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Review on FRP Strengthened Concrete Structures: Current Advances, Challenges and Emerging Innovations

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Abstract. Fiber-Reinforced Polymer (FRP) composites have revolutionized the rehabilitation of aging concrete structures by addressing limitations of traditional materials, such as corrosion susceptibility and heavyweight. FRP variants—carbon, glass, basalt, and aramid—offer exceptional strength-to-weight ratios, corrosion resistance, and adaptability, enabling non-invasive retrofitting via externally bonded (EB) laminates, near-surface mounted (NSM) bars, and prefabricated grids. These techniques enhance flexural, shear, and seismic performance in beams, columns, and bridges, exemplified by long-term durability in projects like Switzerland's Ibach Bridge. Emerging innovations include nanotechnology-enhanced adhesives to mitigate debonding, machine learning models for predictive structural analysis, and sustainable bio-based FRPs derived from renewable resources. However, challenges persist in interfacial durability, fire resistance, and standardized design protocols, particularly under environmental stressors or elevated temperatures. While FRP reduces lifecycle emissions and energy consumption compared to steel, economic viability and long-term performance in extreme conditions require further validation. Future research must prioritize fire-resistant formulations, predictive aging models, and interdisciplinary collaboration to optimize FRP's role in sustainable, resilient infrastructure. This review synthesizes advancements and unresolved gaps, guiding practical implementation and fostering FRP's potential in modern structural engineering.

Keywords: Fiber-reinforced polymer, Structural strengthening, Nano-adhesives, machine learning, Bio-composites

1. Introduction

Fiber-reinforced polymer (FRP) composites have revolutionized the strengthening and rehabilitation of aging concrete structures by addressing limitations of traditional materials like corrosion, heaviness, and high maintenance [1,2]. FRP materials, including carbon (CFRP), glass (GFRP), basalt (BFRP), and aramid (AFRP) variants, offer a compelling alternative due to their exceptional strength-to-weight ratios, corrosion resistance, and adaptability [3,4]. These properties enable

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lightweight, non-invasive retrofitting techniques that minimize structural disruption while significantly enhancing load-bearing capacities and service life [5]. The application of FRP in concrete structures spans diverse elements, from beams, columns, and slabs to large-scale infrastructure such as bridges. Externally bonded (EB) laminates, near-surface mounted (NSM) bars, and prefabricated grids have proven effective in improving flexural, shear, and seismic performance [6,7]. For instance, FRP wrapping boosts column ductility in seismic zones, while bridges like Switzerland's Ibach Bridge demonstrate long-term durability and cost savings [8-10]. Despite these successes, challenges persist in standardization, interfacial debonding, and fire resistance, necessitating innovative solutions.

Recent advancements integrate nanotechnology to enhance adhesion and mechanical properties, while machine learning predicts structural behavior more accurately [11 ,12]. Sustainable bio-based FRPs using lignin or plant resins align with environmental goals but face scalability and durability hurdles.

Though FRP reduces CO_2 emissions and energy use compared to steel, economic viability and long-term performance under extreme conditions remain critical concerns [13]. This review synthesizes current research on FRP-strengthened concrete structures, examining their advantages, applications, emerging trends, and unresolved challenges. By addressing gaps in durability, fire resistance, and standardized protocols, this work aims to guide future research and practical implementation, ensuring FRP technologies realize their full potential in sustainable, resilient infrastructure development [14].

2. Advantages of frp materials

FRP materials offer several notable advantages in structural rehabilitation. FRP manufacturing processes vary significantly, with key methods including filament winding and pultrusion. Winding involves wrapping fibers around a mandrel, producing cylindrical components like pipes or tanks, and is highlighted for creating standardized FRP elements in bridge applications, as shown in Figure 1 [15]. Pultrusion, a continuous process pulling fibers through a resin bath and heated die, is widely used for FRP bars and profiles [16, 17]. This method ensures high fiber alignment and cost efficiency, especially for structural bars [18]. Regarding matrix materials, thermosetting resins (e.g., epoxy, polyester) dominate FRP production due to their rigidity, thermal stability, and chemical resistance post-curing [17]. In contrast, thermoplastic resins allow reheating and reshaping but are less common in structural FRPs due to lower mechanical performance [18]. Advances in thermoset-based processes, like resin transfer molding (RTM), enable large-scale FRP component fabrication with stable quality, promoting their adoption in infrastructure [15].

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Figure 1: Types of FRP [19]

2.1. High strength to weight ratio

FRP materials are primarily categorized based on the type of reinforcing fiber used, such as carbon, glass, basalt, and aramid. As summarized in Table 1, different types of FRPs exhibit varying tensile strength, density, and strength-to-weight ratios, leading to distinct performance characteristics. CFRP is renowned for its high strength and stiffness, making it ideal for applications requiring lightweight yet robust materials [20]. GFRP is the most commonly used FRP due to its cost-effectiveness and versatility. BFRP offers superior strength and alkali resistance, making it suitable for harsh environments [21]. AFRP is valued for its high tensile strength and ballistic resistance, often used in protective applications [22].

Table 1: Types and Key Properties of FRP

Type	Tensile Strength (MPa)	Density (g/cm³)	Strength-to-Weight Ratio	Key Features	Applications
CFRP	1,755–3,600	1.55–1.76	4–5	High strength, light weight	Aerospace, bridges
GFRP	3,450	2.11–2.70	2.15–2.7	Affordable, corrosion-resistant	Marine, chemical structure
AFRP	1,700–2,500	1.38–1.39	1.9–4.4	Ultralightweight, expensive	Impact protection, safety gear
BFRP	1,000–1,600	2.70–2.89	1.0–1.2	Low cost, durable	Budget-friendly construction

2.2. Corrosion resistance

The corrosion resistance of FRP constitutes a pivotal advantage driving their widespread adoption across engineering disciplines. CFRP excels in harsh environments, CFRP demonstrates superior thermal stability, withstanding sustained temperatures up to 1000°C and transient exposure as high as 1100°C. At extreme temperatures exceeding 450°C, CFRP retains partial strength (about 20%) despite significant resin degradation [23]. This corrosion immunity makes CFRP an ideal choice for

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bridges and offshore platforms persistently exposed to salt spray and corrosive agents. GFRP similarly exhibits robust corrosion resistance, particularly against saline water and chemical substances, thereby finding extensive use in shipbuilding, chemical pipelines, and storage tanks. Table 2 summarizes the durability of GFRP.

Table 2: Durability of GFRP

Reference	Exposure Conditions	Key Findings
Dejke (2001)	Alkaline solution, concrete, water (60°C)	Strength loss reduction stabilized after 1 year; more loss in concrete
Yamaguchi et al. (1997)	Creep rupture test	Failure at 29% of initial strength
Benmokrane & Mohamed (2016); Gooranorimi & Nanni (2017)	5–8 years, Canadian bridges	No chemical damage; stress stayed below 25% of ultimate strength
Mi-às et al. (2015)	700 days of lab loading	5% strength loss; modulus unaffected
Kemp & Blowes (2011)	5–8 years, bridge cores	No damage; validated for reinforcement
Jesús D. Ortiz et al..(2019)	15–20 years in service	Bars kept ~85% of initial strength

AFRP further demonstrates superior corrosion resistance, making it a prime candidate for marine and industrial applications requiring durable containers, piping systems, and protective structures. BFRP distinguishes itself through exceptional chemical durability, enabling long-term service in aggressive environments such as chemical processing plants and wastewater treatment facilities. The corrosion-resistant properties of FRP not only extend structural lifespans and reduce maintenance costs but also enhance operational safety and reliability. Consequently, these materials empower engineers with expanded design flexibility and innovation potential in addressing complex engineering demands.

2.3. Ease of installation

FRP materials enhance concrete reinforcement through lightweight, high-strength properties, enabling simple installation (e.g., NSM: cutting grooves, adhering FRP, curing) [2]. Prefabrication slashes on-site time, while low skill requirements and short curing minimize building disruption, reducing costs. Studies reveal 45° installation angles outperform 60° and 90° in displacement control[24]. Increasing FRP layers improves flexural strength but weakens ductility beyond three layers, necessitating balance via simulations or tests. A systematic design strategy optimizes construction efficiency (prefab/on-site workflows) and structural synergy. Recommended parameters (45°–60° angles, 2–3 layers) enhance strength-ductility balance. Properly designed FRP systems boost concrete beams' load capacity while preserving ductility, offering cost-effective solutions for retrofitting and post-disaster recovery [24].

3. Applications of FRP in strengthening concrete structures

FRP composites have emerged as a versatile solution for enhancing the structural performance of reinforced concrete (RC) elements. Common applications include EB and NSM systems for repairing beams, columns, slabs, and walls. FRP wraps or laminates are widely employed to improve flexural, shear, and axial capacities while increasing ductility in seismic regions by confining concrete columns [2, 18]. Techniques such as wet lay-up, pre-cured adhesives, and internal FRP reinforcement address issues like cracking and corrosion resistance. For instance, FRP grids and bars replace steel in bridge decks due to their high stiffness and lightweight properties, while NSM rods enhance flexural strength in retrofitted beams [20]. These applications highlight

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FRP's adaptability in both new construction and rehabilitation, driven by its durability and design flexibility.

3.1. Beams, columns, and slabs

FRP composites, renowned for high strength, lightweight properties, and corrosion resistance, are extensively utilized in concrete structure rehabilitation. For column strengthening, EB-FRP laminates in full-wrapping or U-jacketing configurations enhance axial capacity and seismic performance by constraining lateral concrete expansion and delaying compressive failure, while U-jacketing improves shear resistance [19]. In beam applications, FRP enhances flexural and shear capacities. Flexural strengthening via bottom/top surface bonding significantly increases ultimate load capacity, particularly post-steel yielding [19]. Shear reinforcement using U-jacketed or side-bonded FRP relies on adhesive quality and anchorage systems, with studies showing FRP anchorage doubles usable strain levels[4]. NSM techniques, embedding FRP bars/strips into concrete cover, exhibit superior bond strength and debonding resistance compared to external bonding [2]. For slabs, FRP grids replacing steel reinforcement improve flexural stiffness and crack control, achieving comparable or superior performance to steel-reinforced slabs with reduced weight [4]. Side-bonded FRP sheets simultaneously enhance flexural-shear performance in space-constrained scenarios.

While FRP techniques (external bonding, NSM, grids) effectively upgrade structural performance, challenges persist in bond durability, interfacial debonding, and standardized design protocols.

3.2. Bridges

FRPs are increasingly utilized for strengthening and rehabilitating concrete bridges due to their high strength-to-weight ratio, corrosion resistance, and adaptability. FRP grids and bars are prominently employed as internal reinforcements for bridge decks and pavements, offering structural efficiency by replacing steel reinforcement while reducing weight [4]. EB-FRP laminates and NSM bars have demonstrated efficacy in enhancing flexural and shear capacities of bridge beams. EB methods improve load-bearing performance by wrapping or bonding FRP sheets to tension zones, though their effectiveness depends on existing reinforcements and bonding quality [15]. NSM techniques reduce stress hysteresis and enable better utilization of FRP tensile strength, particularly when combined with anchorage systems to mitigate interfacial debonding [19]. Full-scale applications include the Ibach Bridge in Switzerland, retrofitted with CFRP strips in 1991, showcasing long-term durability [4]. Further innovations include prefabricated FRP bridge decks, which reduce construction time and lifecycle costs while resisting corrosion and fatigue [18]. Despite progress, challenges persist in standardized design codes and material variability, necessitating further research to optimize FRP integration in bridge engineering.

3.3. Seismic retrofitting

FRP composites have emerged as a pivotal material for seismic retrofitting due to their high strength-to-weight ratio, corrosion resistance, and adaptability to structural geometries. FRP systems effectively address deficiencies in non-seismically designed RC structures by enhancing joint shear capacity, relocating plastic hinges, and preventing brittle failure modes. For instance, FRP wrapping in principal stress directions significantly improves joint shear strength, while anchoring techniques

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using FRP anchors or mechanical devices mitigate debonding risks, a critical factor in retrofit effectiveness [25]. Experimental studies demonstrate that diagonal FRP configurations (e.g., “X”-shaped layouts) combined with steel angles enhance ductility by transferring damage to beams, though debonding remains a challenge without proper anchorage [26]. FRP also facilitates plastic hinge relocation in beams, reducing yield penetration into joints and improving energy dissipation . In corner joints with slabs, CFRP anchorage through predrilled slots achieves a 70% strength increase and ductile failure mechanisms, albeit with reduced stiffness compared to RC jacketing. Despite these benefits, practical limitations persist, including obstruction by transverse beams or slabs and low fire resistance, prompting innovations like intumescent coatings [25].

4. Emerging trends and innovations

Recent advancements in nanotechnology-enhanced FRP composites have introduced novel processing techniques like nanoparticle dispersion, nanofiber alignment, and nano-coatings (e.g., silica, CNT), improving mechanical properties and surface functionality. These innovations enable tailored solutions for aerospace (e.g., airbus weight reduction), automotive, and biomedical sectors [27].

4.1. Integration with nanotechnology

Recent advancements demonstrate that nanotechnology significantly enhances the mechanical properties, interfacial adhesion, and durability of FRP composites. The incorporation of nanomaterials, such as carbon nanotubes (CNTs) and silicon-based nanoparticles into epoxy adhesives has improved bond strength and load transfer efficiency in FRP-concrete systems, particularly in NSM retrofitting techniques [28]. Studies highlight that nanomaterial-modified epoxy adhesives (NMEAs) mitigate premature debonding in EB-FRP systems by enhancing interfacial slip resistance and thermal stability [28, 29]. CNT-enhanced adhesives in EB-FRP applications have shown increased tensile strength and reduced delamination risks, though their use remains limited to specific configurations.. Emerging research explores hybrid nanofillers (e.g., carbon- and silicon-based combinations) to optimize adhesive performance for diverse FRP types, including aramid FRP (AFRP), broadening application potential in flexural and shear retrofitting [29]. However, challenges persist in scaling these innovations, particularly in ensuring long-term durability under environmental stressors like chloride exposure, which necessitates predictive modeling for property retention [30]. Future directions emphasize investigating nanomodified adhesives in torsion retrofitting, cyclic loading, and extreme conditions (e.g., fire), as well as developing cost-effective nanofillers for large-scale infrastructure use [28, 31].

4.2. Artificial intelligence and machine learning

Recent advancements in machine learning (ML) have significantly enhanced the predictive capabilities for FRP applications in structural engineering. Traditional design guidelines for FRP-strengthened RC members, reliant on empirical methods, face limitations in accuracy due to restricted datasets. ML techniques, including neural networks, support vector regression (SVR), and ensemble models like XGBoost, have demonstrated superior performance in predicting structural behaviors such as moment capacity and failure modes. For instance, Zhang et al. highlighted XGBoost’s effectiveness in unifying prediction models for FRP-strengthened beams, outperforming SVR and ANN . Explainable AI (XAI) frameworks, such as explainable gradient-boosted trees

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(ExGBT), have improved transparency in predicting FRP failure mechanisms and moment capacities, addressing historical hesitancy among engineers due to ML's opacity [32].

For FRP-concrete bond strength, ensemble models like CatBoost achieved exceptional accuracy (R^2=0.98), with parametric analyses emphasizing the dominant influence of FRP material and geometric properties over concrete parameters [12]. Gene expression programming (GEP)-derived empirical expressions further validated these findings, aligning with ML-driven insights [12]. Super-learner ML models have also advanced flexural capacity predictions for FRP-RC beams, outperforming code-based equations through optimized hyperparameter tuning [33]. Despite progress, challenges persist in model interpretability and engineers' reliance on traditional methods, underscoring the need for expanded datasets and real-world validation [32, 34].

4.3. Sustainable and bio-based FRP materials

Recent advancements in sustainable and bio-based (FRP) materials highlight progress in balancing environmental objectives with structural performance. Partial bio-based epoxy resin blends, such as those derived from wood/vegetable by-products (WV, 41% bio-content), cashew nut shell liquid (CN, up to 40% bio-content), and epoxidized linseed oil (ELO, up to 40% bio-content), achieve tensile strengths comparable to conventional epoxies. Notably, WV-carbon and ELO-glass FRPs retain 77% and exceed 13% of conventional epoxy's strength, respectively, while CN-glass FRPs exhibit a 15% reduction at peak bio-content [35]. Novel bio-based unsaturated polyester resins encapsulate glass fibers with mechanical properties surpassing petroleum-derived counterparts, despite a marginal (~10%) reduction in glass transition temperature [36]. Lignin-based epoxy composites blended at ≤75 wt% bio-content demonstrate tensile/flexural strengths comparable to BPA-based resins, alongside robust adhesion [37]. However, natural fiber-reinforced biocomposites face durability limitations under hygrothermal aging, necessitating surface treatments to mitigate moisture-induced interfacial degradation [38]. Preliminary studies confirm bio-resins' feasibility in FRP-strengthened concrete structures, though standardization of processing parameters and environmental durability data remain critical for broader adoption [39]. Together, these developments underscore bio-based FRPs' potential as sustainable alternatives, contingent on resolving challenges in long-term performance and scalability.

5. Challenges and research gaps

Current challenges include the scalability of nanomaterial-enhanced FRP composites, interfacial compatibility, and long-term environmental durability [40]. Persistent research gaps involve predictive models and standardized guidelines [37].

The long-term durability of FRP composites is significantly influenced by environmental factors, material composition, and interfacial interactions. Studies highlight that moisture absorption, chemical degradation (e.g., alkali-silica reactions), and microstructural changes lead to progressive mechanical strength loss in FRP systems [40]. For instance, GFRP degradation under alkaline conditions is primarily pH-dependent, necessitating design prioritization of pH mitigation over salinity control [40]. In hybrid FRP-steel joints, moisture initially enhances adhesion but compromises long-term bond strength, emphasizing the need for predictive models [37]. Comparative analyses reveal varying chemical resistances: E-glass fibers are prone to acid corrosion, while ECR-glass and carbon fibers exhibit superior durability [37, 41]. Fire resistance remains a critical gap, with limited guidelines requiring further investigation [37]. Surface modifications, such as protective coatings (e.g., albumin multilayers), and hybrid material designs

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(e.g., basalt/carbon hybrids) enhance environmental resilience [37, 42]. Continuous advancement in predictive modeling and accelerated aging protocols is urged to optimize FRP application in infrastructure [43, 44].

Besides, the mechanical performance of FRP composites under elevated temperatures exhibits significant degradation, particularly when temperatures approach or exceed the resin's glass transition temperature Tg. Experimental studies reveal that temperatures below Tg cause minor strength reductions (<20%), whereas temperatures above Tg lead to rapid deterioration due to resin softening, debonding, and decomposition [23, 45]. For FRP bars, tensile strength retention drops linearly to near-zero at ~500°C, with critical degradation observed between 300–330°C [45]. Similarly, FRP laminates/sheets experience scattered but severe strength losses (68–94%) above 400°C, attributed to varying fabrication methods and fiber-resin ratios [45]. Comparative studies highlight that GFRP and BFRP generally outperform CFRP under elevated temperatures, though diameter and resin type also influence thermal resistance [23, 45]. Fire-protection systems (e.g., coatings) delay degradation but lose effectiveness beyond 700°C, as FRP-concrete interfaces and resin integrity fail [46]. These findings emphasize the need for material-specific design guidelines to address FRP's vulnerability to elevated

As for ecnomic and environmental impact, existing studies demonstrate that FRP composites offer significant environmental benefits over conventional steel reinforcement in concrete structures. Garg and Shrivastava found that replacing steel with GFRP, BFRP, and CFRP rebars reduced global warming impacts by 439%, 400%, and 399%, respectively, alongside energy consumption reductions of 500% for BFRP [47]. Inman et al. reported BFRP reduced ozone depletion by 21% and human toxicity by 787% compared to steel [48]. Strengthening RC beams using CFRP achieved up to 6996% lower CO_2 emissions versus reconstruction, highlighting its eco-efficiency [49]. Economically, Cadenazzi et al. noted FRP-reinforced bridges, though shorter-lived, required less maintenance and incurred lower environmental costs [50]. However, ACI Committee emphasized challenges in durability under harsh conditions, which may offset long-term savings [51]. Overall, FRP adoption reduces lifecycle emissions and energy use, yet further studies integrating economic-environmental trade-offs are needed to optimize decision-making [52].

6. Conclusion

FRP composites have revolutionized the rehabilitation and strengthening of concrete structures, offering unparalleled advantages over traditional materials, including high strength-to-weight ratios, corrosion resistance, and adaptability to complex geometries. Their applications in beams, columns, slabs, and bridges demonstrate significant improvements in flexural, shear, and seismic performance, as evidenced by successful retrofitting projects like the Ibach Bridge. Techniques such as EB, NSM, and prefabricated FRP grids have enabled cost-effective, minimally invasive solutions that extend structural lifespans while reducing maintenance demands.

Despite these advancements, challenges persist in achieving widespread adoption. Long-term durability under environmental stressors—such as moisture, alkali exposure, and elevated temperatures—remains a critical concern, particularly for resin-dominated properties and interfacial bond integrity. Fire resistance limitations and the lack of standardized design codes further hinder practical implementation. Emerging innovations, including nanotechnology-enhanced adhesives and machine learning-driven predictive models, show promise in addressing these gaps by optimizing material performance and design accuracy. Concurrently, sustainable bio-based FRP materials align with global decarbonization goals but require further validation for scalability and durability.

Economically, FRP composites demonstrate lifecycle benefits through reduced emissions and energy consumption compared to steel, yet their initial costs and uncertainties in extreme conditions necessitate balanced cost-environmental trade-off analyses. Future research must prioritize interdisciplinary approaches to refine predictive aging models, develop fire-resistant formulations, and establish universal design protocols. Collaborative efforts among academia, industry, and policymakers will be pivotal in translating laboratory breakthroughs into real-world applications. By overcoming current limitations, FRP technologies can fully realize their potential as a cornerstone of resilient, sustainable infrastructure in an era of escalating environmental and structural demands.

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