Their experimental results showed that surface defects were the primary form of damage to the machined surface, leading to increased surface roughness. Based on these findings, they proposed a new milling strategy that accounts for fiber orientation to minimize the formation of surface cavities.

Sui and Wang [36] conducted slot milling on unidirectional CFRP laminates at four different fiber orientations to investigate the machinability of CFRP composites in relation to process parameters and fiber orientation. Their results revealed that both the fiber orientation and chip thickness had significant effects on cutting forces.

Wang et al. [37] improved the micro-connection method and developed an effective research device for measuring the interfacial shear strength between carbon fibers and epoxy resin. This method was found to be highly efficient and reliable, with displacement-load curves confirming its accuracy. During use, CFRP composites experience external loading, leading to interfacial creep between the fibers and matrix, which ultimately results in interfacial slip.

Shioya et al. [38] established a relationship between the ultimate tensile strength of unidirectional carbon fiber/resin composite strands and the interfacial shear strength at the fiber/matrix interface. They discovered that the tensile strength of the composite strands does not increase consistently with the interfacial shear strength. Instead, it reaches its maximum at a particular level of interfacial shear strength.

In [39], the behavior of thin-walled beams reinforced with carbon fibers (CFRP) was investigated. A comparative experimental study was conducted on the connection between steel members and CFRP, considering various surface preparation techniques. The performance of CFRP-reinforced beams was then analyzed under critical loading conditions, both with and without the CFRP reinforcement. The findings demonstrated that the load-bearing capacity of the beams improved with CFRP reinforcement.

The study in [40] examined the dynamic crushing characteristics of unidirectional CFRP composites under two types of loading: dynamic three-point bending and axial crushing. Experimental and numerical simulation results showed that delamination significantly influences dynamic deformation during bending.

In [41], both experimental and numerical analyses were presented on the static behavior of steel beams reinforced with CFRP tapes. Various geometries of CFRP reinforcement were applied to traditional I-beams, which were then subjected to three-point bending tests.

Al-Emrani et al. [42] carried out experimental research on the behavior of composite steel–CFRP elements and performed Finite Element Analyses. By testing various combinations of CFRP and adhesive, they observed different cracking modes. The composite elements exhibited distinct behaviors, with noticeable differences in yield and ultimate strengths.

Szewczak et al. [43] conducted four-point bending tests on thin-walled sigma beams reinforced with adhesive CFRP tapes. The goal of the study was to examine the effect of adhesive layer thickness on deformations and displacements in the beams. The results indicated that the load value at which damage occurred in the adhesive joint decreased as the adhesive layer thickness increased.

Colombi and Fava [44] investigated the fatigue behavior of steel/CFRP joints subjected to tensile forces. The joints, which consisted of two steel plates and two CFRP tapes bonded with epoxy adhesive, exhibited detachments at stress concentration points that propagated along the CFRP/adhesive interface. Their findings also indicated that the fatigue limit was largely unaffected by variations in the strength factor.

Li et al. [45] examined the bonding behavior between CFRP and steel, evaluating various types of epoxy adhesives and their impact on failure modes, bond-slip relationships, and bond strength. The results showed that the failure modes varied depending on the adhesive and material combination used. Some specimens failed due to interface disconnection, exhibiting brittle failure, while others experienced cohesive failure or CFRP delamination, which was marked by plastic failure.

In [46], a study was conducted to analyze the effect of test methods and epoxy adhesives on CFRP-steel joint behavior using both double and single shear bonded joints. The study focused on parameters such as joint type, adhesive type, and adhesive thickness. The results revealed that the type of joint influenced the ultimate load, interfacial shear stress, and CFRP strain but did not affect the bond-slip relationship or failure mode.

Lepretre et al. [47] performed experimental studies to assess the effectiveness of CFRP composites in prolonging the fatigue life of aged, cracked metal structures. The specimens, which had a single crack originating from a rivet hole, were tested. The results demonstrated that applying CFRP plates effectively slowed crack propagation and significantly extended the fatigue life of the structures.

CFRP composites are extensively utilized for the strengthening, rehabilitation, and repair of reinforced concrete elements [48]. Their application has been proven to significantly improve the bending and shear strength of damaged construction components.

In another study [49], the focus was on the diagnosis and rapid repair of long-serving metallic materials. The research explored the use of CFRP composites for structural retrofitting and rehabilitation, an area with considerable research. The study also emphasized the need to consider the potential degradation of CFRP-retrofitted structures due to external influences. Composite patching was found to be an effective method for reinforcing and repairing cracked composite structures.

In a study by Soutis et al. [50], the effectiveness of bonded external patches for repairing compression-loaded CFRP laminates was assessed. The research explored different repair methods for composite structures, including mechanical fixation, adhesive bonding, external patching, and flush patching. The study highlighted the importance of surface preparation quality and composite patch design in achieving a strong and durable bond. It was concluded that micro-buckling of carbon fibers was the primary failure mechanism.

Cheng et al. [51] investigated the tensile behavior of composite structures repaired with externally bonded patches. Several patch configurations were tested, including variations in placement order and patch positioning on both sides of the original structure. The study analyzed the damage progression and failure modes of the repaired slabs and proposed a crack model for the original structure. Results indicated that high stress concentrations at the longitudinal edges of circular patches and at the transverse edges of holes led to early damage initiation. The initiation of damage was also affected by various external factors.

Nguyen et al. [52] studied the behavior of reinforced concrete beams connected to CFRP plates, which formed part of the structure's flooring system. The research focused on the effects of plate length, rebar ratio, and concrete cover thickness on beam performance, with a particular emphasis on brittle concrete cracking. The most frequent failure mode observed in reinforced concrete structures with CFRP reinforcement was the delamination of the composite material.

Wan et al. [53] examined the influence of water presence during and after CFRP application on the bond between concrete and CFRP. Three different levels of water or humidity were tested, and the results were compared to specimens tested under dry conditions. The study found that the presence of water during CFRP application significantly weakened the bond quality.

Nawaz et al. [54] explored the use of structural lightweight concrete reinforced with CFRP composites, focusing on the bending strength of the reinforced beams. The research demonstrated that the bending strength of the reinforced beams was notably higher than that of the control beams.

In study [55], experimental investigations were conducted on the bending behavior of beams reinforced with CFRP composites in the tensile zone. Key parameters such as maximum load, deflection, failure mode, stiffness, and stress distribution were analyzed. The findings indicated that the proposed reinforcement method effectively improved the strength, stiffness, and overall safety of the structure.

In [56], the application of CFRP composites to reinforce wooden ceiling structures under bending loads was examined. The study highlighted the promising potential of this reinforcement technique, especially for the restoration and enhancement of historic wooden construction elements.

Conclusion:

This paper provides a thorough literature review on the use of Carbon Fiber Reinforced Polymer (CFRP) as a structural reinforcement material. It discusses the properties of CFRP, its application in retrofitting and rehabilitation of structures, and its integration with various materials such as steel, concrete, and wood. The paper also presents examples of practical CFRP applications.

The strength of existing concrete structures is influenced by several factors, including the design, dimensions, and condition of the materials. CFRP, a lightweight yet strong material composed of carbon fibers embedded in a resin matrix, stands out for its exceptional tensile strength, durability, and superior strength-to-weight ratio. These qualities make it an efficient and reliable choice for construction. The growing adoption of CFRP in the construction industry is propelled by its manufacturing advantages and versatile applications.

In addition to the basic manufacturing processes, further development of production techniques and anchoring systems is essential for the widespread use and commercial success of high-strength CFRP. For CFRP to be effectively applied in structural reinforcement and rehabilitation, it is crucial to understand its application methods, failure mechanisms, and to establish clear design standards and guidelines. Moreover, research is needed to assess CFRP's performance under various load conditions.

CFRP has already found significant applications in fields such as bridge construction, aerospace, automotive manufacturing, and sporting goods. As the production, development, and improvement of CFRP continue to evolve, it is expected to play an increasingly important role in the advancement of modern construction technologies.

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