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Strengthening of Reinforced Concrete Beams Using FRP Composites: A Review

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Abstract: Reinforced concrete (RC) structures are prone to gradual deterioration over time, influenced by factors such as increased service loads, exposure to highly aggressive environmental conditions, and the natural aging of materials. Among the various retrofitting techniques available, the use of Fiber-Reinforced Polymers (FRP) externally bonded composite materials has proven to be one of the most effective solutions for restoring or even enhancing the structural performance of such elements. This paper presents a thorough review of over sixty experimental, analytical, and numerical studies focused on the application of FRP composites in strengthening RC beams. It critically examines advancements in FRP technology, material characteristics, and key parameters such as fiber type, orientation, bonding configuration, and failure mechanisms. Additionally, significant attention is given to finite element modelling (FEM) approaches and model-selection strategies employed to simulate the structural behaviour of FRP-strengthened beams. Key challenges, including nonlinear material modelling, bond behaviour at interfaces, and premature debonding issues, are addressed. The paper also highlights essential research directions needed to develop reliable performance-based design and analysis frameworks.

Keywords: Reinforced concrete (RC), fiber-reinforced polymer (FRP), structural strengthening, flexural behaviour analysis, shear capacity enhancement, finite-element modelling (FEM), and overall structural performance evaluation.

I. INTRODUCTION

Reinforced concrete (RC) structures are prone to gradual deterioration over time, influenced by factors suchas increased service loads, exposure to highly aggressive environmental conditions, and the natural aging of materials. Among the various retrofitting techniques available, the use of Fiber-Reinforced Polymers (FRP)externally bonded composite materials has proven to be one of the most effective solutions for restoring or even enhancing the structural performance of such elements. This paper presents a thorough review of over sixty experimental, analytical, and numerical studies focused on the application of FRP composites in strengthening RC beams. It critically examines advancements in FRP technology, material characteristics and key parameters such as fiber type, orientation, bonding configuration, and failure mechanisms.

Additionally, significant attention is given to finite element modelling (FEM) approaches and model-selection strategies employed to simulate the structural behaviour of FRP-strengthened beams. Key challenges, including nonlinear material modelling, bond behaviour at interfaces, and premature debonding issues, are addressed. The paper also highlights essential research directions needed to develop reliable performance based design and analysis frameworks. Reinforced concrete has long been the predominant construction material worldwide due to its structural efficiency, durability, and cost-effectiveness. However, a substantial portion of existing RC structures often large-scale requires strengthening or rehabilitation. This necessity arises from factors such as reinforcement corrosion, poor structural detailing, material degradation, and increasing service loads. Traditional retrofitting methods, including steel jacketing and external post-tensioning, often exacerbate issues by adding significant dead weight, complicating construction processes, and remaining susceptible to corrosion-related deterioration.

The demand for lighter, non-corroding, yet highly durable materials led to the adoption of fiber-reinforced polymer (FRP) composites starting in the late 1980s. These materials are characterized by their exceptional tensile strength, low density, and excellent fatigue performance, making them particularly suitable for structural retrofitting applications. Early studies, such as those by Meier, demonstrated the feasibility of externally bonding carbon fiber laminates to bridge girders as a means of repair and reinforcement. Subsequent experimental trials confirmed that applying external FRP sheets and plates significantly improves the flexural and shear capacities of concrete beams. Consequently, the use of FRP in structural strengthening has been formally adopted in major design guidelines like ACI 440R and FIB Bulletin 14. Despite numerous research efforts and updated design guidelines confirming its effectiveness, the behaviour of RC beams reinforced with FRP remains complex.

This complexity stems from interactions between concrete cracking, steel reinforcement yielding, and bond behaviour at the interface between FRP and concrete. In many cases, FRP delamination has been identified as a primary failure mechanism. This issue prevents the material from achieving its full tensile strength and highlights the necessity of integrated experimental, analytical, and numerical investigations to understand these coupled mechanisms fully. Finite element modelling (FEM) has emerged as one of the most vital tools for addressing these challenges. It enables accurate simulations of both global and local behaviour in FRP-retrofitted RC beams while facilitating reliable performance predictions before full-scale testing. This review synthesizes key findings from experimental, analytical, and numerical research conducted primarily between 1987 and 2010. It focuses on the mechanical properties of various FRP materials, the efficacy of diverse strengthening configurations, observed failure mechanisms, and validated finite-element modelling techniques. The ultimate objective is to compile a comprehensive knowledge base that will drive the development of robust design methodologies and advanced simulation strategies for FRP-strengthened reinforced concrete structures.

II. FRP COMPOSITES: TYPES AND PROPERTIES

Fiber reinforced polymers (FRPs) are advanced composite materials composed of strong fibers embedded within a polymeric matrix, most commonly epoxy resin. The primary functions of the matrix include transferring stress between fibers, providing environmental protection, and forming a robust bond with the concrete substrate. This bond ensures resistance to corrosion in steel and prevents material degradation. FRPs are known for their anisotropic behaviour, meaning they exhibit maximum strength and stiffness along the direction of the fibers. Compared to traditional reinforcing materials, FRPs offer several advantages, including exceptionally high tensile strength-to-weight ratios often far exceeding those of steel excellent resistance to chemical and corrosion damage, versatility in forms such as sheets, plates, or rods, and being non-magnetic. However, FRPs exhibit linear-elastic behavior until failure, lacking ductility. Consequently, designs incorporating FRPs must prioritize measures to prevent brittle failure.

A. Carbon Fiber-Reinforced Polymer (CFRP):

Carbon Fiber Reinforced Polymer (CFRP): CFRP is one of the most effective materials recommended for flexural strengthening applications because of its high elastic modulus, superior tensile strength, and excellent fatigue performance. Even though its high cost is a barrier for not using this material widely, it is still often suggested for critical structures where the performance and endurance that come with it would be worth the extra cost.

B. Glass Fiber Reinforced Polymer (GFRP):

GFRP is a more cost-effective and readily available alternative to CFRP. It features lower stiffness and a significantly higher tendency to deform, making it particularly suitable for shear strengthening applications and low-strength retrofitting projects where high material stiffness is not essential.

C. Aramid Fiber Reinforced Polymer (AFRP):

Aramid fiber-reinforced polymer (AFRP) is known for its exceptional tensile strength and superior impact resistance, making it a highly reliable option. However, AFRP is susceptible to damage from moisture and ultraviolet radiation, necessitating the use of protective coatings to maintain its durability, particularly in outdoor environments exposed to harsh conditions.

D. Basalt Fiber-Reinforced Polymer (BFRP):

Basalt fiber-reinforced polymer (BFRP) has emerged as an increasingly attractive option due to its
environmentally sustainable nature, serving as a viable alternative to conventional FRP materials. BFRP is characterized by its strong thermal stability, competitive mechanical properties, and relatively moderate cost, making it a suitable choice for structural strengthening applications. Since the effectiveness of stress transfer and adhesion largely depends on the matrix, ensuring proper surface preparation of the concrete substrate is critical for maintaining durable bond performance. Research has shown that failure in FRP retrofitted reinforced concrete (RC) structures is often driven by premature de-bonding at the FRP concrete interface rather than fiber rupture. As a result, factors such as adhesive thickness, curing temperature, and the surface roughness of the concrete play pivotal roles in determining stress transfer efficiency and the overall structural integrity.

Property	CFRP	GFRP	AFRP	BFRP
Density (kg/m³)	1600–1900	1800–2000	1300–1400	2600–2800
Tensile strength (MPa)	2000–4500	1000–2400	1200–2800	1500–3000
Elastic modulus (GPa)	150–300	35–80	70–120	90–110
Ultimate strain (%)	0.8–1.5	1.5–3.0	2.0–3.5	2.0–2.8
Typical resin	Epoxy	Epoxy	Vinyl ester	Epoxy
Bond to concrete (MPa)	>2.0	1.5–2.0	1.8–2.2	~2.0

III. DURABILITY AND FRP STRENGTHENING TECHNIQUES

The long-term durability of FRP-strengthened reinforced concrete (RC) members largely depends on the performance of the FRP-concrete interface in challenging environmental conditions. Factors such as UV radiation, persistent moisture, freeze-thaw cycles, and elevated temperatures can degrade the polymer matrix and weaken the adhesive bond. To mitigate these effects, protective coatings and effective sealing measures are essential. Nevertheless, laboratory studies indicate that well-designed FRP systems can maintain a high percentage of their initial strength, even after prolonged environmental exposure. In fact, some accelerated aging tests have demonstrated strength retention levels of up to 80%.

A. Externally Bonded FRP (EB-FRP):

This remains one of the most widely utilized techniques for strengthening reinforced concrete (RC) members. It involves the application of FRP layers or plates to the tension zones of RC elements using epoxy adhesives. The method has demonstrated significant effectiveness in enhancing flexural strength and improving stiffness. However, a key limitation is the potential for brittle debonding failures. To mitigate this drawback, anchoring systems such as transverse U-wraps and mechanical fasteners are commonly employed.

B. Near-Surface Mounted FRP (NSM-FRP):

This method introduces a shift in the installation of FRP bars and strips by embedding them into grooves cut into the concrete cover. The NSM-FRP system generally delivers enhanced bond performance, improved environmental protection, and reduced visual impact. However, inadequate groove preparation or use of improper adhesives can lead to bond-slip failures. Alternatively, wrapping and confinement techniques, which involve applying partial or full FRP jackets, remain common methods to enhance the shear capacity and torsional resistance of reinforced concrete (RC) elements. Research has also explored hybrid strengthening approaches that integrate FRP with traditional materials such as pre-stressed steel tendons or internal reinforcement. These combined systems improve serviceability, increase ductility, reduce deflections, and delay crack propagation. Nonetheless, careful attention is required to ensure stiffness compatibility, preventing premature failure. Numerous field applications in bridges, buildings, and marine structures have demonstrated the practical effectiveness of FRP retrofitting. As a result, it stands out as one of the most reliable solutions. With proper construction practices, this method ensures short installation times minimal service disruptions, and long-term durability.

IV. EXPERIMENTAL EXAMINATIONS

A. Overview of Experimental Studies

Since the early 1990s, comprehensive experimental programs have been conducted to estimate the flexural and shear behaviour of corroborated concrete(RC)shafts strengthened with fiber- corroborated polymer(FRP) mixes.

Disquisition byChajes et al., Arduini and Nanni, Aiello and Ombres, and Bencardino et al. has constantly demonstrated significant advancements in weight capacity, stiffness, and crack control when using FRP mounts. Despite the enhanced performanceachieved in these samples, utmost tests concluded with either the debonding of the FRP laminates or separation of the concrete cover, rather than failure of the emulsion material itself. These findings have stressed that the interfacial bond behaviouris the primary factor governing the ultimate capacity of analogous systems. Chajes et al.(1994) an Early Evaluation of Flexural Performance and Failure Mechanisms. The experimental study carried out by Chajes et al.(1994) stands as one of the introducing regular examinations into the flexural strengthening of corroborated concrete

(RC) shafts using externally clicked fiber- corroborated polymer(FRP) laminates. This influential disquisition notonly set the stage for advancements in this field but also slip light on pivotal factors affecting the performance of structural rudiments. The study involved testing RC shafts with externally clicked carbon and glass FRP wastes applied to the pressure face under monotonic loading conditions. Results demonstrated a significant increase in ultimate flexural capacity compared to un-strengthened control samples. This improvement wasattributed to the high tensile strength of the FRP laminates, which absorbed a substantial portion of the tensile force after concrete cracking and internal brand bolstering yielding passed. In addition to strength enhancement, the addition of FRP especially increased the stiffness of the system, particularly during thepost- cracking and preyieldingstages. The fibers constrained the propagation of flexural cracks, performing in lower and narrower crack conformations. Span diversions due toservice loads were significantly reduced, pressing the effectiveness of FRP systems in conserving mileage performance. Still, the study also revealed that failures primarily passed through brittle mechanisms. FRP debonding initiated at laminate edgesor major flexural cracks, where peak shear and normal stresses concentrated at the interface. In several samples, concrete cover separation caused by shear passed dueto slant cracking and shelling of the concrete caste located above the FRP and below the internal underpinning, leading to unlooked-for and disastrous failure. Measures ofFRP strains at failure constantly fell below the rupture strain of the emulsion material, indicating that bond strength rather than the tensile capacity of the FRP was the controlling factor for strength advancements. This vital observation prodded farther disquisition into FRP concrete interfacial behaviour, performing in advancements in strain limits, face drug ways, harbourage systems, and necessary styles suchas near- face- mounted (NSM) FRP. The findings of Chajes et al. handed a robust experimental base that continues to shape current FRP design canons, establishing themas fundamental contributions to this field of structural engineering Aiello and Ombres (2004)The stress- strain behaviourand model evidence of corroborated concrete (RC) beams strengthened with fiber- corroborated polymer (FRP) paraphernalia took a significant step forward through the disquisition conducted by Aiello and Ombres (2004). Their study contributedprecious experimental data that eased both logical and numerical model evidences. Beyond strength assessment, their work also concentrated on covering strain distribution in concrete, internal brand underpinning, and external FRP laminates throughout the entire loading process. The samples, which were vastlyinstrumented, revealed three distinct behavioural stages during the tests. The first stagedisplayed an elastic response across all paraphernalia, characterized by direct behaviour

Until concrete cracking passed. Post-cracking led to a drop in stiffness as tensile forceswere shared between the brand underpinning and FRP laminates. Once the brand underpinning reached its yield point, the FRP came the primary weight- bearing elementin pressure, further reducing stiffness until ultimate failure. A noteworthy donation from their study was the precise dimension of FRP strain distribution along the shaft length.

Peak strains were linked around the mid-span or under concentrated loads, with a rapid-fire- fire drop towards the ends of the laminate. This strain localization stressed stressattention zones, recognized as induction points for debonding. One of the mostpoignant aspects of their disquisition was the experimental determination of the maximum strain FRP laminates could endure former to debonding. The measured debonding strainwas especially lower than the ultimate rupture strain of FRP paraphernalia, emphasizing that interfacial bond failure is the critical factor governing the ultimate performance of strengthened shafts. These obediences form a foundation for developing strain predicated design criteria and advanced logical models suitable of predicting brittle debonding failures with lower delicacy.

Table 2: Experimental Highlights:

Author(s)	Year	Strengthening Type	Key Observation

Saadatmanesh& Ehsani	1991	EB-CFRP plates	Flexural,↑60%,brittle debonding.
Arduini & Nanni	1997	EB-CFRP sheets	Stiffness ↑45%, early cover separation
Grace et al.	1999	CFRP strips	Improved negative-moment capacity
Nanni & Khalifa	2000	EB-CFRP U-wraps	Shear capacity ↑70%
Aiello & Ombres	2004	EB-CFRP sheets	Controlled crack width
Bencardino et al.	2005	EB-CFRP laminates	Increased ductility

V. SIGNIFICANCE OF EXPERIMENTAL FINDINGS

Overall, the results of the experimental investigations provide strong evidence that FRP composites are the most reliable materials in the repairing of RC beams from the strength, stiffness, and serviceability points of view, but at the same time, they reveal that the major failure mechanisms are still premature debonding and concrete cover separation. The need for implementing realistic bond behaviour, effective strain limitations, and anchorage considerations in both analytical and numerical models is clearly shown through the experimental data. The outcomes have gradually changed the course of the modern FRP strengthening design provisions and are still directing the research in this area.

Table 3 : Summarizes representative results from major experiments.

Author(s)	Year	Strengthening Type	Key Observation
Saadatmanesh& Ehsani	1991	EBC FRP plates	Flexural strength↑60%,brittle failure by debonding
Arduini& Nanni	1997	EBCFRP sheets	Stiffness improved ≈45%;early cover separation observed
Graceetal.	1999	CFRP strips (neg.moment)	Improved negative moment capacity
Nanni& Khalifa	2000	CFRPU-wraps	Shear capacity 70%
Aiello& Ombres	2004	EBCFRP sheets	Controlled cracks pacing and width

VI. ANALYTICAL AND NUMERICAL STUDIES ON FRP STRENGTHENING OF BEAMS

A. *Analytical Modelling Approaches*

Analytical models play a crucial role in anticipating the structural behaviour of FRP-strengthened reinforced concrete (RC) beams without relying entirely on costly and time-intensive experimental programs. Over the past three decades, researchers and scientists have focused on developing various analytical formulas, progressing from basic elastic methods to more advanced nonlinear and fracture mechanics-based approaches.

1) *Elastic Analysis Based on ACI 440:*

The elastic analysis method utilized by ACI 440 (1996) for reinforced concrete (RC) members strengthened with external fiberreinforced polymer (FRP) systems is primarily grounded in the classical transformed-section technique. This method advances beyond standard RC theory by explicitly accounting for the stiffness contribution of the externally bonded FRP laminates, while adhering to the assumption of linear-elastic behaviour for all material components. It operates under the premise that concrete, internal steel reinforcement, and FRP laminates participate fully, ensuring strain compatibility throughout the section. To integrate these materials, steel reinforcement and FRP are converted into equivalent concrete areas using modular ratios derived from their respective elastic moduli. This approach allows the application of standard flexural mechanics principles. Subsequently, key section properties such as the neutral axis position, transformed moment of inertia, and elastic stress distribution can be calculated effectively. The transformed-section technique is particularly effective for performing serviceability-level analyses both at the onset of cracking and afterward. During this process, concrete initially resists tensile stresses while FRP's contribution remains modest. Once cracking occurs, tensile forces are transferred to the steel reinforcement and FRP laminate, resulting in a reduction of stiffness. Nevertheless, the overall stiffness remains greater than that of an un-strengthened beam. By incorporating the high elastic modulus of FRP, the method effectively captures the enhanced post-cracking stiffness, a characteristic that has been confirmed through experimental evidence. However, ACI 440 explicitly outlines that this elastic model should not be applied to predict ultimate strength or failure modes. The method overlooks critical factors such as material nonlinearities, steel yielding, progressive cracking, and premature FRP debonding. Consequently, it provides conservative predictions of stresses and deflections under service conditions but falls short in evaluating ultimate flexural capacity. Despite these limitations, the transformed-section technique laid essential groundwork for more advanced nonlinear models, establishing a robust analytical framework for integrating FRP systems into structural design practices.

2) *Elastic Formulation Using the Transformed-Section Method*

In the case of an RC beam that has been strengthened with an externally bonded FRP, an elastic analysis is performed under the hypothesis of a flawless bonding between concrete, steel, and FRP, and linear strain compatibility throughout the cross-sectionThe modular ratios are defined as:

$$n_s = \frac{E_s}{E_c}, \qquad n_f = \frac{E_f}{E_c},$$

- E_s = elastic modulus of steel
- E_f = elastic modulus of FRP
- E_c = elastic modulus of concrete

The steel reinforcement area **As** and theFRP area**Af**are transformed into equivalent areas as**:**

$$A_s' = n_s A_s, \qquad A_f' = n_f A_f$$

Determining the depth of the neutral axis involves ensuring the equilibrium of forces within the transformed section.

Subsequently, the moment of inertia for the transformed section is calculated using the parallel-axis theorem, completely disregarding the compressive part of the concrete in cracked sections. Once the bending moment is determined, the stresses in the concrete, steel, and FRP are derived by applying elastic flexural theory.

$$\sigma = \frac{My}{I_t}$$

- σ = stress in the material
- M = bending moment
- y = distance from the neutral axis
- I_t = transformed moment of inertia

Corresponding strains are calculated using Hooke's law:

$$\varepsilon = \frac{\sigma}{E}$$

This method ensures that concrete, steel reinforcement, and FRP experience identical strain levels under service-load conditions. The transformed moment of inertia is determined using the parallel-axis theorem, focusing solely on the compressive concrete. Once the bending moment is established, material stresses are calculated using elastic flexural theory, while strains are derived through Hooke's law. This ensures strain compatibility between materials under service loads across the structure's entire lifespan.

3) Nonlinear Analytical Models Based on Bond–Slip and Fracture Mechanics:

Nonlinear analytical models represent a significant shift by explicitly accounting for bond-slip behaviour and fracture mechanisms at the interface between FRP and concrete, unlike earlier elastic-based approaches. The 2002 research by Smith and Teng marked a pivotal development in this field. These models propose that failure in externally bonded FRP systems occurs at the interface as a fracture event rather than through material rupture. The interfacial interaction is governed by a local bond-slip relationship, which defines the link between shear stress and relative slip at the FRP-concrete interface. Simplified bilinear or nonlinear bond-slip laws are applied, starting with an initial elastic bonding phase, followed by progressive softening due to damage accumulation and micro-cracking. The introduction of fracture mechanics principles fundamentally shifted the focus to interfacial fracture energy, which is quantified as the area beneath the bond-slip curve. This energy parameter represents the work needed to completely detach the FRP from the concrete substrate and is more influenced by the concrete's tensile strength and surface properties than by FRP strength. The governing differential equations describing stress distribution along the bonded FRP length reveal stress concentrations near the laminate ends and crack locations, consistent with experimental observations. A key finding of these models is the concept of effective bond length, indicating that any additional bonding length beyond this does not notably enhance load transfer capacity. This insight has provided a rational basis for understanding premature debonding and facilitated the development of strain-based design limitations, now embedded in modern FRP design standards.

4) Failure Prediction Models and End-Stress Concentration:

Accurately predicting failure requires accounting for stress concentrations at the laminate ends and within bonded regions. Malek et al. (1998) significantly contributed to this understanding by developing analytical equations that quantify the effects of end-stress concentrations, which are often overlooked in simplified models. Their findings demonstrated that stress intensification at free edges and terminations can dictate the initiation of damage, even when average stress levels remain within permissible limits. The introduced stress concentration factors relate local stress levels to nominal applied stresses and are influenced by geometry, material properties, and boundary conditions. These models help elucidate observed empirical failures, such as interfacial debonding and the separation of concrete covers, which typically originate near the FRP ends. Recognizing the influence of end-stress concentrations has greatly enhanced the reliability of both analytical and numerical predictions, serving as a foundation for the development of finite-element and fracture-based modelling techniques. From a design perspective, these models inform strategies for localized mitigation measures, including tapered laminates, improved anchorage systems, and optimally designed bonding lengths.

VII. NUMERICAL MODELLING AND FINITE-ELEMENT ANALYSIS

Finite Element Modelling (FEM) is widely acknowledged as a reliable and essential numerical technique for studying the behaviour of reinforced concrete (RC) beams strengthened with fiberreinforced polymer (FRP) systems.

Unlike closed-form analytical methods, FEM provides a more detailed representation of material heterogeneity, stress redistribution, crack progression, and interfacial debonding mechanisms all critical factors influencing the performance of externally bonded FRP composites. Consequently, advanced computational tools such as ANSYS, ABAQUS, and MATLAB have become standard for assessing serviceability responses, analysing failure mechanisms, and optimizing the design of FRP-retrofitted RC structures.

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A. Review of Previous Numerical Investigations

Studies conducted indicate that the FEM technique is a reliable approach for replicating the experimental behaviour of RC beams influenced by the presence of FRP. In their 2003 study, Yang et al. created a modelling of interfacial behaviour for better analysis and predictions.

1) Present Numerical

virtual environment to analyse this phenomenon, assuming failure due to concrete cover separation and concentrating on predicting stress concentrations near the FRP termination zones. Their findings highlighted that premature debonding primarily stems from the interaction between the FRP laminate, adhesive layer, and concrete cover. This underscores the importance of accurate.

Study:

In the current study, a linear elastic finite-element model was developed using MATLAB to analyse FRP-strengthened reinforced concrete T-beams. The model incorporated gross sectional properties and effectively replicated laboratory boundary conditions and loading scenarios. Despite excluding nonlinear material behaviour, the model successfully captured initial stiffness and early-stage deflection trends. Validation was performed by comparing its results with those derived from IS 456 (Bureau of Indian Standards, 2000). Deviations observed in predictions were primarily attributed to assumptions about stiffness and the approach used to simulate cracks. These findings indicate that while the proposed FEM approach is suitable for evaluating serviceability levels, it has limitations in accurately predicting ultimate strength and failure modes. The finite-element modelling process offers significant advantages in analysing FRP-strengthened RC components. It provides a highly detailed examination of stress redistribution and interaction effects among concrete, steel reinforcement, and FRP composites. While it is possible to obtain such localized responses using simplified analytical methods, finite-element modelling achieves this with greater precision. Additionally, FEM enables virtual testing of various reinforcement configurations, reducing experimental costs and development time, making it a compelling alternative to traditional approaches. However, the accuracy of FEM predictions depends heavily on assumed material properties and constitutive laws governing FRP-concrete bond behaviour. Nonlinear analysis, though capable of enhancing the model's accuracy, demands substantial computational resources, specialized expertise, and validation against experimental data to ensure reliability.

2) Comparison of FRP Types and Cost–Performance Implications

The application of various fiber-reinforced polymer (FRP) materials in strengthening reinforced concrete (RC) beams presents diverse mechanical and economic considerations. Each material offers distinct advantages and limitations. Among them, carbon fiber-reinforced polymer (CFRP) consistently demonstrates superior elasticity, tensile strength, and resistance to fatigue across all processing stages. On the other hand, glass fiber-reinforced polymer (GFRP) stands out for its affordability. However, its low elastic modulus and high ultimate strain can result in greater deflections under load. Aramid fiber-reinforced polymer (AFRP) and basalt fiber-reinforced polymer (BFRP) systems are recognized for their moderate mechanical performance, showcasing notable ductility and energy absorption capacities. Nevertheless, their behaviour under load introduces challenges in controlling their failure modes within structural applications. When the same strengthening ratios are applied, beams reinforced with CFRP exhibit approximately 20–30% higher load-carrying capacity compared to those reinforced with GFRP. Although CFRP is typically more expensive, studies by Grace et al. (1999) and Nanni (1995) indicate that its higher initial cost can be justified, especially in critical infrastructure projects. These costs are offset by reduced installation times, lower maintenance requirements, and enhanced long-term durability.

B. Numerical–Experimental Correlation and Future Directions

Experimental and numerical methods have been utilized to evaluate the stiffness and load-deflection behaviour both during the forming phase and under in-service load conditions. The findings confirm that FEM predictions are largely dependable. However, discrepancies between experimental and numerical results become more pronounced as approaches are made toward the failure point. This is primarily attributed to the simplified bond-slip formulations and concrete damage models employed in simulations. Considering the various effects that concrete undergoes throughout its lifecycle, advancements in numerical modelling should focus on integrating cohesive-zone-based debonding laws, advanced damage-plasticity models for concrete, and time-dependent durability factors to ensure enhanced accuracy in predicting ultimate states.

Overall, FEM has proven to be a robust and reliable method for evaluating FRP-strengthened RC beams while offering valuable design solutions. When paired with experimental validation and precise material modelling, numerical simulations can enable insightful performance analyses, identification of failure mechanisms, and cost-effective strengthening strategies for structural applications. Similarly, Martinez et al. (2008) made significant strides in numerical modelling by employing a serial parallel mixing theory designed to simulate the composite interaction between FRP and concrete materials with contrasting stiffness properties. This approach was a notable highlight of their work. The results showed a strong correlation with experimental load-deflection data, while the model exhibited improved accuracy in predicting stress transfer mechanisms along the bonded interface. On the other hand, Li et al. (2006) explored the impact of FRP thickness on flexural behaviour through nonlinear finite-element analysis. Their deflection predictions under service loads aligned closely with experimental data, with an overall discrepancy of about ±10%. Nonetheless, comparisons under ultimate load conditions revealed larger variances, primarily resulting from oversimplified models for concrete cracking and FRP debonding propagation in the simulations.

1) Finite-Element Modelling Strategies

The precision of FEM forecasts heavily relies on the choice of models and elements. Most of the time, concrete is represented by three-dimensional solid elements, while depending on the thickness and configuration of the strengthening, FRP laminates can be either represented by shells or trusses. The steel reinforcement is normally modelled as either embedded trusses or discrete bars with bilinear stress-strain properties that imitate yielding.

To a large extent, constitutive models prescribe linear elastic behaviour for the FRP up to rupture, nonlinear damage or plasticity formulations for the concrete to account for cracking and crushing, and elastic-plastic behaviour for the steel reinforcement. The interaction of FRP and concrete is an essential part of the numerical model and is usually represented by cohesive zone models or contact-based elements with bond-slip relationships.

Refining of the mesh is necessary at bonded interfaces and laminate ends where stress gradients are very steep and localized damage is expected. The conditions at the boundaries and loading arrangements are usually set to imitate the experimental configurations, e.g., a simply supported beam with four-point or two-point loading. These choices in modelling make it possible to realistically simulate the whole response while at the same time causing the localized interfacial phenomena to be captured.

2) Model Validation and Parametric Applications

As a result of comparing numerical models with experimental results, the mandatory requirement of establishing confidence in FEM predictions has been satisfied. Consistently and in different studies it is reported that the numerical and experimental load–deflection responses at serviceability levels match well and the deviation is typically within 10%. However, near the ultimate load accuracy usually drops due to difficulties in simulating progressive cracking, concrete softening, and interfacial debonding.

Nonetheless, FEM has been very effective for parametric investigations. Numerical studies have made it possible to systematically assess the effects of FRP thickness, bonded length, fiber orientation, anchorage systems, and hybrid strengthening configurations. The parameters that can be varied in this way greatly reduce the need for large-scale experimental programs and thus facilitate rational design optimization.

VIII. DISCUSSION AND CONCLUSIONS

A. Discussion:

Over the once three decades, externally clicked fiber- corroborated polymer(FRP) systems have been considerably studied as a largely effective system for buttressing concrete(RC) shafts throughout their life cycle. Original trials demonstrated that externally applied FRP plates and wastes significantly boost the flexural capacity and stiffness of RC rudiments. Still, these early studies revealed a critical limitation the structural fracture was n't mandated by the essential strength of the FRP accoutrements but by the effectiveness of stress transfer at the interface between the FRP and the concrete. By the mid-to-late 1990s, as exploration progressed, attention shifted from simply strengthening structures to relating predominant failure modes. A recreating observation during trials was debonding and separation of the concrete cover, which frequently passed before full application of the FRP's tensile capacity. These failures, generally set up at FRP termination points or areas with significant cracking, were driven by interface geste, precluding the optimized performance of the FRP material.

Accordingly, earlier design hypotheticals counting solely on material strength were challenged, emphasizing the need to prioritize bond gesteas the critical design parameter.

This shift directed assiduity norms, directly impacting design recommendations grounded on studies and reports participated with professionals and the public. The early 2000s marked a new phase in exploration on resin- concrete systems and FRP operations, exploring not only flexural and shear strengthening but also rigidity and utility advancements. Examinations into externally clicked CFRP systems verified notable earnings in ultimate strength; still, they also stressed cases of dropped relegation rigidity due to inadequate harborage or confinement measures accompanying the strengthening process. This consummation underlined the significance of transitioning toward rigidity concentrated designs rather than counting solely on strength improvement, reshaping design principles to address both functional robustness and structural adaptability.

Contemporaneous studies of cracking gesteshowed that the operation of FRP distance has the capability to reduce the range of cracks, takelonger time for the propagation of cracks, and ultimately, make utility performance standing more underworking loads. In resemblant, the logical and numerical modeling styles also progressed a lot. The finiteelement system offered a comprehensive understanding of the strain in the interface, bond – slipmechanisms, and cover separation failures which are veritably hard to descry by the experimental system.

All these studies explosively supported the point that accurate vaticination of FRP- strengthened ray gesterequires unequivocal modeling of interfacial damage and debonding marvels. The use of simplified elastic or impeccably clicked hypotheticals was proved to be shy for landing the ultimate geste. The literature shows a clear development from feasibility- grounded trial to performance- grounded assessment with the support of advanced numerical simulation. The unseasonable debonding issue has been the main debit of externally clicked FRP systems indeed after times of exploration and development in material characterization, modeling and design guidelines. This ongoing problem has brought up the need for new harborage results, better interface engineering, and strengthening ways that can offer a good combination of strength, rigidity, andcontinuity.

Research Phase Representative Studies Dominant Theme Key compliances Early studies(1991 – 1996) Saadatmanesh& Ehsani; Chajes et al;ACI 440R- 96 Feasibility and bond gesteSignificant strength earnings; bond governs failure development phase (1997–1999) Arduini & Nanni; Grace et al. Strengthening of cracked RC shafts Effective build of damaged members; early debonding Design connection (2000 – 2002) Nanni & Khalifa; Bencardino et al. Shear strengthening and guidelines Capacity improvement; need for standardized rules Performance evaluation(2003 – 2005) Alagusundaramoorthy et al; Aiello & Ombres Cracking, deformability, rigidity Strength increase with reduced.ductility; bettered utility. Advanced modeling(2003 – 2008) Yang et al.; Martínez et al. Numerical and FE simulation accurate vaticination requires bond – slip modeling.

Research Phase	Representative Studies	Dominant Theme	Key Observations
Early studies (1991–1996)	Saadatmanesh& Ehsani; Chajes et al ; ACI 440R-96	Feasibility and bond behavior	Significant strength gains; bond governs failure
Development phase (1997–1999)	Arduini & Nanni; Grace et al.	Strengthening of cracked RC beams	Effective retrofit of damaged members; early debonding
Design consolidation (2000–2002)	Nanni & Khalifa; Bencardino et al.	Shear strengthening and guidelines	Capacity enhancement; need for standardized rules
Performance evaluation (2003–2005)	Alagusundaramoorthy et al; Aiello & Ombres	Cracking, deformability, ductility	Strength increase with reduced.ductility; improved serviceability.
Advanced modeling (2003–2008)	Yang et al.; Martínez et al.	Numerical and FE simulation	Accurate prediction requires bond–slip modeling

B. Conclusions:

A thorough examination of experimental, logical, and numerical studies unequivocally demonstrates that externally clicked FRP systems, particularly CFRP, are largely effective at enhancing the flexural and shear performance of corroborated concrete shafts. These systems constantly ameliorate cargo- carrying capacity, stiffness, and crack control across colorful strengthening configurations. Still, the use of FRP ways is constantly constrained by challenges similar as concrete cover separation and unseasonable debonding.

These issues significantly limit the capability to completely exploit the high tensile strength of FRP accoutrements. Similar brittle, affiliate- controlled failure modes are critical in defining the ultimate gesteof the corroborated rudiments and remain a crucial handicap to designing with lesser trustability. Thus, a design approach grounded simply on strength is inadequate; lesser emphasis must be placed on bond geste, harborage effectiveness, and rigidity. The development of design guidelines and logical models has made substantial progress, supported by expansive experimental data and the advanced operation of finite- element simulations.

Still, there's still a need to conduct further exploration to decide effective harborage systems, distortion capacity, and continuity when exposed to environmental conditions. Unborn exploration should concentrate on innovative mongrel strengthening design approaches, advanced interface engineering results, and developing intertwined design approaches wherenon-linear experimental and simulation results are encompassed. Eventually, to draw a concluding comment, it may be said that FRP mixes are a largely effective and durable system to repair RC shafts, handed performance conditions at interface failure are addressed adequately.

The steady growth in performance- grounded and continuity- informed designs means that performance assessment and design verification by computer simulations and

a prerequisite of the wide and dependable operation of FRP strengthening systems in large civil engineering constructions.

IX. WORK DONE ON STRENGTHENING OF BEAMS BY FRP

For over three decades, the application of fiber-reinforced polymers (FRPs), primarily composed of carbon (CFRP) and glass (GFRP) fibers, has been extensively researched as a method for strengthening reinforced concrete (RC) beams. Early experimental studies focused on assessing the flexural performance of RC beams externally reinforced with FRP plates or sheets. In 1991, Saadatmanesh and Ehsani demonstrated significant improvements in flexural capacity and stiffness achieved with bonded CFRP laminates. Subsequent studies by Arduini and Nanni in 1997 and Alagusundaramoorthy et al. in 2003 further validated the effectiveness of CFRP in enhancing load-carrying capacity and ductility for both precracked and uncracked beams. In addition, Aiello and Ombres in 2004 showed that FRP reinforcement delayed the yielding of steel reinforcement while reducing crack widths, thereby improving overall serviceability.

Research on shear strengthening and bond performance has also been conducted with similar rigor. For instance, Bencardino et al., in studies conducted in 2002 and 2005, emphasized the importance of proper FRP design and anchorage to prevent premature debonding. Chajes et al. explored the stress transfer mechanisms at the FRP-concrete interface in 1996, while Nanni and Khalifa in 2000 demonstrated that externally bonded CFRP composites significantly enhance shear capacity.

Additionally, detailed design guidelines were published in key resources such as FIB Bulletin 14 (2001) and ACI Committee 440 (1996). These experimental investigations have been supplemented by numerical and analytical studies. Yang et al. in 2003 developed finite element models to replicate cover-separation failures, which enabled them to precisely capture critical interfacial stresses. Later, Martínez et al. proposed the serial-parallel mixing theory in 2008 to analyse the composite action between FRP and concrete.

The study of economic and performance aspects was undertaken by Grace et al. (1999), who concluded that the higher initial costs of CFRP could be compensated by the savings in installation and the long lifespan of the material. All these studies have confirmed that CFRP is the best option if the aim is to get more stiffness, strength, and fatigue performance, while GFRP is a good alternative for moderate-strength applications due to its lower cost. To sum up, the studies have indicated that FRP reinforcement very much improves flexural and shear performance, crack control, and good retrofitting of RC structures that have deteriorated or are under-strength.

Experimental verification was the main focus of early work, while modern research is increasingly integrating numerical modelling to optimize FRP layout, predict failure modes, and assess long-term performance, thus providing the foundation for current design codes and engineering practice.

X. DIRECTIONS FOR FUTURE WORK

Improved anchorage systems and interface engineering are expected to play a major role in future research aimed at debonding prevention. Not only that, but also ductility oriented strengthening strategies like hybrid FRP–steel systems and pre stressed FRP laminates should be developed as an absolute necessity.

It is still not very clear how long the materials would last under different conditions such as environmental exposure, fatigue, and sustained loading, thus requiring a thorough investigation. In addition to that, unified bond–slip and failure models are necessary to support performance-based design and increase reliability.

Eventually, conducting both laboratory and numerical experiments on continuous beams and full structural systems will widen the scope of FRP strengthening techniques in actual infrastructure.

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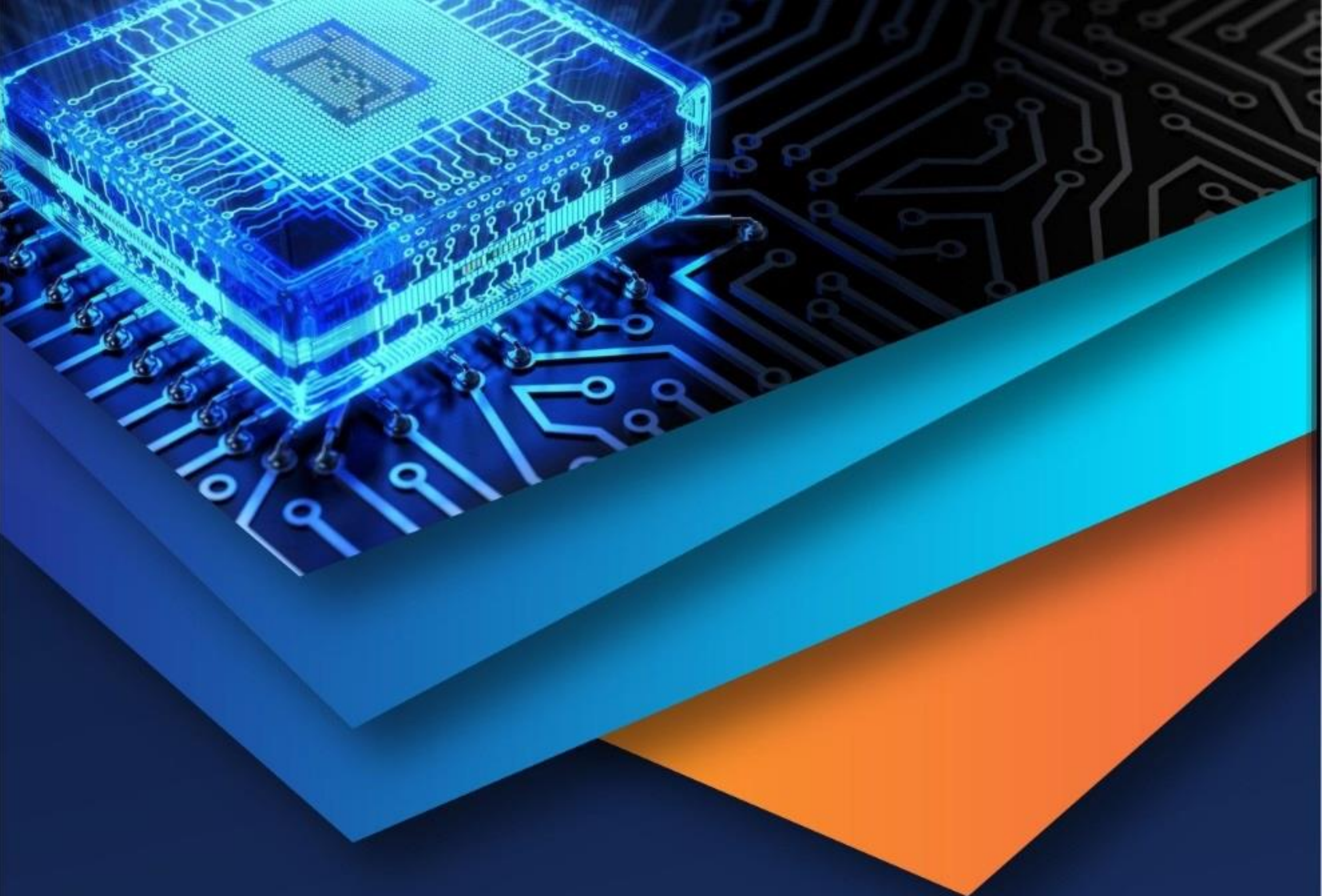

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