

STRENGTHENING OF EXISTING STRUCTURES USING FRP COMPOSITES

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ABSTRACT The rapid deterioration of civil infrastructure worldwide has increased the demand for innovative rehabilitation and strengthening techniques. Fibre-Reinforced Polymer (FRP) composites have emerged as one of the most effective materials for upgrading the structural performance of existing buildings, bridges, columns, beams, slabs, and masonry components due to their superior mechanical properties, corrosion resistance, lightweight nature, and ease of installation. This review synthesizes current research developments, field applications, design considerations, bonding behaviour, failure modes, durability issues, and comparative performance of FRP systems. Carbon, glass, basalt, and aramid fibre composites are evaluated with respect to tensile capacity, ductility, and cost-effectiveness. The paper also discusses externally bonded (EBR), near-surface mounted (NSM), and wrapping techniques commonly used for structural retrofitting. Further emphasis is placed on long-term durability under environmental exposure, fire resistance limitations, bond–interface degradation, and sustainability implications. Results from recent experimental and analytical studies demonstrate that FRP composites significantly improve flexural strength, shear resistance, confinement, fatigue life, and seismic performance. Despite their proven advantages, issues such as debonding, temperature sensitivity, and long-term creep present challenges for field implementation. The review concludes by highlighting future research needs including hybrid FRP systems, nanomodified composites, advanced monitoring techniques, and life-cycle assessment for sustainable rehabilitation strategies.

Keywords: Fibre-Reinforced Polymer (FRP), Retrofitting, Structural Strengthening, Carbon FRP, Shear Strengthening, Externally Bonded Reinforcement, Durability, Debonding Failure, RC Structures.

1. INTRODUCTION

Rapid urbanization, ageing infrastructure, increased load demands, and environmental deterioration have created a pressing need for strengthening existing structures. Conventional

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strengthening methods (steel plates, jacketing, concrete overlays) often suffer from corrosion, increased weight, and installation difficulties (Teng et al., 2016). To overcome these limitations, Fibre-Reinforced Polymer (FRP) composites have become widely accepted in structural engineering applications. FRP materials such as Carbon FRP (CFRP), Glass FRP (GFRP), Basalt FRP (BFRP), and Aramid FRP (AFRP) are particularly advantageous due to high strength-to-weight ratios, corrosion resistance, and rapid installation (ACI 440R-17).

This paper reviews recent advancements in FRP strengthening techniques, focusing on material properties, application methods, behavioural mechanisms, durability challenges, and field performance. The aim is to develop a comprehensive understanding suitable for researchers, engineers, and policymakers.

2. FRP MATERIALS FOR STRUCTURAL STRENGTHENING

FRP composites consist of continuous fibres embedded in a polymeric resin matrix that provides shape, protection, and stress transfer capability. Common fibres include carbon, glass, aramid, and basalt, each offering unique mechanical characteristics.

2.1 Properties of FRP Components

FRP materials exhibit linear elastic behaviour up to failure, high tensile strength, and low density (Hollaway & Teng, 2008). Their mechanical properties vary depending on fibre type, resin system, fibre volume fraction, and manufacturing process.

Table 1. Typical Mechanical Properties of FRP Fibres

Fibre Type	Tensile Strength (MPa)	Modulus (GPa)	Density (g/cm ³)	Durability
CFRP	3500–5000	200–600	1.6	Excellent
GFRP	1200–2400	50–80	2.5	Moderate
AFRP	2800–3500	70–125	1.4	Good
BFRP	1500–3000	45–90	2.7	Good

(Adapted from Teng et al., 2016; ACI 440R-17)

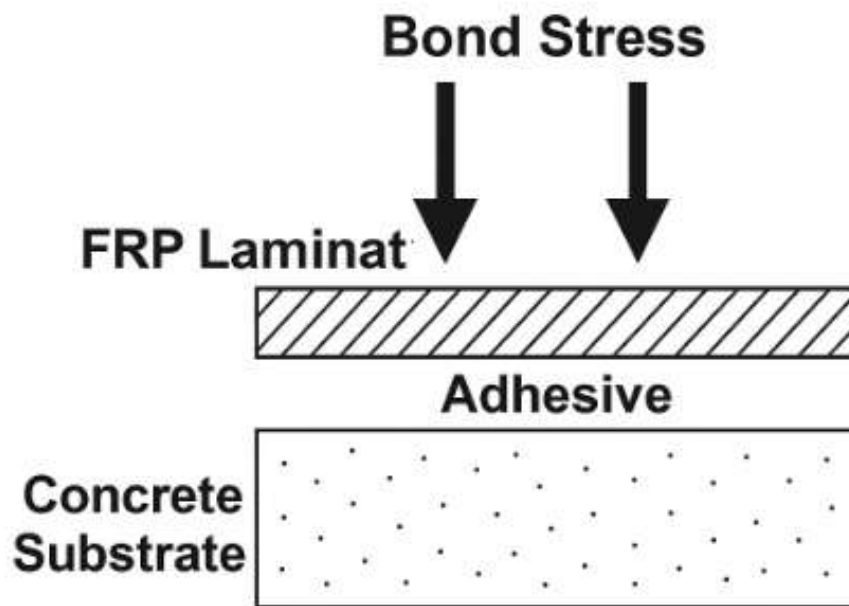


Figure 2.1 Mechanism of Bonding Between FRP Laminates and Concrete Substrate

2.2 Types of FRP Systems

FRP materials are available in several forms:

- **Sheets/ fabrics** (for wrapping)
- **Plates and laminates** (for flexural strengthening)
- **Bars and rods** (NSM reinforcement)
- **Prepregs** (advanced manufacturing)

Each type is selected based on structural requirements.

3. STRENGTHENING TECHNIQUES USING FRP

3.1 Externally Bonded Reinforcement (EBR)

EBR is the most common method where FRP sheets or plates are bonded to the substrate surface using epoxy. It is widely used in beams for flexural and shear strengthening (Triantafillou, 2012). Surface preparation plays a critical role in developing adequate bond strength.

3.2 Near-Surface Mounted (NSM) FRP

NSM involves embedding FRP rods or strips into grooves cut in the concrete cover (De Lorenzis & Teng, 2007). This technique provides higher bond strength and better protection against environmental exposure.

3.3 FRP Wrapping (Confinement)

FRP jackets are effective for enhancing axial compression capacity and ductility of columns. CFRP wraps increase confinement pressure and delay spalling (Lam & Teng, 2009).

3.4 Hybrid and Advanced Strengthening Systems

Recent studies examine hybrid FRP-steel systems, nanomodified FRPs, and shape-memory polymers to address limitations of conventional FRPs (Zhou et al., 2020).

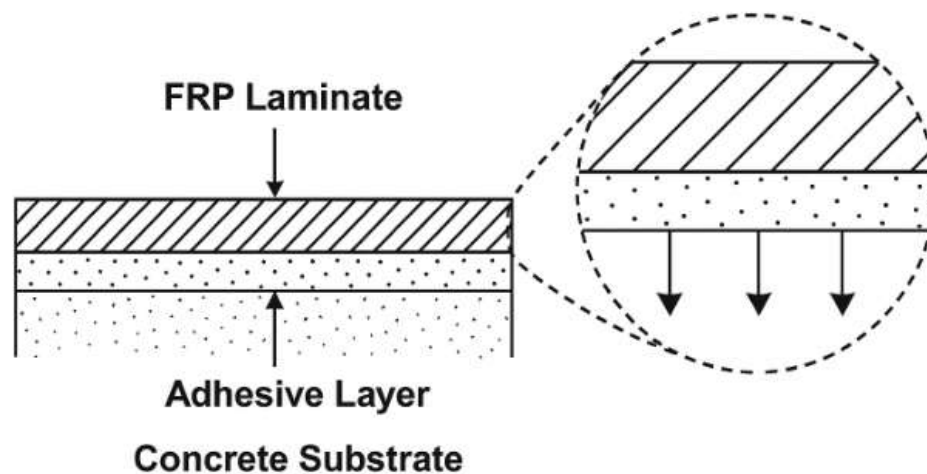


Figure 3.1 Flexural Strengthening of Reinforced Concrete Beams Using Externally Bonded FRP

4. STRUCTURAL APPLICATIONS OF FRP COMPOSITES

FRP systems are used across a wide range of structural components.

4.1 Strengthening of Reinforced Concrete Beams

FRP plates enhance flexural capacity significantly, with CFRP outperforming GFRP due to superior stiffness (Teng et al., 2016). For shear strengthening, U-wraps or side bonding are commonly used.

4.2 Strengthening of Columns

Circular and square columns wrapped with CFRP show improved ultimate load, ductility, and seismic resistance (Lam & Teng, 2009). Confinement effectiveness depends on fibre orientation and number of layers.

4.3 Strengthening of Slabs

FRP laminates applied on the tension face increase punching shear and flexural capacity. NSM bars improve crack control and stiffness (Barros et al., 2007).

4.4 Strengthening of Masonry Structures

FRP composites improve out-of-plane resistance, shear strength, and seismic performance of masonry walls (Triantafillou, 1998).

4.5 Applications in Bridges

FRP systems are widely used in bridge deck strengthening, girder repair, and fatigue enhancement under cyclic loading (El-Safty & Davis, 2011).

5. MECHANICAL BEHAVIOUR AND FAILURE MODES

The structural performance of FRP-strengthened elements depends on bond behaviour, stress distribution, and failure mechanisms.

5.1 Bond Behaviour

The FRP-concrete bond is critical for load transfer. Debonding failure is common and limits strengthening efficiency (Sato et al., 2017).

5.2 Flexural Behaviour

FRP plates delay yielding of steel reinforcement and increase moment capacity. Failure may occur by plate debonding or concrete crushing.

5.3 Shear Behaviour

FRP shear wraps resist diagonal tension cracking, but anchorage quality is essential to prevent premature failure.

5.4 Compressive Behaviour (Confinement)

Confined concrete exhibits bilinear stress–strain behaviour with enhanced ductility (Lam & Teng, 2009).

Table 2. Improvement in Capacity Due to FRP Strengthening

Structural Element	Type of FRP	Increase in Strength (%)	Failure Mode
RC Beam (Flexural)	CFRP Plate	25–80%	Debonding / Crushing
RC Column	CFRP Wrap	40–150%	Rupture / Spalling
RC Slab	GFRP Plate	20–60%	Delamination
Masonry Wall	CFRP Sheet	30–70%	Shear Cracking

(Adapted from Lam & Teng, 2009; Triantafillou, 1998)

6. DURABILITY AND ENVIRONMENTAL EFFECTS

FRP composites are vulnerable to:

- **High temperatures** (loss of resin stiffness)

- **UV exposure**
- **Moisture/alkali attack**
- **Freeze–thaw cycles**

Elevated temperatures (above glass transition temperature, T_g) can reduce strength drastically (Bisby, 2003). Moisture diffusion leads to matrix softening and fibre–matrix debonding.

Durability evaluation is essential for lifecycle prediction.

7. DESIGN CONSIDERATIONS AND GUIDELINES

7.1 International Codes

- **ACI 440.2R-17**: Guide for strengthening concrete structures using FRP
- **fib Bulletin 14**
- **ISO 10406**

These guidelines provide procedures for determining flexural, shear, and confinement capacity.

7.2 Design Limitations

- Linear elastic behaviour until brittle failure
- Debonding before material rupture
- Limited fire resistance
- Need for proper surface preparation

7.3 Safety Factors and Reduction Coefficients

Partial safety factors account for environmental reduction, creep-rupture, and fatigue degradation.

8. CHALLENGES AND LIMITATIONS

Despite the significant advantages of Fibre-Reinforced Polymer (FRP) composites in retrofitting and strengthening existing structures, several challenges and limitations remain that affect their widespread adoption and long-term performance. One of the most critical limitations is the **brittle failure mechanism** of FRP materials, as they behave linearly elastic until rupture and do not provide a ductile warning before collapse. This characteristic imposes strict design controls and reduction factors to ensure safety under unpredictable loading scenarios. In flexural applications, the most frequently observed failure mode is **debonding at the FRP–concrete interface**, which often occurs prematurely before the laminate reaches its full tensile strength. This phenomenon is influenced by substrate surface quality, adhesive properties, and stress concentrations, and it can significantly limit strengthening efficiency.

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Another major challenge is the **temperature sensitivity** of FRP systems. Polymer matrices exhibit reduced stiffness, strength, and bonding capacity when exposed to temperatures approaching or exceeding the glass transition temperature (T_g) of the resin. During fire events or exposure to high heat, this reduction becomes severe, resulting in rapid degradation and potential bond failure. To mitigate this, fire protection coatings or insulation layers are often required, but these increase cost and installation complexity. Similarly, **environmental durability concerns** such as moisture ingress, alkali attack, freeze–thaw cycles, and ultraviolet radiation contribute to long-term degradation of both the laminate and adhesive interface. Although CFRP shows superior resistance to corrosion and environmental exposure, GFRP and AFRP are more vulnerable to chemical attack, necessitating protective systems or selection of high-performance resins.

The **dependence on skilled workmanship** also poses a challenge. Proper installation requires meticulous surface preparation, controlled environmental conditions, accurate resin mixing, and correct laminate placement. Inadequate workmanship can lead to void formation, weak bonding, misalignment, or uneven adhesive thickness, all of which compromise structural performance (ACI 440.2R-17). Additionally, many FRP systems demand stringent quality assurance procedures, including non-destructive testing, strain monitoring, and performance verification, which may not be readily available in all construction environments.

Economic factors also limit FRP adoption in some contexts. Although FRP materials offer a favourable strength-to-weight ratio, the **initial cost of CFRP laminates is relatively high**, especially for large-scale bridge retrofits or multi-storey building rehabilitation projects. This cost factor, combined with the need for specialized labour and inspection, can discourage implementation despite long-term savings from durability and reduced maintenance. Another limitation is related to **compatibility with substrate conditions**. For instance, severely deteriorated or moisture-laden concrete surfaces may not develop sufficient bond strength, requiring preliminary rehabilitation before FRP can be applied.

In structural analysis, modelling FRP–concrete interaction remains complex. The **nonlinear bond–slip behaviour** and progressive interface degradation are difficult to simulate accurately using conventional design equations. Although advanced finite element models have improved prediction accuracy, significant variability in field conditions continues to challenge the reliability of standardized design assumptions. Furthermore, FRP systems are prone to **creep rupture and long-term fatigue**, especially under sustained loads or cyclic environments, raising concerns in bridge engineering and seismic retrofitting applications.

Lastly, the **lack of universal design codes and standardized guidelines** across regions creates inconsistency in engineering practice. While documents such as ACI 440, fib Bulletin 14, and ISO 10406 offer guidance, these standards are still evolving and require continuous refinement based on emerging research and long-term field performance data (ACI 440.2R-17). This evolving design framework may hinder confident adoption of FRP solutions by engineers and regulatory authorities.

9. CONCLUSION

The use of Fibre-Reinforced Polymer (FRP) composites has transformed the field of structural rehabilitation by offering high-strength, lightweight, corrosion-resistant, and easy-to-install solutions for ageing infrastructure. This review highlights that FRP composites significantly enhance the flexural, shear, and axial capacity of reinforced concrete, masonry, and steel structures through various strengthening techniques such as externally bonded reinforcement (EBR), near-surface mounted (NSM) systems, and confinement using wraps. Despite their proven structural benefits, several challenges—including brittle failure modes, bond-interface degradation, temperature sensitivity, and long-term durability concerns—continue to influence design and implementation. The effectiveness of FRP systems strongly depends on substrate preparation, environmental conditions, workmanship quality, and appropriate selection of fibre type and resin system.

Furthermore, while international guidelines such as ACI 440 and fib Bulletins provide valuable design frameworks, ongoing refinement is necessary to incorporate new findings on durability, fire performance, creep behaviour, and hybrid strengthening systems. Recent advancements, including nanomodified polymers, hybrid FRP-steel systems, automated application technologies, and smart monitoring tools, indicate a promising future for FRP strengthening. Overall, FRP composites remain one of the most reliable and adaptable solutions for the sustainable strengthening and life-extension of existing structures. Continued research, field validation, and development of standardized design methodologies will further enhance confidence and expand the global adoption of FRP-based retrofitting.

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