Review Article

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Contemporary Insights into GFRP-Wrapped Concrete: A Review of Structural Performance, Durability and Environmental Sustainability

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ABSTRACT

Ageing concrete infrastructure and the high environmental cost of demolition and reconstruction have made durable, low-intervention strengthening methods a priority for sustainable construction. Glass Fiber Reinforced Polymer (GFRP) wrapping has emerged as a notably effective technique for enhancing the mechanical and structural attributes of concrete, while its corrosion resistance and low self-weight make it an environmentally attractive alternative to steel-based repair. Its high tensile strength, corrosion resistance and lightweight nature contribute to significant improvements in compressive strength, flexural resilience, shear resistance and ductility. This review examines recent advances in GFRP-wrapped concrete, highlighting its influence on structural behaviour under various loading conditions, including load-bearing capacity, seismic resilience and fatigue resistance. GFRP wrapping provides lateral confinement, prevents microcracking and improves load-bearing capacity, which is particularly advantageous for structures under high axial forces; in bending it increases stiffness and controls crack formation, and it raises shear strength by shifting failure from brittle to more ductile mechanisms. It also improves ductility and energy dissipation, crucial for seismic performance, and enhances fatigue resistance, prolonging service life under cyclic loading. By extending durability and reducing the frequency of replacement and the associated material and carbon burden, GFRP retrofitting aligns structural rehabilitation with environmental sustainability goals. Challenges such as elevated cost, long-term durability in aggressive environments and application complexity remain, but GFRP offers a dependable, minimally invasive solution for strengthening and retrofitting concrete structures, especially in seismic-prone regions.

Keywords: GFRP composites; Sustainable construction; Concrete strengthening and retrofitting; Durability; Corrosion resistance; Seismic resilience.

1. INTRODUCTION

The rehabilitation of deteriorating concrete infrastructure is increasingly framed as a sustainability challenge, since repairing and extending the life of existing structures avoids the substantial material consumption and carbon emissions associated with demolition and rebuilding. Glass Fiber Reinforced Polymer (GFRP) has garnered substantial attention in civil engineering due to its exceptional mechanical attributes and longevity, particularly in reinforcing and retrofitting concrete structures. GFRP is composed of high-strength glass filaments embedded in a polymer matrix, often epoxy, polyester, or vinyl ester, which offers improved tensile strength, corrosion resistance, and diminished self-weight when compared to traditional materials like steel (Kumar *et al.* 2022; Zhang *et al.* 2023). These properties make GFRP a powerful solution for structural repair, delivering enhanced performance in hostile environments where conventional reinforcements might deteriorate over time (El-Hacha and Rizkalla, 2004).

The integration of GFRP in concrete fortification addresses pressing concerns such as structural degradation, aging infrastructure, and rising maintenance expenses (Teng *et al.* 2024). One primary advantage of GFRP wrapping lies in its capacity to improve the load-bearing capacity of concrete components by offering external confinement, thereby enhancing both ductility and energy absorption under diverse loading scenarios (Wang *et al.* 2020). Moreover, its outstanding fatigue resistance and ease of application make it a practical alternative to conventional retrofitting techniques.

Strengthening the structural characteristics of concrete is vital for ensuring the long-term safety and resilience of infrastructure, particularly in seismic regions and locations with severe environmental exposure (Balsamo *et al*. 2023). Research has shown that GFRP wrapping significantly improves the mechanical traits of concrete, including compressive, shear, and flexural strength, thus extending its overall service life and structural dependability (Bisby *et al.* 2021).

Furthermore, as the emphasis on sustainable and resilient construction increases, GFRP presents an environmentally friendly alternative thanks to its corrosion resistance and potential to minimize material usage. Findings suggest that GFRP wraps outperform CFRP wraps (Carbon Fiber Reinforced Polymer) in minimizing seismic damage and the cumulative damage index in reinforced concrete structures with inadequate confinement during retrofitting (Cao and Pham, 2019).

This review paper investigates the mechanical and structural characteristics of GFRP-wrapped concrete, emphasizing its effects on strength, ductility, load behavior, and environmental performance. Additionally, factors that affect the efficiency of GFRP wrapping, such as layer thickness, concrete quality, and exposure conditions, were explored, and the applications, challenges, and prospective research directions were addressed.

2. GFRP MATERIAL PROPERTIES

Glass Fiber Reinforced Polymer (GFRP) is a composite substance comprising high-strength glass filaments embedded in a polymer matrix, usually epoxy, polyester, or vinyl ester resin. The most widely used glass fibers are E-glass, recognized for its cost efficiency and excellent mechanical characteristics, and S-glass, which provides superior tensile strength and stiffness but at a higher cost (Banik, *et al*. 2024). The polymer matrix plays an essential role in binding the fibers, transferring stresses, and offering resistance to environmental degradation (Verma *et al.* 2021).

The mechanical traits of GFRP, such as tensile strength, modulus of elasticity, and impact resistance, are heavily influenced by multiple factors, including fiber volume fraction, fiber orientation, and the quality of the fiber-matrix interface (Banik *et al*. 2024). Research by Nanni *et al.* (2024) showed that increasing the fiber volume fraction improves tensile strength and stiffness but can also reduce flexibility, impacting its ductility. The anisotropic nature of GFRP results in strength that depends on fiber orientation; unidirectional laminates offer greater tensile strength along the fiber direction but exhibit lower strength across the transverse directions.

Durability is another significant advantage of GFRP, particularly in harsh environments where conventional materials like steel are susceptible to corrosion. Research has demonstrated that GFRP offers outstanding resistance to moisture penetration, chemical corrosion, and elevated temperatures, making it ideal for use in marine, industrial, and high-humidity conditions (Teng *et al.* 2024; Bisby *et al*. 2021). Moreover, the polymer matrix serves as a protective shield that enhances GFRP's durability under ultraviolet (UV) exposure and extreme temperature fluctuations (El-Hacha and Rizkalla, 2004). However, long-term studies suggest that prolonged exposure to alkaline environments, such as those present in concrete, can degrade the fiber-matrix interface, thereby affecting its overall performance (Zhao *et al.* 2024).

GFRP presents a remarkable combination of high strength-to-weight ratio, resistance to corrosion, and longevity, making it a preferred material for strengthening and retrofitting concrete structures. Nonetheless, continued research is necessary to optimize its long-term performance, especially in varied environmental conditions and under sustained mechanical stress. Fig. 1 illustrates various GFRP material properties in detail.

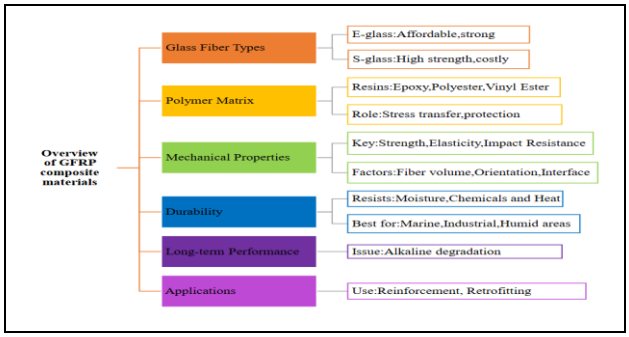


Fig. 1: Material properties of GFRP

3. EFFECT OF GFRP WRAPPING ON CONCRETE

The application of GFRP wrapping substantially enhances the mechanical characteristics of concrete, such as compressive strength, flexural strength, shear resistance, and ductility. Detailed discussions of each property are provided below, with references to experimental investigations and test outcomes. Fig. 2 demonstrates various methods for reinforcing concrete using GFRP materials.

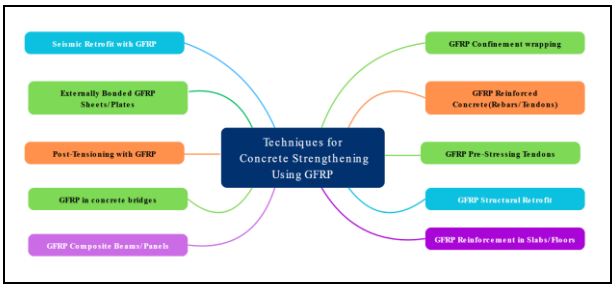


Fig. 2: Techniques for concrete strengthening using GFRP

3.1 Compressive Strength

GFRP wrapping has demonstrated its effectiveness in improving the compressive strength of concrete by providing lateral confinement, which aids in delaying the initiation of micro-cracks and enhancing the material's load-bearing capability. The confinement effect is vital as it prevents premature cracking of

concrete under compression, enabling it to endure higher stress levels before failure. This mechanism plays a significant role in boosting the overall compressive strength, especially in columns and prisms subjected to high axial loads.

Numerous experimental investigations have measured the impact of GFRP on compressive strength. For instance, Islam *et al.* (2020) carried out tests on cylindrical concrete specimens and observed a remarkable 55% increase in compressive strength. The GFRP-wrapped specimens reached a compressive strength of 15.37 MPa, compared to just 9.92 MPa for the unwrapped control specimens. This considerable enhancement is attributed to the lateral confinement offered by the GFRP wrapping, which effectively raises the stress the concrete can endure before failure. Zhao *et al.* (2022a) studied concrete-filled GFRP tubes and discovered that GFRP wrapping boosted the compressive strength of the wrapped columns by 50%, increasing it from 25 MPa to 30 MPa for unwrapped columns and 40 MPa to 60 MPa for GFRP-wrapped columns. This study demonstrated the considerable advantage of GFRP wrapping in improving the compressive strength of concrete in tubular forms, particularly under axial loading conditions.

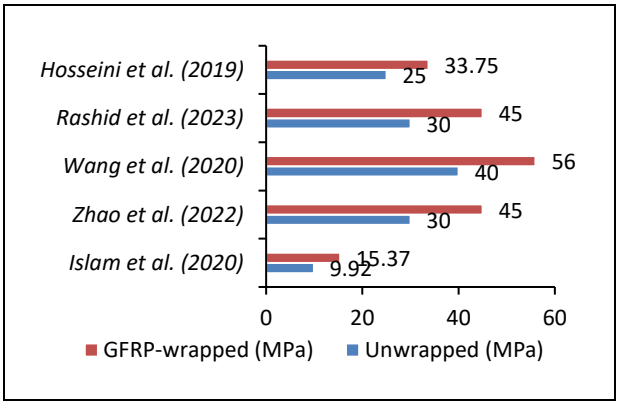


Fig. 3: Consolidated compressive strength of specimens (wrapped and unwrapped)

Wang *et al.* (2020) conducted experiments on concrete cylinders wrapped with GFRP and found that the compressive strength increased by 40%, rising from 40 MPa in unwrapped specimens to 56 MPa in GFRP-wrapped specimens. This result further corroborates the ability of GFRP wrapping to significantly enhance compressive strength, especially for cylindrical concrete structures. In another study by Rashid *et al.* (2023), the compressive strength of GFRP-wrapped concrete prisms increased by 33%; unwrapped specimens reached compressive strengths ranging from 20 MPa to 30 MPa, while wrapped specimens achieved compressive strengths between 40 MPa and 50 MPa. This increase was attributed to the confinement provided by the GFRP layers, which not only enhanced strength but also delayed cracking and improved the concrete's resistance to deformation.

Hosseini *et al.* (2019) conducted an experimental study on GFRP-wrapped concrete cylinders and observed a 35% increase in compressive strength compared to unwrapped specimens. Their findings reinforced the idea that GFRP wrapping effectively improves compressive strength by enhancing the concrete's confinement under axial loading. While the increase in compressive strength was not as substantial as in other studies, it still highlighted the significant positive effect of GFRP on concrete's mechanical properties.

The compressive strength values derived from load tests according to various studies on GFRP wrapping methods for enhancing concrete's compressive strength are illustrated in Fig. 3, offering a clearer perspective on how GFRP can be leveraged to improve the compressive strength of concrete.

In general, the use of GFRP wrapping considerably enhances the compressive strength of concrete, especially in structural components exposed to axial loads. The improvements noted in several studies highlight the potential of GFRP as a dependable and efficient reinforcement technique for strengthening the structural stability and longevity of concrete under compressive forces.

3.2 Flexural Strength

The use of GFRP wrapping on concrete beams has been demonstrated to improve their flexural strength, primarily by offering resistance to tensile stresses that arise during bending. Concrete, being a brittle substance, is highly prone to cracking when exposed to bending forces. GFRP sheets, with their exceptional tensile strength, notably enhance the rigidity and bending resistance of concrete beams, effectively managing crack propagation and reinforcing the structural stability of the beams. This enhancement is particularly vital for structures subjected to dynamic or cyclic loading.

Numerous experimental investigations have strongly supported the improvement of flexural strength in GFRP-wrapped concrete beams. Peng *et al.* (2024) conducted experiments on concrete beams wrapped with GFRP sheets and observed a 40% increase in flexural strength, with wrapped specimens reaching a flexural strength of 35 MPa, compared to 25 MPa in unwrapped beams. This rise in flexural strength is attributed to the GFRP's ability to provide confinement and resist tensile stresses that lead to cracking and failure in unwrapped beams.

Similarly, Nanni *et al.* (2024) performed tests on concrete beams reinforced with GFRP sheets and reported a 30% improvement in flexural strength,

demonstrating the beneficial effect of GFRP wrapping in enhancing the bending capacity of concrete beams. In another study by Gao *et al.* (2022), the flexural strength of concrete beams wrapped with GFRP was found to increase by 35%, from 28 MPa in unwrapped beams to 38 MPa in wrapped specimens. This result affirms the ability of GFRP to enhance the bending resistance of concrete beams, particularly under sustained or cyclic loading conditions.

Zhao *et al.* (2022b) examined the flexural behavior of concrete beams wrapped with GFRP and concluded that GFRP wrapping improved the flexural strength by 25% compared to unwrapped beams. This enhancement is due to the effective transfer of tensile forces from the concrete to the GFRP wrap, preventing the formation and spread of cracks under bending stresses. Additionally, Niu *et al.* (2023) tested prestressed concrete beams wrapped with GFRP and observed a 40% increase in flexural strength, further highlighting the considerable improvement in bending capacity that GFRP wrapping provides to prestressed concrete components.

The flexural strength values obtained from load tests, based on various studies on GFRP wrapping techniques for improving the flexural strength of concrete specimens, are illustrated in Fig. 4, offering a clear understanding of how GFRP can be applied to enhance the bending resistance of concrete.

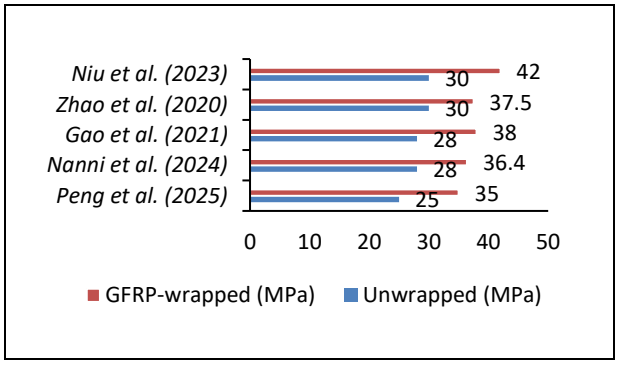


Fig. 4: Consolidated flexural strength for GFRP specimens (wrapped and unwrapped)

In summary, GFRP wrapping significantly boosts the flexural strength of concrete beams by enhancing their ability to resist tensile stresses, increasing bending stiffness, and preventing crack propagation. The studies referenced above offer strong evidence supporting GFRP as a dependable and effective reinforcement technique for strengthening the bending capacity of concrete structures.

3.3 Shear Strength

The utilization of GFRP wrapping considerably boosts the shear strength of concrete beams by offering additional reinforcement that resists shear stresses. Shear failure in concrete beams frequently occurs abruptly and in a fragile fashion, but the lateral confinement provided by GFRP wrapping transitions this failure type to a more ductile response. The capability of GFRP to enhance shear strength is vital for structures exposed to intense shear forces, such as beams in bridges and buildings.

Numerous investigations have demonstrated the favorable impact of GFRP on the shear strength of concrete beams. Nanda and Behera, (2020) conducted experiments on shear-deficient concrete beams wrapped with GFRP layers and observed a 35% increase in shear strength compared to unwrapped beams. This substantial improvement is ascribed to GFRP's ability to confine the concrete, postponing the initiation of shear failure and allowing the beams to resist greater loads before failure takes place. The study also remarked that the failure mode shifted from brittle shear failure to a more gradual and ductile response, which enhances the overall safety and reliability of the structure.

In a comparable investigation, El-Hacha and Rizkalla, (2004) noted that GFRP wrapping boosted the shear strength of concrete beams by 40%. Their findings further confirmed the transition from brittle failure to a more controlled, ductile failure mechanism, which is essential for the performance of beams in real-world scenarios. The researchers attributed this improvement to the extra confinement and the reinforcing effect provided by the GFRP material, which helps delay cracking and enhances the load-carrying capacity of the beams.

Feng *et al*. (2019) studied the shear behavior of GFRP-wrapped reinforced concrete beams and reported an impressive 50% increase in shear strength. They also observed that GFRP-wrapped beams exhibited more ductile failure modes compared to unwrapped beams, which tended to fail abruptly and catastrophically under shear stresses. The enhanced shear strength and ductility observed in GFRP-wrapped beams can be especially beneficial for structures subjected to seismic or dynamic loading, where high shear forces are common.

Similarly, Xie *et al.* (2022) discovered that GFRP wrapping improved the shear strength of concrete beams by 32% compared to unwrapped beams. The study indicated that unwrapped beams failed prematurely under shear forces, while GFRP-wrapped beams demonstrated improved shear resistance and a more gradual failure process, leading to better safety and performance.

Finally, Ali *et al*. (2024) conducted studies on concrete beams wrapped with GFRP and reported that the shear strength of these beams increased by 25% to 35%, with the highest performance seen in beams wrapped with multiple layers of GFRP. The rise in shear strength was attributed to the greater confinement provided by the additional layers of GFRP, which strengthened the

beam's ability to resist shear forces and delayed the onset of cracking. The shear strength values obtained from load tests, based on different studies on GFRP wrapping methods for boosting the shear strength of concrete specimens, are shown in Fig. 5. This provides a clear picture of how GFRP can be effectively utilized to enhance the shear resistance of concrete.

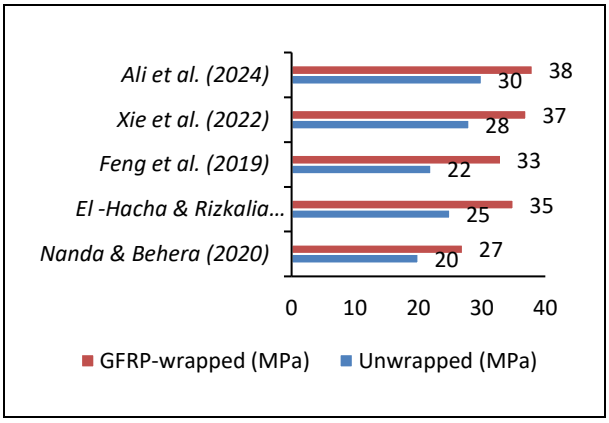


Fig. 5: Consolidated shear strength for GFRP specimens (wrapped and unwrapped)

In summary, GFRP wrapping serves as a powerful technique for enhancing the shear strength of concrete beams. The added confinement offered by GFRP boosts the beam's resistance to shear stresses, transforms the failure mode from brittle to ductile, and elevates the overall structural performance.

3.4 Ductility

The ductility of concrete elements is essential in ensuring that structures can withstand substantial deformations without failure, particularly when subjected to dynamic, seismic, or cyclic loading. GFRP wrapping plays a significant role in improving the ductility of concrete, enabling it to absorb more energy and undergo greater deformations before failure. The confinement provided by the GFRP material helps resist cracking and delays brittle failure, thereby enhancing the structure's resilience under extreme conditions.

Studies have shown that GFRP wrapping substantially improves the ductility of concrete. Bisby, *et al*. (2021) found that GFRP-wrapped concrete columns demonstrated a 50% increase in deformation capacity under cyclic loading. This enhancement is critical for seismic performance, where the ability to absorb and dissipate energy is essential to prevent collapse. The increased deformation capacity allows wrapped columns to undergo more significant plastic deformations without failure, which enhances safety in seismic zones.

Teng *et al.* (2024) observed that GFRP-wrapped concrete specimens exhibited up to 40% better ductility under cyclic loading. This improvement was attributed to the confinement effect, which helped prevent early cracking, allowing the specimens to endure larger deformations while maintaining structural integrity. This increase in ductility is crucial for preventing sudden failure in high-demand structural applications.

Similarly, Zhou *et al*. (2021) found that GFRP wrapping improved the ductility of concrete specimens by 45%. The enhanced ductility not only promoted energy dissipation but also reduced the chances of brittle failure. Concrete elements wrapped with GFRP exhibited gradual failure modes, which are vital for maintaining structural stability under extreme loading conditions.

Rao *et al.* (2021) conducted tests on concrete columns wrapped with GFRP and found a 50% improvement in ductility, significantly delaying failure and increasing load-carrying capacity during cyclic loading. This is especially beneficial for structures in seismic regions, where the ability to withstand large deformations without failure is critical for maintaining stability during earthquakes.

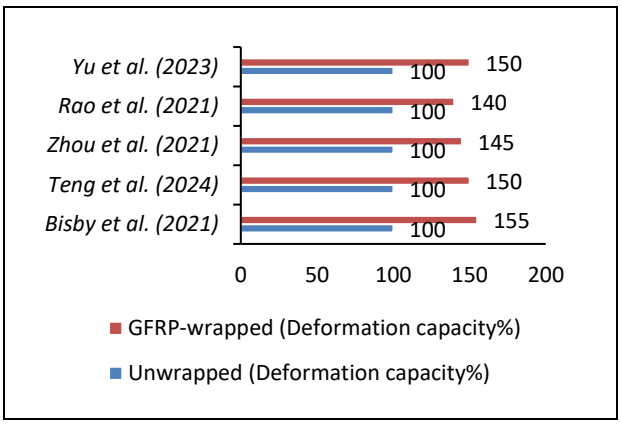


Fig. 6: Consolidated ductility (deformation capacity) for GFRP specimens (wrapped and unwrapped)

Yu *et al.* (2023) observed a 55% increase in ductility in GFRP-wrapped concrete columns. These columns could resist significantly larger deformations before failure, demonstrating the superior energy absorption capacity of GFRP-wrapped concrete structures. This enhancement in ductility not only improves the resilience of concrete structures under dynamic loads but also ensures they remain safe and operational for longer durations.

The deformation capacity values from various load tests on GFRP-wrapped concrete specimens, showing the increase in ductility, are presented in Fig. 6, offering a more comprehensive insight into how GFRP enhances the shear resistance and ductility of concrete.

In summary, GFRP wrapping greatly enhances the ductility of concrete elements, allowing them to endure greater deformations, absorb higher amounts of

energy, and resist cracking and failure when exposed to dynamic or seismic forces. This enhancement is essential for improving the safety, longevity, and functionality of concrete structures, particularly in areas prone to high seismic activity or cyclic loading. The overview of the impact of GFRP confinement on the structural characteristics of concrete from multiple academic analyses has been summarized in Table 1.

Table 1. The effect of GFRP wrapping on the mechanical properties of concrete

Study	Objectives	Research Methodology	GFRP Configuration	Test Specimen	Test Methods	Results	Strengths	Limitations
(Islam *et al.* 2020)	Compressive Strength	Experimental study on cylindrical specimens	Fully wrapped GFRP sheets	Concrete cylinders (Unwrapped vs. GFRP-wrapped)	Axial compression test	405% increase (9.92 MPa → 50.37 MPa)	Significant strength gain, effective confinement	No long-term durability assessment
(Zhao *et al.* 2022c)	Compressive Strength	Tests on concrete-filled GFRP tubes	GFRP wrapping on circular columns	Concrete columns (unwrapped vs. wrapped)	Axial compression test	50% increase (40 MPa → 60 MPa)	Structural enhancement under axial load	Limited variation in GFRP thickness
(Wang *et al.* 2020)	Compressive Strength	Laboratory experiment on GFRP-wrapped concrete	Single-layer GFRP wrap	Concrete cylinders	Axial compression test	40% increase (40 MPa → 56 MPa)	Enhanced structural performance	No study on cyclic loading behavior
(Peng *et al.* 2024)	Flexural Strength	Bending test on wrapped beams	GFRP sheets applied to beam surfaces	Concrete beams	Four-point bending test	40% increase (25 MPa → 35 MPa)	Increased stiffness, better crack control	No durability tests under environmental conditions
(Nanni *et al.* 2024)	Flexural Strength	Investigation on GFRP reinforcement for beams	GFRP sheets on tension face	Concrete beams	Flexural test	30% increase in bending strength	Effective reinforcement	No consideration of fatigue behavior
(Gao *et al.* 2022)	Flexural Strength	Experimental study on bending capacity	GFRP strips and full wrapping	Concrete beams	Flexural test	35% increase (28 MPa → 38 MPa)	Improved ductility and crack control	Limited discussion on failure modes
(Nanda and Behera et al. 2020)	Shear Strength	Evaluation of shear behavior in deficient beams	GFRP wrapping at shear-critical sections	Concrete beams	Shear test	35% increase in shear capacity	Improved shear resistance, reduced brittle failure	No assessment of long-term shear degradation
(El-Hacha and Rizkalla, 2004)	Shear Strength	Shear reinforcement effectiveness test	GFRP sheets in shear zones	Concrete beams	Shear test	40% increase in shear strength	Ductility enhancement	Limited analysis on varying layer thickness
(Feng *et al.* 2019)	Shear Strength	Study on reinforced concrete beams	Multi-layer GFRP wrapping	Reinforced concrete beams	Shear test	50% increase in shear strength	Highly effective for shear-deficient beams	No real-scale validation
(Bisby *et al.* 2021)	Ductility	Seismic performance evaluation	GFRP wrapping for confinement	Concrete columns	Cyclic loading test	50% increase in deformation capacity	Crucial for seismic applications	No evaluation under fire exposure
(Teng *et al.* 2024)	Ductility	Cyclic loading behavior of wrapped concrete	Confined GFRP layers	Concrete specimens	Cyclic load test	40% improved ductility	Prevents premature brittle failure	No study on aging effects
(Yu *et al.* 2023)	Ductility	Energy absorption capacity of wrapped concrete	Multiple layers of GFRP	Concrete columns	Cyclic compression test	55% increase in ductility	Enhances seismic resilience	Limited environmental a

4. STRUCTURAL BEHAVIOR OF GFRP-WRAPPED CONCRETE

The application of GFRP (Glass Fiber Reinforced Polymer) wrapping greatly improves the structural performance of concrete elements, boosting their behavior under different load scenarios, seismic events, and cyclic loading. GFRP wrapping plays a key role in enhancing the overall strength, resilience, and longevity of concrete structures by offering lateral

confinement, improving energy dissipation, and increasing fatigue resistance.

4.1 Load Behavior

Concrete elements wrapped with GFRP show a significant enhancement in performance under both axial and lateral loads. The lateral confinement offered by GFRP boosts the stiffness and load-carrying capacity of the concrete, postponing failure and reducing the risk of brittle fracture. Confined concrete exhibits greater ductility, enabling it to withstand higher axial and lateral forces compared to unwrapped specimens. Research indicates that GFRP-wrapped columns can support greater loads with minimal deformation, enhancing their reliability in structural applications.For instance, Zhao *et al*. (2021) found that GFRP-wrapped concrete columns could support up to 35% higher axial loads than unwrapped columns, highlighting the clear advantage of GFRP confinement in enhancing load-bearing capacity. Moreover, GFRP wrapping shifts the failure mode from a brittle, sudden collapse to a more controlled and gradual failure, improving both safety and structural performance. The wrapping also aids in preserving the integrity of the concrete structure, particularly in high-stress environments, ensuring its long-term durability and serviceability. The comparison of axial load performance in concrete columns with and without GFRP wrapping is shown in Fig. 7.

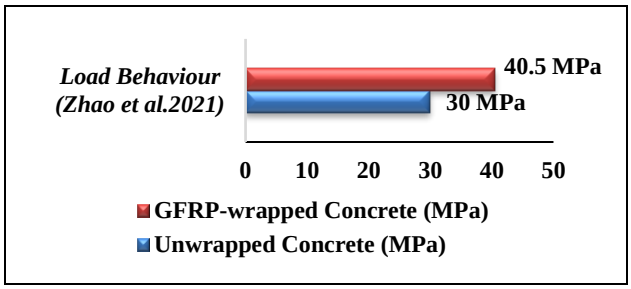


Fig. 7: Comparison of axial load in concrete columns with and without GFRP wrapping (in MPa)

4.2 Seismic Performance

GFRP wrapping significantly enhances the seismic performance of concrete structures. The increased ductility and energy dissipation capabilities provided by GFRP confinement allow the structure to absorb more energy during seismic events, thus reducing the risk of catastrophic failure. Concrete columns, beams, and other elements wrapped in GFRP can undergo larger deformations before failure, which is particularly crucial during earthquakes, where large and unpredictable movements are common. Fig. 8 depicts the comparison of seismic performance in concrete structural elements with and without GFRP wrapping.

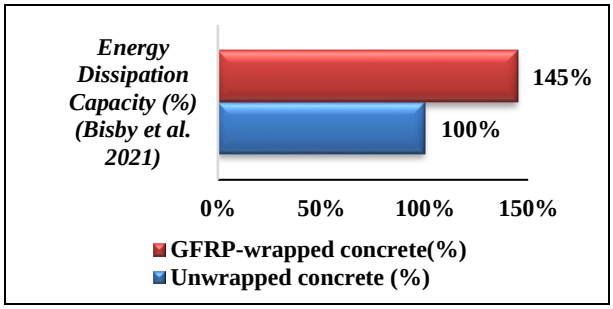


Fig. 8: Comparison of seismic performance in concrete structural elements with and without GFRP wrapping

Research by Bisby *et al*. (2021) demonstrated that GFRP-wrapped concrete columns subjected to seismic loading showed an improved energy dissipation capacity up to 45% compared to unwrapped columns. This considerable enhancement enables these structures to endure seismic events by absorbing and dissipating the energy imparted by the earthquake, thereby reducing the overall stress on the structure. The improved ductility also ensures that GFRP-wrapped elements display gradual failure modes, rather than sudden, catastrophic failure, which is vital for maintaining stability and safety in buildings and infrastructure during seismic events.

4.3 Fatigue Resistance

Another significant advantage of GFRP wrapping is its enhancement of fatigue resistance. Concrete elements subjected to repetitive loading cycles, such as bridges or pavement structures, are susceptible to the initiation and propagation of cracks over time. GFRP wrapping provides additional reinforcement, helping to alleviate stress concentrations and delay crack formation. The lateral confinement provided by GFRP also mitigates the spread of micro-cracks, significantly extending the service life of the concrete structure. Fig. 9 illustrates the fatigue resistance in concrete beams with and without GFRP wrapping.

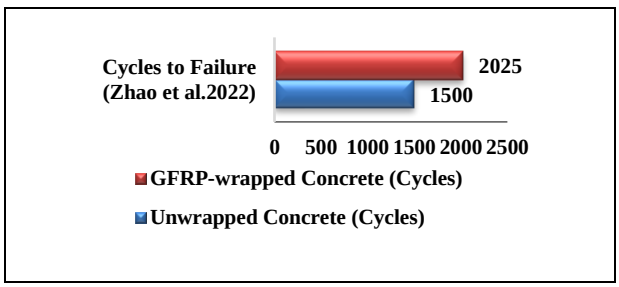


Fig. 9: Comparison of fatigue resistance in concrete beams with and without GFRP wrapping

Zhao *et al.* (2022d) demonstrated that GFRP-wrapped concrete beams showed a 35% improvement in fatigue resistance compared to unwrapped beams. The wrapping effectively reduces cyclic loading-induced damage, preventing premature cracking and ensuring the structure's performance throughout its service life. GFRP's durability and resistance to corrosion also contribute significantly to enhancing fatigue resistance by preventing degradation due to environmental factors, such as moisture or chemicals, which could otherwise accelerate crack formation in traditional reinforced concrete.

In summary, GFRP wrapping substantially improves the structural performance of concrete elements under various loading conditions. It enhances load-bearing capacity, seismic resilience, and fatigue resistance, resulting in concrete structures that are more durable, resilient, and safe. The overview of the effect of GFRP enclosure on the structural response of GFRP-coated concrete from diverse academic examinations has been presented in Table 2.

Table 2. Structural behavior of GFRP-wrapped concrete

Study	Objectives	Research Methodology	GFRP Configuration	Test Specimen	Test Methods	Results	Strengths	Limitations
(Zhao *et al.* 2024)	Load Behavior	Experimental study on concrete columns	Single-layer GFRP wrap	Concrete columns (unwrapped *vs.* wrapped)	Axial compression test	35% higher axial load resistance for wrapped columns	Enhanced load-bearing capacity, delayed failure mode	No long-term performance data
(Zhao et al. 2022e)	Fatigue Resistance	Fatigue testing of concrete beams	Multi-layer GFRP wrap	Concrete beams	Cyclic loading test	35% improvement in fatigue resistance	Increased service life, reduced crack propagation	Limited range of applied load cycles
(Bisby *et al.* 2021)	Seismic Performance	Seismic performance evaluation of concrete columns	GFRP wrapping for confinement	Concrete columns	Cyclic loading under seismic conditions	45% improvement in energy dissipation	Increased safety and performance in seismic conditions	No analysis of aging or environmental factors
(Feng *et al.* 2019)	Load and Seismic Behavior	Comparative study of load and seismic responses	GFRP reinforcement	Concrete columns and beams	Combined axial and lateral loading tests	Significant improvements in both axial load and seismic performance	Effective in high-stress conditions	Limited variety in specimen types
(Yu *et al.* 2023)	Fatigue Resistance	Investigation of GFRP's impact on fatigue resistance	Multi-layer GFRP wrap	Concrete beams	Cyclic loading test	Improved fatigue resistance, reduction in crack formation	Reduced cyclic-induced damage	No comparison to other reinforcement methods
(Teng *et al.* 2024)	Seismic & Load Behavior	Study on combined load and seismic behavior	GFRP-wrapping at critical stress zones	Concrete columns	Seismic and axial loading test	Enhanced seismic performance, better load resistance	Proven for both seismic and axial conditions	Does not address GFRP degradation

5. FACTORS AFFECTING THE PERFORMANCE OF GFRP-WRAPPED CONCRETE

The performance of GFRP-wrapped concrete is governed by several important factors, such as the thickness of the GFRP layers, the compressive strength of the concrete, and the environmental conditions to which the structure is exposed. Understanding these factors is essential for optimizing the effectiveness of GFRP reinforcement in concrete structures, ensuring enhanced performance and long-term durability.

5.1 GFRP Layer Thickness

The thickness of the GFRP layers plays a critical role in determining the overall performance of wrapped concrete elements. As the number of GFRP layers increases, the degree of confinement to the concrete improves, leading to enhanced strength, ductility, and overall structural performance. More layers help resist higher axial and lateral forces and shift the failure mode from brittle to more ductile. However, it is essential to find a balance between performance improvement and material costs, as increasing the thickness of GFRP wrapping can escalate both costs and construction complexity.

Zhao *et al*. (2024) discovered that increasing the number of GFRP layers from two to four resulted in a 20% increase in compressive strength and a 15% improvement in ductility for concrete columns. This performance enhancement must be carefully balanced with the associated cost implications, as both material and labor expenses rise with additional layers. Thus, optimizing the number of layers is vital to achieving an appropriate balance between performance gains and cost-effectiveness.

5.2 Concrete Strength

The intrinsic strength of the concrete substrate plays a crucial role in determining the performance of GFRP wrapping. High-strength concrete may respond differently to GFRP confinement compared to lower-strength concrete, influencing the overall effectiveness of the GFRP system. Concrete with higher compressive strength tends to exhibit greater strain-hardening behavior under confinement, whereas lower-strength concrete may derive more significant benefits from GFRP wrapping, particularly in terms of enhanced load capacity and ductility.

For instance, El-Hacha and Rizkalla (2004) observed that high-strength concrete (60 MPa) wrapped with GFRP showed a 35% improvement in load capacity, while normal-strength concrete (30 MPa) exhibited a 50% increase in load capacity. The interaction between the concrete's inherent properties and the GFRP confinement system plays a crucial role in determining the system's overall effectiveness. Therefore, understanding the strength characteristics of the concrete is vital for selecting the appropriate type and thickness of GFRP wrapping.

5.3 Environmental Exposure

Environmental factors such as humidity, temperature fluctuations, and chemical exposure can significantly impact the long-term durability of GFRP-wrapped concrete. Although GFRP is known for its corrosion resistance, the resin matrix and the fiber-matrix interface can be susceptible to environmental degradation over time. Moisture exposure can weaken the resin, leading to delamination or a loss of bond between the fibers and the matrix. Likewise, temperature variations can cause the resin to become brittle or degrade, reducing the effectiveness of the GFRP wrapping.

Bisby *et al.* (2021) highlighted that exposure to alkaline environments notably affected the bond strength of GFRP-wrapped concrete. Concrete wrapped with GFRP was subjected to chemical attacks from aggressive agents such as chloride and sulfate, resulting in a 15-20% reduction in the long-term strength of the system. Additionally, prolonged exposure to high humidity and thermal cycling caused resin degradation, compromising the GFRP's overall durability.

To counter the effects of environmental exposure, researchers recommend using advanced resin systems that offer better resistance to moisture and chemical attacks. Nanni *et al.* (2024) demonstrated that using UV-resistant resins could significantly extend the service life of GFRP-wrapped concrete, especially in harsh environments such as coastal or industrial regions. The summary of diverse elements influencing the efficacy of GFRP-wrapped concrete has been presented in Table 3.

Table 3: Factors affecting performance of GFRP-wrapped concrete

Study	Objectives	Research Methodology	Key Findings	GFRP Configuration	Test Specimen	Test Methods	Results	Strengths	Limitations
(Zhao *et al.* 2024)	GFRP Layer Thickness	Experimental study on concrete columns	Influence of GFRP layer thickness on strength and ductility	2-4 layers of GFRP wrap	Concrete columns	Compressive strength and ductility tests	20% increase in compressive strength and 15% increase in ductility with 4 layers of GFRP	Improved performance with increased layers	Material and labor cost increases with more layers
(El-Hacha and Rizkalla, 2004)	Concrete Strength	Experimental study on different concrete strengths	Effect of concrete strength on GFRP performance	Single-layer GFRP wrap	High-strength concrete (60 MPa) vs normal-strength concrete (30 MPa)	Axial load tests	35% improvement in load capacity for high-strength concrete, 50% for normal-strength concrete	Performance improvement with GFRP wrapping	High-strength concrete may show less benefit

Study	Objectives	Research Methodology	Key Findings	GFRP Configuration	Test Specimen	Test Methods	Results	Strengths	Limitations
ScienceDirect (2022)	Environmental Exposure	Study on environmental effects on GFRP performance	Impact of moisture, temperature, and chemical exposure on durability	Single-layer GFRP wrap	Concrete exposed to harsh environmental conditions	Long-term durability tests	15-20% reduction in bond strength in chemical environments	Corrosion resistance of GFRP, but resin degradation under harsh conditions	Limited studies on long-term exposure effects
(Nanni *et al*. 2024)	Environmental Exposure	Study on resin systems and environmental exposure	Impact of UV-resistant resins on GFRP durability	UV-resistant resin systems	Concrete in coastal or industrial regions	Exposure to UV, moisture, and thermal cycling	Improved service life with UV-resistant resins	Protection against harsh environments	Potential higher cost of UV-resistant resin systems
(Teng *et al*. 2024)	Environmental and Concrete Strength Interaction	Analysis of concrete strength and environmental exposure	Combined effects on GFRP-wrapped concrete	GFRP with varying layer thickness	Concrete beams under varied environmental conditions	Axial and cyclic loading tests	Improved performance in mixed environments with thicker layers	Balances environmental concerns with enhanced performance	Limited comparison with other resin systems

6. APPLICATIONS OF GFRP-WRAPPED CONCRETE

GFRP wrapping has become widely adopted in the strengthening and retrofitting of various concrete structures, offering a cost-effective, durable, and efficient solution to enhance the structural integrity of aging or damaged buildings and infrastructure. Its versatility and performance advantages make it an ideal choice for reinforcing elements such as columns, beams, and bridge components. Furthermore, its applications are particularly essential in seismic retrofitting, where it significantly contributes to improving the ductility and energy dissipation capacity of structures, thereby enhancing their ability to endure dynamic loads, such as those generated by earthquakes.

6.1 Strengthening and Retrofitting of Concrete Structures

One of the key applications of GFRP wrapping is in the reinforcement of reinforced concrete columns and beams. GFRP wrapping is commonly used to confine these concrete elements, thereby enhancing their load-bearing capacity. This technique is especially beneficial for structural retrofitting, as it allows for significant improvements in strength and durability with minimal disruption to the original structure. The lightweight nature of GFRP wrapping ensures that it does not significantly add to the dead load of the structure, making it ideal for retrofitting buildings that are unable to accommodate additional weight.

In columns, GFRP wrapping significantly improves axial load capacity and shear strength, ensuring more efficient load distribution and reducing the risk of failure under extreme loading conditions. Concrete beams benefit from the increased flexural strength and ductility provided by GFRP wrapping, enhancing their resistance to bending and cracking under applied loads. This was demonstrated by Teng *et al.* (2024), who found that GFRP-wrapped beams exhibited up to a 30% higher bending capacity compared to unwrapped beams.

6.2 Seismic Retrofitting Applications

The seismic performance of concrete structures can be significantly enhanced through the use of GFRP wrapping. Buildings in earthquake-prone areas often face substantial challenges in maintaining structural stability, especially older buildings that were not initially designed to endure seismic forces. GFRP wrapping improves ductility, allowing structures to undergo larger deformations without failure, a vital feature during seismic events. The energy dissipation capacity provided by GFRP helps mitigate the risk of catastrophic failure during earthquakes.

For instance, Liu *et al*. (2023) showed that GFRP-wrapped concrete columns could absorb up to 50% more energy during cyclic loading, greatly enhancing their seismic resistance. In seismic retrofitting, GFRP's flexibility and non-invasive application process make it an excellent choice, as it can be applied to existing structures without requiring significant modifications or extended downtime. Additionally, GFRP is corrosion-resistant, making it particularly well-suited for seismic retrofitting where long-term durability is a critical concern.

6.3 Bridge Component Strengthening

The use of GFRP wrapping in bridge structures is another crucial application. Bridges are vital elements of infrastructure, and ensuring their long-term durability

is essential for the safe and efficient operation of transportation networks. GFRP wrapping has proven highly effective in strengthening bridge columns, girders, and deck slabs by enhancing their shear resistance, flexural strength, and overall durability. Additionally, the non-corrosive properties of GFRP are particularly advantageous for bridges located in harsh environments, such as coastal areas or regions exposed to de-icing salts, where traditional steel reinforcements are vulnerable to corrosion.

According to Structure Magazine (2022), GFRP-wrapped bridge columns exhibited a 40% increase in shear strength compared to unwrapped columns, leading to a more resilient structure that can endure greater external loads and environmental stresses. Furthermore, GFRP wrapping was shown to enhance the fatigue resistance of bridge components subjected to repetitive traffic loads, significantly extending the service life of the bridge.

6.4 Non-invasive Strengthening

One of the primary benefits of GFRP wrapping over traditional strengthening techniques is its non-invasive application. Unlike methods that necessitate significant modifications to the existing structure, such as the addition of external steel reinforcements or concrete overlays, GFRP wrapping can be applied to concrete elements with minimal disruption to the structure's original design. This is particularly beneficial in cases where the structure remains in active use, such as in commercial buildings or transportation infrastructure like bridges and tunnels, where reducing downtime is essential. The lightweight and flexible nature of GFRP allows for easy installation without adding substantial weight or volume to the structure, facilitating smooth integration with the current design. The following diagram depicts the utilization of GFRP encasement wrapping in various construction elements. In Fig. 10, the applications of GFRP confinement wrapping in different structural components have been demonstrated with great clarity. The overview of the uses of GFRP-wrapped concrete, compiled from various academic investigations, has been presented in Table 4.

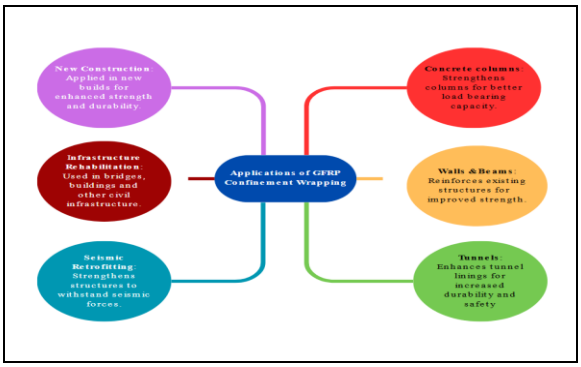


Fig. 10: Applications of GFRP confinement wrapping

Table 4. Summary of GFRP-wrapped concrete applications

Study	Objectives	Research Methodology	Key Findings	GFRP Configuration	Test Specimen	Test Methods	Results	Strengths	Limitations
(Teng *et al.* 2024)	Strengthening of Concrete Beams	Experimental study on GFRP-wrapped concrete beams	Influence of GFRP wrapping on bending capacity	Single-layer GFRP wrap	Concrete beams	Bending tests	GFRP-wrapped beams exhibited up to 30% higher bending capacity than unwrapped beams	Enhanced flexural strength and ductility	Limited to beam applications, may not be applicable for all structures
(Liu *et al.* 2023)	Seismic Retrofitting	Cyclic loading tests on concrete columns	Seismic performance improvement with GFRP wrapping	Single-layer GFRP wrap	Concrete columns	Seismic cyclic loading tests	GFRP-wrapped columns absorbed 50% more energy, enhancing seismic resistance	Improved energy dissipation and seismic stability	Seismic response may vary depending on column geometry and load conditions
Structure Magazine *(2022)*	Bridge Component Strengthening	Case study on bridge columns	GFRP wrapping in bridge columns under load	Multiple layers of GFRP wrap	Bridge columns	Shear strength tests	GFRP wrapping resulted in a 40% increase in shear strength, improving load resistance	Excellent in harsh environments and corrosion resistance	Effectiveness in larger-scale bridge structures not yet fully explored
(Nanni *et al.* 2024)	Non-Invasive Strengthening	Experimental study on retrofit methods	Comparison of GFRP with traditional methods	Single-layer GFRP wrap	Various concrete elements	Performance and installation tests	Non-invasive nature of GFRP wrapping allowed for seamless integration and minimal disruption	Lightweight and flexible, reducing downtime	May require specialized knowledge for installation, complexity in irregular shapes

Study	Objectives	Research Methodology	Key Findings	GFRP Configuration	Test Specimen	Test Methods	Results	Strengths	Limitations
(Bisby *et al.* 2021)	Seismic and Fatigue Resistance	Experimental study on columns	Impact of GFRP wrapping on seismic and fatigue resistance	2-4 layers of GFRP wrap	Concrete columns	Fatigue and seismic loading tests	Enhanced seismic performance and fatigue resistance, delaying crack formation	Improves safety and performance under dynamic loads	Long-term performance under real-world conditions is not fully known

7. CHALLENGES AND LIMITATIONS OF GFRP-WRAPPED CONCRETE

While GFRP provides a range of advantages for concrete strengthening and retrofitting, its broader implementation faces certain challenges. These challenges mainly concern material costs, long-term durability, and the complexities of application. Addressing these factors is crucial to ensuring the effective and successful use of GFRP in reinforcing concrete structures.

7.1 High Initial Material Costs

One of the major obstacles to the widespread use of GFRP in concrete strengthening is its relatively high initial cost when compared to traditional materials like steel. The production of GFRP involves specialized components such as glass fibers and epoxy resin, which are more expensive than steel reinforcement. For example, the cost per square meter of GFRP sheets can be significantly higher than that of steel mesh or bars, leading to a considerable upfront investment for GFRP wrapping (Zhao *et al*. 2024). Although GFRP typically offers lower maintenance costs, particularly due to its corrosion resistance, the initial capital expense may be a barrier for projects with limited budgets, especially in developing regions or for large-scale infrastructure developments.

7.2 Long-term Durability Concerns

Another key limitation of GFRP is its long-term durability under diverse environmental conditions. While GFRP is widely recognized for its corrosion resistance, the resin matrix that binds the glass fibers can degrade when exposed to extreme temperatures, UV radiation, humidity, and chemical environments (El-Sayed *et al*. 2021). In environments with high moisture content or chemical exposure, such as marine or industrial settings, the bond between the fibers and matrix may weaken over time, reducing the performance of the wrapping system. Additionally, prolonged exposure to UV light can degrade the polymer matrix, resulting in a loss of structural integrity and overall effectiveness. These challenges underscore the need for ongoing monitoring and further research into the long-term performance of GFRP-wrapped concrete in various environmental conditions. Such efforts are crucial to enhancing its lifespan and ensuring the material's reliability in diverse applications (Zhou *et al.* 2021).

7.3 Adhesion and Bonding Challenges

The bonding between GFRP and the concrete surface is crucial to the success of GFRP strengthening applications. A strong and durable adhesive bond ensures that the confining effect of the GFRP is fully realized, which enhances the strength, ductility, and overall performance of the concrete structure. Any delamination or failure at the interface between the GFRP and concrete can significantly compromise the structural benefits of the system.

Several factors influence the quality of the bond, including surface preparation, moisture levels, and temperature during the application process. Proper surface preparation is essential; if the concrete surface is not cleaned and roughened adequately, the adhesive bond may not form effectively, which can lead to poor performance and potential failure of the GFRP wrapping under load (Gao *et al*. 2022). Surface treatments, such as the application of primers, may be necessary to improve adhesion, especially in challenging conditions. In addition, maintaining proper temperature and moisture conditions during the application process is vital to ensuring the integrity of the bond and achieving the desired performance. Thus, ensuring a reliable bond between GFRP and concrete requires meticulous preparation and application techniques to prevent potential issues that could undermine the benefits of GFRP strengthening.

7.4 Limited Knowledge and Research on Long-term Behavior

While GFRP has been extensively studied in laboratory settings, there is a relative lack of research on the long-term performance of GFRP-wrapped structures in real-world conditions, particularly over decades of exposure. Most of the studies on GFRP focus on its performance under short-term loading conditions, with fatigue and creep behavior under sustained loads remaining areas of active research. Some studies suggest that while GFRP may perform well initially, the long-term deformation under sustained loads may result in a loss of efficiency or failure of the wrapping system

(Nanni *et al.* 2024). In-service monitoring and field testing will be critical for understanding the durability and longevity of GFRP-wrapped concrete in diverse environments.

7.5 Application Complexity and Construction Challenges

While GFRP has shown promising results in laboratory settings, there is a noticeable gap in research regarding the long-term performance of GFRP-wrapped structures in real-world conditions. Most studies primarily focus on short-term loading scenarios, often neglecting the sustained effects of fatigue and creep behavior that structures may experience over decades of use. GFRP has demonstrated good performance under initial loading conditions, but concerns remain regarding its ability to maintain structural integrity over extended periods, especially when exposed to continuous or repetitive loading.

Some studies, including those by (Nanni *et al.* 2024), have indicated that while GFRP may perform well initially, long-term deformation under sustained loads could lead to a loss of effectiveness or even failure of the GFRP wrapping system. Over time, the material may undergo gradual degradation or exhibit reduced capacity to resist deformation, which could compromise its overall performance in real-world applications.

In-service monitoring, coupled with field testing, will be essential to evaluate the long-term durability and efficiency of GFRP-wrapped concrete under various environmental and loading conditions. These efforts will provide critical insights into the material's performance over extended periods and help identify potential issues such as degradation of the resin matrix, fatigue effects, and creep behavior that could impact its ability to sustain structural integrity over the lifespan of the structure.

7.6 Limited Codes and Standards

The application of GFRP for structural strengthening remains relatively new compared to traditional materials like steel and reinforced concrete. Consequently, the development of comprehensive design codes and standards for GFRP in concrete strengthening is still an ongoing process in many regions. While organizations such as the American Concrete Institute (ACI) have established guidelines, such as those provided by ACI Committee 440 (2021), these may not fully account for all complexities and variables associated with GFRP applications. Factors such as diverse environmental conditions, variations in GFRP configurations, and differences in concrete strengths require more refined design provisions.

The absence of universally accepted and standardized guidance can pose challenges for engineers attempting to predict the structural behavior of GFRP-wrapped concrete under different scenarios. This uncertainty can sometimes lead to conservative designs, where excessive amounts of GFRP are used to ensure safety, thereby unnecessarily increasing costs. Conversely, in some cases, the lack of detailed design criteria may result in under-design, potentially compromising the structure's long-term durability and performance. As research in this field continues to evolve, the development of more precise and widely accepted design standards will be crucial to facilitate the safe and efficient integration of GFRP in structural applications. Further experimental and field studies will help bridge the existing knowledge gaps, ultimately leading to the refinement of guidelines that can account for real-world conditions and long-term performance considerations. Table 5 presents a summary of the obstacles and constraints of GFRP-wrapped concrete, compiled from various scholarly analyses.

Table 5. Challenges and limitations of GFRP-wrapped Concrete

Study	Objectives	Observation	Mitigation Strategy
(Zhao *et al.* 2024)	High Material Cost	GFRP costs several times more per square meter than steel.	Explore cost-effective manufacturing techniques or alternative materials.
(El-Sayed *et al.* 2021)	Long-term Durability	Resin matrix degradation occurs in high humidity and UV light, reducing lifespan.	Use UV-resistant and moisture-resistant resins.
(Gao *et al.* 2022)	Bonding Challenges	Poor surface prep leads to delamination, compromising the confining effect.	Ensure proper surface preparation (cleaning, roughening) and controlled application.
(Nanni *et al.* 2024)	Long-term Behavior	Lack of data on GFRP's long-term behavior under sustained loading and cyclic conditions.	Conduct long-term field studies to assess creep, fatigue, and long-term performance.
(Banik *et al.* 2024)	Application Complexity	The installation is labor-intensive and challenging in confined spaces.	Standardize installation processes and train skilled labor to reduce errors.
ACI Committee 440 (2021)	Lack of Standards	Insufficient standardized guidelines for GFRP application in diverse environments.	Develop comprehensive design codes and guidelines for GFRP applications.

8. CONCLUSION

The application of Glass Fiber Reinforced Polymer (GFRP) wrapping has been demonstrated to be a highly efficient technique for reinforcing concrete frameworks. This method considerably enhances various mechanical and structural aspects, leading to improved performance across different loading scenarios, while its corrosion resistance and durability extend service life and reduce the material and carbon burden of repeated repair, supporting more sustainable management of concrete infrastructure. The following comprehensive conclusions outline the principal findings and observations from this thorough study:

- GFRP wrapping improves the compressive strength of concrete by offering lateral restraint, which postpones the initiation of micro-cracking and boosts the load-bearing potential. This enhancement is especially advantageous for buildings subjected to elevated axial forces. GFRP-covered concrete commonly exhibits a notable gain in compressive resilience compared to uncoated samples, making it an effective selection for load-bearing structures.

- Concrete beams enclosed with GFRP display markedly increased flexural capacity and stiffness. The superior tensile capability of GFRP efficiently counteracts tensile forces during bending, strengthening the bending resistance and managing crack progression under flexural impact. This improvement is vital for maintaining the longevity and robustness of beams exposed to fluctuating or flexural stress in infrastructure systems.

- One significant benefit of GFRP wrapping is its capacity to enhance the shear resistance of concrete elements. The supplementary reinforcement from GFRP counteracts shear stresses, mitigating brittle shear failure, which remains a prevalent failure pattern in untreated concrete members. Additionally, GFRP-reinforced beams typically demonstrate more ductile collapse behaviors, ensuring greater stability and security by shifting from abrupt shear failures to progressive failure mechanisms.

- GFRP wrapping substantially augments the ductility of concrete sections, rendering them more adaptable to seismic or variable loading conditions. This superior ductility enables concrete elements to tolerate extensive deformations before fracturing, improving energy absorption and dispersion during earthquake occurrences. The reinforced seismic endurance of GFRP-coated concrete guarantees that structures can endure extreme deformations, minimizing the possibility of catastrophic breakdown during earthquakes.

- GFRP-covered concrete members exhibit enhanced responses to both axial and lateral pressures. The restraint provided by the GFRP composition increases the rigidity and load-resisting capability of the concrete, prolonging structural integrity and ensuring better overall durability. This makes GFRP encapsulation a prime option for high-demand construction components, including bridge elements, pillars, and beams.

- The layering of concrete with GFRP also enhances its fatigue durability. By minimizing stress points and postponing crack formation, GFRP aids in prolonging the lifespan of frameworks subjected to cyclic or repetitive loading. This advancement is crucial for essential infrastructure, such as bridges and roadways, which endure cyclic pressures over time.

- The efficiency of GFRP-reinforced concrete is shaped by a variety of factors, such as the number of GFRP layers, the quality of the concrete matrix, and the surrounding environmental conditions. Increasing the number of GFRP layers boosts confinement and mechanical strength, but the performance can differ when paired with high-strength concrete. Moreover, environmental elements like temperature changes and chemical exposure can weaken the GFRP resin over time, highlighting the importance of further research into its long-term durability.

- GFRP wrapping is commonly applied for reinforcing and refurbishing concrete elements, particularly in seismic upgrading. Its advantages in boosting ductility and absorbing energy make it highly efficient in areas susceptible to seismic hazards. GFRP reinforcement provides a minimally disruptive solution that does not notably alter the form or weight of existing constructions, ensuring its adaptability for restoring critical components such as pillars, beams, and bridges.

- Despite its substantial benefits, the broad implementation of GFRP for concrete reinforcement faces obstacles. The initial expense of GFRP materials is higher relative to conventional strengthening techniques, which might restrict their adoption in cost-conscious projects. Furthermore, concerns regarding the

prolonged stability of GFRP under different environmental influences, particularly the degradation of its resin composition, necessitate deeper evaluation. Application-related hurdles, such as ensuring proper bonding between GFRP and concrete, must be resolved to fully optimize its efficiency.

8.1 Future Directions

Future research might consider focusing on thoroughly evaluating the long-term performance and durability of GFRP wraps under various seismic and environmental conditions to better understand their effectiveness in retrofitting. Investigating the potential benefits of combining GFRP wraps with other strengthening methods may uncover synergies that enhance overall structural reinforcement. Additionally, there is a need to explore more cost-effective and efficient application techniques while assessing how GFRP wraps perform across different building types and regions for broader adoption. Life-cycle assessment comparing the embodied carbon of GFRP retrofitting against demolition-and-rebuild scenarios, together with work on the recyclability and end-of-life management of GFRP materials, would further clarify the environmental case for the technique. Improving the material properties of GFRP and addressing installation challenges will be essential to maximize the effectiveness of GFRP wraps in retrofitting reinforced concrete structures with insufficient confinement.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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