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An Updated Review on the Effect of CFRP on Flexural Performance of Reinforced Concrete Beams

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Abstract

This detailed review looks at how carbon fiber-reinforced polymer (CFRP) may be used to improve the flexural capacity of reinforced concrete (RC) beams. It investigates the history, characteristics, and research trends of FRP composites, assesses various flexural strengthening methods utilizing FRP, and addresses the predictive power of finite-element (FE) modeling. The assessment highlights the importance of enhanced design codes, failure mode mitigation, and improved predictive modeling methodologies. It emphasizes the advantages of improving FRP reinforcement levels to meet code expectations and covers issues, such as FRP laminate delamination and debonding. The findings highlight the need of balancing load capacity and structural ductility, as well as the importance of material behavior and failure processes in accurate prediction. Overall, this review offers valuable insights for future research and engineering practice to optimize flexural strengthening with CFRP in RC beams.

Keywords Carbon fiber-reinforced polymer (CFRP), Flexural strengthening, Reinforced concrete (RC) beams, FRP laminate delamination, Predictive modeling, Structural durability

1 Introduction

Fiber-reinforced polymer (FRP) has gained significant recognition as a prevalent material choice for enhancing the structural integrity of reinforced concrete (RC) constructions (Issa & Abou Jouadeh, 2004; Issa et al., 2005, 2009; Jahami et al., 2018, 2019; Khatib et al., 2021). Its remarkable effectiveness in augmenting the load-carrying capacity and rigidity of RC beams has propelled the widespread interest in employing FRP flexural strengthening techniques. Numerous investigations, encompassing both experimental and analytical approaches, have been conducted to examine the behavior of FRP-strengthened RC beams under diverse loading conditions. These investigations have yielded important insights into the mechanical characteristics, failure mechanisms, and design criteria of FRP-strengthened RC beams. This issue has received substantial attention in the field of structural engineering and has emerged as a feasible approach for retrofitting and rehabilitation of existing RC structures.

Multiple studies have explored various methodologies for enhancing the flexural strength of reinforced concrete (RC) beams using fiber-reinforced polymer (FRP) and biobased resins (Bonacci & M. Maalej, 2001; Chen et al., 2019a, 2019b; Eisa et al., 2021; Ferrari et al., 2013; McSwiggan & Fam, 2017; Wight et al., 2001). Chen et al. (2019a) and Chen et al. (2019b) specifically examined the flexural behavior of RC beams fortified with a hybrid bonding approach and observed that augmenting FRP thickness and applying confinement measures resulted in increased load-bearing capacity and improved ductility performance. Wight et al. (2001) showed a FRP prestressing approach that can increase serviceability while reducing stresses in reinforcing steel. Bonacci and M.

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Maalej (2001) discovered that adhesively attached FRP is a good way to strengthen reinforced concrete beams. McSwiggan and Fam (2017) studied the use of biobased resins in flexural strengthening and discovered that an epoxidized pine oil resin mix had bond strength equivalent to standard epoxy; however, the furfural alcohol bio resin had a weak bond. Eisa et al. (2021) studied the effects of substituting 50% of the sand with crumb rubber on the flexural strength of RC beams reinforced with carbon fiber-reinforced polymers (CFRP) strips, concluding that using CFRP strips enhanced the yield and ultimate loads. Finally, Ferrari et al. (2013) developed a strategy for reinforcing RC beams by utilizing a high-performance composite with steel fibers, followed by the application of CFRP sheets, which improved beam performance. More study is needed, however, to refine the offered approaches and provide design recommendations.

Other research has been carried out to enhance prediction models for the structural behavior of FRP-strengthened RC beams (Ceci et al., 2012; Zhang et al., 2022). Zhang et al. (2022) suggested a method based on experimental data to predict flexural capacity using the ensemble learning (EL) algorithm. Other machine learning (ML) methods were surpassed by their models, and a reduction factor of 0.85 is proposed for developing FRP-strengthened RC beams. Ceci et al. (2012) reported two experimental data sets focusing on the debonding failure process of FRP–RC beams. According to the findings, existing models were unsuitable for forecasting the failure loads of FRP-reinforced beams, and it is critical to calibrate design equations using structural reliability criteria to achieve acceptable levels of safety. The study also stressed the need of taking into account the influence of the FRP–concrete interface, resin characteristics, and the installation procedure, and it suggested further full-scale beam testing to validate current models at all relevant scale levels. Overall, these investigations offer useful insights into how to improve the accuracy and reliability of prediction models for FRP-strengthened RC beams.

Some research has been done to look at the flexural performance of FRP-strengthened RC beams with end anchoring (Galal & Mofidi, 2009; Zhou et al., 2018). Zhou et al. (2018) evaluated five specimens and created a prediction model, demonstrating that H-type end anchoring enhances the peak load and ductility of beams substantially. Furthermore, the investigation unveiled that interfacial slip diminishes the cohesive connection between the concrete and the FRP laminate. In pursuit of enhancing the flexural capacity and ductility of RC beams, Galal and Mofidi (2009) conducted an in-depth analysis of a novel hybrid system comprising an FRP sheet and ductile anchors. The technique was discovered to improve beam strength and ductility by preventing early peeling of the CFRP sheet. While further testing is required to generate design criteria, the suggested system is predicted to be more cost effective and quicker than current rehabilitation systems.

Several studies have looked at the bonding behavior of FRP-reinforced RC components (Naser et al., 2012; Teng & Yao, 2007; Yao et al., 2005). Yao et al. (2005) conducted an experimental investigation on FRP-strengthened RC flexural components and discovered two types of debonding failures, the influence of FRP debonding strain on FRP strip axial stiffness, and the need of adequate anchoring length for FRP strip. In their 2007 study, Teng and Yaoa meticulously examined plate end debonding failures within RC beams that were reinforced using either thin FRP or steel plates. They proposed a debonding strength model that factored in both the bonded plate and the internal steel shear reinforcement. A subsequent study by Naser and his colleagues in 2012 looked into concrete prisms fitted with CFRP plates through a single shear pullout test. The researchers found that a bonded length of 180 mm was the most effective for attaining the maximum load capacity. In addition, they concluded that the finite-element (FE) model they developed, complete with interface components, served as a reliable instrument for simulating bond behavior between CFRP laminates and concrete surfaces during design-oriented parametric analyses. Based on these findings, it is recommended that further research be conducted to create more precise debonding strength models for FRP-strengthened RC components.

Several scholarly studies have delved into the exploration of the fatigue behavior exhibited by RC beams that have been reinforced with FRP, as noted in the works of Guo et al., 2021a, 2021b, and Ekenel et al., 2006. A recent endeavor by Guo et al. in 2021 led to the formulation of a theoretical model that anticipates the fatigue behavior of FRP-strengthened RC beams when they are exposed to cyclical stress. The model took into account interfacial features as well as two failure mechanisms. High peak loads raised the shear stress of the CFRP–concrete interface, increasing the potential of intermediate crack (IC) debonding failure, according to the study. Ekenel et al. (2006) examined seven RC beams strengthened with two different FRP systems and discovered that FRP strengthening enhanced fatigue life, decreased fracture propagation, and marginally reduced ductility.

Several research have been undertaken to study the durability of FRP laminates used for RC member strengthening under various loading scenarios (Ceroni et al., 2006; Derkowski, 2015; Hawileh et al., 2016). Hawileh et al. (2016) studied the mechanical deterioration of laminates comprised of carbon, basalt, and their hybrid combinations at extreme temperatures.

The mechanical characteristics of FRP composite sheets dropped at higher temperatures, according to the study, with carbon laminates being the most impacted. For improving the strength of RC members and the fire resistance of FRP strengthening systems, a hybrid mix of basalt and carbon laminates was advised. In the realm of research, Derkowski (2015) conducted an examination on the application of prestressed composite laminates as a means to address the pilling-off failure mechanism found in externally bonded FRP composites utilized for reinforcing RC structures. The investigation emphasized the significance of comprehensively comprehending the behavior of the materials and elements involved. Similarly, Ceroni et al. (2006) explored the long-term resilience of FRP rebars implemented in RC components. This paper examined the design technique used in international codes, as well as the reduction variables taken into account for durability performance. The findings emphasize the need of taking material features and interaction processes into account when evaluating the service life of RC components made of FRP materials.

The purpose of this review paper is to offer a complete overview of the current state of the art in FRP strengthening of RC beams in flexure. The scope of this review is confined to the application of FRP composites for flexural reinforcement of RC beams, with an emphasis on the flexural characteristics that impact the strength and stiffness of RC beams, such as ultimate strength, Failure mode, deflection, and ductility. The review will provide new equations for these characteristics, compare them to the present ACI code, and give suggestions for practicing engineers on the usage of FRP composites for flexure strengthening of RC beams. The review will also highlight future research directions, such as the development of novel FRP materials and strengthening techniques, as well as the assessment of the long-term behavior of FRP-strengthened RC beams.

2 Advancements in FRP Composites: History, Applications, Properties, and Research Trend

2.1 History

In 1905, Leo Baekeland created Bakelite, the world's first synthetic plastic, by reacting phenol and formaldehyde (Takagren, 2015; Trueman, 2015). In the 1930s, the aviation industry pioneered research on the commercial application of FRPs, while Owens-Illinois found mass manufacturing of glass strands in 1932. In 1936, Du Pont created a suitable resin for combining with fiberglass to create a composite material, which was the earliest progenitor of contemporary polyester resins. FRPs began to show promise as a structural and construction material. Glass, carbon, and aramid fibers are still prominent categories of fiber used in FRP, which has been a significant part of the polymer industry since the mid-twentieth century (Erhard, 2013).

2.2 Applications

According to Anandjiwala and Blouw (2007), fiber-reinforced composites are widely employed in a variety of applications (Fig. 1). According to the application distribution of these materials, the automobile sector accounts for 31% of utilization, followed by the construction

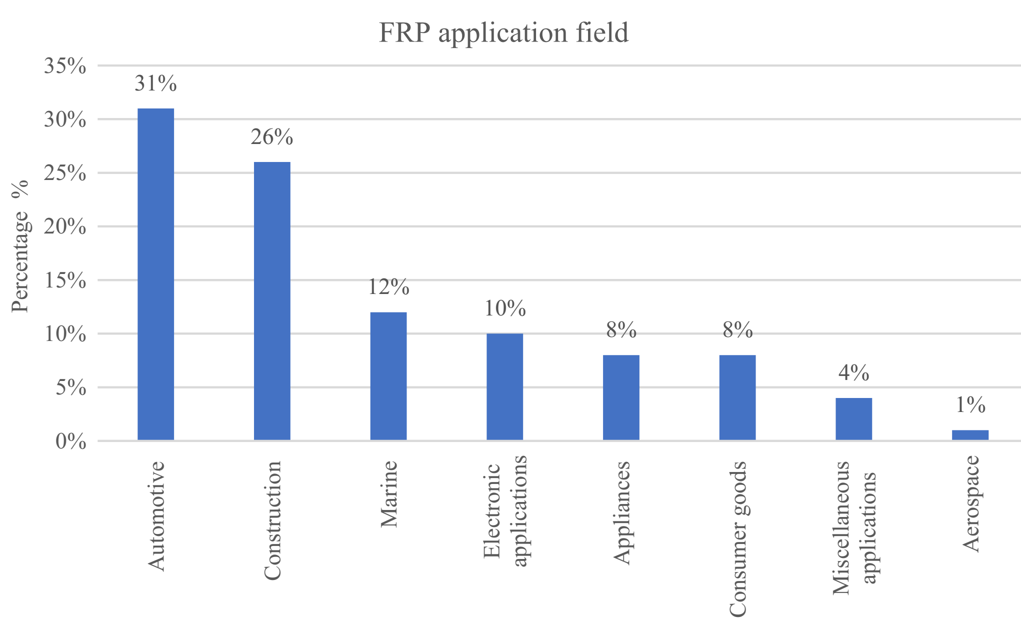

Fig. 1 Diverse range of industrial applications of fiber-reinforced polymer (FRP)

industry with 26% (Friedrich & Almajid, 2012; Guha, 2021; Balla et al., 2023; C. Toduț et al., 2023; Hadi et al., 2022; Tran et al., 2022). The maritime industry is responsible for 12%, while electronic applications and appliances are responsible for 10% and 8%, respectively (Neşer, 2017; Thomas, 2019). The consumer products business contributes 8%, while miscellaneous applications provide 4% (Thomas, 2019). Finally, just 1% of the utilization is accounted for by the aircraft sector (Thomas, 2019). The data of Anandjiwala and Blouw (2007) underlines the wide range of applications for fiber-reinforced composites and the considerable influence these materials have on numerous sectors.

2.3 Types and Properties

FRP composite reinforcements find widespread application in the field of civil engineering. These reinforcements are produced through the pultrusion process, employing a variety of fibers, including carbon (CFRP), glass (GFRP), basalt (BFRP), and aramid (AFRP) (Banibayat & Patnaik, 2015; Mohamed Amine Ammar, 2014). Because of its cheaper cost, E-GFRP is the most often used material, although BFRP is a more expensive option with higher strength, alkali resistance, and a nearly endless supply. Due to its low compressive strength and high cost, AFRP is not a popular material for structural bars, but it is perfect for ballistic-resistant textiles (Palmieri et al., 2012). Because of the carbon supply and production procedures, CFRP has the highest strength and the largest range of strengths among FRP materials (Zhou et al., 2016). In addition, it exhibits superior resistance to fatigue and creep failure when compared to alternative FRP materials. Despite its higher cost, this is offset by its exceptional strength and resilience against fatigue and cyclic failures (Liu et al., 2010). Table 1 presents the key mechanical properties of FRP composites.

Table 1 FRP properties (Adhikari, 2009)

	Tensile strength (MPa)	Modulus of elasticity (GPa)	Ultimate strain
CFRP	1200–2250	100–147	0.012–0.017
GFRP	600–710	30–46.4	0.015–0.020
AFRP	70–123	2.3–3.4	0.014–0.043
BFRP	1000–1100	50–70	0.022

2.4 Research Trend

In recent years, there has been a rise in interest in researching FRP flexural beam strengthening. The number of publications published on the issue has continuously grown since 2001, as indicated in Fig. 2 on recent research trends in this discipline. The proportion of papers published between 2001 and 2004 was the lowest at 6.1%, while the greatest rate was found between 2012 and 2013, at 18.2%. The percentage of publications published between 2018 and 2019 was likewise considerable, at 16.7%. According to the statistics, there has been an increase in interest in the issue of FRP flexural beam strengthening, with researchers concentrating more recently. This rise might be related to growing knowledge of the benefits of employing FRP composites in concrete structure strengthening, as well as the necessity to overcome the problems encountered in this field of study.

Figure 3 depicts the proportion of publications published in various journals since 2001 on the structural

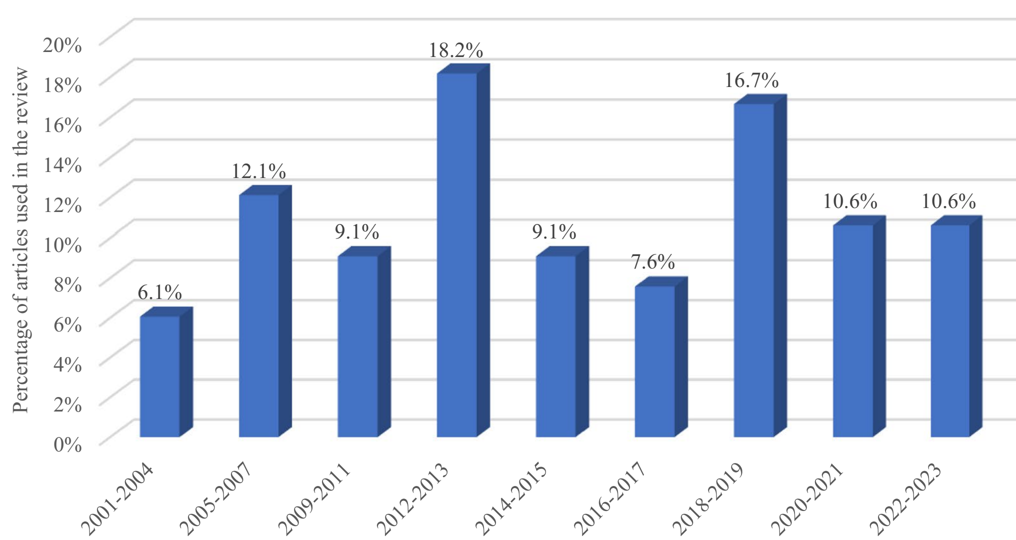

Fig. 2 Distribution of published articles on FRP flexural beam strengthening by year of publication (2001–2023)

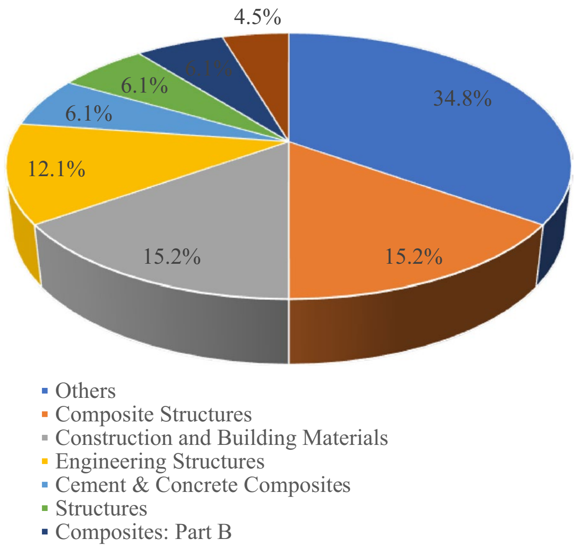

Fig. 3 Journal distribution of publications on FRP strengthened beams since 2001

behavior of beams enhanced using FRP. It can be noted that Composite Structures and Construction and Building Materials each had 15.2% of the papers published, showing a significant contribution to the subject of CFRP strengthening in both publications. Engineering Structures accounted for 12.1% of all articles, a sizable amount. Furthermore, Cement & Concrete Composites, Structures, Composites: Part B, and Journal of Composites For Construction had fewer articles, ranging from 4.5% to 6.1%, but they are still major outlets for research in this subject. Furthermore, 34.8% of the articles were published in other journals, showing a sizable number of publications outside of the major structural engineering journals. This publication distribution among journals is critical for academics and practitioners to determine the most significant sources of knowledge for the structural behavior of FRP-enhanced beams.

3 FRP Matrix

Resin, often known as the matrix, is an important interacting component in many fiber-reinforced polymer (FRP) composites (Gay, 1991). The selection of resin during the manufacturing process is critical, since it has a considerable influence on the mechanical characteristics of these composites. Polyesters, epoxies, and vinyl esters are preferred thermosetting resins because of their advantageous properties, such as heat stability, chemical resistance, decreased creep, and stress reduction (Gay, 1991; Zhou et al., 2016). Thermoplastic polymers, on the other hand, are unsuitable for civil engineering applications due to their limited resistance to creep and temperature impacts. Fiber-reinforced polymers (FRPs) are made up of fibers and a matrix, with the fibers bearing the applied loads and the matrix maintaining fiber consistency, load transmission, and environmental protection (Shokrieh & Omidi, 2009). Table 2 shows the main mechanical properties of different thermosetting resins.

Table 2 Characteristics of thermosetting resins as fiber-reinforced polymer (FRP) Matrices (Gay, 1991)

Resin	Specific gravity	F_{ten} [a] (MPa)	E_t [b] (GPa)	Cure shrinkage (%)
Epoxy	1.2–1.3	55–130	2.7–4.1	1–5
Vinyl ester	73–81	1.1–1.3	3.0–3.3	5.4–10.3
Polyester	1.1–1.4	34–103	2.1–3.4	5–12

[a] Tensile strength

[b] Tensile modulus

Epoxy resin, a basic component or cured end product of epoxy resins, is widely used to reinforce the surface of RC components by integrating a compound in the 1–3% range (Miller et al., 2001). To achieve optimal efficacy, a greater quantity of mastic in relation to the toughened restorative agent is generally required, often in ratios, such as 1:1 or 2:1. Epoxy resins can be categorized into two distinct types: glycidyl epoxy resins and non-glycidyl epoxy resins. Non-glycidyl epoxy resins are commonly referred to as cycloaliphatic or aliphatic resins, while glycidyl epoxy resins encompass glycidyl ether, glycidyl ester, and glycidyl amine variants. Epoxy serves various purposes, such as a bonding agent, a moisture-resistant sealing resin in mechanical textiles, and a coating substance. Noteworthy characteristics of epoxy include its ability to cure as a thin film, superior resistance to microcracking compared to polyester resin, and a tensile elongation failure range of 3.5–4.5% (Önal, 2014). During epoxy applications, precise control of adhesive quantity and ambient temperature is crucial. In addition, epoxy resin facilitates fiber bonding (matrix to fiber), thereby enhancing flexural and compressive strengths, impact and shear strength of the laminates, as well as damage tolerance (Önal, 2014).

Vinyl ester resin is a sophisticated compound, formulated through the esterification process of an epoxy resin with an unsaturated monocarboxylic acid. The resultant product is subsequently dissolved in a regressive solvent, such as styrene, to achieve a mass content within the range of 35–45% (Miller et al., 2001). This resin is extensively used to bind GFRP and BFRP applications (Önal, 2014). When compared to epoxy and polyester resins, vinyl ester has higher toughness and fatigue resistance (Boinard et al., 2000). Vinyl ester resin is often advocated for use as an internal reinforcement in fiber-reinforced polymer (FRP) structures due to its exceptional resistance to environmental conditions (Chen et al., 2006).

Moreover, it has been observed that vinyl esters exhibit lesser creep resistance when cured at room temperature compared to when post-cured at 93 °C (Johnson et al., 1998).

Polyester resin has found extensive application within the FRP composite industry, primarily due to its cost-effectiveness and robust performance attributes. These attributes include resistance to corrosion, rapid curing, user-friendliness, and its ability to withstand high temperatures as well as catalysts (Chen et al., 2006). It does, however, have certain limitations, such as a low modulus of elasticity and a narrow augmentation range of 5–15%. Polyester is also susceptible to creep (Noorunnisa Khanam et al., 2010). Polyester resin exhibits a tensile elongation at failure of 1–2%, in contrast to regular epoxy resins which display a tensile elongation at failure ranging from 3.5% to 4.5%. Due to its cost-effectiveness, polyester resin is commonly employed in glass fiber-reinforced polymer (GFRP) composites for the facing layers of sandwich-style bridge decks. However, in environments with high saturation, vinyl-ester resins are typically preferred (Chen et al., 2006). In compression and tension testing, Fernie and Warrior (2002) recorded a significant surge in ultimate tensile strength, up by 115%, along with a steady 43% enhancement in modulus for continuous filament random mat glass with additional polyester content.

4 Categories of Flexural Strengthening Using FRP

4.1 CFRP Sheets

Numerous studies have been conducted to investigate the effectiveness of CFRP sheets in strengthening RC beams subjected to flexural stresses. In a comprehensive study conducted by Ashour et al. (2004), an empirical assessment of 16 RC beams strengthened with CFRP laminates was performed. A predictive model was developed as a means to determine the flexural load capacity of the investigated beams. Findings highlighted that the reinforced beams demonstrated increased load capacities, albeit with a trade-off of diminished ductility, when juxtaposed with their control counterparts. Remarkably, the primary mode of failure for most of the reinforced beams was the brittle peeling failure of the adjacent concrete cover to the CFRP sheets, regardless of their proximity to their flexural capacities. The extension of CFRP sheets to envelop negative or positive moment zones did not preclude the occurrence of peeling failure, even in scenarios, where tensile rupture of the CFRP sheets transpired. With regard to continuous beams, the increased bending moment capacity due to external reinforcement surpassed the load capacity of the continuous beam. The study proposed that, based on elastic principles, to avert the brittle peeling failure of the FRP laminates, the calculated shear stresses at the adhesive layer should be kept below 0.80 N/mm^2.

Pham and Al-Mahaidi (2004) investigated the failure causes and the effects of various factors on debonding modes in 18 rectangular-reinforced concrete beams. The study's findings can be summarized as follows. First, debonding occurred at the mid-span and end of the beams due to significant shear stress in the concrete, which measured about 1 MPa. Second, two critical characteristics impacted FRP performance: the ratio of FRP bond length in the shear span to concrete depth and the ratio of laminate stiffness to tension reinforcement stiffness. The effectiveness of the FRP was shown to rise with bond length and decrease with FRP quantity applied. Furthermore, parameters such as concrete cover and shear reinforcement quantity were discovered to have a negligible effect on the debonding process. Steel clamps were discovered to be an effective solution for preventing end debonding and increasing beam ductility by retaining friction between the delaminated fibers and the concrete. It was also discovered that even after FRP debonding, the RC beams kept their initial strength. The researchers also discovered that beam theory produced reasonably accurate estimates of FRP strain levels.

In a detailed study conducted by Hosny et al. (2006), the behavior of RC T-beams, enhanced with hybrid FRP laminates, was explored. The comprehensive testing of twelve beams revealed that the use of CFRP or GFRP laminates significantly increased the maximum load-carrying capacity, though at the cost of reduced ductility. However, improved ductility was achieved when a mixture of CFRP and GFRP laminates was utilized. An optimal reinforcement strategy was identified, involving the placement of CFRP laminates on the beam's sidewalls and GFRP laminates at the base. The study also affirmed that using the strain compatibility method can accurately predict the beams' behavior, provided a strain limit of 50% of the maximum values for both CFRP and GFRP is respected.

Toutanji et al. (2006) conducted a thorough examination of the flexural behavior of eight RC beams subjected to four-point bending. This comprised 8 beams fortified with carbon fiber sheets bound with an inorganic epoxy, including one control beam. The findings demonstrated a positive correlation between the number of carbon fiber layers and the load-bearing capacity of the RC beams. Beam failure for those strengthened with three and four layers of carbon fiber occurred due to carbon fiber sheet rupture, while FRP delamination was the cause of failure in beams with five and six layers. Strengthened beams showed less ductility compared to the control beam. Consistent with previous research, the ultimate strain of the CFRP reinforcement, bonded with an inorganic epoxy, was established to be 0.0060 mm/mm. To further substantiate these findings, a moment–deflection model was developed and validated using data from this study and other investigations, yielding a satisfactory degree of agreement. The research underscores the need for further exploration into the bond-controlled failure of inorganic epoxy systems and the debonding failure of FRP attached to RC beams.

Hamid et al. (2009) evaluated the usefulness of externally bonded CFRP sheets in enhancing the flexural strength of HSC beams. Six beams with varied arrangements of CFRP sheets were tested experimentally. The beams' behavior was studied using FE models. The following were the important findings: the FE models agreed well with the experimental data, allowing for exact prediction and design principles for FRP strengthening. The bonding of CFRP sheets improved flexural strength, particularly in beams with lower steel reinforcing ratios. Tensile steel stresses exceeded CFRP strains. The concrete fibers' compressive strain remained linear until failure, unaffected by concrete cracking or tension steel yielding. CFRP decreased compression fiber strain. Despite a brittle failure mechanism, steel and CFRP-reinforced beams showed enough deformation capacity. As steel reinforcing grew, the extra strength supplied by CFRP decreased. CFRP raised the strength of poorly reinforced beams substantially but had a lower effect on moderately reinforced beams. results for energy ductility were almost twice as high as results for displacement ductility. In the bending moment zone, CFRP strain was uniform, slightly greater at load sites, and dropped linearly along the shear span.

Kim and Shin (2011) performed an in-depth exploration of the structural properties of RC beams that had been retrofitted with hybrid FRPs. Utilizing four-point bending tests, the study evaluated a range of factors, such as ductility, crack development, failure mechanisms of the samples, and the repercussions of preloading on the retrofitted RC beams. The research outcomes demonstrated that the employment of hybrid FRPs led to improvements in the ultimate strength and stiffness of the beams. It was found that the sequence of application of distinct FRPs had a considerable effect on the strength, rigidity, and ductility of the retrofitted beams. The beams displayed optimal strength and ductility when glass fiber was applied prior to the use of carbon fiber. Furthermore, the research determined that preloading influenced the structural behavior of the beams, lessening the strengthening benefits of hybrid FRPs in comparison with beams without preloading. However, this adverse effect could be counteracted by repairing cracks before the attachment of FRPs. Finally, the study highlighted that failure occurred in the retrofitted RC beams before the hybrid FRP sheets reached their fracture point. This observation underscores the necessity for a reevaluation of retrofitting design strategies to optimally utilize the potential of hybrid FRPs.

Attari et al. (2012) undertook a comprehensive analysis to determine the effectiveness of external fortification systems on RC beams, utilizing GFRP and CFRP fabric. The research encompassed the examination of various reinforcement setups, including the application of unidirectional glass and carbon fibers with U-anchorages, and the use of a bidirectional glass–carbon fiber hybrid fabric. The study was based on the repeated loading of seven RC beams, and the ensuing assessment of their strength, rigidity, ductility, and failure mechanisms. Concurrently, the researchers developed an analytical model with the aim of accurately predicting the flexural failure of RC components. The outcomes of the study indicated a strong correlation between the model's predictions and the observed behavior of RC beams under load. In addition, the experimental results suggested that the use of a dual-layer glass–carbon FRP fabric as a reinforcement strategy for RC structures presents a cost-effective solution.

Jankowiak (2012) investigated RC beams reinforced with CFRP strips numerically and experimentally. The beams were tested to see how efficient the reinforcement was in terms of load bearing capability. Different preloading states were investigated, and analysis was performed using FE modeling. The following are the key findings: due to debonding of the CFRP strips, all reinforced beams broke brittlely. When compared to beams without strips, the improvement in load bearing capability varied from 24% to 30%. The reduction in deflection at failure ranged from 33% to 37%. When beams were unloaded to dead weight before adding the strips, the most efficient strengthening was found. The utilization of adequate concrete fracture energy and a proper description of the tensile concrete were critical for accurate results. The numerical model was tested effectively and proven beneficial for assessing RC beams reinforced with composite materials, potentially providing a future alternative to labor-intensive and expensive laboratory experiments.

Dong et al. (2013) conducted an empirical study on the flexural and flexural–shear fortification of RC beams using CFRP and GFRP sheets. The research scrutinized various enhancement arrangements involving CFRP and GFRP sheets and evaluated their impact on the performance of retrofitted RC beams. The study's findings suggested that the flexural–shear strengthening configuration significantly augmented the stiffness, peak strength, and strain-hardening behavior of RC beams, to a greater degree than merely applying flexural strengthening. The study also encompassed the development of theoretical computations to project the bending and shear capacities of the tested beams, with these predictions subsequently contrasted against the equivalent experimental data.

Ali et al (2014) investigated the effect of CFRP mechanical anchorages on the flexural performance of CFRP sheets and plates used in externally strengthened RC beams. The study's primary goal was to evaluate the load-bearing capability and ductility of the beam specimens. This study's significant findings included: beams with anchors had a greater delamination load than those without anchors, albeit further statistical analysis with a larger sample size is required to fully assess the significance of this increase. The ductility of the beam specimen without reinforcement was the highest, whereas the ductility of the beams reinforced with CFRP sheets and plates and supported by CFRP anchors was the lowest. The addition of anchors had no discernible effect on the flexural stiffness of the beam specimens.

In their research, Xie et al. (2014) examined the impact of pre-damage level, shear span-depth ratio, and CFRP thickness on the flexural performance of pre-damaged RC beams fortified with CFRP. The empirical findings led to the following conclusions: the application of CFRP substantially enhances the flexural load-bearing capacity of pre-damaged RC beams while not affecting stiffness, yield loads, or ultimate loads. The shear span–depth ratio plays a significant role in influencing the failure mechanism and load-bearing capacity of reinforced RC beams. As the shear span–depth ratio decreases, there may be a transition in the failure mechanism from IC debonding to cover separation at the CFRP end, with IC debonding beams presenting higher load-bearing capacities. CFRP usage is improved by increasing the shear span ratio. Higher CFRP levels contribute to improved load bearing capacity and flexural stiffness in beams failing due to IC debonding, but this tendency does not apply to beams collapsing due to cover separation near the CFRP end. However, increasing the thickness of the CFRP affects the ductility of the strengthened beams.

Cosgun (2016) investigated the use of CFRP to strengthen RC beams. The study included experimental and computational assessments of 16 RC beams with different concrete strength classes and reinforcing schemes. The following are the important findings: the ultimate load-bearing capabilities of CFRP strengthened flexural and shear beams were comparable. Shear failure was seen in all CFRP-reinforced flexural beams, which was most likely caused by increased stiffness in the center area. In addition to shear failure, shear beams exhibited plate end debonding, demonstrating the impact of reinforcing layout. The deflection values and ductility of the CFRP strengthened beams were comparable. The effect of CFRP on load–displacement behavior was comparable for beams of various concrete strength classes. Although the failure processes vary, the ultimate load capacity and ductile behavior of CFRP-reinforced flexural and shear beams with various reinforcing schemes were similar. The numerical analysis results matched the experimental data well, with a difference of 2–7%, showing consistency and adequate accuracy.

Salama et al., (2019) evaluated the flexural capacity of RC beams that had been externally reinforced with side-bonded CFRP sheets using epoxy adhesives. Nine RC beams were evaluated, with the performance of side-bonded and standard bottom-bonded strengthening methods compared. The results revealed that the side-bonded approach was marginally less efficient at improving flexural characteristics. The flexural strength of bottom-bonded specimens improved by 62–92%, whereas side-bonded specimens increased by 39.7–93.4%. However, ductility at failure was reduced by 42.3–62.5% when compared to the control beams. Steel yielding occurred prior to CFRP debonding, with larger reinforcement ratios resulting in quicker debonding. Fiber depth and stress distribution were blamed for the efficiency difference. Increasing the breadth of side-bonded CFRP sheets resulted in very minor gains. Flexural strength was appropriately anticipated by the ACI440.2R-08 design requirements. Overall, side-bonded CFRP strengthening was less effective but still generated considerable strength gains.

Choobbor et al., (2019) examined the efficacy of flexural strengthening in RC beams utilizing hybrid BFRP and CFRP sheets. Nine RC beams' experimental and numerical findings were examined. The research indicates that the flexural strength of reinforced beams increased by 28–75% in comparison with beams that were not strengthened. In addition, increasing the number of basalt sheets in the hybrid laminate improved ductility by as much as 31.1% for beams having the same layer count. In addition, altering the arrangement of the FRP sheets did not impact the functionality of beams featuring two or three layers of FRP laminates. The accuracy of finite-element (FE) models in estimating ultimate load bearing capacity and deflection of RC beams reinforced with hybrid FRP laminates was validated, with percentage deviations ranging from 1% to 11% and 2% to 12%, respectively.

Hadi et al., (2022) studied numerous FRP systems to find the best efficient way for retrofitting and strengthening RC beams. The study's findings led to the following conclusions. For starters, there was a remarkable agreement between the experimental results and the American Concrete Institute (ACI) connections. Second, among the many FRP mechanisms examined, the hybrid strengthening approach demonstrated more ductility than the control beam and other FRP mechanisms. Furthermore, the hardening slope and absorbed energy were found to be larger in all FRP mechanisms than in the control beam, with the hybrid type displaying the greatest values.

Nawaz et al., (2022) investigated the flexural behavior of all lightweight concrete (ALWC) beams reinforced with CFRP sheets. Experiments were carried out on fifteen specimens, with variables, such as reinforcement ratio, number of CFRP layers, and pre-loading taken into account. The results revealed that CFRP boosted the ultimate load bearing capacity of the beams substantially, with a variety of improvements. Delamination was the most common failure mode, which was slowed by CFRP sheets. With more CFRP layers, stiffness, yield load, and post-cracking stiffness improved, but ductility dropped. The strength of pre-loaded specimens was greater. Flexural strength predictions based on various design standards overstated testing results. More study on other lightweight aggregates and large-scale beams with varied concrete strengths and CFRP reinforcement is proposed.

In the experimental study conducted by Hashemi et al. (2022), low-strength concrete (LSC) elements, which are susceptible to seismic and static loads, were reinforced using FRP strengthening. Two primary aspects were investigated: first, the impact of rebar planting to increase the initial compressive strength for FRP reinforcement, and second, the effectiveness of CFRP confinement in enhancing the strength of rebar-embedded specimens. A total of 38 standard concrete cylinders were tested, with variables, including rebar dimensions, concrete strength, and CFRP sheet count. Statistical analysis revealed the significant role played by CFRP confinement, combined with rebar embedment, in increasing the load-bearing capacity of LSC concrete, as supported by experimental results. Rebar planting demonstrated a strength enhancement of up to 53%, rendering certain LSC specimens eligible for CFRP confinement.

4.2 Near Surface Mounted (NSM) Bars

Extensive study has been carried out to determine the efficiency of NSM bars in strengthening the structural reinforcement of RC beams subjected to flexural stresses. Dias and Barros (2011) scrutinized the effectiveness of the NSM technique in augmenting the shear strength of T-section RC beams with low concrete durability. The experimental approach of this study involved assessing the effects of different CFRP shear fortification configurations on various parameters. These included load-bearing capacity, stiffness, peak stress levels in CFRP laminates, and the mechanisms leading to failure. The NSM approach was found to be successful in RC beams with a low concrete strength of 18.6 MPa. Following shear crack development, the CFRP shear strengthening designs enhanced both maximum load and load-carrying capacity. Concrete strength was important, with increased strength resulting in better efficacy. Inclined laminates outperformed vertical laminates in terms of shear capacity, while increasing the proportion of laminates enhanced shear capacity. However, an increase in the percentage of existing steel stirrups had a negative impact on the NSM technique's effectiveness. The proposed formulation for NSM shear strengthening provided reliable estimates, with predicted CFRP contribution at 75% of experimental results.

Singh et al., (2014) evaluated the performance of flexure- and shear-strengthened beams to control beams. A parametric research was carried out using numerical modeling, and the results were confirmed using experimental data. Based on numerous characteristics, the research gave guidance for the appropriate positioning and use of FRP bars. The diameter and strength of the FRP bars were discovered to be key considerations. FRP bars set at a 45° angle to the beam axis were most effective for shear strengthening, whereas vertical bars were least effective. The study also determined the optimum shear strength by determining the minimum groove distance, groove width, and spacing between NSM FRP bars. The geometry of the NSM FRP bars has no effect on strength increase.

Haddad and Almomani (2017) studied the possibility of restoring the flexural performance of thermally damaged concrete beams using NSM CFRP strips. Two sets of beams were exposed to varied circumstances, including 2 h of heating at 600 °C. The NSM CFRP strips were used to repair/strengthen half of the beams in each set, while the other half functioned as controls. Four-point loading tests were used to assess mechanical performance, which included load capacity, stiffness, ductility, and bond strength. Heating considerably lowered load capacity while improving ductility, according to the findings. Strengthening intact beams with NSM CFRP strips increased load capacity and stiffness, but mending heat-damaged beams resulted in mechanical performance loss. With longer NSM CFRP strip embedment lengths, the overall performance factor suggested that mending heat-damaged beams was possible. The minimal contribution of the restoration techniques to restoring the original mechanical performance was ascribed to considerable bond strength loss. With an average prediction error of 9%, analytical projections for ultimate load capacity closely matched experimental data.

Chellapandian et al., (2019) performed flexure experiments on RC beams with and without FRP strengthening utilizing various approaches, such as NSM, external bonding (EB), and combinations of both. The study team performed a complete three-dimensional, nonlinear finite-element analysis, which was supplemented with analytical predictions generated from the beams' sectional responses. This confirmed finite-element (FE) model laid the groundwork for additional experiments, such as calculating the ideal NSM edge distance and CFRP ratios. The findings of this study provided some crucial insights. For starters, the use of Hybrid FRP strengthening significantly increased load-bearing capacity, with hybrid-strengthened beams retaining a significant amount of residual capacity following the rupture of NSM laminates. Second, hybrid FRP strengthening outperformed standalone NSM or EB strengthening in terms of energy absorption capacity. Finally, for both unconfined and FRP-confined concrete, theoretical predictions based solely on sectional calculations tended to underestimate experimental data.

Dong et al., (2019) conducted an in-depth study on the performance of concrete beams reinforced with FRP bars, anchored using high-strength cement grout and corrugated sleeves. This methodology-controlled crack expansion, with ten beams tested under four-point bending conditions. Results demonstrated that FRP-reinforced beams had superior flexural capacity compared to steel-reinforced beams. The use of grouted FRP bars within sleeves did not affect failure modes, with these beams showing more deflection before concrete crushing, suggesting an early warning sign of impending failure. Axial stiffness of FRP bars impacted the behavior of FRP-reinforced beams, with an increase in stiffness improving flexural capacity, structural rigidity, and reducing crack width. The use of high-strength grout and corrugated sleeves led to a notable reduction in crack widths, thus improving serviceability performance. In addition, the study highlighted some discrepancies in current standards (e.g., ACI 440.1R, CSA S806-12, GB 50608-2010) for predicting crack spacing and strain coefficients, indicating the need for further research to refine crack-width equations.

Panahi et al., (2021) studied the efficiency of FRP composite-based flexural strengthening solutions for reinforced concrete beams. NSM, EB, and a mixture of the two were among the approaches investigated. The impacts of material characteristics, geometry, and configurations on the flexural behavior of the strengthened beams were studied using ABAQUS software. The results showed that beams with NSM FRP rods had much higher flexural capacity and stiffness than control beams, while mid-span deflections were lower. With increasing material strength and embedding length, the ultimate bending moment and stiffness of the beams rose. The study also discovered that increasing the diameter of FRP rods increased the ultimate bending moment while decreasing mid-span deflection and ductility. The strengthened beams' load–deflection behavior followed a tri-linear pattern, beginning with linear elastic behavior, then reinforcement usage and enhanced load-carrying capacity, and finally an increase in mid-span deflection. Furthermore, broader sheet widths boosted the load-carrying capability of beams reinforced with EB FRP sheets, albeit at the expense of lower ductility compared to narrower sheets.

4.3 FRP Bars and Grids

Some researches concentrated on the usage of FRP bars and grids in concrete components. Liu et al. (2020) investigated the crack development in GFRP- and CFRP-reinforced beams using lightweight concrete (LWC) and self-compacting lightweight concrete (SFLWC). They found that the use of SFLWC and increased clear span length decreased maximum crack width at lower loads, and higher reinforcement ratios also reduced crack width throughout the loading process. All CFRP-reinforced beams met the 0.7 mm fracture width requirement at service load, whereas some GFRP-reinforced specimens showed non-conservative crack widths. The research found that the inclusion of steel fibers effectively reduces the fracture width at service load for lower reinforcement ratios, although it slightly augments it for higher ratios. The experimental results corroborated the reliability of ISIS-M03 and ACI 440.1R formulas for predicting crack width, while flagging inaccurate estimates presented by GB 50608. A novel model for predicting crack width in NWC beams reinforced with FRP, which accommodates both lightweight aggregates and steel fibers, was proposed. This model demonstrated a commendable level of accuracy in its predictions.

In their 2021 research, Guo et al. conducted four-point bending tests to examine the shear behavior and enhancement effects of RC beams fortified with polypropylene-engineered cementitious composite (PP-ECC) and FRP grids. The study explored varied reinforcement levels of FRP grids and diverse beam shear span ratios. Findings indicate that the application of ECC layer alone resulted in a minor increase in peak loads, but it exhibited a smoother failure process and successfully conveyed shear forces through the bridging effect of PP-ECC. The shear resistance was contributed by both vertical and horizontal FRP grids, though the latter accounted for only 30% of the resistance when compared to the former. The interaction between stirrups and FRP grids occurred ahead of shear cracks, followed by partial debonding at the interface, particularly in specimens with multiple layers. Furthermore, an analytical method for predicting shear capacities in RC beams reinforced with ECC/ECC–FRP grids was proposed, and its accuracy was validated through a comparison with the test results.

Hassanpour et al. (2022) studied the effectiveness of using GFRP bars as compressive reinforcement in RC beams, considering singly and doubly reinforced configurations. The study evaluated their impact on load-bearing capacity, ductility, stiffness, and failure modes. The findings revealed a limited enhancement of flexural strength, with a maximum 5% increase in flexural capacity for doubly reinforced beams and an 8% strength gain in GFRP–RC cylinders compared to controls. Concrete's compression strain limited this improvement. For singly reinforced specimens, the presence of compressive GFRP bars reduced stiffness (up to 16%) but enhanced curvature (up to 10%) and ductility (up to 35%). In addition, a novel ductility assessment method based on deformations near peak and peak load capacity was introduced, predicting ductility gains from compressive bars and identifying distinct failure modes.

Kadhim et al. (2022) examined the effectiveness of carbon–fiber-reinforced UHPC overlays in strengthening RC beams. The research employed a robust FE model validated against experimental data. A parametric study of 68 models investigated key factors, including reinforcement ratios, concrete strength, overlay thickness, and interface conditions. The CFRP-reinforced UHPC overlays significantly enhanced ultimate load capacity and ductility, eliminating cracking failures. Varying the CFRP reinforcement ratio resulted in a substantial ultimate load increase (112–463%) compared to control beams. The study also developed an analytical model for design purposes based on parametric study outcomes and regression analysis.

5 Flexural Analysis of FRP Strengthened Beams

5.1 Overview

This section presents an analysis of 124 RC beams that have been reinforced with FRP sheets to enhance their flexural performance (Ali et al., 2014; Ashour et al., 2004; Attari et al., 2012; Chen et al., 2018; Choobbor et al., 2019; Cosgun, 2016; Dong et al., 2013; Hadi et al., 2022; Hamid et al., 2009; Hosny et al., 2006; Jankowiak, 2012; Kim & Shin, 2011; Nawaz et al., 2022; Pham & Al-Mahaidi, 2004; Salama et al., 2019; Toutanji et al., 2006; Xie et al., 2014). Various types and ratios of FRP were employed in the strengthening process. The analysis encompasses several key aspects, including maximum load capacity, mode of failure, ultimate and yield deflection, ductility, and stiffness. To assess the extent of improvement or degradation in these aforementioned outputs, an enhancement ratio (ER) is utilized, which is computed as follows:

$$ER\% = \frac{Output\,f\ for\ strengthened\ specimen - Output\ for\ control\ specimen}{Output\ for\ control\ specimen} \times 100 \quad (1)$$

A negative value indicates a decrease in the output relative to the control specimen, while a positive value signifies an increase in the output.

5.2 Ultimate Load Capacity

One of the significant outcomes to be examined in any analysis is the ultimate load capacity. In this review, the load capacity of the strengthened beams was compared to the capacity predicted by the ACI code. The results are depicted in Fig. 4, where the y-axis represents the experimental (EXP) load capacity in kN, and the x-axis represents the load capacity as forecasted by the ACI code in kN. It is evident from the red dotted line in Fig. 4 that, for the majority of specimens, the actual load capacity exceeded the predicted value according to the ACI code. Furthermore, a trend line with the equation $y = 1.1514\times$ can be derived, indicating that the actual load capacity for RC beams reinforced with FRP is, on average, 15% higher than the capacity predicted by the ACI code. This finding validates the equation proposed by the ACI code in terms of the flexural capacity of RC beams strengthened by FRP composites.

In addition, Fig. 5 illustrates the relationship between the FRP reinforcement ratio (ρ_f) and the Effective Reinforcement (ER) of the ultimate capacity for the reinforced beams. The value of ρ_f for each beam was determined using the following equation:

$$\rho_f = \frac{A_f}{b \times d_f} \quad (2)$$

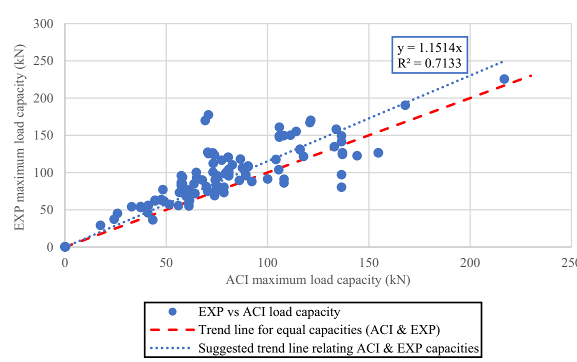

Fig. 4 Comparative analysis of load capacity between experimental findings and ACI Code predictions

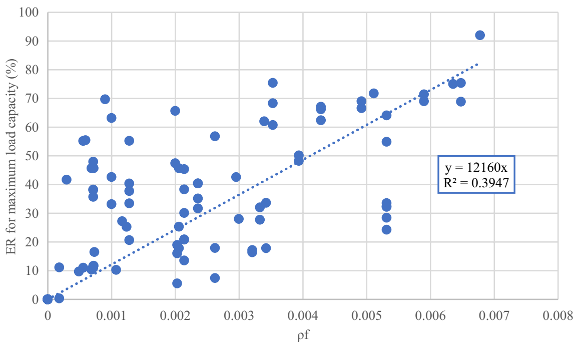

Fig. 5 Enhancement Ratio (ER) of ultimate load as a function of FRP reinforcement ratio (ρ_f)

where ρ_f is calculated as the ratio of A_f (cross-sectional area of the FRP sheets) to the product of b (beam width) and d_f (effective depth of the FRP sheets). Across all beams, ρ_f ranged from 0 (indicating no strengthening) to 0.007, while the ER varied from 0% (without reinforcement) to 92%. Equation (3) establishes the correlation between the ER of the ultimate capacity and ρ_f as

$$Y = 12160X \tag{3}$$

where Y represents the ER of the ultimate load and X denotes ρ_f. The coefficient of determination (R^2) for this equation is 0.76, indicating the reliability of the formula.

5.3 Failure Mode

The findings from the review of previous studies on flexural CFRP strengthened beams reveal four distinct failure modes: FRP debonding, FRP laminate delamination, FRP laminate rupture, and flexural failure. To evaluate each failure mode, the ratio between the yielding load (P_y) and the ultimate load at failure (P_u) was analyzed. Figure 6 illustrates these ratios for the different failure modes.

For specimens that failed due to FRP debonding, the (P_y/P_u) ratio ranged from 0.77 to 0.99, with an average of 0.85. Similarly, specimens that experienced FRP laminate delamination exhibited ratios between 0.57 and 0.99, with an average of 0.85. In contrast, the (P_y/P_u) ratio for specimens that failed through FRP laminate rupture ranged from 0.52 to 0.94, with an average of 0.78. Finally, specimens that failed due to flexural failure had ratios between 0.3 and 0.99, with an average of 0.78.

These findings indicate that the failure modes associated with FRP laminate delamination and FRP debonding have the highest average (P_y/P_u) ratios, suggesting lower load ductility compared to FRP laminate rupture and flexural failure. In other words, the specimens that failed due to FRP laminate delamination and debonding exhibited less ability to sustain load before reaching ultimate failure compared to those failing through other modes.

The findings of this study, which analyzed 124 beams, indicate that a significant majority of the specimens (78.2%) had experimental ultimate loads (Pu(EXP)) higher than the predicted ultimate load based on the ACI code (Pu(ACI)). However, approximately 21.8% of the specimens exhibited lower experimental ultimate loads compared to the predictions by the ACI code, as illustrated in Fig. 7a.

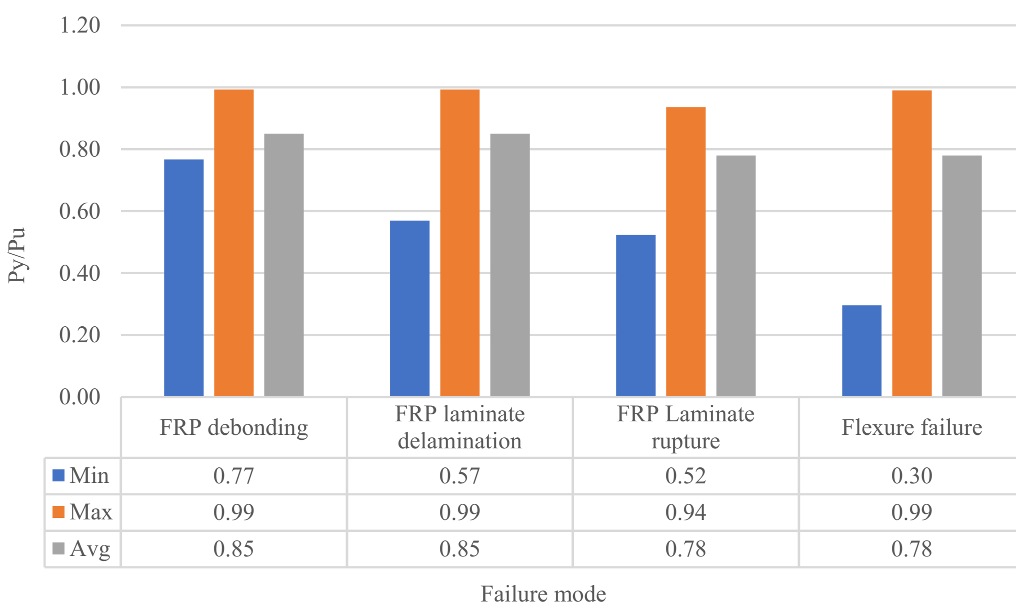

Fig. 6 Comparison of yielding load to ultimate load ratios (P_y/P_u) for different failure modes in flexural CFRP strengthened beams

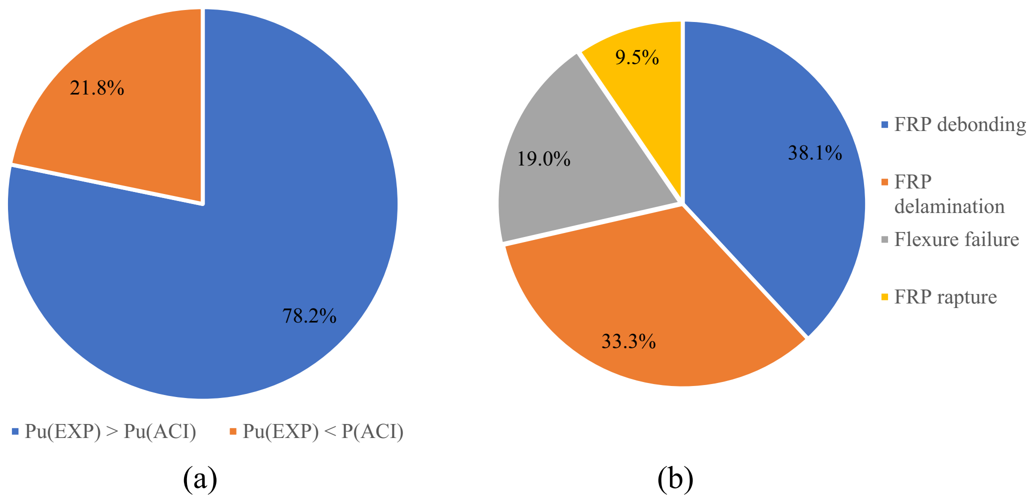

Fig. 7 Comparison of experimental ultimate load (Pu(EXP)) and ACI code predicted ultimate load (Pu(ACI)) for CFRP-strengthened beams: (**a**) overall distribution and (**b**) failure modes of specimens with lower experimental ultimate loads

Further investigation revealed that these 21.8% of specimens that displayed lower Pu(EXP) values had diverse failure modes. Among them, approximately 38.1% failed due to FRP debonding, 33.3% experienced FRP delamination, 19% encountered flexural failure, and 9.5% suffered from FRP rupture, as depicted in Fig. 7b.

These findings indicate that a significant portion (around 81%) of the specimens with lower Pu(EXP) than Pu(ACI) exhibited failure modes other than the conventional flexural mode. This highlights the importance of considering and understanding the various failure mechanisms that can occur in CFRP-strengthened beams beyond the standard assumptions of flexural failure. It emphasizes the need for more comprehensive design guidelines that can account for these alternative failure modes and enhance the reliability of predictions for ultimate loads in practice.

5.4 Ductility

Preserving ductility in RC beams is crucial, thus necessitating a comprehensive examination of the impact of flexural FRP strengthening on their ductility. This study incorporates two indicators: displacement ductility (λ_d) and energy ductility (λ_e). Displacement ductility denotes the ratio between the displacement recorded at the point of failure (δ_u) and the displacement observed at the yield level (δ_y). Similarly, energy ductility is characterized by the ratio between the energy dissipated at the point of failure (E_u) and the energy dissipated at the yield level (E_y). It is noteworthy to mention that the energy dissipated corresponds to the area under the load deflection curve, encompassing the cumulative energy dissipation throughout the loading process. The following formulas were adopted in estimating displacement and energy ductility ratios:

$$\lambda_d = \frac{\delta_u}{\delta_y} \tag{4}$$

$$\lambda_e = \frac{E_u}{E_y} \tag{5}$$

The enhancement ratio (ER) for λ_d was determined for the FRP-reinforced beams examined in this study and compared to the ratio of effective FRP reinforcement to effective steel reinforcement ($\rho_{f-s} = \frac{A_f \times E_f}{A_s \times E_s}$). As depicted in Fig. 8, there exists a correlation between the ER for λ_d and ρ_{f-s}, as defined by the following equation:

$$Y = -214.91X \tag{6}$$

In Eq. (6), Y represents the ER for λ_d, while X denotes ρ_{f-s}. The coefficient of determination (R^2) for this equation is 0.73, indicating a satisfactory level of accuracy. Based on this equation, it can be observed that as the

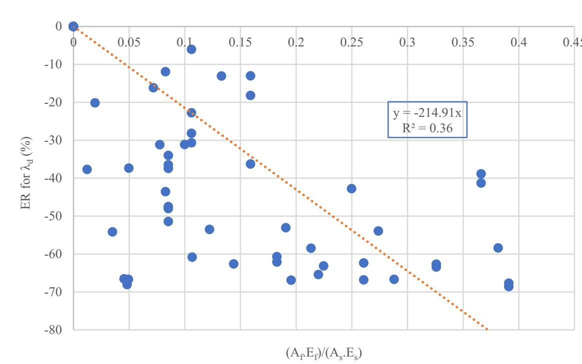

Fig. 8 Correlation between ER for λ_d and FRP-to-steel reinforcement ratio ρ_{f-s}

ratio of FRP reinforcement generally increases, ductility decreases, with a reduction of approximately 75% observed for $\rho_{f-s} = 0.35$. The suggested equation holds true for ρ_{f-s} values ranging from 0 to 0.4.

To assess the decline in ductility, the enhancement ratio (ER) for λ_d was plotted against the ER for ultimate load capacity, as depicted in Fig. 9. Analysis of the figure reveals a discernible relationship between the ER of ductility and the ER of ultimate load, characterized by the following equation:

$$Y = -0.84X \tag{7}$$

Here, Y represents the ER for ductility, while X signifies the ER for ultimate load. The coefficient of determination (R^2) for this equation is 0.79, indicating a reasonably accurate fit. Notably, for each 1% increment in strength resulting from FRP strengthening, there is an associated reduction of 0.84 in displacement ductility. It should be noted that both Eqs. 6 and 7 could be further improved by incorporating additional data from future studies involving FRP-strengthened beams.

On the contrary, the enhancement ratio (ER) in energy ductility (λ_e) can be associated with ρ_{f-s} factor, as depicted in Fig. 10. It is worth noting that as ρ_{f-s} increases, the ER for (λ_e) decreases. The relationship between the variables can be expressed as follows:

$$Y = -251.10X \tag{8}$$

Equation (8) establishes a relationship between Y, denoting the ER for λ_e, and X, representing ρ_{f-s}, the ratio of FRP reinforcement to steel reinforcement. The coefficient of determination (R^2) for this equation is 0.74, indicating a commendable level of accuracy. Analysis of the equation reveals that as the ratio of FRP reinforcement generally increases, a corresponding decrease in ductility is observed, with a significant reduction of approximately 88% recorded for $\rho_{f-s} = 0.35$. Notably, the proposed equation holds valid for ρ_{f-s} values ranging from 0 to 0.4.

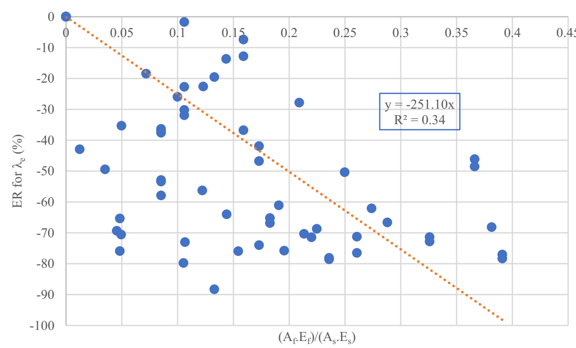

Fig. 10 Correlation between ER for λ_e and FRP-to-steel reinforcement ratio ρ_{f-s}

Figure 11 illustrates the correlation between the ER for λ_e and the ER of ultimate load capacity, allowing for an evaluation of the decline in ductility. The relationship between the two variables can be described by the equation:

$$Y = -0.91X \tag{9}$$

Here, Y represents the ER for λ_e, while X signifies the ER for ultimate load. The coefficient of determination (R^2) for this equation is 0.76, indicating a reasonably accurate fit. It is important to note that for each 1% increase in strength resulting from FRP strengthening, there is a corresponding reduction of 0.91 in energy ductility. In addition, it should be acknowledged that incorporating further data from future studies involving FRP-strengthened beams has the potential to enhance the accuracy and reliability of both Eqs. 8 and 9.

These correlation analyses provide valuable insights into the relationship between the ratio of FRP reinforcement to steel reinforcement, and the resulting enhancement in the ductility of the beams. The equations derived from these analyses offer a useful tool for predicting the ductility behavior of reinforced beams based on the chosen ratio of FRP to steel reinforcement. Researchers and practitioners in the field can utilize these equations

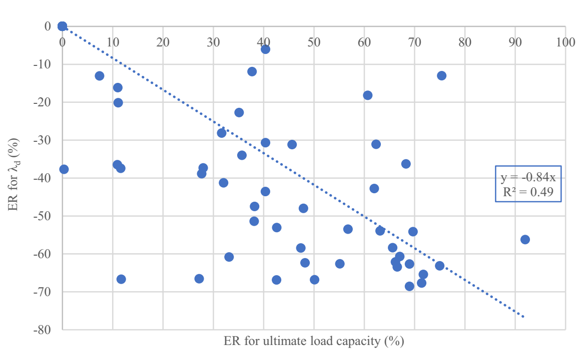

Fig. 9 Correlation between ER for λ_d and ultimate load capacity

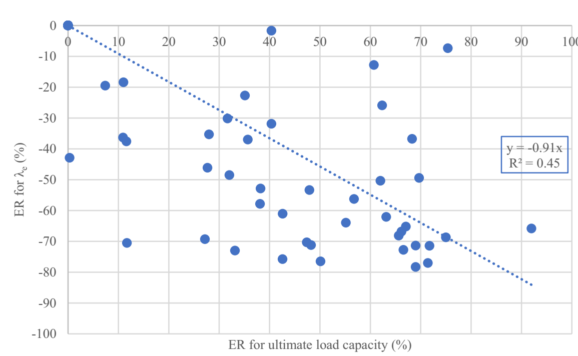

Fig. 11 Correlation between ER for λ_e and ultimate load capacity

to optimize their design decisions and ensure that the desired level of ductility is achieved for various reinforcement ratios within the specified range.

5.5 Flexural Stiffness

Prior studies have demonstrated the influence of FRP strengthening on the stiffness of beams. This effect extends to both elastic and inelastic beam stiffness (Fig. 12). In Fig. 13, the relationship between the enhancement ratio of elastic stiffness (K_e) and ρ_{f-s} is illustrated. It is evident that an increase in ρ_{f-s} corresponds to an increase in K_e. The relationship between the two variables can be described by the equation:

$$Y = 159.64X \quad (10)$$

where Y represents the ER for K_e, while X denotes ρ_{f-s}. The coefficient of determination (R^2) for this equation is 0.79, indicating a satisfactory level of accuracy. Based on this equation, it can be observed that as the ratio of FRP reinforcement generally increases, K_e increases, with an increase of approximately 40% observed for $\rho_{f-s} = 0.25$. The suggested equation holds true for ρ_{f-s} values ranging from 0 to 0.3.

These findings demonstrate that the utilization of FRP in beams can significantly increase their elastic flexural stiffness, thereby resulting in higher load capacities and reduced deformations. It has been shown that the ER of elastic stiffness (K_e) exhibits a substantial increase with higher ratios of FRP to steel reinforcement ρ_{f-s} (Fig. 13). This enhanced stiffness plays a critical role in improving the load-carrying capacity of the beams and minimizing deformations under applied loads. By effectively strengthening the beams with FRP, engineers can achieve structural elements that exhibit enhanced performance, increased load-carrying capabilities, and reduced deflections, thus enhancing the overall structural integrity and resilience of the system.

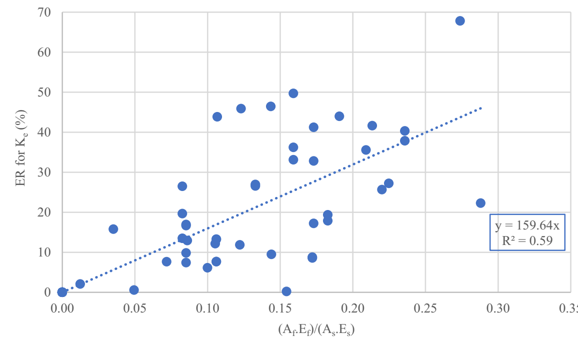

Fig. 13 Correlation between ER of elastic stiffness (K_e) and ρ_{f-s} in FRP strengthened beams

The analysis of Fig. 14 reveals important insights into the impact of ρ_{f-s} on the inelastic stiffness (K_i) enhancement of RC beams. The results indicate that the optimal ρ_{f-s} range for achieving the highest average ER is between 0.05 and 0.1, with an ER of 514.4%. Within this range, FRP reinforcement significantly improves the inelastic stiffness of the beams, enhancing their structural response and energy dissipation capabilities. These findings highlight the efficacy of FRP strengthening as a retrofitting or design strategy for increasing the robustness and resilience of RC structures.

However, exceeding a ρ_{f-s} of 0.1 results in diminishing returns, with ER decreasing to 293.1% for $\rho_{f-s} = 0.1$ to 0.15 and 296.9% for ρ_{f-s} of 0.15 to 0.2. These diminishing returns suggest that higher reinforcement ratios may not yield substantial benefits in terms of inelastic stiffness enhancement. Structural engineers and designers should be mindful of this threshold to avoid over-reinforcing the beams beyond the point of optimal performance. Striking a balance between reinforcement levels and desired outcomes is crucial to achieve efficient energy dissipation and structural response.

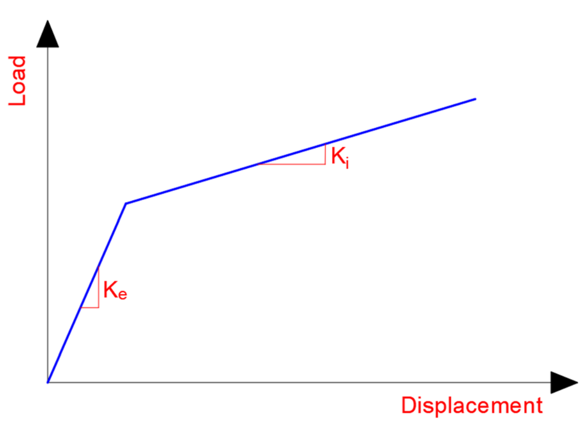

Fig. 12 Elastic stiffness (K_e) vs. inelastic stiffness (K_i)

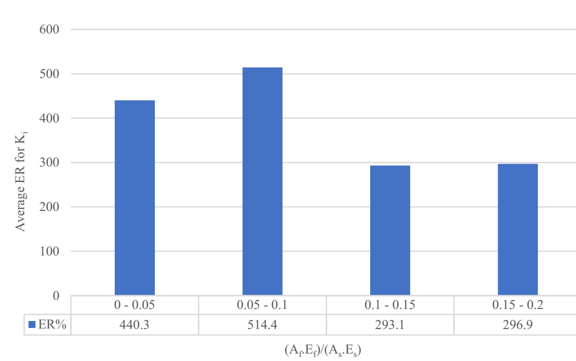

Fig. 14 Effect of ρ_{f-s} on inelastic stiffness enhancement in RC beams strengthened with FRP

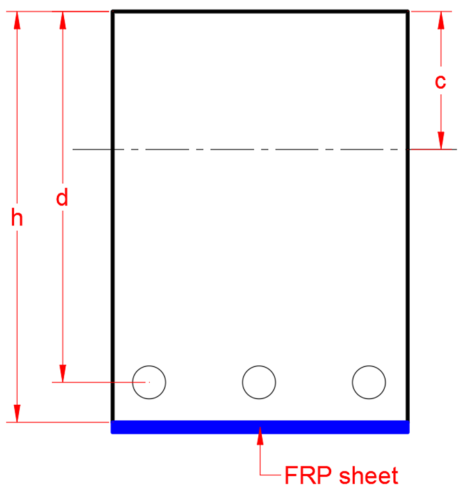

Fig. 15 FRP strengthened beam with annotations

5.6 Neutral Axis and Section Classification

The utilization of FRP sheets as a means of reinforcing flexural members, particularly RC beams, has gained considerable attention due to its potential to enhance structural performance. In the context of strengthening RC beams, one significant effect observed is the increase in the neutral depth to effective depth (c/d) ratio depicted in Fig. 15. This ratio is a crucial parameter in assessing the structural efficiency and load-carrying capacity of beams. Figure 16 provides valuable insights into the relationship between the c/d ratio and ρ_{f-s}, as depicted by the enhancement ratio (ER) for the c/d ratio. The data presented in the figure reveals a clear linear trend between the ER and ρ_{f-s}. As ρ_{f-s} value increases, signifying a higher proportion of FRP sheets applied to the beam's flexural region, there is a corresponding increase in the c/d ratio. The findings demonstrate that the incorporation of FRP sheets in flexural strengthening measures contributes to a notable improvement in the c/d ratio.

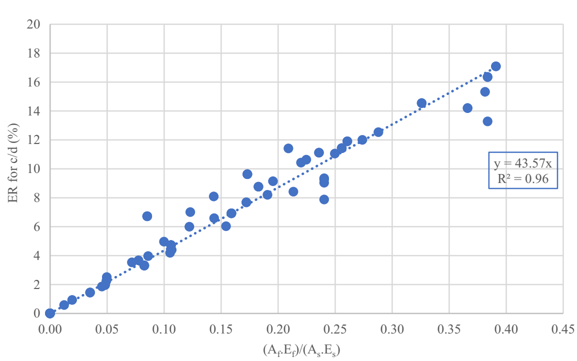

Fig. 16 Relationship between the ER of c/d and ρ_{f-s} in flexural strengthening of RC beams

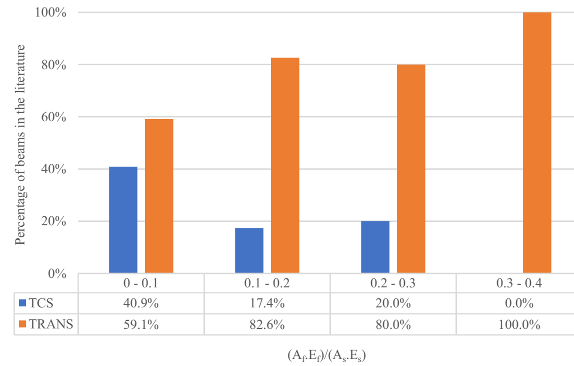

Fig. 17 Distribution of section classifications based on ρ_{f-s}

Specifically, a substantial enhancement of 17% in the c/d ratio was achieved when ρ_{f-s} value reached 0.4. The relationship between the two variables can be described by the equation:

$$Y = 43.57X \tag{11}$$

where Y represents the ER for c/d, while X denotes ρ_{f-s}. The coefficient of determination (R^2) for this equation is 0.98, indicating a satisfactory level of accuracy. It can be concluded that high values of ρ_{f-s} could lead to change the classification of section from tension-controlled section (TCS), which is corresponding to c/d less than or equal to 3/8, to compression control section (CCS), which is corresponding to c/d greater than or equal to 3/5, or to transition section (TRANS), which lies between TCS and CCS. Figure 17 presents a comprehensive overview of the type of sections observed in various studies reviewed, categorized based on ρ_{f-s} values. The percentages represent the distribution of TCS and TRANS among all the beams examined in the review article.

For ρ_{f-s} range of 0 to 0.1, TCS sections accounted for 40.91% of the total, while TRANS sections constituted the remaining 59.09%. This indicates that a significant majority of the beams fell into the TRANS category in this range, which indicates a reduction in ductility. Moving to ρ_{f-s} range of 0.1–0.2, the distribution shifted noticeably. TCS sections accounted for 17.39% of the beams, while TRANS sections saw a significant increase to 82.61%. This shift indicates a transition towards a higher proportion of TRANS sections as ρ_{f-s} value increases. In ρ_{f-s} range of 0.2–0.3, the distribution remained similar to the previous range, albeit with a slight variation. TCS sections constituted 20.00% of the beams, while TRANS sections accounted for 80.00%. Interestingly, for ρ_{f-s} range of 0.3–0.4, a unique observation emerges. All the beams reviewed in this range were classified as TRANS sections, resulting in a distribution of 0.00% for TCS sections and 100.00% for

TRANS sections. This suggests that in cases, where the FRP ratio reaches higher values within this range, the entire section is predominantly treated as a transition section. This again proves the negative effect of FRP strengthening on beams' ductility as demonstrated previously in Sect. 5.4. This shows that designers should choose carefully the ratio of FRP reinforcement, such that the beam stays as TCS.

5.7 FRP Ultimate Strain

Figure 18 provides an in-depth discussion on the ultimate strain in FRP sheets, shedding light on the comparison between experimental and theoretical values. The analysis of the ratio between $\varepsilon_{fu\text{-}Exp}$ and $\varepsilon_{fu\text{-}Theo}$ offers valuable insights into the discrepancies and variations observed in the data.

Among the specimens, B1, B4, B5, and B12 stand out with ratios exceeding 1, indicating that the ultimate strain measured in the experimental work surpasses the predicted theoretical values. This suggests that the FRP sheets in these cases exhibited higher ductility and capacity to withstand greater strains before failure than initially anticipated. These findings highlight the importance of considering real-world conditions and material behavior in designing and predicting the performance of FRP sheets.

Conversely, specimens such as B2, B3, B6, B7, B10, and B11 display ratios below 1, suggesting that the ultimate strain observed in the experiments fell short of the theoretical expectations. This could be attributed to various factors such as material variations, testing conditions, or limitations of the theoretical models used for prediction. Further investigation into these cases could help identify the reasons behind the disparities and refine the theoretical models accordingly.

Regarding the failure modes observed in the specimens, the majority exhibited rapture (R) as the primary mode of failure, which aligns with the expected behavior of FRP sheets under high strain conditions. However, it is worth noting that specimens B7, B16, B17, B18, and B19 displayed FRP delamination (D) as the failure mode. This delamination phenomenon refers to the detachment or separation of layers within the FRP sheets, which can significantly impact their overall performance and structural integrity.

Figure 19 provides further insights into the average ratios of ultimate strains for specimens that failed in rapture and FRP delamination modes. The data reveals that, on average, the ultimate strain ratio for specimens failing in rapture mode is 85.71%, indicating that the experimental ultimate strain corresponds to approximately 85.71% of the theoretical prediction. In contrast, for specimens experiencing FRP delamination, the average ultimate strain ratio is 71.81%, implying that the experimental ultimate strain amounts to approximately 71.81% of the theoretical expectation. These ratios underscore the importance of understanding and accounting for the distinct failure modes when analyzing FRP sheet behavior and designing structures.

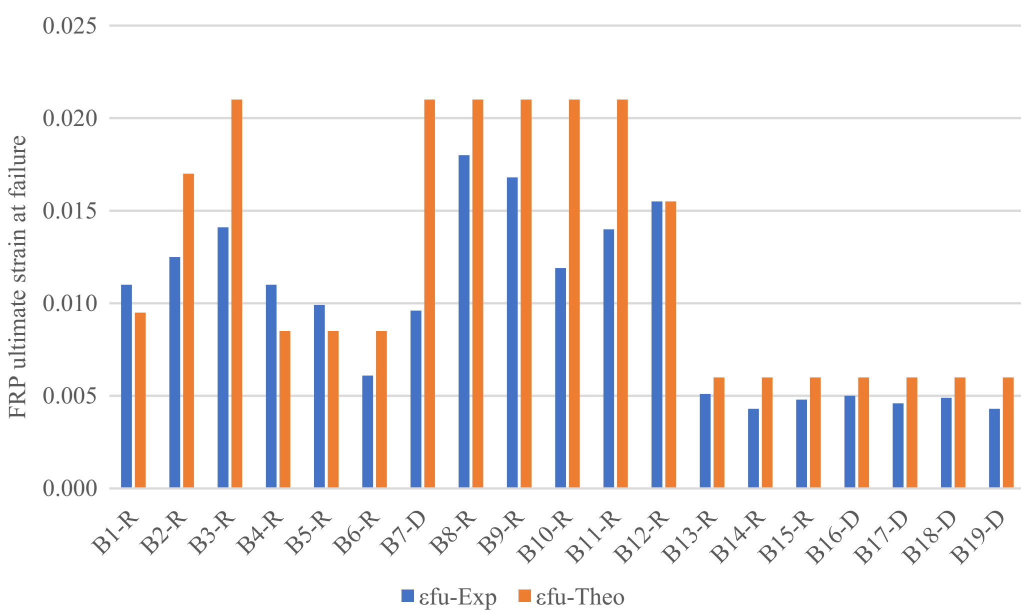

Fig. 18 Comparison of ultimate strain in FRP sheets—experimental vs. theoretical values and failure modes

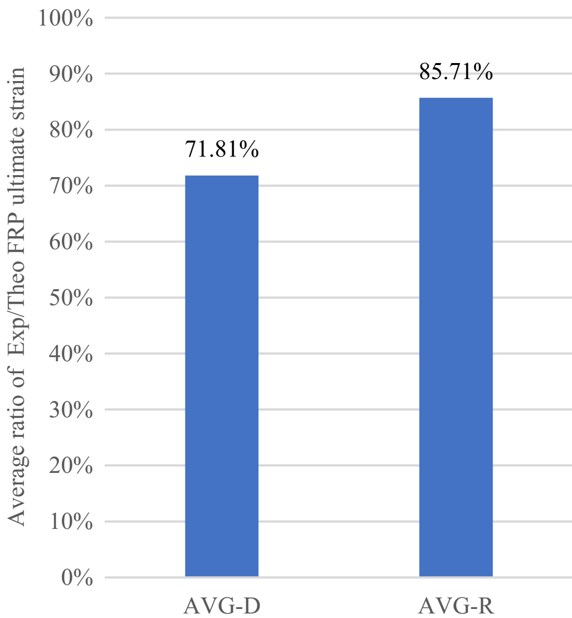

Fig. 19 Average ratio of experimental and theoretical ultimate strains for rapture and FRP delamination failure modes in FRP sheets

6 Finite-Element Modeling (FEM) of FRP-Strengthened Beams

FE modeling of RC beams reinforced with FRP materials in flexure has received a lot of attention (Hawileh et al., 2019; Heydari et al., 2023; Kara & Ashour, 2012; Sudipta Sasmal et al., 2012). In their 2005 study, Lu et al. established a meso-scale finite-element model using MSC. MARC software to mirror the debonding behavior of FRP-to-concrete bonded joints. In this model, compressed and fractured concrete are treated as elastic–plastic and smeared crack materials, respectively. The model uses extremely small elements (0.25–0.5 mm) to simulate the creation and expansion of fractures in the concrete layer near the adhesive layer. It also factors in the impact of element size while imitating the tensile and shear behavior of cracked concrete. The reliability of this model was validated through a comparison of predicted outcomes with selected experimental results, showcasing its ability to predict key parameters such as ultimate load, effective adhesion length, and strain distributions in the FRP sheet at different load levels. Furthermore, the model accurately predicted failure modes and suggested that the debonding phenomenon in the studied connections stems from the creation and eventual failure of slanted meso-scale cantilever columns in the concrete. The study also provided a methodology for estimating the local bond-slip curve at the FRP and concrete interface using data from the finite-element research.

Barbato (2009) proposed FRP–FB-beam, a simple and efficient two-dimensional frame FE approach for precisely modeling the response of RC beams strengthened with externally bonded FRP strips and/or plates. The FRP–FB-beam incorporates distributed plasticity, takes into account diverse failure modes, and can represent multiple anchoring systems. The FE approach correctly predicted the ultimate load-carrying capacity of beams under bending stress, and the results agreed well with the actual data. It provided mesh refinement simplicity and efficiency, automatically compensated for axial and bending behavior, and supported nonlinear material constitutive models. This FE method is suitable for analyzing RC frame structures strengthened with FRP and enables efficient parametric studies.

Zhang and Teng (2014) developed a unique two-dimensional, nonlinear finite-element approach for estimating end cover separation failures in flexure-strengthened RC beams reinforced with externally bonded or NSM FRP reinforcements. The novel FE technique accounted for a wide range of critical parameters, allowing for precise forecasting. These included an accurate representation of cracked concrete's tensile and shear behavior, meticulous modeling of the bond–slip interaction between steel rebars and concrete, careful treatment of the bond–slip interactions between FRP and concrete in both shear and normal directions, and a special emphasis on the critical debonding plane at the steel tension bar level. The numerical results derived from this unique FE methodology, for the first time, elucidate that radial stresses significantly influence cover separation failure and, thus, must be factored in for accurate predictions.

To explore the flexural behavior of originally damaged RC beams repaired using FRP plates, Zidani et al. (2015) created a finite-element model. To mimic the interface behavior, the numerical model took into account material nonlinearity and included a traction–separation rule. The model's validation against experimental data revealed good agreement. The results show that nonlinear finite-element analysis combined with a suitable constitutive model successfully predicts the behavior of restored beams. Including the FRP–concrete contact in the model increases load capacity and failure mechanisms dramatically. The research also shows that rebuilding originally damaged beams successfully recovers strength while improving load capacity and stiffness. Plate separation failure is more likely in severely damaged beams with pre-existing fractures and yielding steel, especially when thick FRP plates are employed for repair. Overall, this study highlights the significance of nonlinear finite-element analysis and the impact of the FRP–concrete interface in the restoration of damaged reinforced concrete beams using FRP plates.

Gotame et al. (2022) investigated corrosion-damaged RC beams strengthened with externally bonded FRP composites using finite-element analysis. According to the study, non-linear finite-element analysis effectively predicted structural behavior and was especially useful in examining the effects of different FRP components. Pitting corrosion had a significant impact on load and deformation capacity, whereas average corrosion had a little impact on load capacity but had no effect on deformation capacity. Accurate corrosion pit modeling was critical for forecasting deformation capacity and failure mechanism. The corroded beams' ultimate load capacity and stiffness were dramatically enhanced after strengthening, successfully inhibiting crack opening. In the scenarios assessed, the integration of intermediate vertical U-jackets failed to enhance the flexural performance. The interfacial characteristics between FRP and concrete, as well as within FRP components themselves, were pivotal in facilitating precise predictions of load-bearing capacity and failure mechanisms. It should be noted that the impact of these interface properties was not consistent and varied in accordance with the specific type of FRP utilized.

Li et al. (2022) developed a Back-Propagation Neural Network (BPNN) model to reliably forecast the initiation of IC debonding in RC beams augmented with FRP. The model, trained and validated using a data set consisting of 101 beams, took into account eight critical parameters, such as the concrete's strength, the tensile reinforcement ratio, and the stiffness of the FRP. The BPNN model output represented the FRP strain at the inception of debonding, thereby indicating the maximum debonding strain of FRP reinforcements. A subsequent design model was formulated using a parametric study and the Levenberg–Marquardt algorithm for nonlinear fitting to preempt IC debonding failure. Both models demonstrated a high degree of precision in predicting IC debonding in FRP-strengthened RC beams.

7 Conclusion

This review offers a thorough examination of the role of CFRP in enhancing the flexural capacity of RC beams. Beginning with an introduction, it dives into the history, applications, properties, and research trends in FRP composites. It further outlines the FRP matrix, unraveling its complexities and exploring its composition. The article then classifies the various methods of flexural strengthening using FRP and subsequently evaluates the performance of FRP strengthened beams, providing detailed flexural analysis. Finally, it emphasizes the potential of FE Modeling to predict the behavior of FRP strengthened beams, detailing the accuracy, challenges, and advancements in this computational tool. Altogether, this review encapsulates the entire spectrum of CFRP's application in flexural strengthening, from its theoretical aspects to its practical implications. The following conclusions can be drawn as follows:

1- Fiber-reinforced composites have widespread use across various industries, with major utilization in the automobile sector (31%), followed by construction (26%), maritime (12%), electronics (10%), appliances (8%), consumer products (8%), miscellaneous applications (4%), and the aircraft sector (1%).
2- Recent years have seen a growing interest in FRP flexural beam strengthening research, as evidenced by a continuous rise in related publications since 2001, peaking between 2012 and 2013, with notable activity between 2018 and 2019, likely driven by increasing awareness of the benefits of using FRP composites in concrete structure strengthening and the need to address challenges in this field.
3- The journals Composite Structures and Construction and Building Materials are leading outlets for research on the structural behavior of FRP-enhanced beams, each contributing 15.2% of papers since 2001, followed by Engineering Structures at 12.1%, while other key journals like Cement & Concrete Composites, Structures, Composites: Part B, and Journal of Composites For Construction, contribute between 4.5% and 6.1%, with a substantial 34.8% of articles published in various other journals.
4- The study concludes that the use of FRP in strengthening RC beams can significantly enhance the actual load capacity beyond ACI code predictions, suggesting the need for code refinement and indicating the potential for strategic manipulation of FRP reinforcement levels to optimize structural performance.
5- The study concludes that flexural CFRP strengthened beams are prone to FRP laminate delamination and debonding, which result in lower load ductility and reduced structural durability, highlighting the importance of design strategies and materials optimization to mitigate these failure modes and improve the overall longevity of the beams.
6- The comprehensive study on the impacts of flexural FRP strengthening on the ductility of RC beams has led to significant findings. It is clear that an increase in FRP reinforcement correspondingly leads to a decrease in both displacement and energy ductility. For displacement ductility, a reinforcement ratio of 0.35 results in approximately a 75% decrease in ductility, with a 0.84 decrease for every 1% increase in strength. In terms of energy ductility, an 88% reduction is observed for a reinforcement ratio of 0.35, with a 0.91 decrease for each 1% increase in strength. While these correlations offer reliable predictive tools

for researchers and practitioners, they also emphasize the need for further refinement through future data incorporation. This study, therefore, underscores the critical importance of a carefully optimized reinforcement strategy to maintain a balance between increased load capacity and structural ductility. As the use of FRP in RC beam reinforcement continues to rise, this equilibrium between enhancement and preservation will be paramount in ensuring structural resilience.

7- The study concludes that flexural FRP strengthening can significantly enhance beam stiffness, both elastic and inelastic, with higher FRP to steel reinforcement ratios leading to increased load capacities and reduced deformations, but there is an optimal range for inelastic stiffness enhancement (ρ_{f-s} of 0.05–0.1), beyond which over-reinforcement provides diminishing returns, highlighting the importance of balanced reinforcement strategies to maximize improvements in stiffness while maintaining structural resilience and integrity.

8- The investigation into the use of FRP sheets in reinforcing RC beams illustrates a linear increase in the neutral depth to effective depth ratio (c/d) with a rising proportion of FRP reinforcement, highlighting the shift in section classification from tension-controlled to transition with increasing FRP reinforcement, which indicates a reduction in ductility and necessitates careful selection of the FRP reinforcement ratio to maintain beams within the desired tension-controlled classification.

9- The observed discrepancies between theoretical predictions and experimental ultimate strain measurements in FRP sheets, and their variance based on failure modes—rapture or delamination—underline the necessity for refining theoretical models to accurately predict real-world conditions while also emphasizing the critical role of understanding different failure modes in determining the performance and structural integrity of FRP-reinforced structures.

10- The research showcases the efficacy and adaptability of finite-element modeling techniques, including two-dimensional frame finite-element approaches, non-linear analysis, back-propagation neural network models, meso-scale models, and unique non-linear methods, in accurately predicting the structural behavior, load-carrying capacity, and failure modes of RC beams reinforced with FRP materials while also emphasizing the critical role of considering factors such as material nonlinearity, interface behavior, and specific failure mechanisms in enhancing the reliability and accuracy of these predictive models.

Based on the conclusions of the discussion, future research and practicing engineers should focus on refining design codes and guidelines to optimize FRP reinforcement levels, enhancing the load capacity of reinforced concrete beams. In addition, there is a critical need to develop strategies to mitigate FRP laminate delamination and debonding, improving the longevity and resilience of FRP-strengthened beams. Furthermore, efforts should be directed towards enhancing predictive modeling techniques by considering material nonlinearity, interface behavior, and failure mechanisms, enabling accurate predictions of structural behavior and informed decision-making in FRP-reinforced structure design and analysis.

Furthermore, an essential avenue for future research involves a comprehensive assessment of the long-term behavior of FRP-strengthened RC beams. Understanding how the mechanical properties of FRP materials evolve over time, and how this impacts the structural performance of reinforced concrete beams, is of utmost importance. This research should encompass durability studies, environmental effects, and aging of the FRP-reinforced components. It should investigate how factors such as exposure to varying temperatures, moisture, and aggressive chemicals affect the integrity of the FRP composites and their bond with the concrete substrate over extended periods. Such a study would not only aid in ensuring the long-term reliability of FRP-strengthened structures but also in developing maintenance and retrofitting strategies for aging infrastructure. This holistic perspective on the long-term performance of FRP-strengthened RC beams is vital for advancing the field of structural engineering and construction practices, especially in the context of sustainable and resilient infrastructure.

Abbreviations

ACI	American Concrete Institute
AFRP	Aramid fiber-reinforced polymer
Af	Cross-sectional area of the FRP sheets
ALWC	All lightweight concrete
BFRP	Basalt fiber-reinforced polymer
BPNN	Back-propagation neural network
b	Beam width
c/d	The ratio of neutral depth to effective depth
CCS	Compression control section
CFRP	Carbon fiber-reinforced polymer
D	FRP delamination
df	Effective depth of the FRP sheets
EB	External bonding
E-GFRP	E-glass fiber-reinforced polymer
EL	Ensemble learning
ER	Enhancement ratio
Eu	Energy dissipated at the point of failure
Ey	Energy dissipated at the yield level
FE	Finite element
FRP	Fiber-reinforced polymer
FRP–FB-beam	Two-dimensional frame FE method
GFRP	Glass fiber-reinforced polymer

HSC	High-strength-reinforced concrete
IC	Intermediate crack
LWC	Lightweight concrete
LSC	Low-strength concrete
ML	Machine learning
NSM	Near-surface mounting
NWC	Normal weight concrete
RC	Reinforced concrete
SFLWC	Self-compacting lightweight concrete
TCS	Tension-controlled section
TRANS	Transition section
PP-ECC	Polypropylene-engineered cementitious composite
Pu	Ultimate load at failure
Py	Yielding load
Pu(ACI)	Predicted ultimate load based on the ACI code
Pu(EXP)	Experimental ultimate loads
R	Rapture
δu	Displacement recorded at the point of failure
δy	Displacement observed at the yield level
λd	Displacement ductility
λe	Energy ductility
ρf-s	Ratio of effective FRP reinforcement to effective steel reinforcement

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Availability of Data and Materials
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Declarations

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The authors are not misrepresenting research results and are maintaining the integrity of this research and its presentation. This manuscript is only submitted to this journal. The submitted work is original and have not been published elsewhere in any form or language.

Consent for Publication
The authors are actively seeking the publication of their work to increase the body of knowledge.

Competing Interests
The submitted paper by the authors whose names appear on the paper, certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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