

A Critical Review on Glass Fiber-Reinforced Polymer Bars as Reinforcement in Flexural Members

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Received: 8 October 2022 / Accepted: 23 March 2023 / Published online: 17 April 2023
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Abstract Since the nineteenth century, reinforced concrete was evolved as a crucial material for construction. This popular composite material is broadly used in different building typologies. However, the decaying of steel rebar due to corrosion is identified as a hindrance that can affect the quality of reinforced concrete structures. In reference to this, the glass fiber-reinforced polymer (GFRP) bar is essential because of corrosion-resistant properties. The researchers performed various tests and numerical analysis to know the response of GFRP-reinforced flexural members in shear and bending. Based on studies over the last decade, this study critically analyzes the response of flexural member reinforced using glass fiber-reinforced polymer (FRP) bars. Understanding the behavior of the FRP bar as the alternating reinforcing material will be aided by this review. Since the GFRP bar has high strength and no yield point, the conventional characterizations of ductility may not be applicable to determine whether GFRP-reinforced concrete components are ductile. Hence, a detailed study is needed to understand the behavior of such structures. This paper explores various properties of GFRP-reinforced beams to appreciate the applications of GFRP reinforcement in flexural members.

Keywords GFRP · Flexural · Corrosion · Application · Deflection · Fibers

Introduction

In reinforced concrete structures, quality, design, and strength are salient features. The concrete has good compressive strength, and it is weak in tension. Due to its strength in compression, concrete was initially used in massive, simple constructions like bridge piers, foundations, as well as heavy walls. After the industrial revolution, designers preferred using reinforcing bars mainly of steel to construct concrete members to strengthen it and enhance its capability to carry tensile stresses. This innovative trend led to the development of reinforced cement concrete (RCC). Once the reinforcing technique evolved, steel bars were mainly used to reinforce concrete structures. This composite material gained appreciation due to its load-carrying capacity [1]. Concrete can resist compression well and protect the corrosion of reinforcing steel bars because steel can rust due to alkalinity. In addition, well-cured and properly compacted concrete with lower ratio of water cement has less permeability, which results in minimizing the penetration of corrosion inducing agents to the steel surface. It is observed that, usually, steel corrosion during its design life is not a major problem in well-maintained structures. If strength and stability requirements are not taken care of in practice, then corrosion of the steel bars in cement concrete has been observed as a common concern of reducing the strength in several RC structures in recent years, especially in an aggressive environment [2, 3]. It is considered the main durability issue, especially when the reinforcement is in contact with chlorides either from ingredients of concrete or from the adjacent situation [2]. In the presence of moisture, the mixture of

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chlorides (de-passivation of steel) as well as CO₂ (concrete carbonation) causes corrosion. Such corrosion of bars leads to concrete deterioration and the loss of efficient functioning of an assembly. At the beginning of the twentieth century, chloride-ion-induced corrosion was the cause of the deterioration of many RCC structures [4]. Different ways of using steel and reducing its corrosion in harsh environments were considered [5]. Epoxy coat and cathodic protection are usually advised to reduce the corrosion of steel bars [6]. Generally, regular assessment and maintenance of steel-reinforced structures will be carried out to check any repair requirements for corrosion resistance [4, 5]. Over the period, to avoid corrosion of steel reinforcement, FRP is evolved as a reinforcing bar that can be used in place of steel bars [6–10]. FRP consists of high stress fibers of small diameters in a polymeric resin matrix. The fiber imparts strength as well as stiffness to the composites, whereas the resin matrix offers stress transmission between the fibers and acts as an adhesive between the concrete and the laminate of the composite [11]. An FRP can have high strength in tension and cannot yield with the orientation of fibers used for reinforcing. The commonly used fibers in FRP bars are aramid, carbon, and glass. This study focuses on understanding the response of glass FRP bars. Under tension, GFRP bars exhibit linear stress–strain characteristics; but they are not ductile and possess lower elastic modulus, unlike steel bars [10]. As a result, FRP reinforcement is not suggested when moment redistribution is needed. FRP bars containing reinforcing fibers can substitute steel rebars in numerous concrete structures, specifically those in a marine setting. The major disadvantage of the GFRP-reinforced section is that it is prone to brittle failure; the hybrid reinforcement with fibers can be considered to resolve the issue of such failure [8–13]. Different marine structures and industry offices are also subjected to corrosion [14] due to an aggressive environment [15–17]. Research is carried out to recommend a substitute for steel with the polymer bar reinforced with various fibers, especially the glass fiber-reinforced polymer bar [18]. It is an innovative complex bar [19] made up of epoxy resin and glass fibers.

A developing country like India will demand various infrastructural projects. Infrastructure includes bridges, dams, roads, and other marine structures. Research shows that compared to conventional materials for such construction usages, combining high-stiffness, high-strength structural fibers with low-weight, low-cost, environmentally resilient polymers will result in durable composite materials [13, 20]. At the beginning of the nineteenth century, FRP materials were considered for temporary structures and infrastructure development [18, 21]. Initially, composite materials were very much expensive. Many studies were conducted to highlight the importance of FRP composites [22]. Tensile strength is a significant consideration in applying FRP

composites in construction [23]. A detailed study on cost efficiency and fire resistance is needed to understand application of FRP bars in construction. FRPs have excellent corrosion resistance [24] and strength in alkaline, chemical, and harsh environments; yet their mechanical properties and combustible properties get affected considerably at elevated temperatures due to the matrix resin properties [25]. Mohamed Saafi investigated that concrete cover significantly affects the temperature of FRP, and around 70 mm cover is needed for FRP-reinforced structures to make it fire resistant [26]. Researchers also presented numerical models to understand FRP-reinforced structural members' behavior under fire. The finite element (FE) analysis presented by Duan et al. accurately predicted the thermal response of FRP-reinforced concrete structures [27]. FE model presented in this research also predicted the anchorage failure of FRP-reinforced members at a high temperature which was a typical mode of failure in fire tests discussed in the literature. T. Morgado et al. presented a study on GFRP columns embedded in partition walls and building facades making them fire resistant [28]. Frequent retrofitting to maintain corrosion damaged steel-reinforced concrete members can lead to higher maintenance cost [29]. In this view, FRP bar can be considered as a replacement for the internal reinforcement to reduce the maintenance cost [30]. Further studies propose concrete flexural and compression members with GFRP reinforcement, which could be used to design the structure in the marine environment where steel corrosion is the primary concern. In the present study, the effort is made to appreciate response of concrete structural members reinforced with GFRP under flexure. Various properties of glass FRP-reinforced flexural members are studied. A brief review of various properties of GFRP-reinforced flexural members will help to understand the response of these rebars.

Fiber-Reinforced Polymer Bar

The fiber-reinforced polymer bar, popularly known as FRP bar [31], can be manufactured using uninterrupted fibers enclosed in the polymeric-resin matrix [32]. The main purpose of a fiber is to carry a load, and the resin will act as a binding material [33, 34], which transfers this load to fibers [27, 28]. Fibers are protected by resin. The appropriate fraction and quantity of fibers considerably affect the stiffness as well as strength of FRP, whereas the resin type used can affect the fracture toughness and failure mechanism [18, 21]. An FRP is manufactured by using different methods like extrusion, weaving, and braiding, and it is anisotropic. Resin curing rate, fiber orientation, manufacturing method, and quality control in production are all variables that influence the bar's characteristics [19, 35]. One of the advantages of using a GFRP bar is that it is

lighter than the steel bar [36–38] and has greater strength, and is non-corrosive [22–24, 39]. The best option is to use GFRP bars, especially in marine applications [36, 40, 41]. As shown in Fig. 1, GFRP is a ridged compound bar with glass fibers embedded in a long-lasting polymeric epoxy resin [42, 43].

The bond stress, elastic modulus, and response under strain are the vital mechanical characteristics to consider when using GFRP rebar in bending components [44]. The stress–strain linear relationship, as depicted in Fig. 2 upto failure, exhibits the behavior of GFRP bars under tension [45].

The GFRP-reinforced beam is often over-reinforced, resulting in brittle failure without warning [30–34]. It can be considered a disadvantage of using GFRP bars. Besides, due to low elasticity modulus [28], GFRP-reinforced members display more significant deformations and broader cracks than beams and columns reinforced using steel reinforcement of a similar cross section and area. A helical shape in the bars can enhance the ductility of the FRP-reinforced elements. In addition, using fibers can effectively regulate deflection and crack width [37, 47]. Table 1 indicates the elastic constant (E_f) and tensile strength (f_t) for GFRP bars used in various experimental studies. It is observed that these bars’ tensile strength is higher than steel reinforcing bars. It is also observed that GFRP bars are very effective in the repair process of reinforced structures, which are damaged due to corrosion [35]. These rebars can drastically improve the flexure strength of the damaged section and enhance the strength of mortar [35]. An onsite load test was performed to confirm the behavior of the repaired structure. Researchers made constant studies to discover other effective measures to overcome the loss due to the repair cost of concrete structures [36, 42, 48]. It is observed that polymeric fibers and rebars, like carbon, aramid [49], and GFRP, are exceptional for repairing and strengthening concrete members because of their outstanding physical and mechanical properties [30, 31].



Fig. 1 GFRP bars

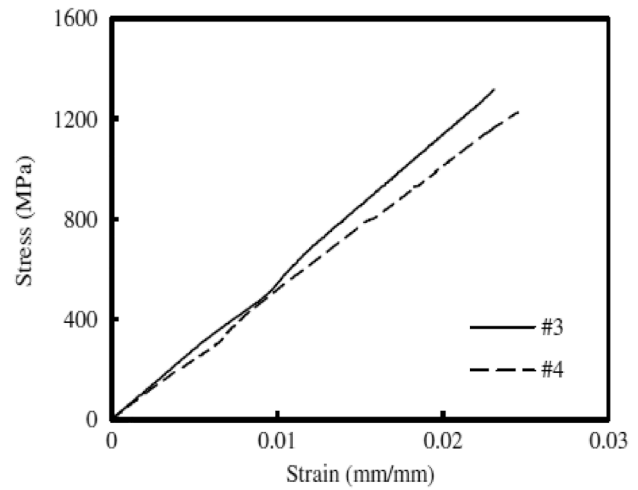


Fig. 2 GFRP bars stress–strain curve [46]

Overview of the Literature

Flexural Behavior

To understand the use of glass FRP as reinforcement in structure, various experimental studies are carried out by researchers and engineers worldwide. This section gives an outline of major experimental studies on such members in the last ten years. The findings of experimental studies are shown in Table 2.

Bazli [67] investigated and tested RCC assemblies with hybrid-reinforced bars, discovering that the novel reinforcement technique exhibits bilinear stress–strain characteristics that can be implemented in new concrete structures.

Table 1 Summary of properties: GFRP reinforcement used in previous studies

References	Ø(mm)	f_t (MPa)	E_f (GPa)
[50]	9.5, 19 and 28.5	700	48
[51]	12.5	664	34.2
[52]	12.9	740	40
[53]	12 and 16	1000	60
[54]	9.5	1100	52.5
[55]	13	941	48.1
[46]	4	1200	50
[56]	4 and 8	620	41
[57]	10	1090	51.6
[58]	12	1000	60
[59]	12	660	44.25
[60]	12	930	40
[61]	16	1184	62

Ø: Diameter; f_t = Maximum tensile strength, E_f : Elastic modulus

Table 2 Summary of experimental studies carried out on GFRP-RC beams

References	f_c (MPa)	No of Specimens	Area of Cross Section (mm ²)	Concrete Grade	Tension Reinforcement			Hanger Bars		Stirrups		Load at first Crack W_c (kN)	Ultimate Load W_u (kN)	Failure Mode		
					Type	\varnothing (mm)	Ratio (%)	Type	\varnothing (mm)	Type	\varnothing (mm)				S (mm)	
[62]	740	6	114 × 153	30	STR	10	1.47	ST	5	STR	5	38	15	75.6	T	
					GFR	10	1.82	-	-	-	-	-	-	14.8	34.7	S
					GFR	16	1.82	ST	5	STR	5	40	55	62.1	T	
					GFR	16	2.73	-	-	-	-	-	55	69.7	S	
[63]	760	7	150 × 200	30	STR	10	0.81	ST	10	STR	6	100	30	39.3	SYCC	
					GFR	9.53	0.59	ST	10	STR	6	100	7	34.2	BF	
					GFR + STR	10	0.59	ST	10	STR	6	100	35	63.5	CC	
					GFR + STR	10	0.89	ST	10	STR	6	100	40	65.9	CC	
					GFR	9.53	0.59	ST	10	STR	6	100	7	36.4	GR	
					GFR + STR	10	0.59	ST	10	STR	6	100	30	60.3	CC	
[64]	970	5	180 × 250	65	GFR + STR	10	0.89	ST	10	STR	6	100	42	77.3	SF	
					STR	16.8	1.25	ST	6	STR	8	130	72.85	299.20	CC	
					GFR	10	0.85	ST	6	STR	8	130	74.05	174.24	BF	
					GFR	10	0.85	ST	6	STR Strip	130	71.75	168.96	BF		
[53]	470	6	190 × 190	50	STR	16	1.20	ST	6	STR	8	130	56.86	234.53	CC	
					GFR	10	0.90	ST	6	STR	8	130	58.03	194.57	BF	
					GF	12	0.99	ST	6	STR	8	70	15	127.4	CC	
					GFR	16	1.78	ST	6	STR	8	70	20	150.2	CC	
[65]	600	9	200 × 250	20	STR	25	2.07	ST	10	STR	6	100	30	252.7	SY & CC	
					GFR	16	0.89	GF	10	STR	6	100	30	81.52	CC & GR	
					GFR	20	1.25	-	-	-	-	-	35	90	-	
					GFR	24	1.80	-	-	-	-	-	30	105	-	
[66]	1000	6	100 × 150	80	GFR	16	0.89	-	-	-	-	-	35	115	-	
					GFR	20	1.25	-	-	-	-	-	35	135	-	
					GFR	24	1.80	-	-	-	-	-	40	145	-	
					GFR	6	0.5	GF	6	STR	4	50	3.1	15	GR	
[66]	1000	6	100 × 150	80	GFR	10	1.00	-	-	-	-	-	3.8	33	CC	
					GFR	12	2.00	-	-	-	-	-	4.0	46.1	CC	
					GFR	6	0.50	-	-	-	-	-	3.3	16.2	GR	
					GFR	12	2.00	-	-	-	-	-	3.0	52.2	CC	

f_t : Tensile Strength of GFRP Bar; \varnothing : Dia of Reinforcement, S: spacing, GFR: GFRP Rebar, STR: Steel Rebar
 Mode of failure—T: Tension; C: Compression, S: Shear; SC: Shear and Compression; GR: GFRP Rupture; CC: Concrete Crushing; SY: Steel Yielding; and BF: Bond Failure

Furthermore, hybrid-reinforced [68] bars outperform traditional reinforcement in weight, corrosion resistance, and strength; additionally, tensile testing shows linear stress–strain characteristics. The beam can withstand more significant deformation than inelastic deformation during testing [69]. Studies were conducted regarding the shear stress of GFRP-reinforced members [70], and it was discovered that longitudinal reinforcement has little consequence on shear capability in GFRP-reinforced beams with various ratios. As a result, usual rational equations can be used to approximate shear strength.

In contrast, during the deformation in shear, the beams reinforced with GFRP were observed to be parallel with RC beams having steel reinforcement. Additionally, shear strength was noticed to be less in beams of GFRP reinforcement than in beams of reinforcing bars of steel [66]. The main reason for the lower shear capability of GFRP-RC members compared to steel RC members is their lower modulus of elasticity leading to smaller compression block depth and weaker aggregate interlock. A shear stress equation was proposed in view of the data received from experimental analysis over the member reinforced with steel, found to be un-conservative in the beams using GFRP reinforcement [71]. Seven RC flexural rectangular members were tested, each with GFRP reinforcement and steel rebars (hybrid reinforcement). Two different types of rebars in two different layers were used near the tensile face of the beam. In addition, two concrete mixes are formed with strength values 30 MPa and 50 MPa, respectively [63]. Experiments with four-point flexure were performed on the flexural member, shown in Fig. 3, for the span of 2.1 m.

It was witnessed that the beam failure was caused due to high deflection. The flexural member reinforced with only GFRP bars showed that at 7 kN load, beam stiffness is changing and increased in load–deflection behavior till it failed at around 56 mm deflection. For steel and hybrid-reinforced beams, a change in stiffness is observed at around 10 kN load and an increase in load–deflection behavior till it fails at around 60 to 70 mm deflection. Also, due to distinct cracks along the middle part progressing in the direction of the beam top, the steel rebar employed for reinforcing had yielded crushing failure in concrete under compression. This failure is observed at the load value of around 40 kN (deflection: average 70 mm). Specimen of the concrete beam

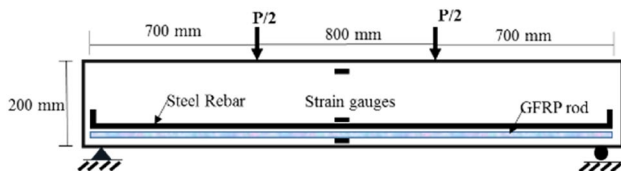


Fig. 3 Test specimen

with lower strength was observed with increased cracks. The beam's failure also occurred due to a slip in the bond of internal rods made of GFRP, where the beams with composite reinforcement showed a mainly crushing failure of concrete. Bond-slip failure for GFRP-reinforced beam occurred at around 34 kN load (deflection at 56 mm). D. H. Tavares conducted experiments on six beams with steel and GFRP bar reinforcement [31]. The beam specimen's cross section was 150 × 300 mm for a 2.9 m span length. The study of the beams was carried out employing a four-point bending experiment.

The observations showed comparatively high strain and lower elastic modulus under rupture. These critical parameters impact the flexure response of beams with GFRP reinforcement. When the beams' behavior reinforced using hybrid reinforcement (GFRP and steel) was evaluated against concrete beams only with steel reinforced, it was observed that regulation of maximum internal tension force and reinforcement stiffness could result in appropriate flexural characteristics of beams reinforced with hybrid reinforcement [72]. Biswarup Saikia studied the performance as well as serviceability of GFRP-reinforced flexural members [64]. In the GFRP-reinforced concrete beams, bars yield mainly because of slip along concrete and bar as well as the post-crack stiffness value reduction. Supplementing the polypropylene fibers did not significantly result in the post-cracking characteristic of beams reinforced using GFRP [73]. The analytical equation is employed to predict load–deflection response for the beams reinforced using GFRP, and predictions were close to the corresponding experimentally observed response [74].

The response of hybrid-reinforced beams in flexure was studied by Wenjun Qu. Eight beams were cast. Two beams used only steel rebars and GFRP, respectively, and the rest of six beams were cast using hybrid reinforcement. The beam length was taken as 1800 mm, whereas the cross-sectional area was 180 × 250 mm. Steel stirrups incorporating 100 mm spacing and 10 mm diameter bars as shear reinforcement were used [75]. Leung and Balendran studied the load vs deformation analysis of concrete beams internally reinforced using GFRP and steel bars. They observed that the presence of GFRP bars and the strength of concrete would significantly affect the maximum load bearing capability and failure pattern of the flexural member [63]. They also observed that flexural strength for the beam reinforced with mixed or hybrid reinforcement is higher. Saikia and P. Kumar experimented with the strength as well as serviceability performance of beams with GFRP reinforcement. It is seen that the serviceability conditions for beams reinforced with GFRP are ruled by maximum crack width [76]. Researchers studied the influence of reinforcement ratio, surface characteristics, and concrete cover on the width and spacing of cracks in GFRP-reinforced elements [77]. It is

observed that more concrete cover gives more crack spacing. For various load cases, the higher value of concrete cover will give scattered results. K. Subramanian and V. G. Kalpana assess the behavior of beams with GFRP reinforcement in flexure. Experimental results were compared to numerical results. They observed that less stiffness of GFRP causes an increase in crack width. Concrete strength will not affect the crack width significantly. The load vs deformation response of numerical and test models was comparable [65]. Goldstone presented studies on the flexure behavior of glass FRP-reinforced HS (high-strength) and UHSC (ultra-high-strength) concrete. Fang Yuan studied the behavior of CFRP-reinforced concrete beams, and concrete was mixed using seawater and sea sand coral aggregates. Linear strain distribution is noted along the beam cross section. Due to the higher moment, the neutral axis shifted to the top of the beam, exhibiting the gradual formation of cracks in flexure [78]. Omar Gouda conducted experimental studies on the serviceability and performance of flexural GFRP-reinforced concrete beams [79]. It is seen that the beam fails due to concrete crushing at the outermost compression layer. The beams with less ratio of reinforcement ($\leq 0.85\%$) showed bilinear behavior in load–deflection, whereas those having high reinforcement ratio exhibited trilinear behavior. An increment in the ratio of reinforcement led to a significant reduction in terms of deformity using deflection as well as energy influenced approaches. Furthermore, for a similar increment in the reinforcement ratio, the flexure capacity in serviceability increased more significantly than the highest moment capability. Omar Gouda also presented studies on “equations of development length” for GFRP bars in reinforced concrete beams. The “equations” proposed by authors showed required effectiveness and reliability in forecasting the development length based on initial stress intercept as per the regression analysis of the end splice test results. After reviewing the flexural behavior of concrete beams with GFRP reinforcement, it can be concluded that the section with GFRP can be designed as over reinforced section and it is flexure critical. The strength of GFRP bars as well as grade of concrete significantly affects the load deflection behavior of the member and load-carrying capacity of the member. The strong confinement in the flexure region by close spaced secondary reinforcement could result in a high index of ductility and maximum capacity with negligible influence on the “post-cracking” stiffness of the beams. Also higher reinforcement ratio can increase ultimate capacity and can decrease deflection at service conditions as well as ultimate load conditions. The concrete covers considerably affect forecast of the “development length” which in turn depends on the bar size. For the development of full bonding stress of the GFRP bars, the cover of concrete to the midpoint of the bar is suggested as 2.5 of bar diameter for nearly all diameters of bar [80].

The failure loads in the tested beams show that the flexure capacity of the concrete beam with hybrid reinforced using hybrid steel/GFRP enhances with an elevated effective reinforcement ratio, ρ_{eff} . The observation implies that ρ_{eff} is one of the prime parameters in determining its flexural capacity for the hybrid reinforcement in the concrete beams using steel/GFRP. This hybrid structure enhances flexural behavior in the concrete beams, whereas the reinforcement using steel improves the ductility in the beams with hybrid reinforcement. R. Mathieu, B. Brahim studied the outcome of aging this bond along with concrete and GFRP bar. Study shows that this mode of bond deformation mainly relies on the bar’s coating layer and surface profile [81]. The coating layer enhances bond performance. The bond strength along GFRP concrete will reduce with increasing immersion time. Under aggressive atmospheric conditions, the study shows that change in bond strength is minor and hence negligible at elevated temperatures.

V G Kalpana cast and studied nine beams for the two-point loading experimentation. For the given beam, a 200×250 mm cross-sectional dimension with an 1800 mm span length. They studied the characteristic behavior of beams reinforced using GFRP bar in the concrete under a two-point loading system with a diameter of bar and grade of concrete as a variable parameters. In the first group, three beams were cast using an actual strength value of 20 N/mm^2 . Also, GFRP bars of diameters 16 mm, 20 mm, and 24 mm were used for the reinforcement along the tension face. In the second phase, beams were cast using the same count of GFRP bar and diameter value with a concrete compressive strength value of 40 N/mm^2 . The last group consists of three beams with the same GFRP bar count and a concrete compressive strength value of 60 N/mm^2 . Two hanger bars (GFRP) with 10 mm diameter were employed for all beams. High-strength concrete embedded with GFRP bar exhibits better performance when compared with regular strength concrete embedded with GFRP bar regarding the load-carrying and deflection capacity because of the high-tension capacity. GFRP bars with depressed stiffness led to enhanced crack width. Mohamed S. Issa experimented with the behavior of beams using fibers to assess mechanical properties like flexure and ductility.

Further, it was noted that adding steel fibers enhances the ductility in FRP-reinforced flexural members by around 300%. The accuracy in the deflection equation varies with varying load levels. More substantial deviations were observed nearer to the ultimate load.

The span to experimental load deviation ratio was comparatively more remarkable than the regularly recognized ratio for the span/250. M.W. Goldston experimented and studied the flexural behavior in the concrete beam with the GFRP-reinforced high and ultra-high strength. Observations were made that using UHSC with 117 MPa is

more advisable for enhancing load-carrying capacity in over-reinforced (GFRP-RC) beams compared with the HSC with 95 MPa [5]. Also, as the strength of concrete is enhanced to 117 MPa, UHSC from 95 MPa, HSC load-carrying capacity is elevated by 13% and 27% for the reinforcement ratio of $p_f = 2.0\%$ and $p_f = 1.0\%$, respectively [56]. Deviation in the middle of the span was noticed to have increased with increasing the concrete strength to 117 MPa, UHSC from 95 MPa, and HSC with the same reinforcement for GFRP-RC beams over reinforced. It is observed that over the period, many studies have been carried out to understand the flexural behavior of GFRP-reinforced concrete members. This discussion highlights the various parameters affecting flexural strength. Hybrid reinforcement, high-strength concrete enhances the flexural behavior of FRP-reinforced concrete structures. Concrete cover, reinforcement ratio, bar spacing, and confinement due to the transverse reinforcement in the bending zone are the parameters required to study the flexural strength of such structures.

Load–Deflection Behavior and Crack Pattern

Lapko and Urbański presented the following observations on deflections based on different methods and experimental studies of FRP bar-reinforced beams [82]. Distinctive to the traditional beams reinforced with steel bars, basalt fiber-reinforced beam exhibits linear behavior between load and deflection. The values obtained from experimental studies are noticeably higher for the FRP-reinforced beam than for deflections of the steel-reinforced beam, as shown in Fig. 4 and Fig. 5. This is because of the lower modulus of elasticity in the FRP bar compared to steel bars.

Figure 4 shows the results of strain-controlled experiments, whereas Fatih et al. presented studies on deflection and bending stress characteristics for hybrid-reinforced concrete (steel-FRP) beams [66]. Deflection results using various numerical techniques are compared with experimental results after applying loading to deformation. Figure 5 shows that numerical methods adequately predict post- and pre-cracking deflections considering stress controlled as well

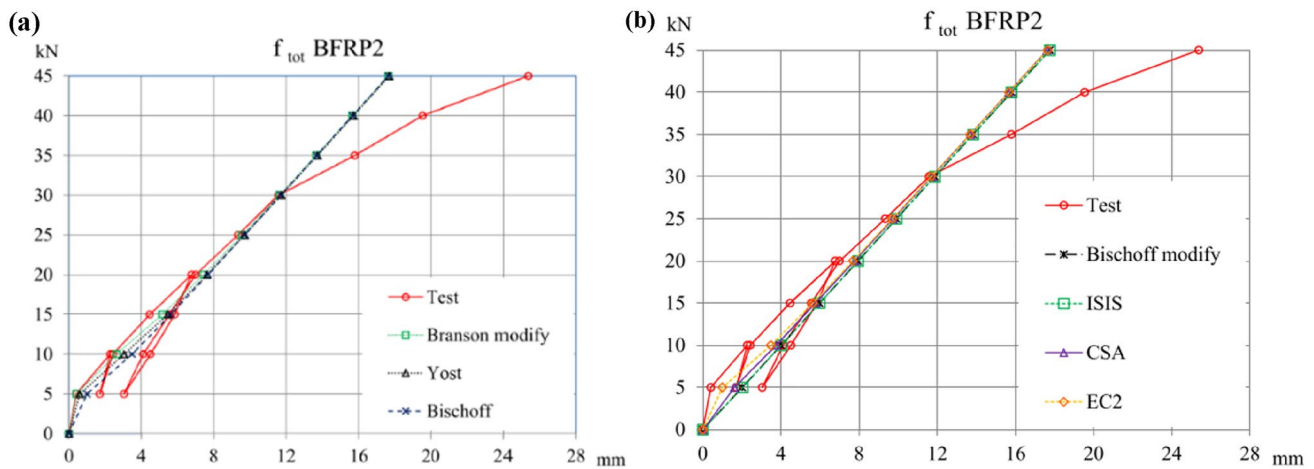


Fig. 4 a Theoretical, b Experimental behavior of load–deflection for FRP-reinforced beam [82]

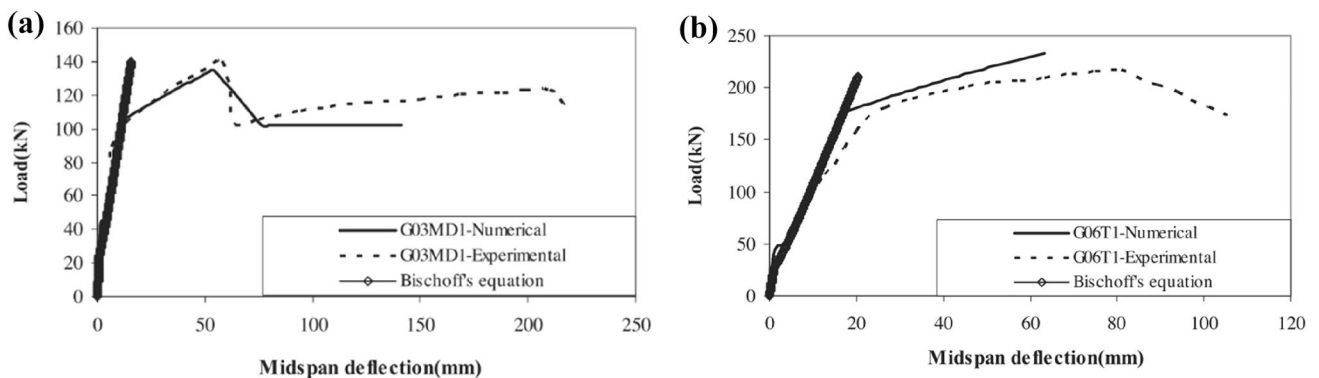


Fig. 5 Load vs deformation relation for concrete beams using hybrid reinforcement (FRP and steel) [66]

as strain-controlled aspects. Figure 5 also shows the comparison of behavior in deflections assumed by the Bischoff model and at the lower load levels after and before the first load cracking. Studies were done by M. Issa et al. to understand the impact of fibers on the GFRP-reinforced beam's flexural behavior [47]. The studies show that numerous kinds of fibers like glass, steel, and polypropylene have enhanced the ductility of a concrete beam (FRP-reinforced) specifically; employing steel fibers increases the ductility of the beam significantly. So, supplementing the steel fibers is one of the solutions to enhance the lower ductility of FRP reinforcement. The load–deflection behavior of lower-strength concrete beams strengthened with GFRP and steel bars is shown in Fig. 6.

It is observed that the pre-yielding behavior for steel (L0) and GFRP-reinforced beam (L2, L5) was identical. Beams reinforced with just (L1) bars (GFRP) depicted changes in beam stiffness at 7 kN load (crack load), and later, the (L1) beam specimen displays an increasing load–deformation behavior until complete deformation. Beam reinforced with only steel (L0) shows post-yield typical horizontal behavior with no noted increment in the load-bearing capability of the beam. After the yielding load of steel bars, the hybrid-reinforced flexure members (L2 and L5) exhibited a rise in the beam's load-holding capability. It is noted that the load–deflection characteristics of (L1) and (H1) were comparable to those of (L2) and (H2). Load-resisting capacities of the beams (H2, H5) are higher with higher concrete grades than the lower grade of concrete (L2, L5). Strain-controlled approach was adopted by the researchers. Figure 7 depicts the load–deformation performance of GFRP-reinforced

concrete beams. The load–deflection behavior of GFRP-reinforced concrete beams reflects a change in the graph at the cracking load.

Initially, the load vs deformation curves' slopes are comparatively greater, suggesting that the stiffness is higher before breaking, resulting in a gradual change in deformation as the load increases. However, the slope decreases after cracking in tensile zones, reducing the stiffness. Figure 7(b) depicts that deflection in steel reinforced concrete beams is slower than the higher deflection value, less than the GFRP-reinforced concrete beams with only by 60%. These outcomes are related mainly to the reinforced material's elastic modulus; the GFRP beams have low elastic modulus and are hence deformed easily. It also shows that special attention should be given to the impact of the reinforcement ratio on structural deformation capacity in members reinforced with GFRP. It is observed that primarily, beams remain stiff and uncracked [83]. When the load increases, cracks are seen in the pure-bending zone [84]. The load vs deflection behavior of beams is close to each other until the service loads. This shows the beams' rigidity. The beam was loaded in tiny increments to a point where it experienced more significant deflections earlier. In deflection at each load addition, the GFRP bars in high-strength concrete performed better than bars in standard strength concrete [85]. Figure 8 depicts the check patterns of failure and the width of cracks on all four sides of the beams made from GFRP-reinforced concrete.

Initiation of cracks occur as the tensile stress is exerted on concrete that exceeds its tension capacity. As compared to plain beams, the rate of crack propagation [86] in GFRP-strengthened beams is slow, and the width of the

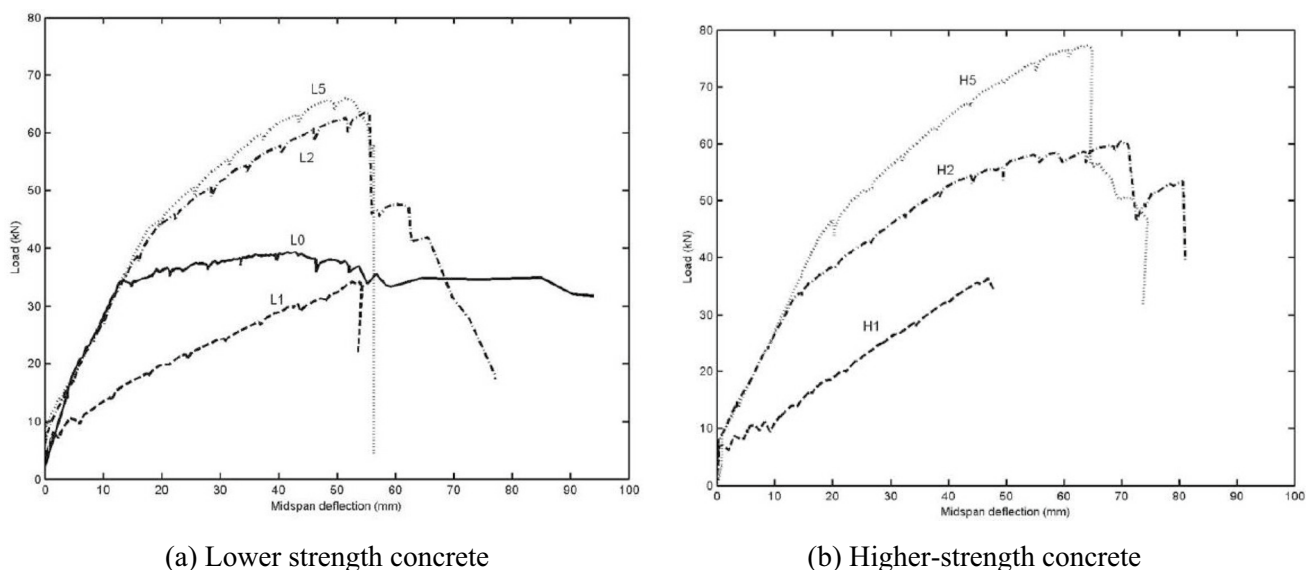


Fig. 6 Load vs deformation curve of beam reinforced with GFRP for various concrete grades [63]

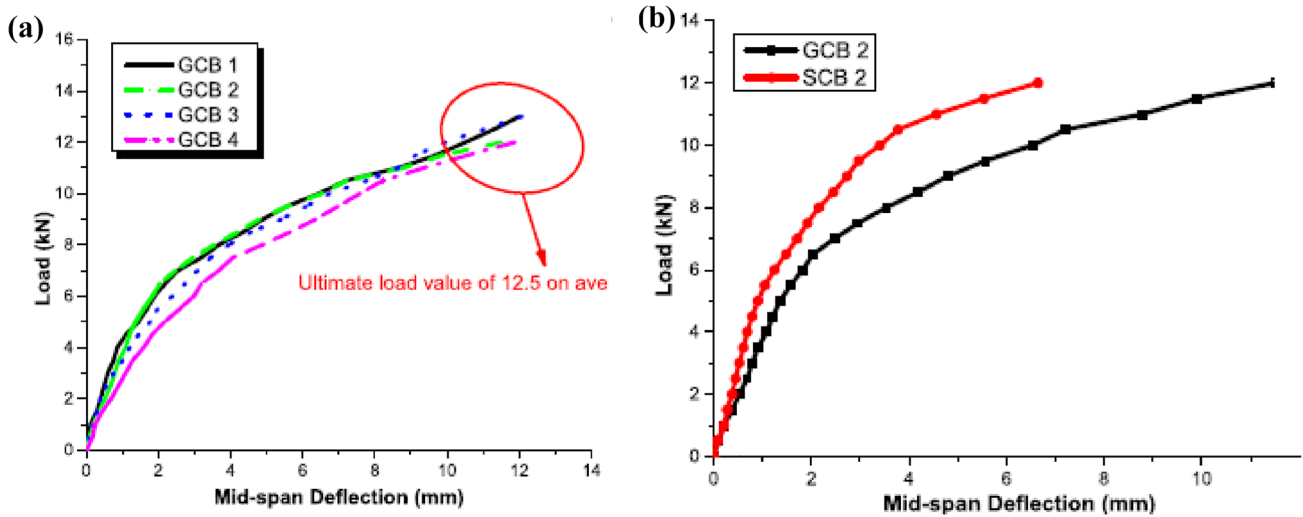
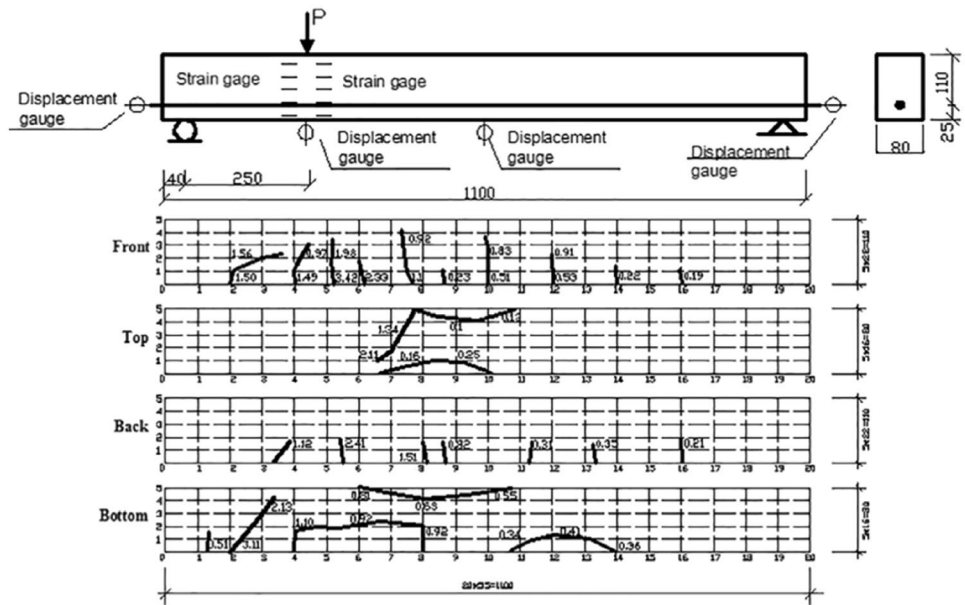


Fig. 7 Load vs deflection plots: a The GFRP-reinforced beams and b The GFRP- and steel-reinforced concrete beams comparison [57]

Fig. 8 Cracks on GFRP-reinforced beam after failure [57]



crack, which corresponds to an ultimate load, is small. Such findings show that the beams made of concrete reinforced with GFRP have higher damage resistance than the beams made from plain concrete. Referring to Fig. 9, it is observed that the flexural strength of hybrid rebars is higher for a concrete beam than that of concrete structures made from either GFRP rods or steel rebars [87].

In addition, more cracks were observed in the hybrid reinforcing system. For the hybrid reinforcements, an increased area of GFRP could provide improvement in

load-carrying capacities. The GFRP bars in hybrid reinforcement enhances post yielding behavior of flexural member. GFRP reinforcement is more effective after yielding of steel reinforcement.

GFRP Concrete Bond Strength

For three decades, experimental and analytical studies have been performed to know the ability of different FRPs as reinforcement in concrete structures.



Fig. 9 Cracks patterns for hybrid-reinforced beam [63]

Researchers have tested the FRP-reinforced beam for bond strength and durability. They also tried to know these specimens' flexural behavior and shear resistance. The specimens used in experimental studies were prepared following ACI-440-3R [88] regulations and tested as per ASTM standards [89]. It is observed that concrete strength, cover, bar diameter [90] as well as confinement provided by transverse reinforcement influence bond strength [85, 86]. The GFRP bar has non-homogeneous, anisotropic, and linear elastic characteristics. Due to this, the bond stress property of glass FRP rods inside the concrete was a critical factor under consideration for its application in concrete structures. Furthermore, because the alkaline pH of concrete is high, ranging from 12.7 to 13.6, earlier research has shown that GFRP rods reinforced in concrete reduced tensile and bond strengths [91].

The bond stress within the concrete and reinforcing bars plays a vital part in concrete structures' stability, safety, and deformability characteristics [92]. Bond strength is a common characteristic considered in reinforced concrete. It is the measure of load transmission between reinforcement and concrete. Bond strength is affected by concrete properties, bar geometry, confinement, development length, and surface conditions of rebar. Research is conducted to understand bond stress in FRP-reinforced concrete structures. Design Code by Canadian Highway Bridge (CHBDC) CSA S6-06 as well as Canadian Code CSA S806-02 [93] gives equations for the development length of FRP bars in conventional concrete, considering the surface of a bar, location of the bar, clear cover, and distance between bars. Hossain K. M. A. et al. presented studies on bond stress properties of glass FRP bars in ultra-high-strength concrete [94]. It is observed that in both higher-strength and ultra-higher stress concrete,

bond strength is reduced with an increment in GFRP bar size. The bond strength reduction was in the range of 10% to 40%, as shown in Fig. 10.

Figure 10 shows that the bond strength for HM (high-modulus) and LM (low-modulus) GFRP bars decreases with increased length of embedment for beam test specimens. This reduction is because of the greater distribution of nonlinear stresses along with the more extended embedded length of the GFRP bar in concrete. Harajli M. and Abouniaj studied the ACI 440 [20] guidelines for the bond strength behavior of GFRP bars in tension [95]. They carried out two bond tests: local bond strength slip response using pullout samples and splice bond strength using beam samples. Figure 11 presents the testing setup for pullout specimens.

Because of the larger concrete cover, the specimens' pullout test was observed to fail in pullout mode, as shown in Fig. 12, which also shows various modes of bond strength failure.

Ahmed G. Bediwy and Ehab F. El-Salakawy assessed the bond stress of GFRP bars embedded in FRC composites [96]. An analytical expression expecting the bond stress of headed-end bars-reinforced specimens containing discrete fibers was suggested. The bond stress formulae, as per various design provisions, were considered. The new model studied the effect of adding different types of distinct fibers into specimens reinforced with headed-end bars. This model produced decent estimates for FRP–FRC specimens.

Fei Yan et al. created 682 pullout test specimens to understand the bond performance of GFRP bars [91]. Figure 13 shows the bond performance evaluation (BPE) model for concrete and steel reinforcement.

The modified bond-slip stress model mBPE shown in Fig. 14 can be expressed by equations in three stages (Eqs. 1–3) [91].

Fig. 10 Effect of rebar type/diameter, concrete compressive stress, and embedment length on bond stress [94]

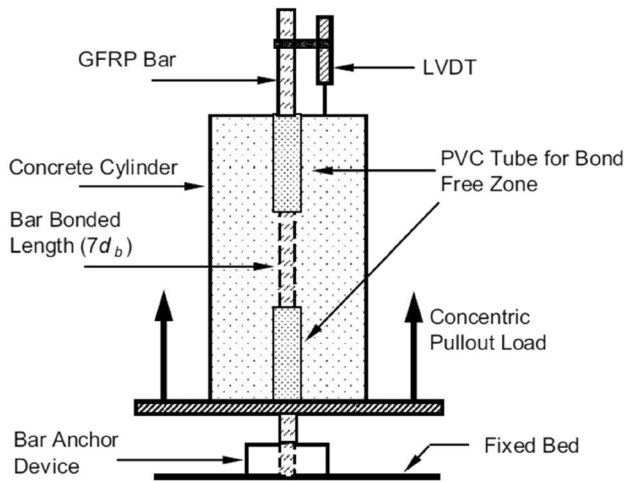
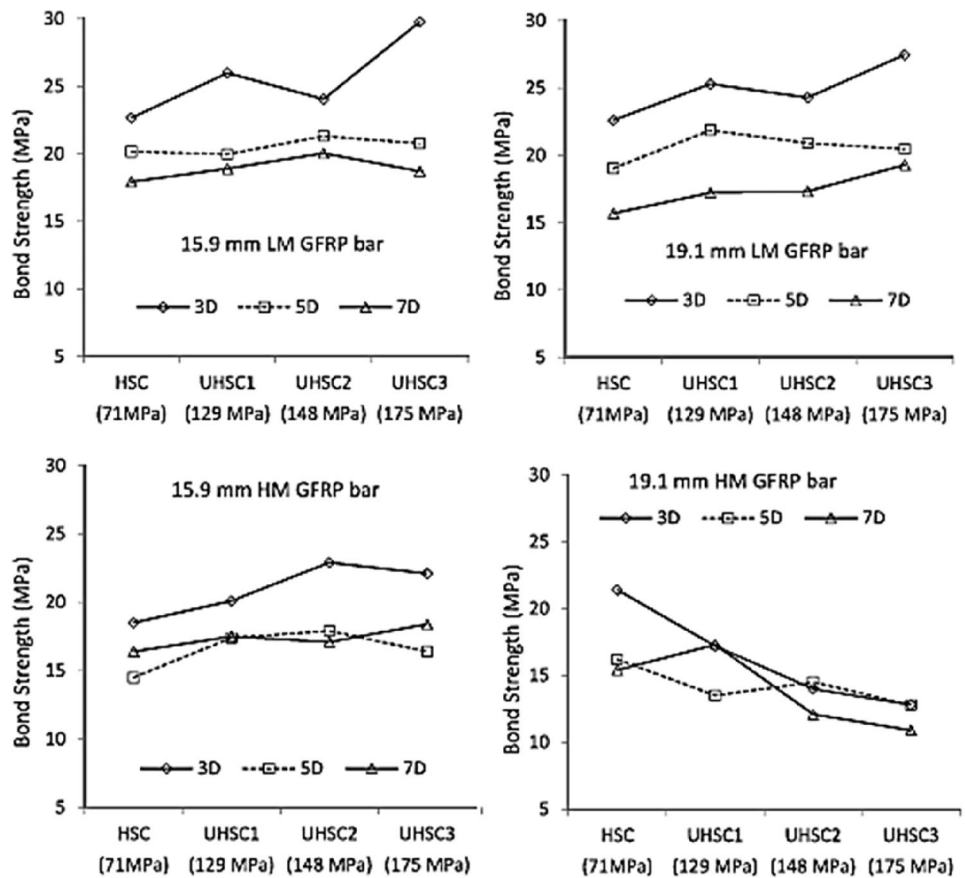


Fig. 11 Test setup for pullout specimens [95]

$$\frac{\tau}{\tau_b} = \left(\frac{s}{s_b}\right)^a \text{ for } 0 \leq s \leq s_b \tag{1}$$

$$\frac{\tau}{\tau_b} = 1 - p\left(\frac{s}{s_b}\right) \text{ for } s_b \leq s \leq s_3 \tag{2}$$

$$\tau = \tau_3 \text{ for } s \geq s_3 \tag{3}$$

where s and τ can be defined as the slip and the bond stress, while s_b and τ_b are the extreme slip and its corresponding bond strength. The result of treatment for a surface on bond stress was considered in an improved model for FRP bar. Bogachan Basaran et al. conducted a detailed investigation of the effect of development length on the bond strength of FRP bars embedded in concrete [97]. The research is conducted for an in-depth analytical study to evaluate bond stress FRP reinforcing bars in concrete. The results of analytical models were compared with experimental results in the literature. Practical algorithms were developed to predict the strengths of bond and FRP reinforcing bars' development lengths with different physical properties. Doost Mohamadi et al. assessed the influence of concrete type on the bond strength of GFRP Bars [98]. It is observed that increasing compressive strength in both normal-weight and lightweight concrete will enhance the bond strength. Due to shape, surface texture, and mechanical properties, GFRP bars indicate lower bond strength with concrete. Applying a proper restraint system, this deficiency can be considered in the design approach. The sand-coated BFRP bars owned higher adhesion and bond strength to concrete than the ribbed

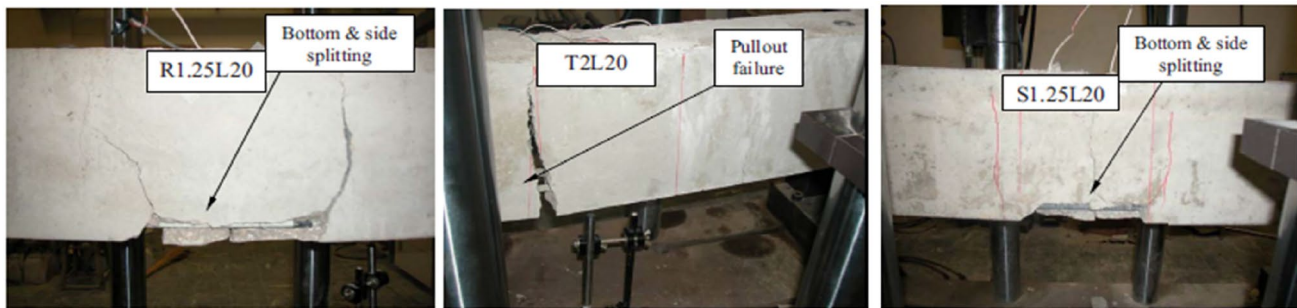


Fig. 12 Bond failure modes of beam specimens [95]

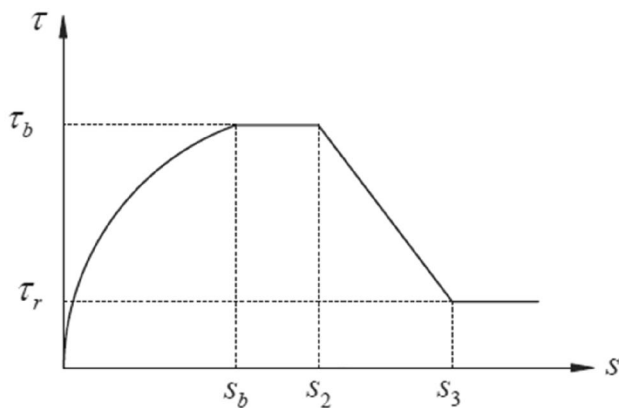


Fig. 13 BPE model for steel rebar [91]

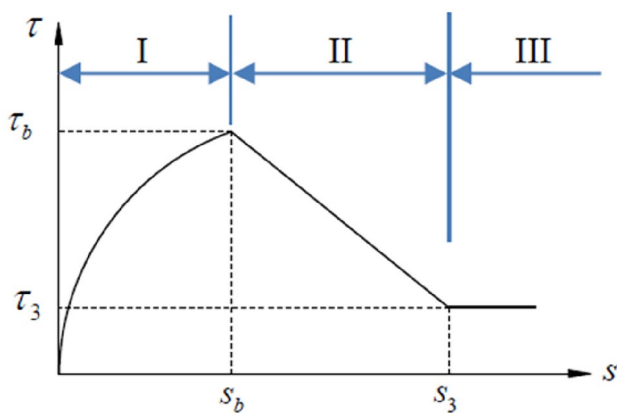


Fig. 14 mBPE model for FRP bar [91]

GFRP bars [99]. The elevated temperature can degrade the bond strength of FRP-reinforced concrete.

Conclusions

The paper reviews the behavior of GFRP-reinforced structural members in flexure and discusses load–deflection characteristics, bond strength, and crack patterns for such

members. The paper aims to critically review the application of GFRP as reinforcing bars in concrete structures, especially in beams. The findings of the literature study are summarized as follows.

- Generally, FRP-reinforced concrete elements are designed based on increased values of safety factors.
- The design guidelines given by ACI and CSA code will be applied to designing GFRP-reinforced concrete structures. However, no specific design codes, especially in the Indian context, are available for such members.
- The lower value of the elasticity modulus and the higher rupture strain in GFRP are the main factors responsible for the higher ultimate strength, lower stiffness, and higher deflection of GFRP-strengthened beams than the steel-reinforced beams. GFRP-reinforced members in flexure outperformed steel-reinforced beams.
- The behavior of the beam in flexure can be enhanced using steel rebar in combination with GFRP reinforcement in terms of increased capacity for carrying the load, higher deflection compared to GFRP-reinforced beam. In the post-cracking stage, GFRP bar, along with the steel bar, is taking more load, and the beam fails in shear. Therefore, shear reinforcement needs to be taken care of.
- The critical load-carrying capability of hybrid-reinforced concrete beams is more compared to beam reinforced using only GFRP and steel, respectively.
- Various investigations on using fibers in GFRP-reinforced concrete members indicate the improvement of mechanical properties of concrete members. The steel fibers can resist macro-cracks. Basalt and glass fibers can resist micro-cracks. The percentage of hybrid fibers is decided based on test results and cost comparison of using fibers in concrete.
- The maximum load-carrying capability in GFRP-reinforced concrete beams with fibers is higher than GFRP-reinforced beams without fibers.
- The literature study showed that reinforcement in hybrid form performs a substantial part in improving the bending stress of beams. It improves the flexural strength of

beams. Load–deflection curves before yielding remain the same for GFRP-reinforced or steel-reinforced flexural members for the same series of compressive strength of concrete.

- GFRP bars are operative for the hybrid reinforcement after reaching the yielding point of steel rebars. Supplementing steel fibers to the concrete members, reinforced using GFRP, is one of the techniques to suppress the lower ductility limitation.
- The effective reinforcement ratios substantially affect the load-carrying capacity of hybrid-reinforced beams more than the axial stiffness ratio between steel and GFRP. Load-carrying capacity increases as the effective reinforcement ratio increases. Corrosion and deterioration of steel-reinforced concrete and high costs to rehabilitate and remediate structures lead to the practical application of GFRP bars.
- Even after some drawbacks, such as low elasticity modulus and lower shear strength due to the greater strength in tension and non-corrosive nature of GFRP bars, it can be considered a better alternative to steel reinforcement. Experimental and analytical studies will be carried out to understand such members' flexural behavior better, and new strength reduction factors for an innovative design approach for GFRP-reinforced concrete members can be developed.
- Despite previous studies, the proposed equations in various studies have limitations in understanding the behavior of GFRP bars in concrete flexure members. There are no standard design guidelines available to address the disadvantages of pure GFRP-RC members. As a result, developing a new methodology or design guidelines is critical for the future use of GFRP rebars in concrete structural members, which would eventually replace steel reinforcing bars with GFRP bars. Thus, corrosion issues in structural elements can be avoided, resulting in a longer life for the structures.

Acknowledgements We would like to thank the Manipal Academy of Higher Education, Manipal, Karnataka, India.

Funding Open access funding provided by Manipal Academy of Higher Education, Manipal. The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Declarations

Conflict of interest On behalf of all authors, the corresponding author declares that there is no conflict of interest regarding the publication of this manuscript.

Ethical Approval On behalf of all authors, the corresponding author declares that we have followed the accepted principles of ethical at

study, and there are no financial or personal conflicts of interest that might have impacted the research reported in this publication.

Human and Animal Rights No animal or human subjects were used in this work. This manuscript is an original paper and has not been published in other journals. We also confirm that there is no way our manuscript is in possible conflict with the ethical standards required by the journal.

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