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A COMPREHENSIVE REVIEW OF THE STRUCTURAL BEHAVIOUR AND PERFORMANCE OF REINFORCED CONCRETE BEAMS STRENGTHENED WITH CARBON FIBER REINFORCED POLYMER (CFRP)

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Abstract

RC beams are frequently used in structure construction, but they can be influenced by several factors like aging, environment, corrosion, excessive load bearing capacity and ineffective design which lead to poor structural behavior. It is necessary to enhance and repair such beams. CFRP is one of the possible methods to increase performance of RC structures because of its high tensile strength, lightweight, corrosion resistance and simplicity in application. The aim of this literature review is the study of structural performance of reinforced concrete (RC) beams repaired using CFRP technique. There are several ways of repairing that include the usage of CFRP sheets and plates, near surface mounted reinforcement and CFRP wrapping. Special attention is paid to flexural and shear capacity, load carrying capacity, deflection, cracking, ductility and failure modes. The influence of CFRP configuration, bond strength, anchorage conditions, concrete properties and environment on CFRP efficiency studied. Also, the pros and cons of different CFRP reinforcing techniques considered.

Keywords: Reinforced Concrete Beams, Carbon Fiber Reinforced Polymer, Structural Strengthening, Flexural Behaviour, Shear Resistance, Structural Rehabilitation.

1. INTRODUCTION

There are many reasons why RC is widely used as a building material; however, the most important one is that it provides high strength, durability, versatility, and cost-effectiveness. This is because RC combines concrete characteristics in compression and steel characteristics in tension making it the perfect material for beams, columns, slabs, and other building elements [1]. However, RC structures can deteriorate due to environmental influences, corrosion of reinforcement, loading beyond its limit, poor construction techniques, and inadequate maintenance. These factors will lead to cracking, loss of stiffness, loss of load-carrying capacity, and hence poor performance of the structure [2].

1.1. Need for Strengthening and Rehabilitation of Reinforced Concrete Beams

The beams which are composed of RC have the tendency of carrying both bending and shear loads. At times because of the change of use, increment in loading demand, mistake during design, aging process and deterioration, the load carrying capacity of the beams will reduce compared to what they used to be before [3]. Conventional methods of strengthening such as the use of steel plate and jacket have the challenges of self-weight, problem of corrosion and complicated installation processes among others. Strengthening using CFRP can offer a way out to these challenges.

1.2. Introduction to Carbon Fiber Reinforced Polymer

CFRP composite is an engineering material composed of carbon fibers reinforced in a polymer matrix usually of epoxy resin [4]. The carbon fiber ensures strength and stiffness, whereas the polymer matrix shields the fiber from any damage and helps transfer the load between the fibers. CFRP materials come in various types such as sheets, strips, plates, fabrics and bars. Because of their low weight, strength to weight ratio, corrosion resistance and flexibility, CFRP is a good material for reinforcement of RC structures. Depending upon structural needs, the CFRP can be applied externally or inside grooves.

1.3. Objectives of the Review

The present review aims to:

1. Examine the properties and different strengthening techniques of CFRP used in reinforced concrete beams.

2. Evaluate the structural behaviour of CFRP-strengthened beams under flexural and shear loading.
3. Analyse the influence of bonding, anchorage, CFRP configuration and environmental conditions on strengthening performance.
4. Compare the effectiveness and limitations of different CFRP strengthening techniques.

Table 1: Summary of Previous Research on CFRP Strengthening and Structural Behaviour of RC Beams

Author, Year	Topic Covered	Title of the Study
Vijayan et al. (2023) [5]	The study analyzed the properties and characteristics of the CFRP materials and their uses in civil engineering. The discussion included the strengths, lightness, and corrosion resistance of the materials.	*Carbon fibre-reinforced polymer (CFRP) composites in civil engineering application—a comprehensive review*
Jahami and Issa (2024) [6]	This review was focused on the effect of CFRP strengthening on the flexural behavior of RC beams. It included different configurations of strengthening, flexural capacity, bonding and its failure modes.	*An updated review on the effect of CFRP on flexural performance of RC beams*
Bahij et al. (2022) [7]	This study has critically evaluated various types and methods of FRP strengthening in RC beams. The application of these strengthening techniques has been explained especially when the beams are subjected to flexure and shear.	*Strengthening reinforced concrete beams by using different types and methods of fiber-reinforced polymers: A critical review*
Solahuddin and Yahaya (2023) [8]	A review was made of the experimental research and Finite Element Analysis done on the structural behavior of FRP-RC beams. It included structural response, deformability behavior, and the influence of numerical simulation on performance.	*A state-of-the-art review on experimental investigation and finite element analysis on structural behaviour of fibre reinforced polymer reinforced concrete beams*
Hegde et al. (2019) [9]	A review was conducted of the CFRP material, its mechanical properties and some of the key properties that include tensile strength, stiffness, lightweight and strength to weight ratio.	*Review on carbon fiber reinforced polymer (CFRP) and their mechanical performance*

2. CFRP STRENGTHENING TECHNIQUES AND THEIR APPLICATION IN RC BEAMS

The use of CFRP for reinforcement helps to increase the load bearing capacity of RC beams. The following section highlights the various ways of application of this method of reinforcement.

2.1. Properties and Characteristics of CFRP Materials

The below-mentioned are the features that make CFRP appropriate for structural reinforcement applications. First of all, CFRP is characterized by great tensile strength and it is able to endure great tensile stresses [10]. In addition, it is very light and hence it imposes no additional dead weight on the structures. It does not corrode electrochemically.

Table 2: General Properties of CFRP and Conventional Steel Reinforcement

Properties	CFRP	Steel
Tensile strength	Very high	High
Density	Low	High
Corrosion resistance	Excellent	Susceptible

Weight	Lightweight	Relatively heavy
Elastic behaviour	Generally linear elastic	Elastic-plastic
Installation	Relatively easy	Often requires heavier installation
Directional properties	Anisotropic	Generally isotropic

2.2. Different CFRP Strengthening Techniques

CFRP Strengthening of beams can be carried out in various ways according to the need of the structure and the requirement of the beams.

- **Externally Bonded (EB) CFRP Sheets and Plates**: The EB reinforcement process involves sticking of the CFRP sheets or plates onto the external surface of the RC beams using epoxy glue [11]. Whether the CFRP sheets would be applied to the external surface of the beam would depend on the type of reinforcement, that is, either flexural or shear reinforcement. Generally, the sheets are applied on the tensile side of the beam.
- **Near-Surface Mounted (NSM) CFRP Reinforcement**: NSM strengthening is achieved through installation of the CFRP strips or bars within the grooves made on the concrete cover [12]. This process uses epoxy adhesive to fill the grooves. The main advantage of NSM strengthening is increased durability of the CFRP reinforcing bars, as well as improved stress transfer between the CFRP strips/bars and concrete. This strengthening method is effective in increasing flexural and shear strength of RC beams [13].
- **CFRP Wrapping and U-Wrapping Techniques**: The CFRP wrap technique involves covering the beam with fiber sheets or parts of the beam. Confinement occurs if the full wrap technique is applied while the U-wrap technique is typically applied to increase resistance against shear failure [14].



Figure 1: Different CFRP Strengthening Configurations in RC Beams

2.3. Surface Preparation, Bonding Mechanisms and Installation Procedures

Surface preparation plays a vital role in ensuring the bonding between CFRP and concrete is effective [15]. This is achieved through the cleaning process, which ensures that dust and other contaminants on the concrete surface are eliminated. Various techniques of surface preparation including grinding may be used in creating the bonding surface. In addition, the epoxy resin adhesive application is carried out at the surface before the application of the CFRP material. The bonding process ensures that stresses are transferred from the concrete beam to the CFRP reinforcement.

2.4. Applications of CFRP in Flexural and Shear Strengthening

The application of the CFRP reinforcing technique can be seen in cases where there is a need for improving the flexural and shear characteristics of RC beams [16]. In the case of flexural reinforcing of RC beams using CFRP, the plates/sheets of CFRP are generally attached to the tension side of the beams, and they have the ability of increasing the tensile strength and thus the loading capacity of the beams. In shear reinforcing of the beams, the plates of CFRP are generally attached to the sides of the beams in U-shape [17].

Table 3: CFRP Strengthening Techniques and Their Structural Applications

Strengthening technique	Typical application	Major benefit	Common limitation
EB sheets	Flexural and shear strengthening	Easy installation	Debonding risk
CFRP plates	Flexural strengthening	High tensile resistance	Anchorage requirements
NSM CFRP strips/bars	Flexural and shear strengthening	Improved protection and bond	Groove preparation required
Full wrapping	Confinement and shear strengthening	Improved confinement	Difficult access
U-wrapping	Shear strengthening	Better resistance to diagonal cracking	Possible end debonding

3. STRUCTURAL BEHAVIOUR AND PERFORMANCE OF CFRP-STRENGTHENED RC BEAMS

This chapter discuss the analysis of RC beams which have been strengthened using CFRPs. The chapter shall be focused mainly on analyzing the important performance characteristics such as flexural strength, shear strength, load carrying capacity, deflections, stiffness, crack behavior, and failure modes [18].

3.1. Flexural Behaviour and Load-Carrying Capacity

Enhancement of flexural strength of concrete beams is among the most frequently employed applications of this material. The strips of the CFRP material are generally applied on the tension side of beams for improving the bending strength of these beams [19]. Previous researches have indicated that there is a significant increase in the capacity to carry load and also in the bending strength due to application of this material. However, such improvement depends upon proper bonding.

3.2. Shear Behaviour and Shear Resistance

Another significant aspect where CFRP has been widely used is that of increasing the shear strength of RC beams. Vertical, diagonal, or even 'U' shaped positioning of CFRP strips/sheets will increase the shear strength of the beam sections which do not have adequate lateral or shearing strength [20]. This helps in resisting the tensile force along the diagonal section and avoid shearing cracking. The parameters affecting the effectiveness of the technique include fiber orientation, anchorage condition, concrete compressive strength, and method of CFRP reinforcing. NSM strengthening technique has proven to be effective in increasing the shearing strength of RC beams.

3.3. Deflection Behaviour and Stiffness Characteristics

Stiffness and deflection are two critical parameters when evaluating the serviceability characteristics of RC beams. In such a case, CFRP retrofitting can enhance the stiffness of a beam because of the added tensile capacity that would decrease the deformations under loading. CFRP EB and NSM technique could be useful for enhancing load-deformation performance, although its effectiveness would depend on the level of reinforcement, bond configuration, and condition of the beam [21]. Nevertheless, CFRP would assist in limiting deflections, although debonding might affect it.

3.4. Crack Development, Crack Width and Failure Mechanisms

The formation of cracks is another critical aspect that is taken into account when assessing the performance of strengthened beams. The use of CFRP reinforcement helps to disperse the tensile forces and could result in decreased widths of cracks in the presence of service loads. Different failure types may be observed based on various strengthening methods and types of bonding [22]. Typical types of failures are CFRP fracture, concrete crush, debonding due to the formation of intermediate cracks, and end debonding with concrete cover separation.

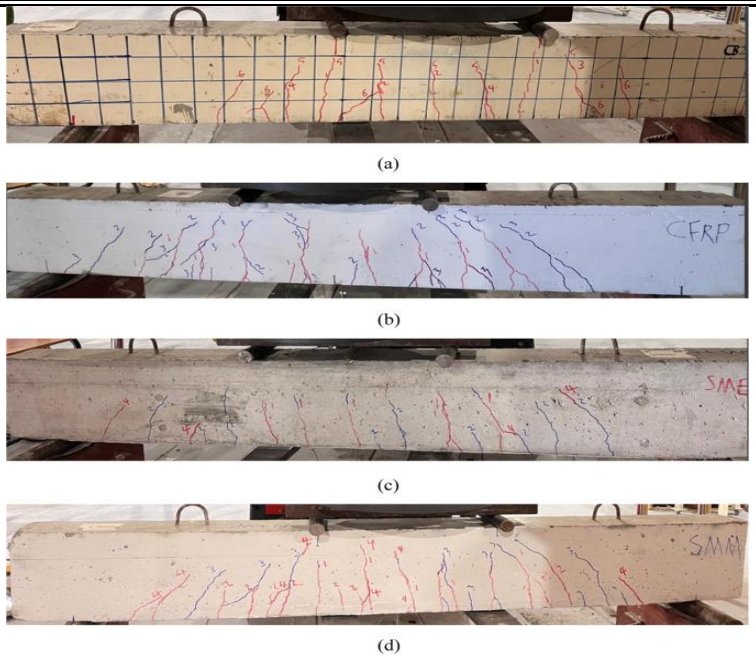


Figure 2: Crack Patterns Observed in Different Reinforced Concrete Beam Specimens

3.5. Ductility, Energy Absorption and Structural Deformation

Ductility is a property that shows how easily a structure can deform without failing, while energy absorption refers to the amount of energy that can be absorbed by a structure under loading. The application of CFRP in structural strengthening increases load capacity and stiffness, but it may not necessarily result in increased ductility because of the linear elastic nature of CFRP up to rupture [23].

Table 4: Structural Performance of CFRP-Strengthened Reinforced Concrete Beams

Performance parameter	Effect of CFRP strengthening	Major consideration
Flexural strength	Improves bending resistance	CFRP quantity and bonding
Shear strength	Improves resistance to diagonal cracking	Fibre orientation and anchorage
Load-carrying capacity	Generally increases ultimate load	Strengthening configuration
Stiffness	Can improve structural rigidity	Bond quality
Crack behaviour	Helps control crack development	CFRP distribution
Ductility	May improve or decrease depending on the system	Failure mechanism
Energy absorption	Depends on deformation and failure behaviour	CFRP arrangement

4. FACTORS INFLUENCING THE PERFORMANCE AND EFFECTIVENESS OF CFRP STRENGTHENING

The factors which influence the performance of RC beams strengthened by CFRP are discussed in this part [24]. The variables considered include the configuration, thickness, fibre orientation, adhesive bonding capacity, anchorage system, condition of concrete and environmental effects among others.

4.1. Influence of CFRP Configuration, Thickness and Fibre Orientation

The structural behavior of RC beams strengthened with CFRPs depends on the number of layers of CFRPs used, thickness of the material, fibre orientation, and method of strengthening. The addition of more layers of CFRPs will lead to the increase in load carrying capacity and stiffness of the beams [25]. In the same way, the fiber orientation also has an impact on the efficiency of the strengthening process. Fibers running in the longitudinal direction are normally used for strengthening the beams through flexural capacity, while the vertical or inclined fibers are used for shear capacity.

4.2. Effect of Bond Strength, Anchorage and Debonding

Bond strength is one of the most crucial parameters influencing the effectiveness of the reinforced beam. Adequate bond strength ensures adequate stress transmission from the concrete substrate to the CFRP. Failure in proper bonding due to inadequate application of the adhesive, surface preparation and anchorage will lead to early debonding. Debonding at the end of the strip and debonding caused by cracks are some of the common types of debonding of EB CFRP strips.

4.3. Influence of Concrete Strength and Existing Beam Conditions

The initial state of concrete and its compressive strength have considerable impact on the efficiency of CFRP strengthening technique. It is important that there must be a strong and good concrete substrate in order to provide for an effective bond between concrete and CFRP sheets [26].

4.4. Environmental Effects, Durability and Long-Term Performance

Environmental factors can also play a role in the longevity and future efficiency of reinforced RC beams through the use of CFRP materials. Moisture, temperature changes, UV light, chemical exposure, and fire environment can have an effect on the polymer matrix and adhesive properties [27]. Even though carbon fibers have high corrosion-resistant properties, the matrix and adhesive layer might deteriorate when subjected to unfavorable environments [28].

4.5. Comparison of Different CFRP Strengthening Techniques

Various methods of strengthening using CFRP provide different amounts of strengthening according to the way that they are installed and their applications [29]. Methods such as EB systems are easier to install, while NSM systems would provide more protection for the CFRP reinforcement and would minimize any possible debonding. Wrapping systems would be appropriate in cases of shear strengthening and confinement [30]. However, their applicability is based on the accessibility of the structure.

Table 5: Comparative Assessment of CFRP Strengthening Techniques

Criteria	EB	NSM	CFRP Wrapping
Installation	Surface bonding	Groove installation	Surface wrapping
Flexural strengthening	High suitability	High suitability	Limited to selected configurations
Shear strengthening	High suitability	High suitability	High suitability
Bond protection	Relatively low	Relatively high	Depends on arrangement
Debonding risk	Comparatively high	Generally lower	Depends on anchorage
Surface preparation	Essential	Groove preparation required	Essential
Main application	Flexural and shear strengthening	Flexural and shear strengthening	Shear strengthening and confinement

5. CONCLUSION

Reinforcement of RC beams by means of CFRP technology is one of the ways to improve the strength of structural members. Such features as high tensile strength, low density, resistance to corrosion and easy installation process

allow considering it as an efficient alternative to other types of reinforcement technologies. As it can be seen from the reviewed literature, the use of CFRP contributes to the improvement of such characteristics as flexural and shear strength, load-carrying capacity, stiffness and crack control. The type of the CFRP application depends on the condition of the RC beam and the needs of its strengthening. However, there are several factors that affect the effectiveness of CFRP technology, including the direction of fibers, thickness of the reinforcement, adhesive strength, anchorage system, concrete quality and environment. Debonding in early period of use, delamination of concrete coverings, poor ductility and deterioration of adhesives are among them. Therefore, a proper choice of materials and correct installation procedure should be used in order to achieve positive results. Further studies should be dedicated to the development of anchorage and bonding systems, the long-term behavior of reinforced RC beams and design methodology.

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