SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I7P105

Volume 13 Issue 7, 64-80, July 2026

Review Article

Enhancing Shear, Flexural, and Torsional Performance of RC Beams Through Advanced Mesh Wrapping Techniques: A State-of-the-Art Review

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Received: 01 April 2026 | Revised: 04 June 2026 | Accepted: 19 June 2026 | Published: 29 July 2026

Abstract - *Many RC structures are deteriorating due to aging, increased service loads, environmental deterioration, corrosion of the reinforcement, and design deficiencies. Therefore, strengthening and retrofitting techniques are essential to improve the performance of RC structures. A promising method for strengthening RC structures is by using fiber-reinforced polymer composites because of their specific strength, rust resistivity and ease of application in construction. Currently, mesh-based reinforcement systems have emerged as an acceptable alternative to conventional FRP sheets based on improved bonding characteristics, improved crack-resistant performance and improved stress redistribution. A systematic review was performed to investigate mesh-induced strengthening techniques for the RC beams under combined shear, flexural and torsional loading conditions. A total of 52 studies published between the years 2000 to 2026 were included for analysis from a variety of databases. The studies were categorized based on the strengthening materials used, wrapping configurations, loading conditions, and performance indicators such as load-carrying capacity, ductility, torsional capacity, crack prevention and energy absorption. The conclusion of the review indicates that while GFRP systems show greater ductility and are usually less costly, CFRP systems typically result in the largest increases in loading capacity. Hybrid FPR systems utilising carbon and glass fibers produced a balanced performance by increasing both loading and deformation capacity. The performance characteristics for strengthening have a direct bearing on how the RC beam behaves. Overall, the inclusion of mesh in the construction improved strengthening techniques and shows strong potential for enhancing the efficiency and durability of RC beams under complex loading conditions.*

Keywords *- FRP, RC beams, Mesh wrapping techniques, Load carrying capacity, Hybrid composites, Torsional strength.*

1. Introduction

Reinforced Concrete (RC) beams are structural elements in the building, they transfer loads from slabs, walls and other structural components to supporting members such as columns and foundations who finally transfer the load into the ground. The structural performance of the RC beams therefore plays a crucial role in ensuring the safety, stability and long-term durability of engineering structures. In today's world, RC structures are experiencing significant deterioration factors like aging, increased service loads on the building, environmental exposure, corrosion, construction defects and design deficiencies. These urbanization and growing infrastructure demands have further intensified these challenges, resulting in many existing structures no longer meeting modern design and safety requirements. Consequently, strengthening and retrofitting of RC beams have become essential strategies for extending the service life of aging structures while maintaining structural reliability. Traditionally, several strengthening techniques are used to improve the structural capacity of deteriorated RC beams. Conventional methods such as steel plate bonding, RC jacketing and steel jacketing are widely applied in rehabilitation projects. Steel plate bonding enhances flexural capacity by joining steel plates to the tension zone of the beam, while jacketing methods increase confinement and stiffness of structural members. Despite having these techniques and efficiency, they have several limitations. The addition of steel or concrete increases the dead load of the structure, which may introduce additional stress on existing structural elements and foundations. Furthermore, steel components are highly susceptible to corrosion in aggressive environments, which reduces durability and increases maintenance requirements. In addition, installation of these strengthening systems is often labor-intensive and time-consuming, causing considerable disruption during rehabilitation works.

Fibre-Reinforced Polymer (FRP) composites are currently being used as an effective substitute material to reinforce RC structures. FRP composites consist of fibers with good strength embedded within a polymer matrix and provide various advantages, such as high tensile strength, corrosion resistance, lightweight characteristics and a superior strength-to-weight ratio. Due to these properties, FRP materials can significantly improve the flexural, shear, and torsional capacities of RC beams without substantially increasing structural weight. Previous studies have demonstrated that externally bonded FRP systems can considerably enhance load-carrying capacity, ductility, crack control and overall structural performance of strengthened beams. [1-4]

Carbon Fiber Reinforced Polymer (CFRP) is one of the most widely used choices of FRP material due to its high tensile strength and stiffness, which enhances the structural integrity of a building/structure. Glass Fibre Reinforced Polymer (GFRP) has a lower cost and has a higher level of ductility than CFRP. Other materials such as Basalt Fiber Reinforced Polymer (BFRP) and Aramid Fiber Reinforced Polymer (AFRP) have also shown promising mechanical and durability properties for strengthening applications [5, 6]. Despite the widespread use of FRP sheets and laminates, conventional sheet-based strengthening systems often suffer from premature debonding at the surface between the FRP material and the concrete substrate, which can significantly reduce strengthening efficiency. Research done recently has developed new FRP strengthening systems to try to solve this problem and provide better bonding characteristics, better crack bridging capabilities, and improved stress redistribution than standard sheet systems. [7, 8]

The distinctiveness of this review is that it gives a combined evaluation of new mesh-based wrapping techniques for RC beams relative to the type of material, the configuration of wrapping, the loading conditions imposed on the structure, the structural performance of the structures, their practical use in field applications, and the future direction for research in this area. [9] In contrast to previous reviews of FRP strengthening methods that primarily provide a summary of individual loadings, this review compares the behaviour and performance of different FRP material types such as CFRP, GFRP, BFRP, AFRP, stainless steel wire meshes, wire mesh-epoxy composites and hybrid systems when they are used to strengthen RC beams subjected to multiple load types: flexural, shear, torsional, and in combination of the aforementioned loading conditions [10]. In contrast to previous reviews of FRP strengthening methods that primarily provide a summary of individual loadings, this review compares the behaviour and performance of different FRP material types such as CFRP, GFRP, BFRP, AFRP, stainless steel wire meshes, wire mesh-epoxy composites and hybrid systems when they are used to strengthen RC beams subjected to multiple load types: flexural, shear, torsional, and in combination of the aforementioned loading conditions. Furthermore, the review identifies limitations associated with all of the above systems, for example, to debonding, expense, durability, suitability for field applications, and lack of long-term performance data. Thus, the current review will provide an enhanced method to facilitate the selection and use of an appropriate mesh-based strengthening system for the practical rehabilitation of existing RC beams. [1, 2, 11].

2. Methodology

The systematic literature review described in this paper was used as a benchmark to assess how effective it was to reinforce RC beams with mesh under the loading conditions of shearing/shear, flexural or bending of the beams, and torsional loads. The systematic literature review was conducted by following the PRISMA guidelines to promote transparency and reproducibility and to ensure adequate and rigorous methods for selection/analysis of relevant studies/works.

2.1. Literature Search Technique

A variety of databases known to be considerable sources of peer-reviewed articles, conference proceedings, and technical reports were utilized in the search for relevant studies like e.g., Scopus, Web of Science, ScienceDirect and Google Scholar. The timeframe for the search spanned 2000-2026 to capture both historic and contemporary research regarding FRP strengthening methods.

A combination of keywords and search terms were applied to identify applicable published materials: (RC beam strengthening) OR (Fiber Reinforced Polymer) OR (FRP Mesh Strengthening) AND (Torsional Strengthening of RC Beams) OR (Flexural Behavior of beams strengthened with FRP) OR (Shear Strengthening with FRP) OR (“Mesh Wrapping Techniques”).

The use of Boolean operators, i.e., “AND” & “OR”, allowed for limiting the amount of output generated by the preceding keyword combinations and provided an exhaustive amount of coverage to find suitable literature.

2.2. Study Screening and Selection

The study followed the PRISMA framework, consisting of four stages, i.e., identification, screening, eligibility assessment and inclusion. At first, 837 publications were identified, and after removal of duplicates and applying a few relevant filters initially, 587 publications were identified through database searches, including Scopus, Web of Science, ScienceDirect, and Google Scholar using predefined keyword combinations relevant to RC beam strengthening, FRP mesh strengthening, torsional and flexural behavior of FRP strengthened beams and shear strengthening using FRP and mesh wrapping techniques.

After removing 299 duplicate and irrelevant records, 288 studies remained for Level 1 filtering, where journal ranking and relevance were evaluated by prioritizing Q1 and Q2 journal publications while excluding less relevant Q3 and Q4 papers. During this stage, 146 studies were excluded, leaving 142 papers for further evaluation. At Level 2 screening, the titles, abstracts, and keywords of the remaining studies were examined for relevance to FRP mesh strengthening of RC beams, resulting in the removal of 48 studies. Consequently, 94 studies were considered for full-text eligibility assessment (Level 3). 42 reports were eliminated from the full-text review because the papers could not be retrieved. Finally, 52 studies satisfied all inclusion criteria and were selected for detailed analysis in the present review. The PRISMA flow diagram illustrating the study selection process for the presented study is shown in Figure 1.

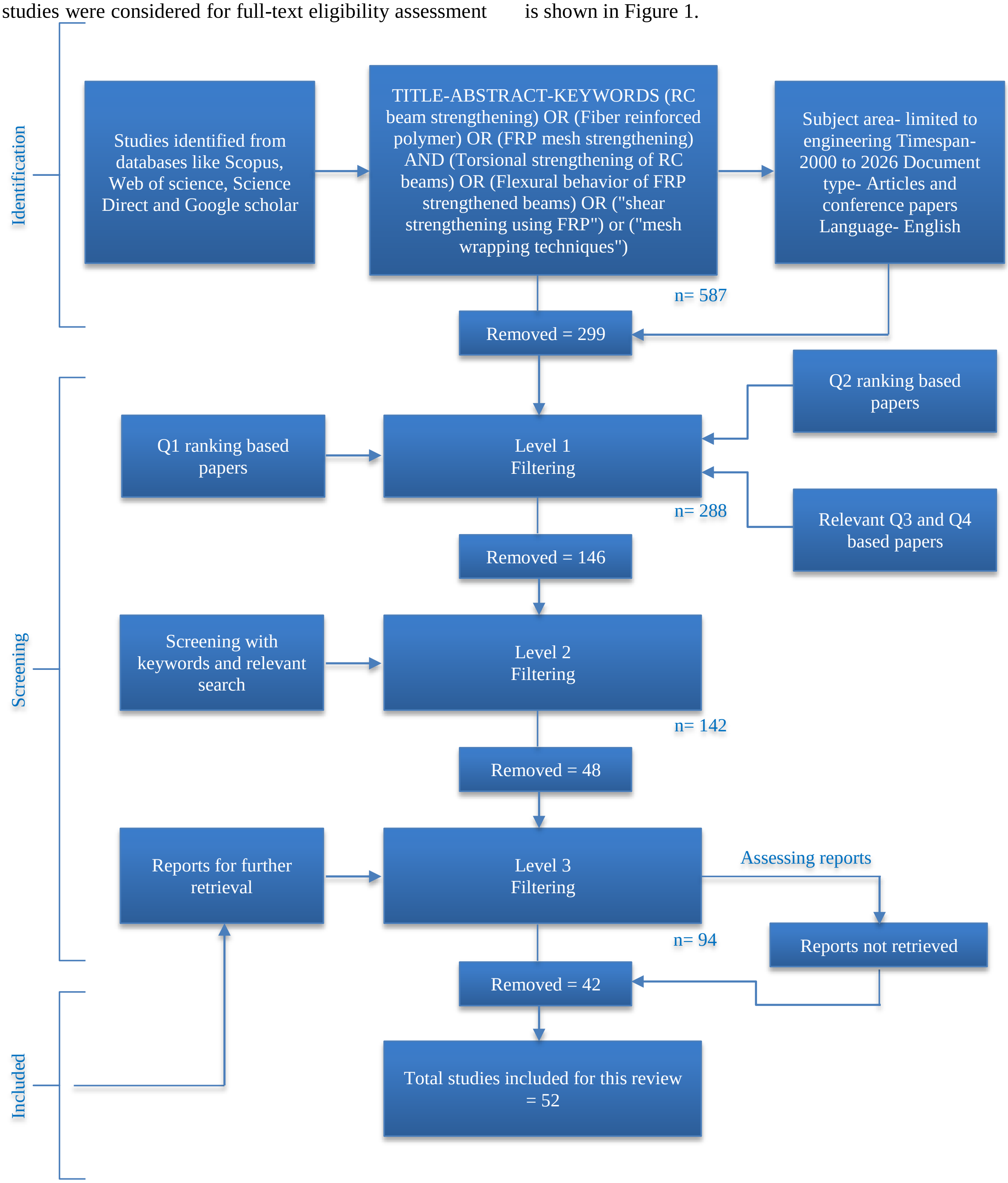

Fig. 1 Methodology for literature review

2.3. Data Extraction and Comparative Analysis

For each of the included publications, data was captured to extract information about mesh-based strengthening systems. The following parameters were extracted from the publications for analysis:

- The type of material being used to strengthen includes CFRP, GFRP, BFRP, AFRP, stainless mesh, and hybrid composite,
- The way that the material is applied, i.e., fully wrapped, partially wrapped or U-wrapped.
- Structural performance characteristics such as load-carrying capacity, ductility, torsional capacity, energy absorption, and crack control
- A comparison of CFRP, GFRP and hybrid/mesh strengthening systems with respect to their respective benefits, as well as their effectiveness for various loading conditions, i.e., flexural, shear and torsional, can be found in Figure 2.

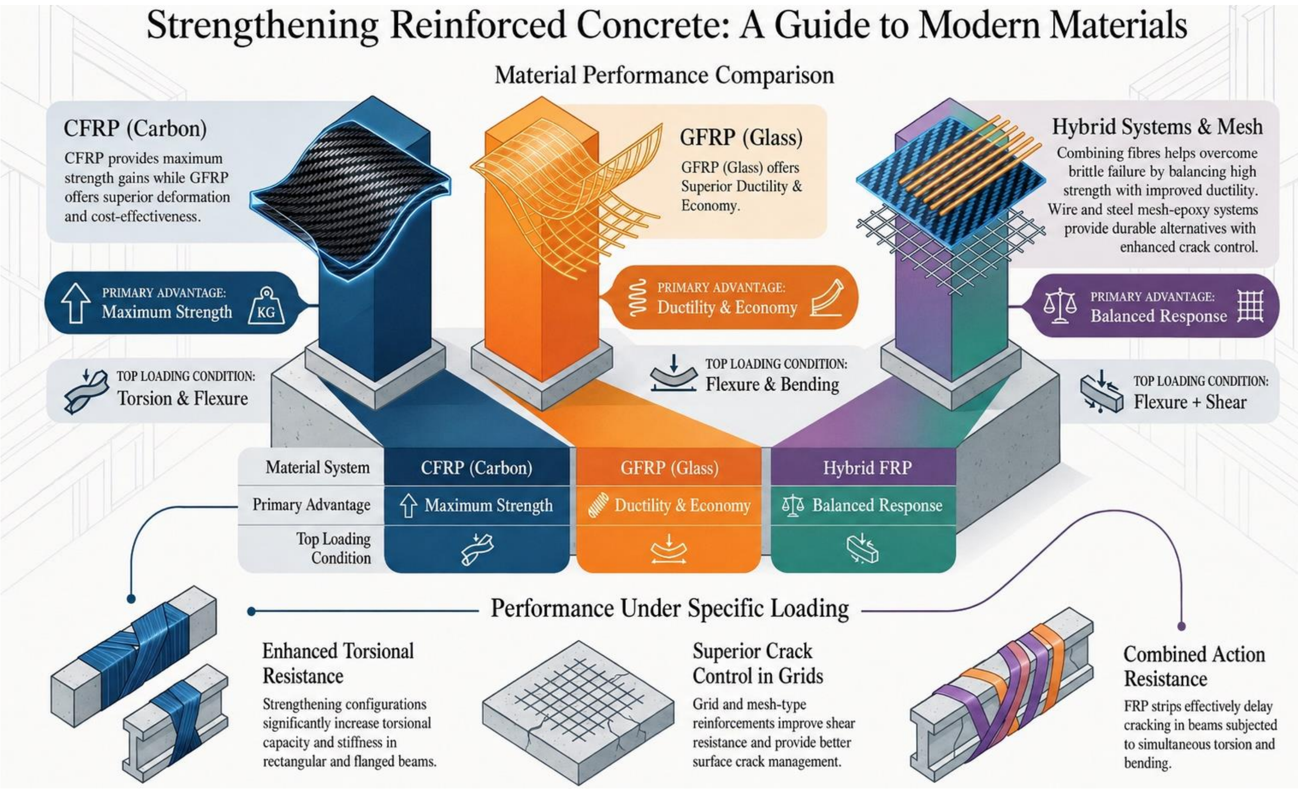

Fig. 2 Material performance comparison for strengthening reinforced concrete

A comparative evaluation of various types of strengthening techniques for reinforced concrete structures was conducted using an integrative synthesis method to identify patterns relative to performance metrics. In addition to assessing each method, the integrative synthesis method allowed identification of gaps in the current body of research and generated recommendations that will help improve the overall strategy for reinforcing concrete structures under multi-axially loaded environments. Table 1 summarizes representative studies included in this review and highlights the strengthening material, loading condition, and key findings reported in the literature.

Table 1. Summary of RC beam strengthening studies

Author	Strengthening Material	Loading Condition	Key Findings
Ameli et al., (2007)	FRP	Torsion	Established that FRP strengthening is effective in significantly upgrading torsional capacity and stiffness.
Askandar et al., (2022)	FRP strips	Torsion + Bending	Improved overall beam response, delayed cracking, and enhanced resistance under interacting stresses.
Askar et al., (2022)	FRP composites	Flexure + Shear	FRP systems are highly effective; CFRP generally provides higher strength gains, while

			GFRP is more economical.
Attari et al. (2012)	CFRP, GFRP, and hybrid FRP sheets	Flexure	CFRP gives the highest efficiency, GFRP contributes better deformability, and hybrid sheets provide a balanced response.
Attia et al., (2023)	GFRP	Flexure	Improved flexural performance, load resistance, and deformation response; offers stable post-cracking behavior.
Chalioris (2008)	CFRP	Torsion	Reported significant gains in torsional strength and improved cracking behavior of RC beams.
Djeddi et al. (2016)	Hybrid FRP system	Flexure + Shear	Improved both strength and ductility while moderating brittle failure tendencies.
El-Mandouh et al. (2022)	FRP-based systems	Torsion	Substantially increased torsional resistance, with effectiveness depending strongly on wrapping configuration.
Guo et al., (2019)	FRP grid–PCM	Shear	Improved shear resistance and crack control due to the grid-based reinforcement mechanism.
Qeshta et al., (2015)	Wire mesh–epoxy composite (WMEC)	Flexure	Reported a clear improvement in flexural strength and crack resistance of RC beams.
Tibhe and Rathi (2016)	CFRP and GFRP fabric	Torsion	CFRP provided greater torsional strength gain, while GFRP offered a more ductile response.

3. Materials and Techniques

This paper outlines the materials and methods used to apply mesh wrapping for the purpose of improving the performance of reinforced concrete beams [12, 13]. Mesh types that have been developed for such applications, including Stainless Steel Wire Mesh (SSWM) [14, 15], wire mesh-epoxy composite meshes (WMEC), GFRP, CFRP and hybrid systems, all can derive from the mesh's high strength, corrosion resistance, and compatibility with concrete. The various application techniques involve using full, U-wrapped, and some partially wrapped configurations and placement options that may optimize confinement and adhesion between the wrap and the substrate. Evaluation has been made on how mesh wrapping improves torsional strength, ductility, crack propagation, and durability in varying environmental conditions for reinforced concrete beams.

3.1. Comparative Performance of FRP Mesh Systems

Although CFRP exhibits the highest tensile strength and elastic modulus among FRP systems, this advantage does not consistently translate into superior structural performance in RC beams strengthened under combined shear, flexural, and torsional loading [3, 16]. Figure 3 presents a stress-strain comparison between FRP materials, i.e., carbon, glass, basalt, aramid fibers and steel used in construction.

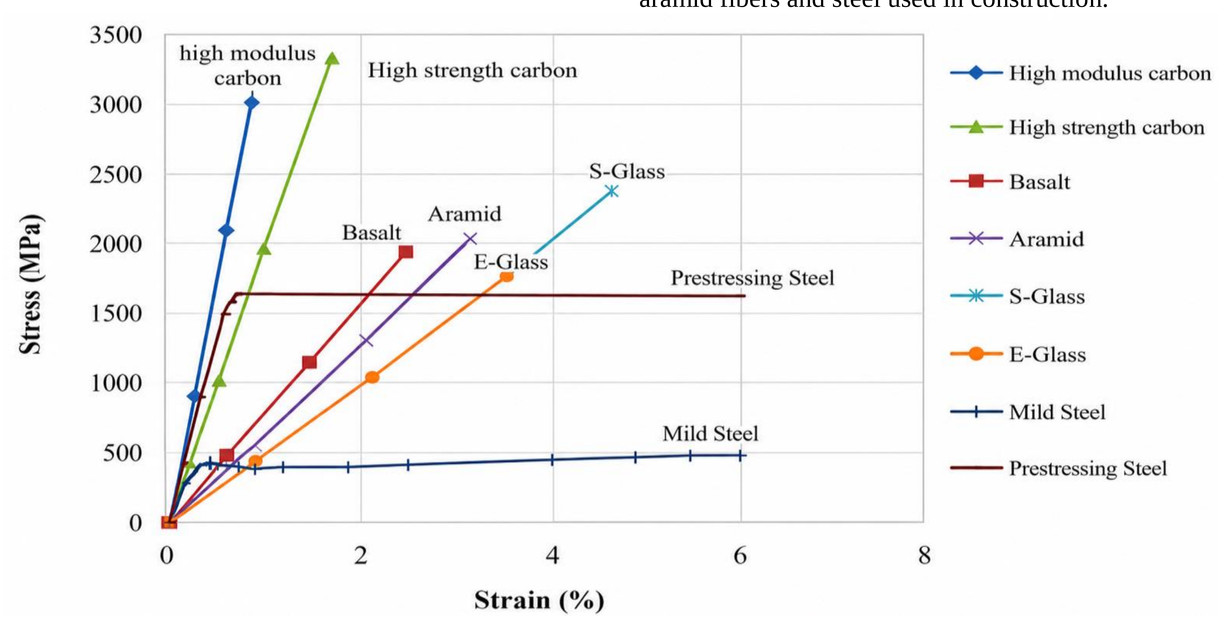

Fig. 3 A comparison of Fiber-Reinforced Polymer (FRP) and steel materials

Experimental studies show that debonding occurs well before brittle failure and is a condition that stops or limits the transfer of stresses effectively and, in turn, limits the ductility of CFRP-strengthened beams, particularly in torsion-dominated situations [17]. On the other hand, GFRP systems, while demonstrating lower overall stiffness than CFRP systems, have higher deformation capacities and thus delayed crack propagation, resulting in greater stability once cracked under cyclic and combined loading conditions [6, 18, 19].

By merging the shear strength/stiffness properties of CFRP and GFRP, hybrid systems will and do provide greater energy dissipation and move in the direction of more ductile modes of failure, which will lessen the disadvantages associated with mono-fibred systems. Table 2 below lists the specific gravity, tensile strength & tensile modulus of various thermosetting resin systems.

Table 2. Thermosetting resin properties of the FRP matrix

Resin	Specific gravity	Tensile strength (MPa)	Tensile Modulus (GPa)
Epoxy	1.2 to1.3	55 to130	2.75 to 4.1
Vinyl ester	73 to 81	1.12 to 1.32	3 to 3.35
Polyester	1.1 to 1.4	34.5 to 103.5	2.1 to 3.45

3.1.1. Performance per Unit FRP Thickness

In flexural strengthening applications, CFRP has the maximum strength efficiency when normalized by FRP thickness [1]. However, under torsional and combination strain, its efficiency reduces, leading to debonding-controlled failure. GFRP systems offer more consistent stress redistribution and better fracture control, even if they need to be thicker to obtain similar strength improvements. In situations where torsional resistance and confinement control behavior, hybrid systems show the highest balanced performance per unit thickness.

3.1.2. Performance Per Unit Cost

When ductility and fracture control are important design goals, GFRP performs better than CFRP on a cost-normalized basis. Even while CFRP reaches a higher peak strength, it frequently has a poorer marginal performance gain per unit cost than GFRP, particularly in torsion-governed beams. Hybrid systems achieve near-CFRP strength levels with significantly increased ductility at lower material costs, offering an intermediate cost-to-performance ratio.

3.1.3. Performance Per Unit Added Weight

Due to its high strength-to-density ratio, CFRP continues to be the most effective material when it comes to performance per unit extra weight. However, brittle failure mechanisms somewhat counteract this benefit. In seismic or fatigue-sensitive applications, GFRP and hybrid systems may be preferred due to their somewhat higher mass but increased energy absorption and ductile response.

Carbon Fiber Reinforced Polymer (CFRP)

When full wrapping configurations are used to achieve successful confinement, CFRP mesh systems often offer the largest increases in ultimate load-carrying capacity and torsional resistance. However, CFRP's high elastic modulus causes large interfacial shear stresses, which often lead to premature debonding in U-wrapped or partially wrapped systems. Because of this, CFRP-strengthened beams frequently show brittle failure modes with little post-peak deformation, especially when torsion-dominated loading conditions are present.

Reinforced Polymer with Basalt Fiber (BFRP)

Made from naturally occurring basalt minerals, BFRP provides a favourable balance between cost and mechanical performance [4, 20, 21]. BFRP is appropriate for RC strengthening applications because it has a lower elastic modulus than CFRP but better interfacial bonding, thermal stability, corrosion resistance, and alkali resistance. Studies on long-term durability show that after extended exposure to changing environmental conditions, BFRP maintains between 70 and 90 percent of its tensile strength. Although BFRP works well under cyclic loading, strength augmentation is limited by its comparatively low stiffness, and brittle failure may happen at high stress levels. However, BFRP is a desirable substitute for strengthening applications where ductility and endurance, rather than peak strength, determine performance due to its excellent strength-to-cost ratio and steady material availability.

Glass Fiber Reinforced Polymer (GFRP)

GFRP mesh systems are less stiff than CFRP, but they have a significantly larger strain capacity [4, 22], which encourages progressive crack development and gradual load redistribution. GFRP-strengthened beams may withstand greater rotations before failing thanks to this behaviour, which improves ductility and energy dissipation. Despite lower peak strength gains, GFRP systems have been shown to outperform CFRP under mixed loading situations where deformation capacity and fracture control determine performance.

Aramid Fiber Reinforced Polymer (AFRP)

AFRP is composed of aramid fibers and synthetic polymers characterized by strong molecular chains that provide excellent strength and heat resistance. These high-performance fibers confer superior tensile strength, stiffness, and thermal stability, with a density approximately 40% lower than that of GFRP. Compared with CFRP, AFRP is more cost-effective and demonstrates superior alkaline resistance.

AFRP maintains a significant portion of its initial strength during cyclic loading [23], exhibiting only a 13% loss, nearly 40% less deterioration than the majority of other FRPs. Due to low compressive strength, AFRP is generally utilized for structures that will be loaded moderately despite having strong mechanical and chemical properties. Some additional advantages of AFRP are high tensile modulus, low elongation prior to fracture and good chemical resistance. However, potential surface degradation from exposure to UV radiation may necessitate using protective coatings to ensure long-term durability. [24].

Table 3. Mechanical properties of FRP meshes

Classes	Yield strength (MPa)	Density (g/cm³)	Tensile strength (MPa)	Specific gravity	Elastic modulus (GPa)	Strain at break %
Steel	500	7.7 to 8.1	350 to 450	7.8	200	0.2
AFRP	1700 to 2500	1.28 to 2.6	1720 to 2540	1.38 to 1.39	41 to 125	1.9 to 4.4
GFRP	600 to 1400	2.11 to 2.7	480 to 1600	1.5 to 2.5	35 to 51	1.2 to 3.1
BFRP	1000 to 1600	2.15 to 2.7	1035 to 1650	2.7 to 2.89	45 to 59	1.6 to 3
CFRP	1755 to 3600	1.55 to 1.76	1720 to 3690	1 to 1.1	120 to 580	0.5 to 1.9

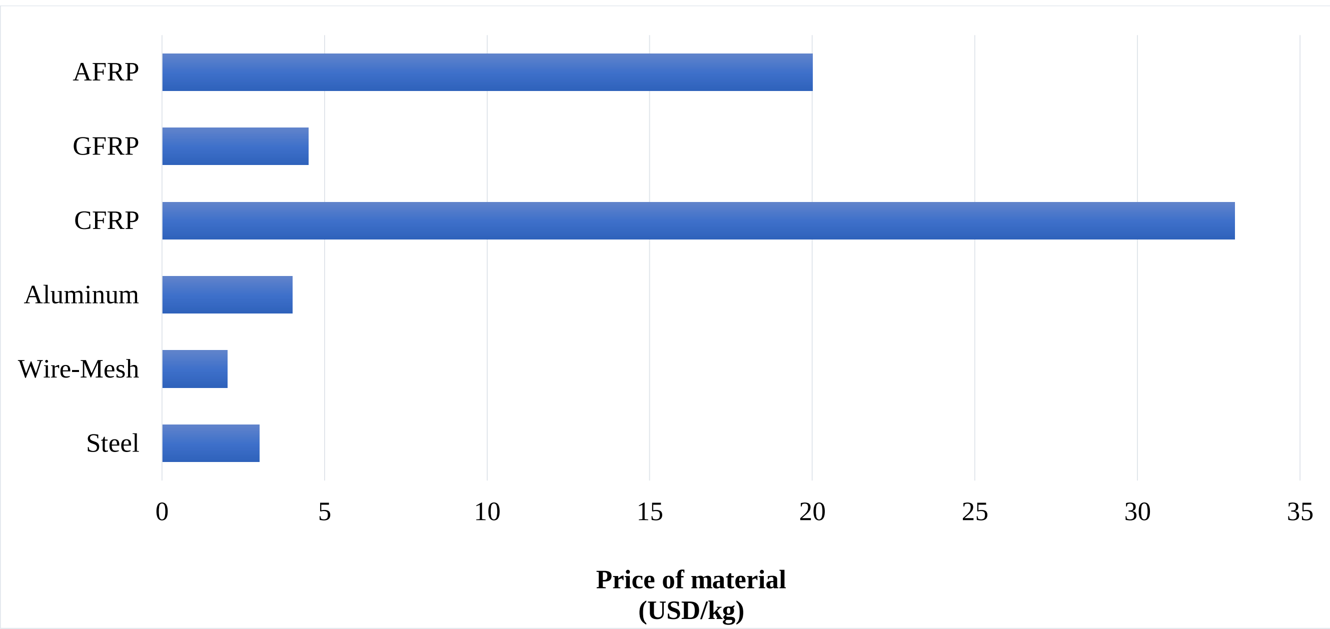

Fig. 4 Prices of different strengthening materials

Illustrating Table 3, there is a wide range of mechanical properties among the different FRP types, including CFRP, which has the greatest tensile strength and elastic modulus, followed closely by AFRP and BFRP, while GFRP is an intermediate strength material and has relatively low density. When compared to most FRPs, steel has a much higher density and modulus, but has a much lower strain capacity.

Such variances indicate that FRP systems are used increasingly often over steel for lightweight/high-strength reinforcement applications. Furthermore, as indicated in Figure 4, the ratio of cost per lb between various materials also helps shape the decision on which material will be selected for use. Generally, materials such as CFRP that are of higher performance usually cost much more than materials such as GFRP or conventional steel.

Stainless Steel Wire Mesh (SSWM)

Because of its exceptional tensile strength, corrosion resistance, and longevity, stainless steel wire mesh is frequently utilized and chosen for structural strengthening. Megash has been the subject of numerous investigations as a possible reinforcing element for reinforced concrete structures, offering enhanced durability and structural integrity. Stainless steel is a highly effective and preferred material for reinforcing members that are affected by rigorous environmental exposure. Although several studies didn't provide quantitative data to assure the performance of stainless wire in steel-reinforced members, there is a large body of evidence on the use of steel wire in RC beam reinforcements. By enhancing the load-bearing capability and preventing cracking during load application, reinforcing fiber mats are usually used in the level of stock at the external surface of RC beams. Steel wire mesh samples are seen in Figure 5.

Fig. 5 Steel wire meshes

Wire Mesh-Epoxy Composites (WMEC)

The literature review showed that using wire mesh-epoxy composites improved the performance of RC beams. In particular, the research found that RC beams with WMEC systems had an increased load-carrying capacity of 47% as compared with the controls. WMEC combines wire mesh woven from dozens of thin wires with the epoxy resin known for superior binding and bonding properties to provide excellent adhesion and enhance the structure's concrete, which delays or prevents cracks and improves the flexural or lateral load performance of the RC beam. WMECs are applied to the surface of the RC beam in various configurations to enhance tensile strength and durability. The epoxy resin is a means of bonding the wire mesh to the concrete.

Meshes made of GFRP and CFRP

Because of their excellent strength by weight ratios and resistance to rusting, especially in stress and torsion, GFRP and CFRP mesh composites are increasingly being used to enhance RC beam systems. One study suggested that beams wrapped with GFRP had an ultimate torque increase of 62%, while beams wrapped in CFRP showed 118% and 163%, respectively, for one- and two-layer applications. [25] GFRP exhibits tensile strength between 690 and 2400 MPa and an elastic modulus of 40.8 to 147 GPa, with a 128% increase in ductility index and energy absorption of 798.32 kN/mm [11]. It also improves crack control and ultimate load capacity (60.48 kN). CFRP offers higher tensile strength (2400–5100 MPa), an elastic modulus of 70 to 90 GPa, and enhances ductility index by 91.10% over GFRP, with an ultimate load capacity of 71.96 kN and energy absorption of 708.69 kN/mm, effectively mitigating cracks. Figures 6 and 7 show specimens of GFRP Sheet and CFRP Fabric, respectively.

Fig. 6 GFRP sheet

Fig.7 CFRP fabric [15]

Hybrid Systems

Hybrid CFRP–GFRP mesh systems have been proposed to reconcile the trade-off between strength and ductility inherent in single-fiber systems [26]. Experimental evidence indicates that hybrid configurations delay the onset of debonding while enabling higher strain development, thereby shifting the governing failure mode from brittle interfacial separation towards more controlled cracking or FRP rupture. These comparative results show improved structural reliability under combined loading.

Table 4. Mechanical properties of mesh materials

Material	Tensile Strength (MPa)	Elastic Modulus (GPa)	Strain at Failure (%)	Density (g/cm³)	Key Advantages
SSWM	~500–1000	~190	~1–2	~7.8	Corrosion resistance, durability
WMEC	~500–800	~100–150	~1–3	~2.5–3.0	Superior adhesion, crack delay
GFRP	690–2400	40.8–147	3.5–5.5	2.5–2.6	Cost-effective, ductile
CFRP	2400–5100	70–90	0.5–1.73	1.85–1.9	High strength, stiffness
HRB	~800–1200	~100–150	~2–4	~2.0–2.5	Strength-ductility balance

3.2. Application Techniques

The structural performance of any type of wrapping generally has a greater influence than either the strength of the materials used in the wrapping or the design of the wrapping itself [10, 27]. The use of a fully wrapped system permits the occurrence of rupture-controlled or concrete-governed failure modes through the introduction of uniform confinement and reduction of interfacial stress concentrations [28]. In contrast, for partially and U-shaped wrapped systems, the predominant mode of failure is through debonding, thereby hindering the magnitude of any strength enhancements that can be realized by the structures [29]. Therefore, the findings demonstrate the need for proper alignment between the strengthening configuration and the intended failure mode, rather than merely relying upon the characteristics of the materials used for strengthening purposes. Table 5 presents a comparative overview of different wrapping configurations used for strengthening RC beams.

Table 5. Comparison of wrapping configurations for RC beam strengthening

Wrapping configuration	Main advantage	Limitation	Suitable performance domain
Full wrapping	Provides maximum confinement and stress redistribution	Difficult to apply where slab-beam junctions exist	Torsion and combined loading
U-wrapping	Practical and economical for field application	More prone to end debonding	Shear strengthening
Side wrapping	Easier installation on accessible beam faces	Limited confinement effect	Local shear improvement
Partial wrapping	Reduces material use and cost	Strength gain depends on correct placement	Localized flexural or shear strengthening
Hybrid wrapping	Balances strength and ductility	Requires careful design and quality control	Combined shear-flexure-torsion performance

3.2.1. Fully Wrapped Configuration

The technique involves utilizing wraps that encircle all portions of the beam; this includes reinforcing materials that are added to all surfaces of the beam and are intended to provide additional support to the beam from torsional and bending forces. In other words, they're intended to spread out all of the weight placed on the beam evenly [30]. According to an experimental study, the complete utilisation of GFRP has been shown to increase both the torsional capacity and loading ability of beams where they are used as a support by a significant amount when compared to beams that were not supported. The ultimate rotating strength of a beam that has been supported by a GFRP wrap will increase by approximately 81.25% more than a beam that has not been supported, representing the greatest amount of total reinforcement and the greatest capability of performance.

3.2.2. U-Wrapped Configuration

The method used in this study involves wrapping additional material around the sides of the beam while leaving both ends exposed. This approach produces a simple, more efficient, and less expensive application of support than if the entire beam were wrapped. In addition, studies have shown that wrapping with U-shaped wraps has resulted in greater shear strength than if just applying to the sides [31]. In fact, using these methods can increase the ultimate torque capacity of a beam by approximately 50% over that of an unwrapped beam and, as a result, produce a better load distribution and higher levels of torsional resistance, especially in areas of stress concentration, such as around perforations or locations of high load.

3.2.3. Partial Wrapping Configurations

Wrapping the strengthening material only about specific sections of the beam allows for reinforcing the most needed areas. In one study, it was found that layering two layers of wrap leads to substantial gains in torsional strength. However, the level of improvement is highly dependent on design. Partial wrapping is cost-effective because it allows for the enhancement of load capacity and ductility to be applied only to the locations of greatest need [32], generally using GFRP or CFRP sheets. Examples of the various wrapping configurations can be seen in Figure 8 (a-c).

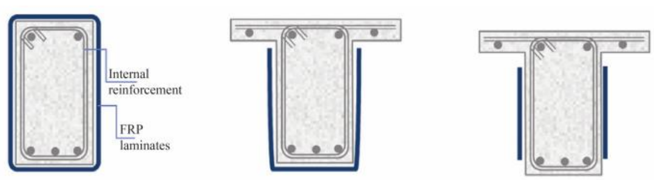

Fig. 8 Wrapping configurations (a) Full wrapping, (b) U-wrapping, and (c) Partial wrapping.

Proper use of reinforcement materials on RC beams at maximum confinement and bond strength requires the method of application selected: Full Wrap, U-Wrap; Partial Wrap. The structural integrity of an RC beam, its effectiveness to control fractures, and the efficiency to transfer loads will all be affected by the application method utilized. Continued development of more effective & reliable methods to apply reinforcement materials will facilitate application and produce better performance across multiple loads & environmental conditions.

3.3. Surface Preparation and Bonding Mechanisms

Bond behaviour is an important factor in determining the efficiency of strengthening, especially for FRP systems with high stiffness [33]. Because localized bond failures can cause premature debonding under torsional pressure, CFRP mesh applications are extremely sensitive to surface preparation and adhesive performance. Systems with lower moduli, like GFRP, lessen the sensitivity to debonding at the expense of peak strength by more evenly distributing interfacial stresses. Hybrid systems decrease interfacial stress gradients, thus prolonging load transfer efficacy and postponing bond-related failure [1, 34]. The strengthening process is shown in Figure 9 (a-c).

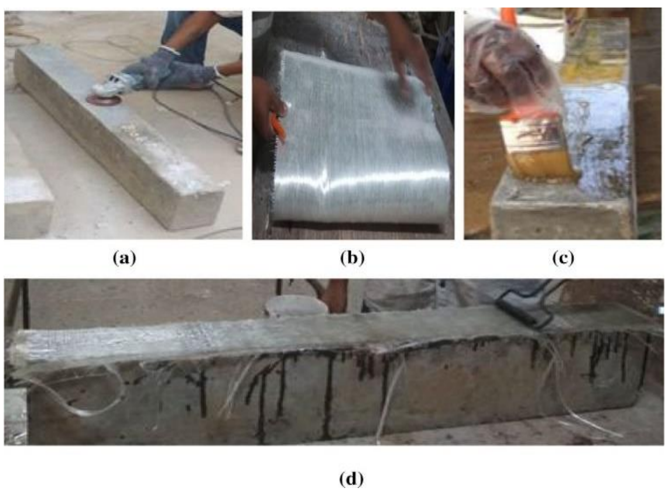

Fig. 9 Step-by-Step strengthening procedure: (a) Surface preparation, (b) GFRP cutting, (c) Epoxy application, (d) Air bubble removal [26].

3.4. Performance Metrics

When determining whether FRP mesh wrapping has improved or not the performance of an RC beam, and how this compares with other methods of reinforcement, several performance indicators need to be evaluated. The performance indicators described here are designed to represent the different aspects of structural enhancements provided by FRP mesh wrapping. For example, the ultimate capacity of load carrying and deformability prior to failure are both key measures of an RC beam's overall strength, while the level of resistance to cracking and impact damage provides a measure of torsional strength and is also an important element of an RC beam's overall performance. Performance indicators include, but are not limited to, ultimate load capacity, ductility, energy absorption, crack control, torsional resistance, crack load and Failure Types.

3.4.1. Load Capacity

The most important aspect of evaluating the ability to strengthen systems to work is load capacity. As the results demonstrated, after being exposed to extreme environmental conditions for two years, the load capacity of beams with mesh reinforcement, either MSM or HSM, increased by an impressive 82 percent [8, 35]. According to data from, as the mesh layer quantities increase [30, 36], ultimately the amount of torque measured at ultimate failure will also increase, increasing GFRP and Steel Mesh wrapped beams on average by 62 percent, 118 percent and 163 percent.

When measured, the control beam with no apertures had a load capacity of 76.42 kN. [23] In contrast, the CFRP beam load capacity was 71.96 kN, while the GFRP beam load capacity was 60.48 kN. Interestingly, the HRB, which had been placed with 0.70 percent steel, achieved the same load capacity as the CFRP beam. Overall, the HRB beams had demonstrated the ability to increase the control beams' load capacity by 94.16 percent, therefore validating HRB as an effective means of improving structural performance.

3.4.2. Ductility

What is more, ductility is an essential parameter for testing the performance of a reinforced beam under high deformation. observed a remarkable enhancement of ductility, in which the ductility jumped by 14%–54% over the control beam [26, 37], noted the steel mesh being restrained through a double wrap, increasing the ductility, permitting the beams to undergo increased deformations without catastrophic failure. Ductility for the GFRP beam was 1.68, and the HRB and CFRP beams demonstrated a ductility of 3.21. This means that both the hybrid and the CFRC reinforced beams exhibit much higher ductility than the control beam. The ductility factor for CFRP- and GFRP-reinforced beams ranged from 0.055 (control beam) to 0.085 (CFRP) and 0.076 (GFRP), respectively, and their capacity when initiating to crack the ductility factor increased proportionally, indicating a better ductility to deform as much as they can, subjected to load without collapsing.

3.4.3. Energy Absorption

Energy absorption is also one of the most important properties to assess the dynamic loading performance of strengthened beams [2, 38]. indicated that beams retrofitted by wire mesh-epoxy and CFRP systems showed 470% more energy dissipation than control beams, indicating a significant enhancement of performance under dynamic loading. The energy absorption capacity of GFRP beams was 798.32 kN/mm, while that of HRB and CFRP beams was 708.69 kN/mm. This parameter represents the energy absorption capability of the beams during loading, an important feature for their application.

3.4.4. Crack Mitigation

The Mitigation of cracks is an important factor for the durability of the strengthened beams [7, 39]. They have reported that the 2-layer wrapped steel mesh can dramatically prevent cracks from extending; therefore, it has improved the resistance to cracks as well as delayed the crack generation. Also observed that strengthened beams had lower crack widths and postponement of initial cracking, which would result in longer service life in terms of durability. High-strength GFRP, CFRP, and HRB beams presented lower crack width and more uniform crack distribution than control beams. This means that utilization of these materials contributes to suppressing the generation of cracks in the structures and enhancing durability.

3.4.5. Torsional Capacity

The maximum torsional moment for CFRP was increased by 101.8% and that of CFRP beams by 83.49% [40-42]. This remarkable increase in torsional resistance demonstrates the efficient reinforcing behaviour of these materials in the case of torsion-loaded beams.

3.4.6. Cracking Load

The control beam has shown a cracking load of 7.81 kN. In contrast, if the CFRP beam obtained a cracking load of 12.433 kN, and the GFRP beam obtained a cracking load equal to 11.39 kN. This demonstrates that the beams' cracking load is significantly increased when CFRP and GFRP are substituted.

3.4.7. Failure Modes

Bond behaviour plays a decisive role in determining whether strengthened beams fail in a debonding-controlled or rupture-controlled manner [19, 43]. High-stiffness systems such as CFRP are particularly sensitive to interfacial stress concentrations, leading to premature debonding if surface preparation or adhesive properties are inadequate. In contrast, lower-modulus systems such as GFRP distribute interfacial stresses more uniformly, reducing debonding risk at the expense of peak strength. Hybrid systems moderate these effects by delaying interfacial failure and enabling greater strain development prior to ultimate failure [6].

4. Comparative Analysis of FRP Strengthening Techniques

To analyze the evolution of mesh-based strengthening methods to Reinforced Concrete (RC) beams, 52 studies were analyzed and systematically classified according to their FRP material type, their strengthening configuration, their loading conditions, and their major structural results. These studies are either experimental, numerical, or analytical in nature and deal with the strengthening of RC beams using CFRP, GFRP, BFRP, AFRP and stainless steel mesh, in addition to hybrid composite systems. Figure 10 represents the advantages of using a full wrap compared to partial strengthening.

Many researchers reported that FRP systems improve the statistics of RC beams when strengthened externally to beams. The major performance characteristics analysed in the literature are load-carrying capacity, ductility, torsional resistance, energy absorption, crack control and mode of failure. It was found that CFRP systems had the best strength improvement; GFRP systems had the best ductility and cost-effectiveness [3, 4, 44]. Hybrid FRP systems have been reported to provide a balanced combination of strength and deformation capacity. [11, 45] When evaluating a structure and how well it performs as designed, it must be remembered that the configuration of the reinforcing material will contribute greatly to how well the structure performs. Complete or full wrapping of the reinforcing material generally will provide a larger improvement in load-bearing capacity than U-wrapping, which can have limited effectiveness by falling apart before any noticeable change in performance can be observed or being deboned prematurely because of localized stress concentration adjacent to the bond surface between the reinforcing materials and the concrete. [29]

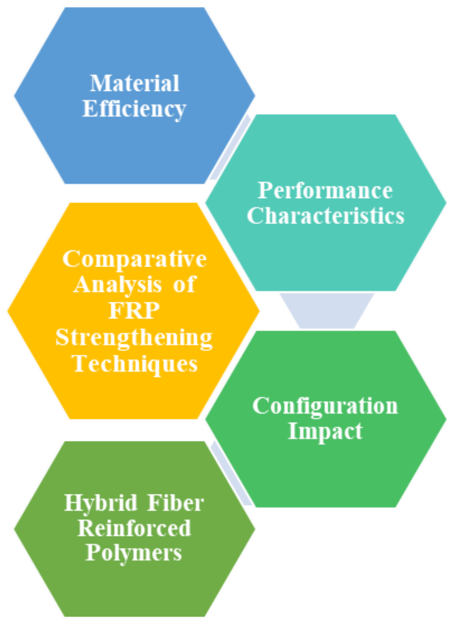

Fig. 10 FRP strengthening techniques

4.1. Material Efficiency

FRP composites are highly valued and a powerful substitute for conventional steel reinforcement because of their superior strength-to-weight ratios and corrosion resistance. [1, 46] of them, CFRP has a far enhanced tensile strength than Glass Fiber Reinforced Polymer (GFRP), which is usually approximately 690 MPa. CFRP frequently reaches values over 2250 MPa. Despite this, GFRP is still a desirable choice due to its cheaper price, which frequently cuts costs by over half when compared to steel. By combining the high-strength capacity of CFRP with the flexibility and affordability of GFRP, hybrid FRP systems that incorporate glass and carbon fibers offer a well-rounded solution. Hybrid composites are particularly well suited for structures that are subjected to complex loading conditions, where ductility and strength are essential, because of this combination [28, 47]. When performance is interpreted on a normalized basis per unit thickness, cost, or added weight, CFRP systems exhibit superior strength efficiency, whereas GFRP and hybrid systems demonstrate more favourable cost- and ductility-normalized performance, particularly under combined loading conditions. To get the most effective and long-lasting reinforcement, selecting the best FRP material ultimately entails considering aspects like mechanical performance, durability, and cost.

4.2. Performance Characteristics

FRP strengthening significantly enhances RC beam performance:

- Flexural Strength: Laminated beams exhibit 33.44% greater failure loads, whereas full wrapping enhances ultimate load capacity by 83.04%. • Ductility: Under dynamic loads, ductility is essential for energy absorption, and hybrid systems increase it by 24.87%.
- Torsional Capacity: With controlled ductile failure modes, full wrapping yields a load capacity that is up to 70% greater than partial approaches [27].

4.3. Impact of FRP Wrapping Configurations on Structural Behaviour

The strength of RC beams is largely dependent on how the FRP material is applied and wrapped around the beam. The way the reinforcement is wrapped will determine how the load is transferred through the wrapped area, how stresses are distributed within the wrapped area, and how the beam behaves under various loading scenarios. In contrast, the method of application will determine how the FRP is applied. Full Wrapping Benefits When used in conjunction with full wrapping of the FRP sheets around the beam, all loads applied to the beam will be enclosed in FRP confinement, enabling consistent load distribution over the whole beam cross-section. The benefits from full wrapping of the FRP will include increased resistance to premature failure (i.e., debonding), which is typically seen in instances of partial wrapping. For example, in various studies, fully wrapped beams had a capacity to carry up to 70% more load than un-trengthened beams and, thus, were deformed more before ultimate failure [28].

The even support through full wrapping provides a uniform manner of providing relative ductile failure modes, allowing for more energy absorption and reduced and more gradual cracking for increased structural safety Limitations of partial and U-wrapping are that although most builders find partial and U-shaped wrapping applications to be easier to apply and less expensive than full wraps, the partial and U-shaped wrapping only provides reinforcement to a limited area located on the beam. When utilizing either a partial wrap or U-shaped wrap on a beam, concentrated stress will occur in the unwrapped areas on the beam, increasing the possibility of either cracking or debonding when subjected to loads. Typically, for beams that use only a partial wrap, there are fewer increases in either strength or flexibility when compared to full wraps. Additionally, this phenomenon is amplified if the beam experiences repeated or dynamic loading during service. Partial wraps may not provide a fully enhanced long-term performance unless designed with combinations of multiple layers and/or hybrid composite materials. Loading and Failure Patterns: When you use a full wrap, this allows for wider distribution of load, allowing for a beam's ability to take on bending/shear/twisting potential. Partial wraps result in a concentration of stress at or near the wrapping, resulting in a more concentrated point of failure. Full wrap will typically fail in a controlled manner over time, while partial wrap often leads to an instantaneous failure due to the higher possibility that a zone may not be reinforced equally.

Overall Considerations for Design: The most appropriate configuration of FRP is often decided based on enhancing performance, but must also be balanced against practical factors such as price and ease of installation, along with the environment that it will be used in. Although a full wrap has the greatest mechanical properties, when a complete wrap is not an option, partial and U-wrapped FRP configurations will probably be more suitable. Using a hybrid of options for both reinforcement type and placement will help produce the greatest results.

4.4. Hybrid Fiber Reinforced Polymers

Hybrid Fiber Reinforced Polymer (HFRP) combines the upper hand of GFRP and CFRP to improve construction capacity to support loads. [34, 48-51] When combined, CFRP's high tensile strength and stiffness with GFRP's substantially higher ductility and cheaper cost result in a hybrid reinforcement system that maintains a large portion of its flexural capacity at quite high temperatures (i.e., 400ºC). Consequently, HFRP systems are key features for fire-resistant and/or durable applications in extreme conditions. In experimental testing along with Finite Element Modeling (FEM) of HFRP strengthened beams, the load-deflection response closely corresponded to predicted values, showing discrepancies of no worse than ±12% for load and ±8% for deflection. This supports the validity of these Finite Element Models for design purposes. The best way to use the full wrapping method in conjunction with hybrid FRP materials will improve load distribution, slow down crack propagation, and increase the ductility of the single FPM systems. When deciding between using either a hybrid or single-fiber system or determining which wrapping configuration, project-specific factors such as expected loading conditions, environmental exposure, and cost constraints must all be considered to determine the most effective method of reinforcing elements.

5. Results and Discussion

The analysis of the selected studies indicates that FRP-based strengthening techniques significantly enhance the structural performance of RC beams under various loading conditions. The reviewed literature consistently demonstrates improvements in key structural parameters such as load-carrying capacity, ductility, torsional resistance, energy absorption, and crack control when FRP mesh or composite systems are applied to RC beams.

5.1. Load-Carrying Capacity

One of the most noticeable improvements in load carrying capacity is observed when there was implementation of FRP is implemented. Numerous experimental investigations have demonstrated a significant increase in the ultimate load capacity of beam specimens when FRP is used as an external reinforcement method. In comparison to other alternatives, the tensile strength and stiffness of CFRP were reported to be better than those of other methods; consequently, CFRP systems typically result in the greatest amount of strength gain.

Several studies show that there is a 60 to 120% increase in the ultimate load capacity of beams depending on how the beams are strengthened and the type of fibers used. Further, in comparison to CFRP systems, the ultimate load-carrying capacity of GFRP systems is improved marginally, but deformation capacity and cost-effectiveness improve when lower-strength GFRP systems are used. Reinforcement systems that use both carbon and glass fibre have demonstrated encouraging results because they provide a compromise between strength and ductility.

5.2. Ductility and Deformation Behavior

Ductility is a key factor in ensuring structural safety as it allows beams to deform further before they fail. The studies reviewed show that the use of FRP strengthens the ductility of RC beams by delaying crack propagation and redistributing stress over a longer length of the beam.

GFRP and hybrid composite systems provide increased deformation capacity, whereas CFRP systems have a higher strength-to-weight ratio but tend to fail in a brittle manner as a result of premature debonding. Hybrid reinforcement methods are thus being encouraged more often because they combine the properties of each material, leading to improved overall structural performance.

5.3. Crack Control and Energy Absorption

Another important benefit of FRP strengthening is improved crack control. The reviewed literature indicates that FRP reinforcement significantly reduces crack width and delays crack initiation. Mesh-based reinforcement systems are particularly effective in this regard because they provide better stress distribution across the strengthened surface.

Energy absorption capacity is also enhanced in strengthened beams. Several experimental studies reported significant increases in energy dissipation under cyclic loading conditions, indicating that FRP systems can improve the structural resilience of RC beams subjected to dynamic or seismic loads.

5.4. Torsional Resistance

Torsional strengthening is another area where FRP systems demonstrate considerable advantages. The reviewed studies show that externally bonded FRP systems can significantly increase torsional capacity, with reported improvements of up to 100–160% depending on the material type and wrapping configuration. Full wrapping configurations generally provide the highest torsional resistance because they offer complete confinement of the beam cross-section.

5.5. Influence of Strengthening Configuration

The performance and efficiency of the strengthened beams are strongly influenced by the wrapping configuration used. Full wrapping systems provide the most effective strengthening because they allow uniform stress distribution and improved confinement. On the other hand, stress concentrations close to the ends of the reinforcement may cause premature debonding in U-wrap and partial wrap configurations. Nevertheless, these configurations are often used in practical applications where full wrapping is not feasible due to accessibility limitations.

Overall, the comparative analysis of the reviewed studies indicates that material type, bonding behaviour, and strengthening configuration are the primary factors influencing the structural performance of FRP-strengthened RC beams. Mesh-based strengthening systems show strong potential for improving both structural capacity and durability, particularly under combined loading conditions.

6. Research Gaps, Challenges, and Future Directions

Even though there has been a lot of research done on reinforcing RC beams using FRP systems, it is still a relatively undeveloped area of study with many gaps. Most past studies have used conventional FRP sheets/laminates, with very few studies conducted on mesh reinforcing systems.

Members reinforced with these mesh-based systems exhibit better bonding behaviour and crack bridging capabilities than RC members reinforced with conventional FRP sheet systems, but there has been little work completed to compare the performance of mesh-based and conventional FRP sheets for the structural performance of RC members.

Another limitation in the current literature includes the fact that most experimental studies look at the behaviour of reinforced RC beams under single flexural, shear, or torsional loading conditions, when in reality, an RC beam is subjected to combined loading conditions of flexural, shear and torsional stresses. Since multiple loading mechanisms are interacting at once, the resulting distribution of stresses and multiple modes of failure cannot be fully understood based on the results from isolated loading studies.

The way in which the strengthening of configuration is created has also not been comprehensively examined with respect to different types of mesh materials and performance criteria in terms of full wrapping, U-wrapping and partial wrapping. Most studies have looked at only specific materials or separate strengthening techniques, limiting their ability to draw generalized conclusions regarding the most effective strengthening methods for real-world structural applications.

In addition to these research gaps, several technical challenges remain associated with FRP strengthening systems. One of the primary concerns is interfacial debonding, which may occur due to inadequate bonding between the cementitious material present in concrete and the FRP material, leading to premature failure of the strengthening system. The long-term durability of FRP systems under fatigue or cyclic loading presents another difficulty since it may eventually affect the structural dependability of strengthened members. In addition, the relatively high cost of advanced FRP materials compared with traditional strengthening techniques continues to limit their widespread application in large-scale infrastructure projects.

Research gaps and future challenges remain in the application of mesh-based strengthening systems for RC beams. First, limited studies are available on the behaviour of strengthened RC beams under simultaneous shear, flexural, and torsional loading. Second, long-term durability data under moisture, temperature variation, corrosion exposure, fatigue loading, and sustained service conditions remain insufficient. Third, the bond behaviour between concrete, adhesive, and mesh reinforcement requires deeper investigation because premature debonding is still one of the major causes of reduced strengthening efficiency. Fourth, the cost-effectiveness and scalability of hybrid and advanced mesh systems need to be validated through full-scale field studies. Future research should therefore focus on combined loading behaviour, long-term durability, reliable bond models, sustainable mesh materials, field validation, and numerical or machine-learning-based prediction models for selecting optimum strengthening configurations.

7. Conclusion

This article will provide a detailed review of how an FRP mesh wrap method can assist RC beams in carrying loads under various combined loads. An example of FRP mesh systems' effectiveness is the greatly improved performance of RC beams based on load carrying capacity, ductility, crack control and energy dissipation. The research that has been done on different types of materials has shown that CFRP demonstrated the greatest increase in strength because of its exceptional tensile strength and stiffness, whereas GFRP had better capacity for deformation and cost savings. Hybrid FRP systems used with combinations of carbon and glass fiber will add advantage in strength and ductility, which makes them particularly well-suited for retrofitting structures.

The effectiveness of the strengthening technique is also somewhat dependent on the configuration used to wrap the reinforcing material. Full wrap provides the most improvement through better confinement and more evenly distributed stress, but when full wrapping cannot be accomplished due to construction conditions or physical limitations of the structure, the U-wrap and partial wrapping configurations can provide reasonable alternatives. Other issues that may arise include those related to interfacial between the FRP and the concrete, performance under repeated cycles of loading and cycling of the material used to fabricate the wrapping means there are challenges related to the high cost of material too.

Some of the latest advances in technology, utilizing designs created with artificial intelligence-based techniques, advanced ways to manufacture materials that can be 3D-printed into reinforcement mesh materials, and developing types of composite materials that will not harm the environment, are available to help alleviate these issues. In summary, FRP mesh wrapping is an effective and adaptable method for strengthening and rehabilitating RC structures that are too old or too damaged to support the loads that are placed upon them. Future research should focus on establishing what type of materials will provide enough strength. There will also need to be research done on how these materials will behave when put through durability testing, and how to produce improved forms of numerical models. After future research occurs, there will be a larger number of FRP systems used in construction and a greater number of FRP schemes used to construct roads in the United States.

Conflicts of Interest

"The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper."

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