

## Carbon Fiber in Structural Reinforcement and Retrofitting

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**Abstract** - The rapid deterioration of civil infrastructure, compounded by seismic vulnerability and environmental exposure, necessitates advanced retrofitting techniques to ensure long-term safety and serviceability. Conventional methods such as steel jacketing and concrete encasement are often limited by increased dead load, corrosion susceptibility, and labor intensity. In this context, carbon fiber reinforced polymer (CFRP) composites have emerged as a highly effective alternative owing to their superior tensile strength, low density, corrosion resistance, and ease of application. This dissertation presents a comprehensive review and synthesis of the application of CFRP in the structural retrofitting of reinforced concrete (RC) and steel members. The fundamental properties, manufacturing processes, and performance characteristics of carbon fibers are first discussed to establish the material context. Subsequently, experimental and analytical investigations on CFRP retrofitting of beam-column joints, RC columns, and entire RC frames are critically examined, with particular emphasis on seismic performance, hysteresis behavior, and energy dissipation. In addition, the role of CFRP in strengthening steel structures is analyzed, including bond behavior, fatigue resistance, and failure modes. The advantages of CFRP, such as high strength-to-weight ratio and durability, are weighed against limitations including debonding, anchorage challenges, and cost considerations. Recent advances in hybrid retrofitting strategies and smart health monitoring of CFRP retrofits are also highlighted. The review underscores that CFRP-based retrofitting significantly enhances load-bearing capacity, ductility, and seismic resilience of structural systems, positioning CFRP as a sustainable and innovative solution for extending the service life of aging infrastructure. Future research directions include cost optimization, large-scale field applications, and integration with digital monitoring technologies for real-time performance assessment.

**Key Words:** CFRP, Retrofitting, Carbon Fiber, Reinforcement, Carbon Fiber Retrofitting

### 1. INTRODUCTION

#### 1.1 Background of Infrastructure Ageing and Seismic Vulnerability

Civil infrastructure such as bridges, buildings, and industrial facilities across the globe is increasingly under pressure due to aging, overloading, and seismic events (Durgadevi et al., 2021). In the United States, more than 60% of bridges are rated as structurally deficient or in need of rehabilitation, while in rapidly urbanizing Asian countries such as India and China, a large percentage of urban reinforced concrete (RC) buildings are beyond their design service life (Sapidis et al., 2024). Aging results in reduced strength, stiffness, and durability of materials, while poor detailing in older construction further amplifies structural risks (Zhou et al., 2024).

Seismic vulnerability adds another dimension to infrastructure deterioration. Earthquakes in Japan (2011), Nepal (2015), and Turkey–Syria (2023) caused widespread collapses of poorly detailed RC frames, underscoring deficiencies in beam-column joints and columns (Lee and Lee, 2025). These failures were often brittle, providing little warning before collapse. The deterioration of concrete structures is further exacerbated by chloride penetration, carbonation, and poor construction quality, leading to corrosion of steel reinforcement and a reduction in structural capacity (Lee and Lee, 2025). The combination of aging and seismic vulnerability makes structural retrofitting a critical necessity for modern societies (Moghadam et al., 2024).

#### 1.2 Need for Retrofitting and Rehabilitation

Replacing existing infrastructure with new construction is often neither economically feasible nor environmentally sustainable. Demolition generates significant waste and carbon emissions, while new construction demands enormous financial resources and time (Ashteyat et al., 2023). Retrofitting, by contrast, offers an efficient solution: it strengthens existing structures, prolongs their lifespan, and reduces downtime.

Traditional strengthening methods include steel jacketing, reinforced concrete overlays, and composite jacketing. Steel jacketing provides confinement but introduces additional dead load and is prone to corrosion (Ashteyat et al., 2023). RC overlays improve strength but reduce usable space and often fail to bond effectively with the existing structure (Zhou et al., 2024). Both methods require heavy labor and prolonged downtime, which are not ideal in urban infrastructure projects (Durgadevi et al., 2021).

Retrofitting is therefore seen as a more efficient alternative to full replacement, as it enhances existing structures without demolition (Sapidis et al., 2024). Rehabilitation using lightweight, durable, and non-corrosive materials allows for safer and cost-effective strengthening. The development of advanced materials, particularly fiber-reinforced polymers (FRPs), has addressed many of the shortcomings of traditional approaches (Lee and Lee, 2025).

#### 1.3 Emergence of Fiber Reinforced Polymers (FRPs)

Fiber-reinforced polymers (FRPs) consist of high-strength fibers embedded in a polymeric matrix, with glass fiber reinforced polymer (GFRP), basalt fiber reinforced polymer (BFRP), and carbon fiber reinforced polymer (CFRP) being the most common (Durgadevi et al., 2021). Among these, CFRP has emerged as the preferred choice for structural retrofitting due to its exceptional tensile strength (2000–4000 MPa), high stiffness, light weight, and superior durability under harsh environments (Sapidis et al., 2024).

Carbon fiber reinforced polymer is non-corrosive and resistant to environmental degradation, such as chloride penetration and carbonation, making it particularly suitable for coastal and

industrial regions (Lee and Lee, 2025). It has been successfully applied in RC beams, slabs, columns, and joints, as well as in steel structures such as bridges and girders (Moghadam et al., 2024). Carbon fiber reinforced polymer provides significant gains in ductility, shear strength, and fatigue life, while its lightweight nature ensures minimal increase in dead load (Ashteyat et al., 2023).

#### 1.4 Traditional Retrofitting Methods

Conventional methods such as steel jacketing and concrete encasement have limitations, including increased dead load, loss of usable space, and susceptibility to corrosion (Durgadevi et al., 2021). For instance, steel jacketing often leads to accelerated deterioration when exposed to moisture, while concrete encasement increases section size and is often impractical in congested urban environments (Lee and Lee, 2025).

By contrast, CFRP retrofitting is easy to apply, requires less labor, and can be carried out with minimal interruption to service. It has shown promising results in both experimental and analytical studies, making it a reliable solution for seismic strengthening (Zhou et al., 2024). Carbon fiber reinforced polymer addresses the limitations due to its lightweight, non-corrosive, and highly adaptable properties. It can be externally bonded as sheets, strips, or laminates with minimal surface preparation. Installation is relatively quick, requiring less downtime compared to traditional techniques (Zhou et al., 2024). Moreover, CFRP retrofitting does not significantly alter the geometry of structural members, making it particularly advantageous in urban settings where space is limited (Saeed and Hejazi, 2025).

#### 1.5 Applications of Carbon Fiber Reinforced Polymers in Retrofitting

Carbon fiber reinforced polymers have been widely applied to RC structures, particularly in beams and column joints, where they prevent brittle shear failures (Sapidis et al., 2024). In columns, CFRP provides confinement, delaying bar buckling and improving hysteresis performance (Lee and Lee, 2025). In steel structures, CFRP laminates improve fatigue resistance and extend service life by reducing crack growth (Moghadam et al., 2024).

Experimental studies consistently report that CFRP retrofitting increases load capacity by 30–60% and ductility by 25–40%, with significant improvements in seismic energy dissipation (Zhou et al., 2024). These benefits make CFRP one of the most effective retrofitting materials available today.

Carbon fiber reinforced polymer has been widely applied to enhance both RC and steel structures:

- **Reinforced Concrete Beams and Joints:** Carbon fiber reinforced polymer wrapping improves shear resistance, delays crack propagation, and prevents brittle failures in beam–column joints (Sapidis et al., 2024). Studies report a 30–40% increase in load capacity and significant improvements in ductility (Ashteyat et al., 2023).
- **Reinforced Concrete Columns (RCC):** Carbon fiber reinforced polymer confinement enhances axial load capacity and hysteresis performance, increasing ductility by up to 40% (Lee and Lee, 2025). Partial wrapping strategies

reduce costs while maintaining most of the performance gains (Zhou et al., 2024).

- **Reinforced Concrete Frames:** Carbon fiber reinforced polymer retrofitting shifts failure mechanisms from brittle column hinges to ductile beam hinges, enhancing seismic resilience (Prieto et al., 2025).
- **Steel Structures:** Carbon fiber reinforced polymer laminates bonded to steel beams extend fatigue life by 2.5 times and increase flexural strength by up to 60% (Moghadam et al., 2024). Hybrid CFRP–steel plate retrofitting strategies further improve bond durability.

These diverse applications highlight CFRP's versatility as a retrofitting material capable of addressing challenges in both RC and steel structures.

#### 1.6 Research Motivation and Objectives

Despite its advantages, CFRP retrofitting faces limitations such as debonding failures, anchorage inefficiencies, and relatively high material costs (Sapidis et al., 2024). Furthermore, large-scale field applications remain limited, and most studies are confined to laboratory conditions (Moghadam et al., 2024).

This dissertation aims to:

- Critically evaluate CFRP applications in retrofitting RC and steel structures.
- Analyze experimental evidence regarding its seismic and fatigue performance.
- Compare CFRP with other FRPs such as GFRP and BFRP.
- Identify research gaps, including anchorage optimization, hybrid retrofitting strategies, and smart monitoring integration.

By addressing these objectives, this work provides a comprehensive understanding of CFRP's role in structural reinforcement and its potential for large-scale applications (Lee and Lee, 2025).

## 2. REVIEW OF LITERATURE

### 2.1 Retrofitting of Reinforced Concrete Structures with FRPs

Reinforced concrete (RC) structures form the backbone of global infrastructure, but their vulnerability to seismic loading, environmental deterioration, and overloading has been repeatedly demonstrated (Durgadevi et al., 2021). Retrofitting using fiber-reinforced polymers (FRPs) has emerged as a sustainable solution to extend the service life of RC structures without resorting to demolition and reconstruction (Ashteyat et al., 2023; Saeed and Hejazi, 2025). The application of fiber-reinforced polymers (FRPs) in retrofitting has transformed structural rehabilitation practices over the last three decades. Unlike traditional techniques such as steel jacketing or RC overlays, FRPs provide high strength-to-weight ratios, ease of installation, and superior durability compared to steel jacketing or RC encasement (Sapidis et al., 2024).

Different types of FRPs like GFRP, BFRP, and CFRP have been applied in beam, column, and slab retrofitting. Experimental studies confirm that FRP-retrofitted beams demonstrate enhanced flexural and shear capacities. For example, CFRP sheets bonded along beam soffits improved ultimate flexural strength by up to 40% and reduced crack propagation by nearly 50% compared to control specimens (Durgadevi et al., 2021). Comparative studies indicate that

while GFRP and BFRP offer cost advantages, CFRP provides superior tensile strength, stiffness, and long-term performance (Zhou et al., 2024). For instance, CFRP-wrapped RC beams demonstrated up to 35% higher load capacity and reduced service deflections by 20% compared to un-retrofitted specimens (Durgadevi et al., 2021). These findings confirm CFRP's suitability for upgrading RC structures in seismic regions.

The global trend has shifted towards FRP retrofitting due to increasing seismic demand. Post-earthquake surveys in Nepal (2015) and Turkey–Syria (2023) revealed that retrofitted structures exhibited better resilience than un-retrofitted buildings (Lee and Lee, 2025). This highlights FRPs as not just a strengthening tool but also a seismic risk mitigation strategy (Moghadam et al., 2024).

## 2.2 Fundamentals of Carbon Fiber

### 2.2.1 Carbon Fiber

Carbon fiber is a polymer and is also known as graphite fiber. It is a very strong material and very lightweight. Carbon fiber is five times stronger than steel and twice as stiff. Though carbon fiber is stronger and stiffer than steel, it is lighter than steel, making it the ideal manufacturing material for reinforcement and retrofitting. These are just a few reasons why carbon fiber is favored by engineers and designers for manufacturing.

### 2.2.2 Brief History of Carbon Fiber

Work on carbon fiber started about 1879 when Thomas Edison baked cotton threads or bamboo silvers at high temperatures, which carbonized them into an all-carbon fiber filament. By 1958, high-performance carbon fibers were invented just outside of Cleveland, Ohio. Although they were inefficient, these fibers contained around 20% carbon and had low strength and stiffness properties.

In 1963, a new manufacturing process was developed at a British research center, which is where carbon fiber's strength potential was realized.

### 2.2.3 Manufacturing Process

Carbon fiber is made from a process that is part chemical and part mechanical. It starts by drawing long strands of fiber and then heating them to a very high temperature without allowing contact with oxygen to prevent the fiber from burning. This is when carbonization takes place, which is when the atoms inside the fiber vibrate violently, expelling most of the non-carbon atoms. This leaves a fiber composed of long, tightly interlocked chains of carbon atoms with only a few non-carbon atoms remaining. A typical sequence used to form carbon fibers from polyacrylonitrile (PAN) involves spinning, stabilizing, carbonizing, treating the surface, and sizing. In figure -1 Manufacturing Process of Carbon Fiber Process Flow Chart is shown in detail.

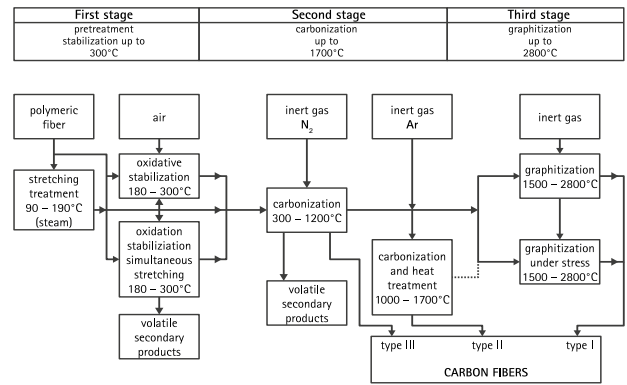


Figure 1. Process flow chart

(doi:10.1002/cite. 330431607 (1971) - Page 2: [https://project-wire-scanner.web.cern.ch/project-wire-scanner/Meetings\\_files/CarbonFibers.pdf](https://project-wire-scanner.web.cern.ch/project-wire-scanner/Meetings_files/CarbonFibers.pdf), Public Domain, <https://commons.wikimedia.org/w/index.php?curid=43757804> )

In a first process step, thin threads are produced from it, which are then wound onto a spool-the so-called PAN "precursor" has been created. (SGL Carbon). Figure 2 describes the overview of production processes.

In the next step, these threads are placed in the oven. First, they are oxidized at 200-300 °C and then carbonized at 1200-1800 °C. What remains are threads with a very high carbon content and high strength. After surface treatment and application of a sizing, the carbon Fiber is wound up and is ready for use. (SGL Carbon)

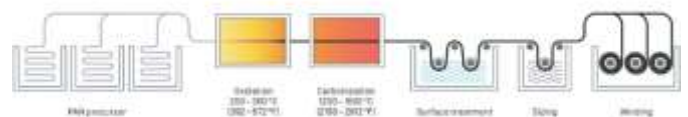


Figure 2. Overview of the production process of our carbon Fibers (© SGL Carbon)

### 2.2.4 Carbon Fiber in Structural Engineering

Carbon fiber has characteristics of high strength, high modulus, low density, and low coefficient of linear expansion compared to titanium, steel, aluminum, and other metal materials. So, it can be called “The King of New Advanced Materials”. A spool of Carbon Fiber is shown in Figure-3.



Figure 3. SikaWrap® 300 C #EN352 Structural Reinforcement FRPs

The tensile strength of carbon fiber is about 2 to 7GPa, and the tensile modulus is about 200 to 700GPa. The density is about 1.5 to 2 g/cm<sup>3</sup>, which is mainly determined by the temperature of carbonization, except for the structure of the precursor. Generally, the density can reach 2 g/m<sup>3</sup> after high-temperature graphitization treatment at 3000 °C. The weight is light, and its weight is lighter than aluminum, and it is less than 1/4<sup>th</sup> of the steel, and 20 times more than the strength of the iron. The thermal expansion coefficient of carbon fiber is different from that of other fibers, and it has the characteristic of anisotropy. The specific heat capacity of carbon fiber is generally 7.12. The thermal conductivity decreases as the temperature rises, and the direction of the fiber parallel to the fiber is negative (0.72 to 0.90), while the direction perpendicular to the fiber is positive. The specific resistance of carbon fiber is related to the type of fiber. This makes the carbon fiber with the highest specific strength and specific modulus in all high-performance fibers.

Carbon fiber is highly fire-resistant but not fireproof. It itself remains structurally sound at very high temperatures, with little strength loss even at 600 °C. It has a high limiting oxygen index (LOI), meaning it requires a much higher oxygen concentration in the air to ignite than is normally present.

### 2.2.5 Carbon Fiber Reinforcement

As an advanced method, CFRP systems are used for structurally strengthening concrete elements in buildings and infrastructure.

Specifically, CFRP sheets or plates made of high-strength carbon fibers embedded in an epoxy resin matrix are bonded to the surface of concrete members such as beams, columns, walls, and slabs by using adhesives.

With their extremely high strength and stiffness properties, these lightweight CFRP materials can increase the flexural, shear, and fatigue strengths of the concrete member.

### 2.3 CFRP in Beam–Column Joints

Beam-column joints are among the most critical regions in reinforced concrete (RC) structures, as they transfer loads between beams and columns and are particularly vulnerable during earthquakes (Sapidis et al., 2024; Zhou et al., 2024). Several experimental investigations have demonstrated that poor detailing in these joints leads to brittle shear failures, which significantly reduce overall structural performance under seismic loading. To address these deficiencies, externally bonded CFRP sheets and CFRP ropes have been applied to improve shear strength and ductility. Studies have shown that CFRP retrofitting enhances the load-carrying capacity of RC beams by 30-40% and reduces service deflections by nearly 20% compared to un-retrofitted control specimens (Durgadevi et al., 2021; Zhou et al., 2024).

In a study, Sapidis et al. (2024) investigated full-scale RC beam-column joints retrofitted with CFRP ropes and monitored their performance using the electro-mechanical impedance (EMI) technique. The results indicated that the CFRP ropes significantly increased the shear strength of the joints and improved energy dissipation under cyclic loading. Furthermore, the integration of EMI monitoring allowed for real-time assessment of retrofitting effectiveness, reducing the need for destructive testing (Sapidis et al., 2024).

Experimental results from Ravikant et al. (2023) further revealed that CFRP-wrapped beam–column joints exhibited improved hysteresis behavior, with more stable loops and reduced stiffness degradation compared to control specimens. The retrofitted joints maintained nearly 80% of their peak load after multiple load cycles, while unretrofitted joints dropped below 50% (Lee and Lee, 2025). This confirms that CFRP not only strengthens joints but also improves their ability to withstand repeated seismic cycles.

The CFRP-retrofitted joints had greater energy dissipation and less stiffness degradation after repeated cyclic loading compared to un-retrofitted joints. Similarly, CFRP wrapping reduced crack widths in beam–column joints significantly, increasing serviceability and delaying brittle shear failures.

Moreover, CFRP retrofitting has proven to be effective in controlling crack propagation in beams. Carbon fiber reinforced polymer strips applied along the flexural tension zone reduced crack widths by 40–50% under service loads, thus increasing serviceability and extending structural lifespan (Durgadevi et al., 2021; Zhou et al., 2024). These findings make CFRP particularly valuable in retrofitting existing urban RC building stock where brittle failure poses significant safety risks.

### 2.4 CFRP in Columns and Hysteresis Performance

Reinforced concrete columns are the primary load-bearing members in buildings, and their failure often leads to catastrophic collapse. Carbon fiber reinforced polymer confinement of columns has emerged as a widely studied strengthening technique, with significant improvements reported in axial load capacity, ductility, and energy absorption (Zhou et al., 2024; Lee and Lee, 2025). Column confinement delays cover spalling, prevents buckling of longitudinal reinforcement, and transforms brittle shear failure into ductile flexural behavior (Lee and Lee, 2025). In hysteresis testing of CFRP-retrofitted columns, Lee and Lee (2025) reported a 25-40% increase in ductility and 30% higher energy dissipation compared to control specimens. The carbon fiber reinforced polymer jackets transformed shear-dominated brittle failures into ductile flexural failures, thereby increasing seismic resilience. Similarly, CFRP confinement increased the axial load capacity of RC columns by up to 50% while reducing residual deformations after cyclic loading (Ashteyat et al., 2023; Wang et al., 2023).

Hybrid approaches, such as combining CFRP with GFRP, have also been tested. While CFRP provides strength and stiffness, GFRP reduces costs, creating a balance between performance and affordability (Saeed and Hejazi, 2025). Partial CFRP wrapping around plastic hinge regions has been reported to provide ductility gains nearly equivalent to those of full wrapping, demonstrating cost-efficient retrofitting strategies (Zhou et al., 2024).

### 2.5 Seismic Performance Improvements in RC Frames

Carbon fiber reinforced polymer retrofitting has been extended to entire RC frames, where global seismic performance is evaluated. Zhou et al. (2024) conducted pseudo-static tests showing that CFRP-retrofitted frames increased peak load by over 40% and ductility by about 30% than control frames.

Importantly, CFRP retrofitting was found to alter the failure mechanisms of RC frames. Control frames typically failed due to brittle column hinge failures, while CFRP-retrofitted frames shifted failure to beam hinges, a more ductile and predictable mechanism (Lee and Lee, 2025). This shift is crucial in seismic design, as ductile failure mechanisms enable structures to sustain large deformations without collapse. Pseudo-static and shake table tests confirm these findings. Wu et al. (2023) demonstrated that CFRP wrapping of columns and joints within RC frames enhanced lateral drift capacity by 25% and delayed stiffness degradation. It was found that CFRP-retrofitted school buildings in seismic-prone regions of India sustained significantly lower damage levels during moderate earthquakes.

Compared with GFRP and BFRP retrofitting of RC frames, CFRP consistently delivered superior improvements in strength and ductility. Their results indicated that GFRP retrofitting increased load capacity by only 15-20%, while CFRP achieved more than double this improvement. These findings highlight CFRP's role as the most effective FRP for seismic retrofitting of RC frames.

## 2.6 CFRP for Steel Structures – Bond Behavior and Failure Modes

Steel structures, particularly bridges and industrial frames, are prone to fatigue cracks and corrosion. Carbon fiber reinforced polymer retrofitting has been applied as a modern alternative to steel plate bonding, offering superior fatigue resistance and flexural strengthening (Delzende Moghadam et al., 2024). Laboratory fatigue tests revealed that CFRP-strengthened steel beams lasted up to 2.5 times longer under cyclic loading than control specimens (Ashteyat et al., 2023).

The effectiveness of CFRP in steel retrofitting depends significantly on the bond behavior between CFRP and the steel substrate. Studies indicate that adhesive thickness, stiffness, and surface preparation critically influence bond strength and durability (Prieto et al., 2025). Failure modes in CFRP-steel systems often involve debonding at the adhesive interface, underscoring the need for anchorage devices or hybrid retrofitting techniques (Delzende Moghadam et al., 2024).

In flexural strengthening applications, CFRP laminates bonded to the tension flange of steel beams, which increased ultimate load capacity by 30–60% depending on adhesive type and thickness (Delzende Moghadam et al., 2024). Bond-slip studies emphasize that adhesive selection plays a critical role: stiff adhesives provide better initial stiffness, while flexible adhesives enhance fatigue resistance (Ashteyat et al., 2023).

Hybrid retrofitting strategies, such as combining CFRP laminates with bolted steel plates, have also been developed to overcome debonding problems. These methods enhance both flexural strength and bond durability, making them suitable for long-span bridges under repeated traffic loading (Sapidis et al., 2024).

## 2.7 Advantages of CFRP

Although CFRP demonstrates the highest strength and durability, cost considerations have led researchers to compare its performance with GFRP and BFRP. Durgadevi et al. (2021) concluded that while CFRP offers the best mechanical performance, GFRP provides a cost-effective alternative for

low-demand retrofitting applications. Basalt fiber reinforced polymer, on the other hand, has gained attention for being environmentally sustainable and offering good thermal resistance (Zhou et al., 2024). The Comparative performance of FRP Types shown in Table-1.

- **High tensile strength and stiffness** → ensure substantial improvement in load capacity (Sapidis et al., 2024).
- **Corrosion resistance** → Carbon fiber reinforced polymer does not rust, making it suitable for marine and humid environments (Lee and Lee, 2025).
- **Lightweight** → adds minimal dead load compared to steel jacketing (Zhou et al., 2024).
- **Ease of application** → Carbon fiber reinforced polymer sheets and laminates can be externally bonded with minimal disruption (Ashteyat et al., 2023).

**Table 1. Comparative Performance of FRPs in Retrofitting Applications**

FRP Types	Tensile Strength	Durability	Cost	Main Advantage	Limitations	References
CFRP	2000-4000 MPa	Excellent	High	High stiffness, corrosion resistance	Cost, debonding risk	Sapidis et al. (2024); Zhou et al. (2024)
GFRP	1000-1500 MPa	Moderate	Low	Cost-effective, widely available	Lower stiffness, moisture sensitive	Durgadevi et al. (2021)
BFRP	1500-2000 MPa	High	Med	Eco-friendly, thermally stable	Less strong than CFRP	Durgadevi et al. (2021)

## 2.8 Limitations of CFRP

Despite its advantages, CFRP retrofitting faces several limitations:

- **Debonding failures:** Poor surface preparation or adhesive selection can cause early debonding, reducing effectiveness (Delzende Moghadam et al., 2024).
- **Anchorage issues:** CFRP sheets often require anchorage devices to prevent peeling and ensure full utilization of strength (Zhou et al., 2024).
- **High cost:** CFRP is significantly more expensive than GFRP or BFRP, limiting its widespread adoption in cost-sensitive regions (Saeed and Hejazi, 2025).
- **Skilled labor:** Application requires specialized training, which is not always available in developing regions (Ashteyat et al., 2023).

These limitations necessitate continued research on hybrid retrofitting (CFRP + GFRP), improved adhesives, and anchorage techniques.

## 2.9 Smart Monitoring with CFRP

Integration of CFRP retrofitting with smart monitoring systems, such as EMI and piezoelectric sensors, allows real-time performance assessment (Sapidis et al., 2024). Sapidis et al. (2024) demonstrated that the electro-mechanical impedance

(EMI) method, combined with piezoelectric (PZT) sensors, effectively detected debonding between CFRP and concrete surfaces. This method enables early detection of failure, reducing maintenance costs and enhancing safety.

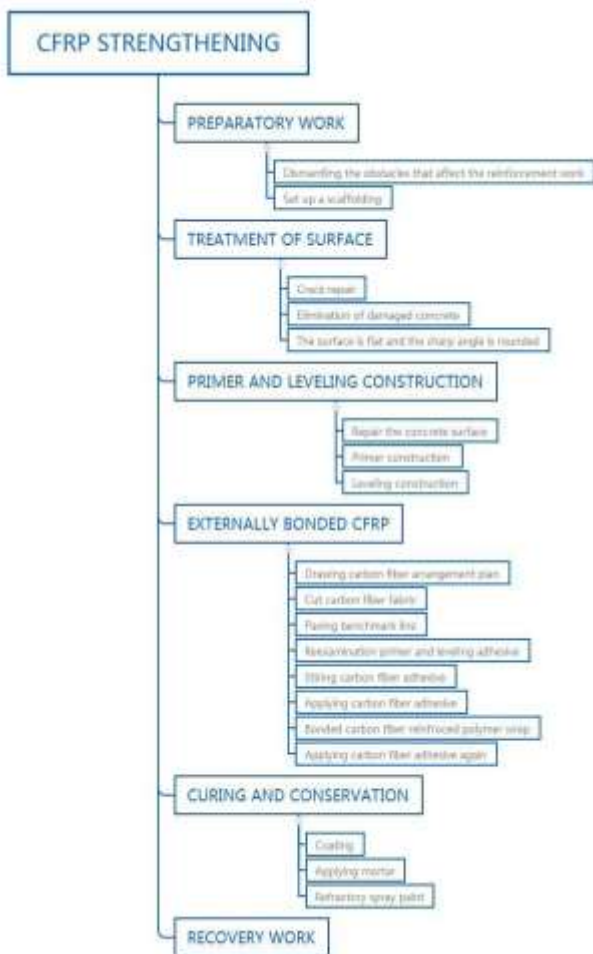
Artificial intelligence and machine learning techniques have been applied to EMI signal data to detect micro-cracks and bond failures with high accuracy (Ashteyat et al., 2023). This transforms CFRP retrofitting from a passive strengthening method into an intelligent structural health management system.

### 3. METHODOLOGIES

#### 3.1 Complete process of CFRP retrofitting

The purpose of bonding CFRP wrap is to reinforce the engineering structure. The construction precautions require that the direction of force be determined. The direction of the bonding fiber cloth is consistent with the direction of force, and it cannot be mistaken. Fiber cloth must be laid flat, not folded or bent. Special rolling wheels must soak the impregnating glue, and the air bubbles must be eliminated.

##### i) Flow chart of FRP strengthening



##### ii) FRP Construction Profile

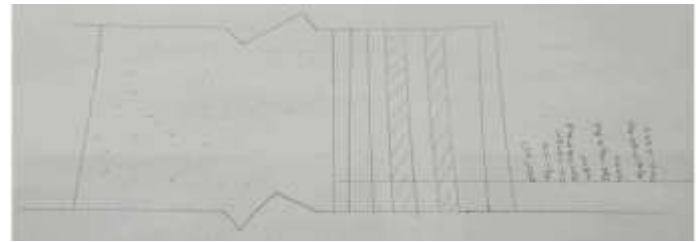


Figure 4. FRP Construction Profile

#### 3.1.2 Construction Procedures and Technologies of CFRP Strengthening.

##### i. Surface treatment of reinforced concrete

- Surface treatment should achieve three objectives: to ensure that the structure body and the Fiber cloth are firmly bonded, to remove rust, decontamination, and to purify the aging parts of the concrete surface; to use structural adhesives to repair cracks, fill holes, adjust height difference, and cut sharp corners, to ensure that the carbon fiber cloth is bonded to a reliable base.
- The exposed part of the reinforcing bar should be treated with anti-rust treatment. If the damage is serious, measures should be taken to remedy it.
- Crack repair. If the crack is more than 5 mm, the high-strength cement mortar is used to pour; the crack width is more than 0.1 mm and less than 5 mm. The special chemical crack-filling glue is used to fill the crack. The crack is mainly injected at low pressure and slowly, and the grinding modification is flat after curing. The crack width is less than 0.1 mm, and the sealing glue is used to seal the crack.
- Surface repair: If there are defects, holes, or honeycomb linen on the bonded concrete surface, repair glue should be used.
  - Repair of defects or holes. In the construction of the original structure or in the later period of operation, the structure will have defects, holes, and a honeycomb-like surface, which must be repaired with repairing glue.
  - Height adjustment. Because of the high and low surface of concrete caused by the dislocation of formwork, it must be repaired before bonding Fibers. Large areas can be repaired with high
- Surface dirt and carbide treatment. By means of disc grinder, sand blasting, and high-pressure water washing, the surface is treated to a flat, regular, non-loose, non-fragile, and non-dirty surface. Oil and grease contaminants are degraded with neutral detergent, dust is removed by high-pressure air gun, and the concrete surface before bonding fiber cloth must be fully dried.
- Angle trimming. To prevent fiber cloth from peeling or pulling up easily when bonding, the fillet can be repaired with repairing mortar, and the fillet radius R should meet the requirements of the specifications. For a prismatic or sharp convex structure, the fibers at the sharp corners will have greater stress concentration, which will easily break the carbon fibers, so it must be treated. The edges and corners can be modified into an arc of radius (R) by a grinder. Surface modification with repair glue and detection with arc gauge ensure that the modification angle radius R meets the requirements of specifications (special structure according to relevant specifications).



Figure 5. Equipment used for grinding and trimming

## ii. Primer Coating

- a. The purpose of using base glue is to strengthen the bond between concrete and fiber cloth or repair glue. The base glue can be immersed in concrete to increase the surface strength of the concrete.
- b. Environmental temperature, humidity, and drying degree of concrete surface affect the bonding performance of the bottom bond. The construction environment temperature should not be lower than 5 °C, humidity should not be higher than 85%, and the drying condition of the concrete surface moisture content should be less than 10%.
- c. The amount of glue should not be too much at one time, and it should be used up within 45-60 minutes after preparation in general; the glue should be stirred by low-speed mechanical stirring, which may heat up during stirring, and the stirring time should not be too long, and 3 minutes is the appropriate time.
- d. Roller brush is used to coat the glue evenly. The amount of coating depends on the type of base glue and the surface condition of the concrete. The concentration of base glue is low, and the general dosage standard is 0.25-0.3 kg/m<sup>2</sup>. The base glue should be coated 1-2 ways. If the concrete is extremely carbonated and the amount of soaking is large, the number of coatings should be increased. After the drying is confirmed by finger contact, the next process (which usually takes a day to maintain) is continued.

## iii. Repairing glue for repairing concrete

- a. The purpose of repairing glue is to ensure that the construction surface is smooth and there is no bubble bulging between the concrete surface and the fiber cloth. The concave-convex holes and height difference of the concrete surface should be repaired.
- b. The base glue should be repaired immediately after drying. If the time interval is more than 10 days, the surface should be polished with sandpaper before using the repairing glue. In the case of a honeycomb linen surface, the concrete surface should be fully coated and repaired. The dosage varies according to the surface condition. The general dosage is 0.5-1.5 kg/m<sup>2</sup>. Usually, curing for 24 hours, confirming curing, and then continuing the next process. When air bubbles occur on the construction surface of the repairing glue due to the internal gas of concrete, the air bubbles are ground flat by an angle mill.

## iv. Impregnating Glue Undercoat

- a. The purpose of applying impregnating adhesives is to bond concrete to fiber cloth. Construction Notes: The impregnating glue must be fully immersed. The special rollers are used to roll the fiber cloth in one direction. The

- arch and corner parts are prone to air retention. The special toothed defoaming drum is used to remove the retained air.
- b. Curing time, the mixing amount of each glue should be calculated according to the coating area in the construction time, and the mixing must be sufficient. Special attention should be paid to the difficult mixing place at the bottom corner of the mixing vessel.
- c. The coating should be uniform, the amount of glue should be based on the soaking fiber cloth, and the glue should not be too much. The excess glue should be extruded by special equipment. The amount of glue should be different depending on the surface condition of the concrete and the specifications of fiber cloth. The general amount of glue used for one layer is 0.5-0.7 kg/m<sup>2</sup>.



Figure 6. Glue Coating

## v) Sticking Fiber Cloth

- (a) The purpose of bonding fiber cloth is to reinforce the engineering structure. The construction precautions are as follows: the direction of force must be determined, and the direction of fiber bonding is consistent with the direction of force and cannot be mistaken; the fiber cloth must be laid flat, not folded, not bent; the impregnating glue must be rolled and soaked with a special rolling wheel, and the air bubbles must be eliminated.
- (b) Cutting dimensions should include overlapping parts in both vertical and horizontal directions. Cutting carbon fibers cannot be folded. Before laying, they must be rolled on a round roll with radius R (> 80mm) to avoid damage. If the cut fabric is not used up on the same day, it should be sealed and stored in a dustless, dry, and sunless place.
- (c) Fiber cloth must be laid along the positioning line. Multilayer pasting should be carried out layer by layer. The second layer must be laid after the first layer is solidified. Multilayer fiber cloth must not be pasted once. When many pieces of fiber cloth are pasted in one place, one piece of the center should be pasted first and then extended to both sides. When the fiber cloth is pasted at the outer convex corner, the fiber cloth should not break. When pasting the concave angle, the rubber roller with the same radius is used to extrude the concave angle, to avoid the pulling force, and ensure the fiber location at the concave angle. When rolling, roll along in the direction of force; do not force back and forth.
- (d) Fiber lap length. In general, the direction of fiber is 100 mm (in Japan, the road engineering and residential engineering is 200 mm). There is no need to overlap between the two pieces in the vertical direction of the fibers (there is also a requirement to overlap more than 30

mm). In the middle of the pasted fabric area, if there are openings, iron plates, and other obstructions, the cutting of the fabric should be planned, and the weakened parts should be prepared for reinforcement.

- (e) Maintenance. In order to prevent rain and dust from adhering to fiber cloth during outdoor construction, it is necessary to use plastic cloth for maintenance. After bonding the fiber cloth, cover it with plastic cloth for more than 24 hours for maintenance. The initial curing time is about 2 days when the average temperature is below 10 °C, and the initial curing time is about 1-2 days when the average temperature is 10-20 °C. The initial curing time is about 1 day when the average temperature is above 20 °C. Complete curing requires a long time. Generally, more than 80% of the cured material can be subjected to loading. The average period required to attain sufficient strength for loading is approximately 7 days when the ambient temperature is maintained above 20 °C, and about 14 days when the ambient temperature is maintained above 10 °C.

**vi) Impregnating Adhesive Coating**

- (a) Purpose: Surface protection or preparation for bonding of the next layer of fiber cloth.
- (b) After coating and before curing, check whether the fabric is floating, bulging, or peeling. If so, it should be repaired immediately.
- (c) Floating and bulging parts, before solidification, are rolled in the direction of Fibers with a defoaming roll to expel bubbles; if floating and bulging have solidified, exhaust holes can be opened and filled with syringe glue.



Figure 7. CFRP Works in Retrofitting

**4. THEORETICAL CONSIDERATIONS**

In reinforced concrete column structures, crack development is a common phenomenon. The various factors and loading conditions are considered for it. It can occur due to structural, material, environmental, or construction-related causes. In this study, only structural cracks are taken into consideration.

Structural Cracks are categorized as the following: -

- **Flexural Cracks-** These cracks, usually vertical cracks, occur in the tension face (Bottom of Beam or Slab) due to the bending moment. Initially, the cracks are narrow near the surface and widen over time under continuous high loading.
- **Shear Cracks-** These cracks have often appeared at a 45-degree angle in the beams. It is caused by excessive shear force and bending moments.

- **Torsional Cracks-** They develop due to twisting force along with bending moments. The pattern is spiral or diagonal around the beam.
- **Column Cracks-** They are vertical cracks due to axial compression, i.e., overload. It can also occur due to eccentricity and buckling load.

**4.1 Retrofitting of RCC Structure using CFRP**

Carbon fiber reinforced polymer strengthening is a modern technique to enhance the load-carrying capacity and durability of existing RCC structures without significantly increasing the dead load, as was used in conventional jacketing by steel.

**4.2 Carbon Fiber Retrofitting Polymer**

Carbon fiber reinforced polymer retrofitting is required as the systems offer a lightweight, corrosion-resistant, and high-strength alternative.

**4.3 Material Properties of CFRP:**

Carbon fiber-reinforced polymer is a composite material consisting of carbon fibers, which provide high tensile strength and stiffness, and an epoxy resin matrix, which transfers stresses and bonds the fibers to the concrete. Comparative mechanical properties are shown in Table 2.

Table 2. Mechanical Properties (Typical Values)

Property	CFRP	Steel
Tensile Strength	2000–4000 MPa	415–550 MPa
Density	~1.6 g/cm <sup>3</sup>	7.85 g/cm <sup>3</sup>
Modulus of Elasticity	150–250 GPa	200 GPa
Corrosion Resistance	Excellent	Poor

**4.4 Forms of CFRP Used in Retrofitting**

- CFRP Sheets (Wet Lay-up)
- Pre-cured CFRP Laminates/Plates
- CFRP Strips
- Near Surface Mounted (NSM) CFRP Bars

**4.5 Applications in RCC Structures**

**4.5.1 Flexural Strengthening of Beams:** CFRP sheets are bonded to the tension face (bottom surface). It increases moment capacity and reduces crack width.

Mechanism: CFRP takes additional tensile stress after steel yields.

**4.5.2 Shear Strengthening:** CFRP sheets are applied in:

- U-wrap configuration
- Full wrap configuration

These improve diagonal tensile strength and prevent shear failure.

**4.5.3 Column Confinement:** CFRP wrapping around columns:

- Enhances compressive strength
- Improves ductility
- Delays buckling of longitudinal reinforcement

- Improves seismic performance

Confinement increases lateral pressure on the concrete core.

#### 4.5.4 Slab and Bridge Strengthening: Used in:

- Bridge girders
- Industrial floors
- Parking structures
- Water tanks

#### 4.6 Installation Procedure (Wet Lay-Up Method)

##### Step 1: Surface Preparation

- Remove loose concrete
- Grind surface
- Repair cracks
- Ensure dry and clean substrate

##### Step 2: Primer Application

- Apply epoxy primer to improve the bond.

##### Step 3: Putty/Levelling

- Fill surface irregularities.

##### Step 4: Resin Application

- Apply saturating resin.

##### Step 5: Placement of CFRP Sheet

- Lay the sheet in the Fiber direction.
- Remove air bubbles using rollers.

##### Step 6: Curing

- Allow proper curing (typically 24–72 hours).

#### 4.7 Design Guidelines

The design of CFRP retrofitting follows limit-state principles.

Major codes:

- American Concrete Institute – ACI 440.2R
- International Organization for Standardization – ISO FRP standards
- IS 15988: 2013 – Seismic strengthening of RC buildings (India)

Flexural Strength Calculation Concept

Ultimate moment capacity:

$$M_u = C \times z$$

Where:  $C$  = compressive force in concrete;  $z$  = lever arm

CFRP contributes tensile force:

$$T_{frp} = A_{frp} \times f_{frp}$$

#### 4.8 Failure Modes in CFRP-Strengthened Members

- FRP rupture
- Debonding from the concrete surface
- Concrete cover separation
- Shear failure
- Anchorage failure
- Debonding is the most common premature failure.

## 5. RESULTS AND DISCUSSIONS

### 5.1 Carbon Fiber Fabrics for Structural Strengthening

SikaWrap® ~600 °C: It is a unidirectional, woven carbon Fiber fabric for installation using the wet application process. Equipped with weft Fibers that keep the fabric stable (heat-set process).

Total Area Weight: 625 g/m<sup>2</sup> with a tolerance of 35 g/m<sup>2</sup>

Fiber Density: 1.81 g/cm<sup>3</sup>

Tensile Modulus: 242 KN/mm<sup>2</sup>

### 5.2 Epoxy Resins

Sikadur®-330 is a two-component, thixotropic epoxy-based impregnating resin and adhesive. It is used as:

- Impregnation resin for SikaWrap® fabric reinforcement for the dry application method
- Primer resin for the wet application system
- Structural adhesive for bonding Sika® CarboDur® plates to even surfaces
- Structural resin for bonding near surface-mounted CFRP

Sikadur® ~31 CF Normal: It is a moisture-tolerant, thixotropic, structural two-component adhesive and repair mortar, based on a combination of epoxy resins and special fillers, designed for use at temperatures between +10 °C and +30 °C.

Compressive Strength: ~65 N/mm<sup>2</sup> Curing at 30 °C for 7 Days

Modulus of Elasticity in Compression ~ 4,600 N/mm<sup>2</sup> (14 days at +23 °C) (ASTM D695)

Tensile Strength in Flexure: 35 N/mm<sup>2</sup> Curing at 30 °C for 7 Days

Tensile Strength: ~22 N/mm<sup>2</sup> Curing at 30 °C for 7 Days

Modulus of Elasticity in Tension ~ 5,000 N/mm<sup>2</sup> (14 days at +23 °C) (ISO 527)

Elongation at Break 0.4 ± 0.1 % (7 days at +23 °C) (ISO 527)

Tensile Adhesion Strength Curing Time Substrate Curing Temperature

### 5.3 Comparison: CFRP vs Conventional Jacketing

A comparative evaluation of CFRP and RC jacketing techniques is shown in Table 3, highlighting their respective advantages and limitations.

**Table 3. Comparative Assessment of CFRP and RC Jacketing Strengthening Techniques**

Parameter	CFRP	RC Jacketing
Added Weight	Very Low	High
Construction Time	Fast	Slow
Section Enlargement	Minimal	Significant
Corrosion	No	Possible
Cost	High	Moderate

**5.4 Seismic Retrofitting Using CFRP wrapping:**

- Improves energy dissipation
- Enhances ductility
- Prevents brittle shear failure
- Increases confinement pressure

**Recommended for column retrofitting in seismic zones.**

**5.5 Durability and Long-Term Performance**

**Factors affecting performance:**

- UV exposure
- Moisture ingress
- Temperature variation
- Freeze-thaw cycles
- Fire exposure

**Protective coatings are therefore recommended.**

**6. CONCLUSIONS and FUTURE PROSPECTS**

**6.1 Advantages of CFRP Retrofitting**

- High strength-to-weight ratio
- Minimal increase in dead load
- Corrosion resistance
- Rapid construction
- No major change in member dimensions
- Suitable for seismic strengthening

**6.2 Limitations**

- High initial cost
- Brittle failure behaviour
- Poor fire resistance unless protected
- Requires skilled labour
- Sensitive to surface preparation quality

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