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Flexural behaviour of hybrid (FRP/steel) reinforced concrete beams: a review

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Abstract

Corrosion on steel reinforcement has a substantial effect on the total lifespan of concrete buildings over time. As a result, researchers are looking at different methods to combat this issue. As a consequence of their remarkable mechanical qualities and resistance to corrosion, fibre-reinforced polymer (FRP) composite bars have gained a large amount of interest from the construction sector. In the construction of reinforced concrete (RC) structures, FRP bars may be used as an alternative to the conventional steel bars. Although the use of steel is effective, corrosion can cause cracking, spalling, and separation of steel bars in RC. Compared to steel-RC beams, FRP-RC beams deflect and shatter more due to their lower modulus of elasticity and a high prevalence of broad cracks than steel-reinforced beams. Also, FRP bars' tensile strength at bent portions is 40-50% lower than that of straight bars. This study aims to evaluate the use of hybrid steel and FRP to reinforce concrete members, avoiding the disadvantages of using one of them as a reinforcement. The results showed that using hybrid reinforcement (steel/FRP bars) in structural components seems to improve building system efficacy by increasing load capacity, ductility, serviceability, and corrosion resistance. This technique can save maintenance costs, extend infrastructure life, and improve sustainability. Also, when the FRP to steel ratio is properly balanced, a desired level of ductility and moment redistribution can be achieved. Additionally, this study suggests conducting more investigations to determine the serviceability and structural properties of combining these materials in the long term.

***Keywords**: Corrosion resistance, ductility, fibre-reinforced polymer, flexural behaviour, hybrid-reinforced concrete beam.*

1. Introduction

Concrete reinforced with steel has proven its long-term effectiveness. However, due to corrosion affecting the steel reinforcement, it can be damaged, especially in harsh environments. As a result, structural damage such as cracking, spalling, and separation of steel reinforcing bars from concrete can occur [1–3]. The imperative for new building materials, characterized by heightened resistance to deterioration, is made evident by the strengthened concrete structures demand a significant budget for maintenance [4].

FRP bars have been proposed as a replacement for steel reinforcement in recent years due to their inherent resistance to corrosion. FRP is a versatile material that can be tailored to withstand a wide range of chemical and temperature environments. When used in the appropriate applications, FRP composites can outlast most alternative materials and require minimal maintenance. FRP's low weight-to-strength ratio can also significantly reduce reinforcement installation costs. In addition to its other desirable properties, such as being non-magnetic, FRP has a high tensile strength [5].

The brittleness of FRP-reinforced concrete (FRP-RC) structures is a consequence of the linear elastic behaviour of FRP under tensile stress, even though FRP materials possess various appealing properties. As a result, it is required by law that beams with FRP-RC fail from the concrete crushing rather than the FRP bars' rupture. Heightened the ratio of reinforcement will elevate the expenditure on both the reinforcement of FRP and the entire building. Furthermore, owing to the diminished FRP bars elasticity modulus, FRP-RC beams deflect more and break wider than steel-RC beams [6]. Despite the potential time and cost savings associated with FRP-RC constructions, the elevated FRP materials primary cost remains a barrier to wider implementation [7, 8].

Recently, there has been a significant amount of studies undertaken on reinforced concrete components that utilize FRP bars [3, 9–27]. Analyzing beams that employed bars with FRP, Adam et al. [13] studied the influence of changing compressive strength of concrete and reinforcement ratio. Through the manipulation of the ratio of reinforcement, researchers successfully mitigated the fracture width and deflection. On the other side, worth noting that FRP bars possess several advantageous characteristics, including a notable strength of tensile, a relatively low elasticity modulus, and a linear deformation response. Additionally, these characteristics contribute to the occurrence of friable failure, the creation of broader fractures, and an increased deflection. As a consequence, these issues have impeded the extensive adoption of FRP structures within the field of civil engineering [28–30].

Hybrid structures that use both FRP and steel reinforcement in concrete offer more benefits than structures use conventional reinforcement or FRP. This integration effectively addresses the durability concerns associated with traditional RC structures and mitigates the brittle failure modes typically observed in FRP-RC structures. The initial introduction of a hybrid FRP/steel reinforcing system occurred in 1995 by Arya et al. [31]. Within this particular system, the placement of steel reinforcement occurs at an internal level, while the positioning of FRP bars takes place at an external level. Hybrid-reinforced beams exhibit better ductility than FRP-RC and surpass steel-reinforced beams in terms of strength and corrosion resistance [32, 33]. Several research on concrete members strengthened by hybrid FRP/steel reinforcement were done [34–39]. These investigations have shown that mixing steel and FRP bars improves RC beams' flexural behaviour.

A contribution to the field of FRP research can be made by this review, which establishes hybrid FRP/steel reinforcement as a viable and effective design solution for concrete beams. It offers a review of the current state of the knowledge and identifies key research gaps, making it a useful resource for researchers and practitioners interested in concrete beams with an FRP/steel strengthening.

2. Engineering properties of FRP

FRP, also recognized as resin, is a composite material comprising fibres incorporated within a polymer matrix. The fibres are held in place by the matrix, which serves the dual purpose of transmitting loads and protecting the fibres from environmental damage. The fibres are the primary determinants of the ultimate strength and elastic modulus of a composite material, as they have significantly greater strength than the matrix. Common fibre types include basalt (BFRP), carbon (CFRP), glass (GFRP), and aramid (AFRP) [40, 41].

FRP has been extensively investigated as a potential substitute for steel reinforcing since its introduction to the construction industry 1960s [42]. FRP is used in the construction sector because it is lightweight, has high tensile strength, is corrosion-resistant and non-magnetic. However, FRP bars exhibit certain shortcomings, including diminished strength of bond, fragile failure, and reduced elasticity modulus [42]. In contrast to bars made of steel, FRP bars display linear elastic stress-strain behaviour in tension (see Figure 1). To improve bond strength, FRP bars are frequently surface-treated with ribs, sand coating, helical wrapping, or braiding. FRP bars created from thermosetting polymers cannot be bent after production, however FRP bars made from thermoplastic resins may be reshaped by applying heat, making them more versatile for varied design schemes [43]. However, the FRP bars' tensile strength at bent portions is 40-50% lower than that of straight bars [43]. Table 1 summarizes the FRP bars' mechanical parameters expected from manufacturers [43, 44]. Where, (E) Elastic modulus, (f_u) Tensile strength, (f_y) Yield strength of steel bar, (ε_u) Rupture strain, and (ε_y) Yield strain.

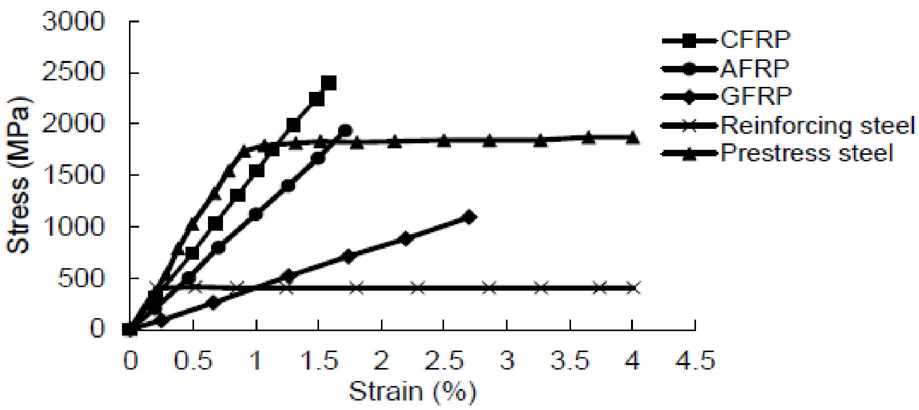

Fig. 1: Steel and FRP bar stress-strain correlations [45].

Table 1: ACI 440.1R (2006) and CAN/CSA S806-12 (2012) standards describe the typical tensile parameters of reinforcing bars composed of various materials [43, 44].

Type	E(Gpa)	f_u (Gpa)	f_y (Gpa)	ε_u(%)	ε_y(%)
GFRP	35.0 – 51.0	0.483 – 0.69	….	1.2 – 3.1	….
AFRP	41.0 – 125.0	1.72 – 2.54	….	1.9 – 4.4	….
CFRP	120.0 580.0	0.6 – 3.69	….	0.5 – 1.7	….
BFRP	30.0 – 80.0	0.8 – 1.68	….	2.6 – 3.1	….
Steel	200	0.483 – 1.6	0.260 – 0.517	6.0 – 12.0	0.14 – 0.25

3. Flexural behaviour of reinforced concrete beams with FRP (FRP-RC)

Several studies have looked at the flexural performance of FRP-RC constructions extensively, as documented in numerous articles [6, 20, 21, 46]. Multiple factors, including strength of concrete compressive, ratio of FRP reinforcement, and kind of FRP, were included in the analyses. Bending characteristics of FRP-RC beams vary significantly from those of steel-reinforced beams. FRP-RC bars are brittle and rapidly fail owing to the linear behaviour of FRP bars. FRP-reinforced beams encountered failure by means of two distinct processes. Cracking concrete and rupturing FRP have both been cited as causes of failure. Alternatively, the act of concrete crushing is preferred because of its ability to function as a proactive mechanism for identifying potential problems [47].

Numerous empirical investigations were undertaken to inspect flexural performance of RC beams strengthened by FRP or steel. These studies have added to the corpus of information on the subject [6, 20, 21, 46]. Their findings showed that when subjected to low loads, GFRP-RC beams display crack width spacing and patterns that closely mimic those observed in steel RC beams. Nonetheless, when subjected to increasing pressures, steel beams showed a lower prevalence of broad cracks than GFRP-reinforced beams [20]. Sam and Swamy's study [46] found that, for a given load, FRP-RC beams manifest a deflection magnitude that exceeds steel-RC beams by a factor of three. Furthermore, the research findings indicate that the existing ACI formulas, which are designed for beams constructed of steel-RC, decrease the GFRP-RC beams deflection. Therefore, it is suggested that these formulas be modified in order to evaluate the FRP beams deflection with more accuracy. Many publications on FRP-RC design recommendations have been published in recent years. The Canadian Standards Association (CSA), the Japan Society of Civil Engineers (JSCE), the International Federation of Structural Concrete (CEB-FIB), and the American Concrete Institute (ACI) code developed by Committee 440 [48–51] are just a few examples of organizations that have established concrete codes.

The FRP reinforcement ratio has a significant effect on the flexural performance of FRP-RC beams. As a result, considerable studies have been conducted on this subject. Theriault and Benmokrane [52], found that in standard RC beams, reducing the width and spacing of flexural cracks could be achieved by raising the reinforcement ratio. Adam et al. [13], and Habeeb and Ashour [26] discovered that raising the ratio of reinforcement significantly reduced width of crack and mid-span deflection in continuous beams while simultaneously enhancing their ultimate flexural capacity. To guarantee compression failure, as per ACI 440.1R-06 recommendations, Kassem et al. [53] suggested adopting a ratio of reinforcement greater than 1.4 times the balanced reinforcement ratios. El-Nemr et al. [54] and Theriault and Benmokrane [52] showed that concrete strength also affects the performance of FRP-RC beams. They found a direct correlation between concrete strength and the ultimate strength of beams with FRP-RC, while the FRP-RC beams' stiffness was found to be independent of concrete strength. Using stronger concrete enlarges, FRP-RC concrete beams' breaking moment [54].

4. Hybrid technology

Hybrid technology is the combination of two or more different technologies to create a new system that is more efficient, effective, or sustainable than any of the individual technologies alone. It is considered one of the most promising ways to improve ductility and durability in structural buildings. Ductility is an essential characteristic of structural components. It refers to the material capability to undergo significant deformation with no loss of integrity. This is important in structural buildings because it provides advance warning of a potential collapse, giving occupants time to evacuate [55]. There are three prevailing strategies for hybrid applications, as follow:

4.1. Enhancing the properties of concrete

FRP-RC structures are purposefully designed with an overabundance of reinforcement to ensure failure is ascribed to concrete crushing. This design method suggests that the ductility of FRP-RC structures is determined by the properties of the concrete material [56]. As a result, enhancing tangible properties is a potential technique for improving the ductility of FRP-RC buildings. Several researchers [56–58] have studied the effects of adding steel fibres into concrete. According to their research, incorporating hooked steel fibres into FRP-RC beams improves their ductility to that of steel beams [57]. Furthermore, when compared to FRP-RC beams without reinforcement, the introduction of fibre reinforcement results in a considerable improvement in ductility, exceeding a 30% increase [56].

Improved ductility and strength properties might be obtained by using a composite made up of different kinds of fibres of varied lengths. The process of mixing fibres with unique chemical or mechanical properties is known as hybridization. Numerous studies [59–65] have demonstrated the use of this strategy. In general, hybrid fibre reinforcement has proven superior physical and mechanical properties when compared to other types of reinforcement. High-modulus fibres, which are often used in the manufacturing of strong concrete, increase the material's strength. Low-modulus fibres, which are often used to provide flexible reinforcement, contribute to greater structural ductility.

4.2. Hybrid FRP bars

To imitate steel's bilinear stress-strain conduct, an alternative technique for enhancing the suppleness of FRP-RC constructions is to employ a composite composed of various fibre types. More of scholarly studies [66–69] have been done to explore the characteristics and performance of these bars. Harris et al. [66] investigated hybrid FRP reinforcing bars formed of Aramid braiding around a core of carbon fibres in their investigation. The hybrid bars performed well during deformation testing and demonstrated better initial resistance to distortion. Furthermore, when compared to steel-RC beams, the tested beams had little to no variation in ductility indices, curvature, or deformations. Cheung and Tsang [68] undertook a series of experiments to explore the mechanical traits and flexural conduct of hybrid reinforcement. They increased corrosion resistance by employing a layered construction, with an Aramid fibre layer sandwiched between the outer carbon fibres and the randomly distributed glass and steel fibres in the core cross-section. Hybrid bars increased ductility of the beam to that of steel-reinforced beams.

Investigation was performed to assess the effectiveness of hybrid FRP/steel bars when used as longitudinal reinforcement (see Figure 2). Where, the hybrid bars were fabricated through the process of encasing a steel core mild, measuring 6 mm in diameter, with GFRP strands, which have a diameter of 2 mm, the hybrid materials exhibited a minor improvement in tensile performance compared to steel bars [67]. However, it is worth noting that the hybrids possessed only half the modulus of elasticity when compared to steel bars. In order to ascertain the optimal hybrid polymer bar, a series of experiments were conducted by Behnam and Eamon [69] wherein five distinct versions were investigated. The researchers conducted an assessment on the rigidity and malleability of the bars and determined that steel-reinforced sections including hybrid fibre bars as flexural elements exhibited satisfactory levels of both strength and ductility [69].

The utilisation of a hybrid bar as a reinforcing element has demonstrated favourable outcomes, as documented in the existing body of scholarly literature. Nevertheless, the implementation of this form of reinforcement necessitates specialised production methods, a factor that is sometimes seen as unfeasible and expensive.

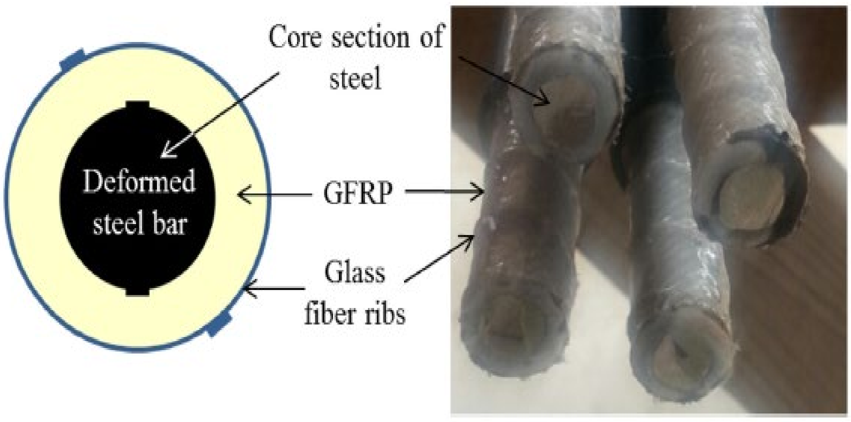

Fig. 2 : GFRP and deformed steel hybrid bar geometry [70] .

4.3. Hybrid reinforcement made of FRP/steel

To Using a hybrid reinforcing system that combines steel and FRP is one approach to overcoming the issue of the FRP-RC beams' low ductility. This method has shown positive results in addressing the issue at hand. According to Aiello and Ombres [71] the ultimate load capacity of these beams is increased when FRP is used. FRP and steel reinforcement are a powerful combination for minimising crack propagation and minimising crack spacing. Leung et al. [72] theoretical findings were proven by constructing mathematical formulas for the balanced reinforcement ratios related with various flexural failure types. Flexural behaviour of hybrid reinforced FRP/steel concrete (HRC) beams manufactured via numerous types of fibres has been studied previously [32, 33, 36–38, 73–78].

Qu et al. [32] discovered that the structural performance of GFRP-RC beams experienced significant improvement with the incorporation of adequate steel reinforcement. Their proposal was based on an effective reinforcement ratio they developed for analytically predicting probable styles of flexural impairment for GFRP-steel hybridized beams made from RC. In addition, they developed a computational model for estimating HRC-beams' flexural strength, with a focus on the expected flexural failure mode of steel yielding followed by concrete crushing. Four different types of beams were studied by Lau and Pam [36] beams with HRC, GFRP-RC beams, beams with steel-RC, and plain concrete beams. Each beam was constructed to fit simple support requirements, and they were all set up in a grid at the same height. They found that the HRC system improved the structural performance of FRP-RC beams more significantly in over-reinforced specimens than in under-reinforced specimens.

Yoon et al. [37] investigated the strength of flexure and steel deflection, GFRP and CFRP-reinforced high-strength concrete beams. There were experimental and analytical methods utilized. Their findings that the issues crack propagation, high deflection, reduced stiffness after cracking, and low ductility in beams with FRP-RC could be effectively addressed by the use of hybrid-reinforcing systems. Yinghao and Yong [38] specifically examined beams with high-strength concrete. These beams were strengthened via an incorporating of GFRP and steel. The objective was to investigate the influence of rebar layer orientation and support design on flexural strength, deflection, and fracture behaviour. The beams in question were made of high-strength concrete and strengthened with a GFRP/steel hybrid.

Ge et al. [33] observed that ductility of hybrid beams made of BFRP and steel reinforcement composites depended critically on the ratio of BFRP to steel reinforcement. They also derived analytical equations for the flexural failure mechanism and occurrence criteria of hybrid RC beams. The structural performance of HRC-beams and their prospective applications were evaluated experimentally by El Refai et al. [74]. They examined nine rectangular beams, six of which were hybrid beams strengthened by equal amounts of GFRP and steel bars. The strengthening of the remaining three beams was solely dependent on GFRP bars. The flexure tests revealed that beams composed only of GFRP bars had poor performance, which improved significantly with the addition of steel reinforcement. The enhancements significantly increased the material's resistance to cracking, its ability to handle heavy loads, and its capacity to bend without breaking.

Qin et al. [75] observed that altering the reinforcement ratio has a substantial effect on the bending behaviour of HRC beams. After creating a three-dimensional finite element model (FEM), six reinforced concrete beams underwent a series of tests to verify the accuracy of the findings. FEM was used to analyze the structural behaviour of HRC-beams under two different reinforcement conditions: heavy reinforcement and minimal reinforcement. This facilitated the examination of how the hybrid reinforcement ratio impacted structures. Regarding HRC beam designs, they advocated for a practice known as "over-reinforcement". Furthermore, they proposed a range of 1.1 to 2.5 for the ratio of FRP to steel reinforcement (A_f/A_s) in order to attain the ideal equilibrium between ductility and strength. Araba et al. [76] conducted a comprehensive analysis of both the theoretical and practical elements of GFRP/steel RC beams. An investigation was conducted to examine the advantages and disadvantages of the beams. Study has shown that HRC beams, when the GFRP to steel ratio is properly balanced, may achieve the desired levels of ductility and moment redistribution requirements.

Pang et al. [39] investigated the HRC beams' ductile failure criterion. The limits of the reinforcement ratio and the flexural strength were considered. Additionally, they combined the GFRP mechanical properties with reinforcement of steel to create a new index of ductility. The effect of a variety of different features on ductility was also explored in their study. Also, Maranan et al. [77] conducted flexural four-point testing and evaluation for GPC beams reinforced with HRC. Hybrid GPC beams performed much better than GPC beam reinforcing with GFRP only.

Almahmood et al. [78] inspected the conduct of six strengthened concrete T-beams continuous. One of the beams were strengthened GFRP bars, whereas remaining five beams was strengthened with a combination of GFRP and steel bars. Looked at effects of using ratio of GFRP to steel reinforcing at the midspan and middle support positions. Found that using steel reinforcement in concrete beams reinforced with GFRP boosted beams' flexural stiffness, ductility, and serviceability by crack breadth and deflection control. Nevertheless, the proportion of steel bars to GFRP in hybrid constructions limits the amount of moment redistribution that can be done. Found that hybrid beams reinforced with varied hybrid ratios in key areas showed a redistribution of almost 43% [73].

Based on these findings, it is clear that additional study is required to get a full comprehension of the intricate interaction that exists between variables like FRP/steel ratio of reinforcement, compressive strength, and the particular FRP bars' kind utilized in the context of HRC-beams. In addition, additional research is essential in order to acquire an in-depth comprehension of the HRC-beams' structural performance built with environmentally benign materials such as geopolymer concrete. Notably, geopolymer concrete is a workable replacement for the standard concrete made with Portland cement [79, 80].

Table 2. presents a summary of previous studies on hybrid (steel/FRP) concrete beams, highlighting main findings and variables investigated in the structural members. The findings are organized by year of publication.

5. FRP bar bonding behaviour in concrete

Bond stress is the shear stress that is transferred between the reinforcing bar and the surrounding concrete. It is critical for proper load transfer between the two materials as well as overall structural performance of reinforced concrete constructions. FRP bars are a relatively new form of reinforcing bar that is gaining popularity in construction industry. In comparison to conventional steel bars, FRP bars offer numerous benefits such as high tensile strength, low weight, and corrosion resistance. In contrast to steel bars, FRP bars exhibit lower bond strength, which is one of their weaknesses [81, 82]. The bonding behaviour of FRP bars can vary significantly from that of standard steel due to differences in surface features [83, 84].

In comparison to research on the steel bars' bonding behaviour and research on the FRP bars' bond performance. The bonding of FRP bars is more complex than that of iron bars due to their various surface properties [85]. Their bonding can be improved through the methods described below:

5.1. Improving bond strength using FRP/steel bars

One of the effective aspects of RC structures is increasing the strength of the bonds. Hybrid reinforcements that combine both steel and FRP stand out as an effective method. The hybrid RC elements showed high strength and ductility when subjected to flexural loads. Inelastic deformation of the steel reinforcement in the hybrid components primarily accounts for this phenomenon. The use of hybrid reinforcement, which consists of steel bars and FRP, is generally regarded as a highly promising technique for improving bonding capacities. The potential to enhance the structural integrity, deformability, and bond behaviour of RC beams is indicated by empirical evidence regarding the use of hybrid reinforcement systems [86–88].

Qu et al. [32] conducted tests on six hybrid GFRP/steel RC beams, adjusting reinforcement and proportion. They additionally devised an analytical framework to anticipate specimen flexural behaviour. The experiments showed a strong bond between GFRP/steel bars and concrete. In contrast, El Refai et al. [74] found that the bond coefficient significantly affects design-criteria-based fracture width predictions. Predictive models with steel bars and GFRP were created to design HRC parts. Ge et al. [33] investigated the bending features of HRC-beams strengthened by steel and BFRP bars. They tested five rectangular beams with simple supports. Three of five beams were strengthened using steel and BFRP bars, while the other two were directly reinforced with steel or BFRP. BFRP beams with steel reinforcement had better bonding, ductility, deflection, and fracture spacing. Overall, the studies have shown that hybrid reinforcement systems can improve the strength bond behaviour of RC beams.

Table 2: Summary of previous studies for hybrid (steel/FRP) concrete beams

Authors	Year	Investigated Variables	Type of beam	Type of FRP	Type of Concrete	Results obtained
Aiello and Ombres [71]	2002	Spacing, width, crack, ductility, curvature, and deflection.	HRC-beams	AFRP	OPC	Steel reinforcement can minimize the deformability of FRP-RC beams in service, reducing sagging and deflection. HRC reduced fracture width and spacing.
Leung and Balendran [72]	2003	Concrete strength with H-GFRP/steel bars	HRC-beams	GFRP	OPC	HRC- beams have higher flexural strength and can undergo more deformation before failure than OPC- -beams reinforced with steel. The superiority of GFRP rods in tensile strength over steel bars explains this difference. However, HRC tend to have more cracks than conventional beams because GFRP rods are more brittle.
Qu et al. [32]	2009	Reinforcement GFRP/steel ratio	HRC-beams	GFRP	OPC	Normal effective reinforcement ratio GFRP/steel-reinforced concrete hybrid beams were ductile, serviceable, and load-carrying.
Lau and Pam [36]	2010	Flexural ductility while retaining high strength attribute of the FRP bars	HRC-beams	GFRP	OPC	HRC-beams are more ductile than pure ones. More over-reinforcement in the beam specimen made FRP-RC beams higher suppleness. Thus, steel reinforcement improves FRP-RC member flexural ductility, and over-reinforcement is recommended in design.
Yoon et al. [37]	2011	The consequence of amalgamated reinforcement employing several tiers of steel or FRP flexural reinforcement on ductility, cracking pattern, post-cracking stiffness, and load-carrying capacity	HRC-beams	GFRP-CFRP	OPC	Hybrid reinforcing systems can be used to control the FRP-RC beams' crack propagation, deflection, post-cracking stiffness, and low ductility.
Yinghao and Yong [38]	2013	Flexural strength, load-deflection and crack behaviours	HRC-beams	GFRP	OPC	Results showed that the best combination for ultimate bending moment was GFRP and steel in the similar exterior layer. These findings suggest that depth of steel bar governed the HRC-beam crack width.
Ge et al. [33]	2015	Crack spacing, crack width, and flexural capacity	HRC-beams	BFRP	OPC	HRC-beams have deflections that are between those of ordinary RC beams and BFRP-RC beams for the same load. The deflection of HRC-beams decreases with increasing area ratio(A_f/A_s) Additionally, the stiffness reduction factor of HRC-beams decreases as (A_f/A_s)increases. Similarly, the HRC-beams' mean crack spacing decreases as (A_f/A_s) decreases.
El Refai et al. [74]	2015	HRC-beam structural characteristics and serviceability.	HRC-beams	GFRP	OPC	Found an increase in deformability, load-bearing capacity, and cracking rigidity when steel reinforcement was incorporated into GFRP-reinforced beams
Qin et al. [75]	2017	Reinforcement ratio	HRC-beams	GFRP	OPC	Over-reinforcing HRC-beams. To balance strength and ductility, they recommended an FRP-to-steel (A_f/A_s) reinforcement ratio of 1–2.5.
Araba and Ashour [76]	2018	Reinforcement ratio	Continuous-HRC-beams	GFRP	OPC	In redistribution of moments between critical sections of continuous beams, reinforcement ratio is critical.
Maranan et al. [77]	2019	Different GFRP-to-steel reinforcement ratios and designs	HRC-beams	GFER	GPC	GPC beam reinforced with GFRP/steel bars has 15% greater serviceability, ductility, and strength than a GPC beam reinforced with GFRP-only beams. Increasing the reinforcement ratio enhanced beam performance. Hybrid GPC- beams bend well.
Almahmood et al. [78]	2020	Midspan and mid support sections' GFRP to steel reinforcing ratios	Continuous THRC-beams	GFRP	OPC	Steel reinforcement enhanced GFRP-RC beam flexural stiffness, ductility, and serviceability.
Araba et al. [73]	2023	Top and bottom beam layers' longitudinal steel, GFRP, and hybrid reinforcing ratios	continuous HRC-beams	GFRP	OPC	The hybrid beams displayed outstanding moment redistribution of up to 43% in the critical portions.

5.2. Improving bond strength using other systems

Several studies have been undertaken on the topic of improving the bonding behaviour of FRP bars and concrete. Depending on the surface properties they possess, bond strength of FRP bars can vary significantly when compared to that of conventional steel. Previous research [83, 89–95] found that the stress transmission mechanism between the performance of GFRP bars and conventional concrete is primarily affected via concrete compressive strength, confinement, embedment length, and bar diameter. In fact, concrete and FRP bars' binding strength is influenced by a variety of factors. The diameter of the bar, the concrete cover thickness, the surface condition of the bar (such as whether it is braided, helically wrapped, ribbed, or sand-coated), the length of the bar embedded in the concrete, the mechanical properties of the bar, and the prevalent climatic conditions are all factors to consider [96, 97]. Alves et al. [98] discovered that bond strength of No. 16 sand-coated GFRP bars was 30-50% greater than the bond strength of No. 19 bars. There is a positive association between the diameter of the bar and the bond stress, which implies that bond stress increases as the bar diameter decreases [83, 92, 99, 100].

Research shows that the concrete's bonding strength is enlarged when sand particles are added to surface of smooth GFRP bars [101]. Similar resistance to pulling can be provided by lugs and surface deformations on the bar [102]. Based on the enhanced mechanical interlock and friction forces, Arias et al. confirmed that coarse sand had a higher bond strength than fine sand (see Figure 3). There are trade-offs associated with increasing embedment lengths, such as increased construction costs and reinforcing congestion, despite the fact that these measures can improve bar anchoring in concrete. The bars can be outfitted with normal hooks, although bending the GFRP material on-site is not advised [103]. Compared to a straight bar of the same diameter, the bent GFRP bar's tensile strength is only around 35% to 40% as strong. This weakening is attributed to various factors, including concentrated stress resulting from curvature at the bend and the inherent fragility of fibres running at right angles to their axis [104, 105]. In light of these limitations, it appears that use headed-GFRP bars is the most viable technique for achieving the necessary ductility (see Figure 4) [106]. Currently, the previous studies on the pullout behaviour of headed-GFRP bars in concrete is notably scarce [107–109]. A previous study has shown that anchor heads, composed of thermosetting polymer material and integrated at the straight GFRP bar end, then cured at high temperatures, can substantially raise the bars' pullout load resistance. This hints at the possibility that headed-GFRP bars can successfully replace bent bars in certain circumstances.

Direct pullout tests have gained popularity as a means of assessing bond behaviour of FRP bars in concrete, mostly due to its straightforward methodology, cost-effectiveness, and widespread accessibility [89, 110, 111]. Furthermore, it is possible to reach the free end of the rod during this test, enabling the measurement of slip at the free end and the installation of equipment within the rod [92].

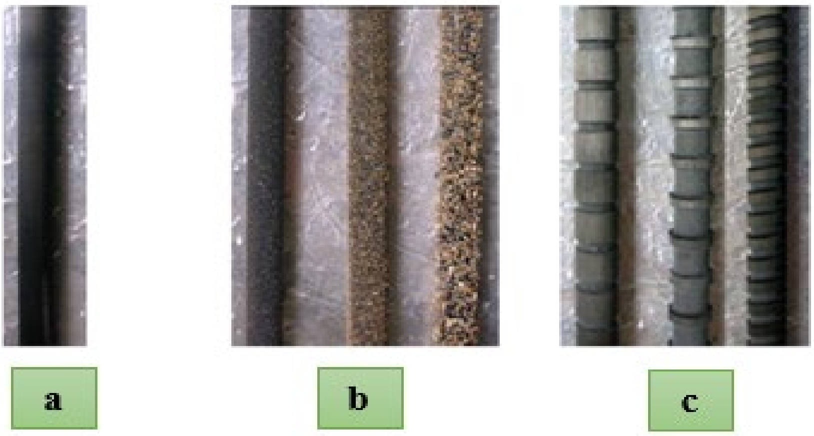

Fig. 3 : Surfaces on FRP bars were either (a) smooth, (b) sand-coated with varying sand granulometry, or (c) machined with varying concrete lug ratio [112].

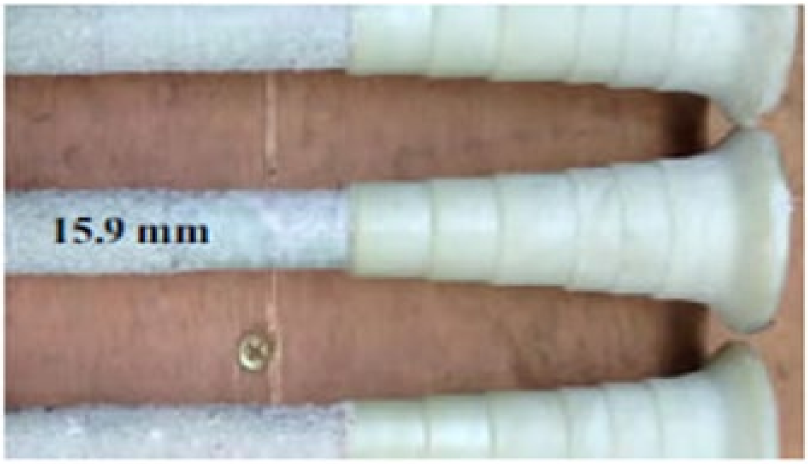

Fig. 4 : Headed-GFRP bars [106].

6. Numerical analysis of hybrid beams made of FRP/steel concrete

Predicting the behaviour of RC structures using analytical models such as the finite element method (FEM) is difficult. This is because RC is composed of two unique materials with differing physical and mechanical properties. Concrete is diverse and difficult to model, but steel/FRP reinforcement is homogeneous and clearly specified. Furthermore, even moderate loads can create nonlinearity in the behaviour of RC structures due to cracking, which becomes more severe as the stresses grow. Bond slip complicates the interaction of concrete and reinforcement. Other elements that influence concrete behaviour include creep and shrinkage. To effectively simulate concrete, reinforcement, and their interactions using FEM, it is critical to carefully select the suitable finite elements. Simulating the structural response of RC-beams has led to the development of numerous FEM. However, models specially designed for predicting the performance of easily bolstered concrete beams reinforced with HRC are yet to be developed [113–116].

Kara et al. [113] used an iterative numerical method to investigate the moment-curvature properties of concrete cross-sections strengthened using an FRP/steel bar hybrid system. The foundations of this method are force compatibility and force balancing. Based on the strain profile, linear interpolation methods are utilised to approximate the strains in concrete, FRP reinforcements and internal steel. One must have knowledge of both the dimensions of the cross-section and the stresses in the materials that comprise it in order to calculate the internal forces acting on it. A full examination requires both the curvature angle and the bending moment. The suggested technique demonstrated good agreement between anticipated and experimental values of HRC-beam curvature and moment capacities

Zhou et al. [114] developed a comprehensive computational model that can be used for the evolution of entire distortions in HRC-beams. Including the softening behaviour of compressive concrete and tension stiffening effect of the tensile zone, the model proves applicable to beams with typical flexural failure mechanisms. Bencardino et al. [115] conducted their computational analyses of HRC-beams using a reliable and simple two-dimensional FEM. Simulating the material's behaviour after a fracture formed was employed to explore the tension stiffening effect of tensile concrete. The study's objective was to formulate an accurate model to analyse the load-bearing capacity and deformation progression of concrete beams reinforced with AFRP and steel bars.

Hawileh [116] used the popular finite element software ANSYS to generate three-dimensional FEM of the specimens studied by Aiello and Ombres [71]. The employment of spring elements in the longitudinal direction successfully simulated the bond-slip phenomenon between the concrete and reinforcing bars. FEM accurately predicted the load-deflection properties of the inspected specimens with an inaccuracy below than 10%. Under assumption of total compatibility between the concrete components and strengthening bars, FEM analysis revealed results that were very consistent with empirical data, indicating a strong connection between the two substances.

7. Conclusion

The presented study demonstrates that FRP reinforcement is a promising new technology for concrete reinforcement. It allows engineers to design concrete structures that are stronger, more durable, and more resistant to corrosion than traditional structures that use rebar. However, FRP bars also have some disadvantages, such as low bond strength. Several systems can improve the FRP bars' bond strength, the most important of which is the hybrid system, which is now widely used. This system provides valuable insights for the future development and design of HRC-beams. The main findings of the current investigation are presented below:

- Corrosion resistance is a key factor in making FRP reinforcement an economically sound choice for retrofitting and strengthening concrete structures, ultimately leading to reduced long-term expenses associated with FRP-RC structures.
- Increasing the FRP reinforcement ratio increases the instantaneous capacity of beams, but it also results in more cracks.
- The lack of ductility in FRP-reinforced beams is the primary drawback of utilizing FRP as a strengthening material. Ductility of FRP-RC members is a problem that has inspired a number of potential solutions.
- Sand-coated GFRP bars have bond strength comparable to that of steel bars, making them a viable substitute for steel bars. This is an important advantage because the bond performance of FRP bars is generally lower than that of steel reinforcement due to the lack of force transferred between the reinforcement and the surrounding concrete.
- HRC is a promising approach for improving the effectiveness of construction materials and creating efficient building systems. It is superior to traditional single-reinforcement (FRP or steel) in terms of load capacity.
- Hybrid reinforcement with steel bars effectively controls the development and width of cracks in beams reinforced with FRP bars.
- Previous studies confirmed that FRP/steel reinforcement ratio and FRP bar type affect the behaviour of hybrid reinforced beams. However, more research is required in this area.
- The FE results showed agreement with the experiment, giving about 10% accuracy for some studies.
- Performance of FRP/steel reinforced concrete beams constructed from environmentally friendly materials is suggested to be investigated. Geopolymer concrete may be a preferable replacement for traditional concrete because it does not require Portland cement, which is a major source of greenhouse gas emissions.

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