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Evaluation of Glass Fiber-Reinforced Polymer Bars as Reinforcement for Flexural Members Using “Ansys software”: A Review

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ABSTRACT:

This critical review examines the use of glass fibre-reinforced polymer (GFRP) bars as an alternative reinforcement material in flexural members. With the increasing demand for sustainable construction materials, GFRP bars have emerged as a promising substitute for traditional steel reinforcement due to their high strength-to-weight ratio, corrosion resistance, and non-magnetic properties. This paper evaluates the mechanical properties, durability, and bond behaviour of GFRP bars in flexural members based on a comprehensive review of existing literature. Additionally, challenges and limitations associated with the use of GFRP bars are discussed, along with recommendations for future research and practical applications.

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

INTRODUCTION:

Reinforced concrete structures are known for their quality, design, and strength. While concrete exhibits excellent compressive strength, it is weak in tension. Initially used in massive, simple constructions like bridge piers, foundations, and heavy walls due to its compression strength, concrete was later reinforced with steel bars to enhance its tensile capacity. This innovative approach led to the development of reinforced cement concrete (RCC), which gained appreciation for its load-carrying capacity [1]. The use of steel reinforcement also protects against the corrosion of reinforcing bars, as steel can rust due to alkalinity. Well-cured and properly compacted concrete with a lower water-cement ratio has reduced permeability, minimizing the penetration of corrosion-inducing agents to the steel surface. However, if strength and stability requirements are not adequately met, corrosion of steel bars within concrete structures can become a significant issue, particularly in aggressive environments [2, 3]. Chloride-ion-induced corrosion, especially when the reinforcement is in contact with chlorides either from concrete ingredients or the surrounding environment, has been a major durability concern, leading to 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 to combat this, various methods have been explored, including epoxy coating and cathodic protection to reduce steel corrosion [6]. Regular assessment and maintenance of steel-reinforced structures are crucial to identifying any repair requirements for corrosion resistance [7]. As an alternative to steel bars, Fiber Reinforced Polymer (FRP) bars, such as Glass Fiber Reinforced Polymer (GFRP), have been developed. FRP bars consist of high-stress Fibers in a polymeric resin matrix, offering high strength and stiffness. GFRP bars, in particular, have been studied extensively due to their potential to replace steel rebars, especially in marine environments [8–13]. In countries like India, with increasing infrastructural projects such as bridges, dams, roads, and marine structures, there is a growing demand for durable composite materials. Research suggests that combining high-stiffness, high-strength structural Fibers with low-weight, low-cost, environmentally resilient polymers can result in durable composite materials, compared to conventional construction materials [13, 20]. Early FRP materials, though initially considered for temporary structures and infrastructure development, were expensive. However, advancements have made them more cost-effective. Tensile strength is a significant advantage of applying FRP composites in construction [21]. FRP bars offer excellent corrosion resistance and strength in alkaline, chemical, and harsh environments. However, their mechanical and combustible properties are significantly affected at elevated temperatures due to the properties of the matrix resin [22]. Efforts have been made to understand the behaviour of FRP-reinforced structural members under fire conditions. Studies have shown that concrete cover significantly affects the temperature of FRP, and adequate cover is needed for FRP-reinforced structures to make them fire-resistant [23]. Numerical models have been developed to predict the behaviour of FRP-reinforced structural members under fire accurately [24]. The use of FRP bars as a replacement for steel reinforcement can significantly reduce maintenance costs, particularly in environments prone to steel corrosion [25]. In this study, we focus on the response of concrete structural members reinforced with GFRP under flexure. Various properties of GFRP-reinforced flexural members are examined to better understand their behaviour.

Fiber-Reinforced Polymer Bar

GFRP is lighter than steel bars and possesses greater strength, making it an ideal choice for construction [26]. Particularly in marine applications, GFRP bars, as shown in Fig. 1, offer durability and reliability [27]. GFRP is a rigid compound bar with glass Fibers embedded in a long-lasting polymeric epoxy resin [28,29]. The bond stress, elastic modulus, and response under strain are vital mechanical characteristics to consider when using GFRP rebar in bending components [30]. The stress–strain linear relationship, as depicted in Fig. 2 up to failure, illustrates the behaviour of GFRP bars under tension [31]. However, GFRP-reinforced beams are often over-reinforced, which can lead to brittle failure without warning [32–34]. This is considered a disadvantage of using GFRP bars. Additionally, due to their lower elasticity modulus [35], 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. Introducing a helical shape in the bars can enhance the ductility of the FRP-reinforced elements. Moreover, using Fibers can effectively regulate deflection and crack width [36]. Table 1 indicates the elastic constant (Ef) and tensile strength (ft) for GFRP bars used in various experimental studies. It is observed that the tensile strength of these bars is higher than steel reinforcing bars. GFRP bars are very effective in the repair process of reinforced structures damaged due to corrosion [37]. These rebars can drastically improve the flexure strength of the damaged section and enhance the strength of mortar [38]. On-site load tests have confirmed the behavior of the repaired structures Researchers have continuously studied other effective measures to overcome the repair cost of concrete structures [39]. It is observed that polymeric Fibers and rebars, such as carbon, aramid [40], and GFRP, are exceptional for repairing and strengthening concrete members due to their outstanding physical and mechanical properties.

Fig. 1 GFRP bars

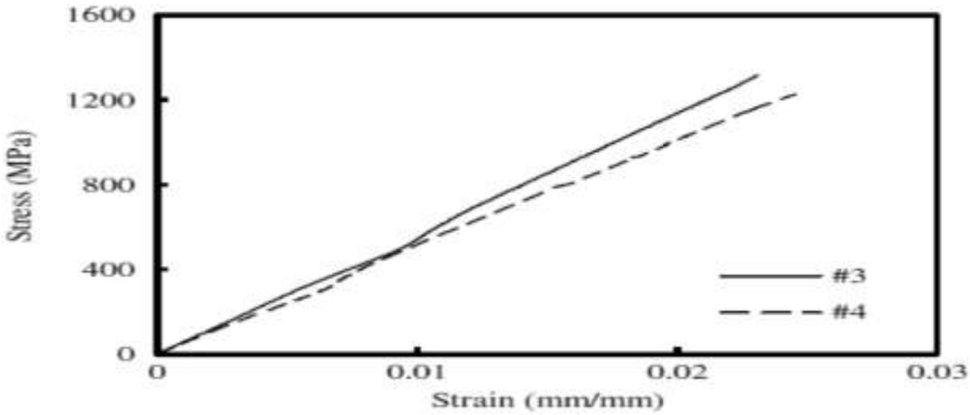


Fig. 2 GFRP bars stress–strain curve [46]

Literature Review:

Hybrid-reinforced bars have demonstrated superior performance over traditional reinforcement in terms of weight, corrosion resistance, and strength. Tensile testing has shown linear stress–strain characteristics, and the beams can withstand significant deformation without experiencing inelastic deformation during testing. Studies on the shear stress of GFRP-reinforced members revealed that longitudinal reinforcement has little effect on the shear capability in GFRP-reinforced beams with various ratios. Therefore, conventional rational equations can be used to approximate shear strength. However, during shear deformation, beams reinforced with GFRP were observed to behave differently from RC beams reinforced with steel. Additionally, the shear strength of GFRP-reinforced beams was found to be lower than that of beams reinforced with steel bars. The lower shear capability of GFRP-RC members compared to steel RC members is attributed to their lower modulus of elasticity, leading to smaller compression block depth and weaker aggregate interlock. A shear stress equation was proposed based on data from experimental analysis of members reinforced with steel, found to be unconservative in beams using GFRP reinforcement. In a study involving seven RC flexural rectangular members, each reinforced with GFRP and steel rebars (hybrid reinforcement), two different types of rebars in two different layers were used near the tensile face of the beam. Additionally, two concrete mixes with strength values of 30 MPa and 50 MPa, respectively, were used. Experiments with four-point flexure were performed on the flexural member for a span of 2.1 m. The beams exhibited high deflection, leading to failure. For beams reinforced only with GFRP bars, the beam stiffness began to change at a load of 7 kN, with an increase in load–deflection behavior until failure at around 56 mm deflection. For steel and hybrid-reinforced beams, a change in stiffness was observed at around 10 kN load, with an increase in load–deflection behavior until failure at around 60 to 70 mm deflection. Additionally, distinct cracks along the middle part of the beams progressed toward the top of the beam, and the steel rebar used for reinforcement exhibited concrete crushing failure under compression, observed at a load of around 40 kN (average deflection: 70 mm). The specimen of the concrete beam with lower strength showed increased cracks. Failure of the beam also occurred due to slip in the bond of internal GFRP rods, while beams with composite reinforcement mainly experienced concrete crushing failure. Bond-slip failure for GFRP-reinforced beams occurred at around 34 kN load (deflection at 56 mm).

D. H. Tavares conducted experiments on six beams with steel and GFRP bar reinforcement. The cross-section of the beam specimen was 150 × 300 mm for a 2.9 m span length. The study of the beams was carried out using a four-point bending experiment. Observations showed comparatively high strain and lower elastic modulus at rupture. These critical parameters impact the flexural response of beams with GFRP reinforcement. When the behavior of beams reinforced using hybrid reinforcement (GFRP and steel) was evaluated against concrete beams reinforced only with steel, 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.

Biswarup Saikia studied the performance and serviceability of GFRP-reinforced flexural members. In GFRP-reinforced concrete beams, bars mainly yielded due to slip along concrete and the bar, as well as a reduction in post-crack stiffness value. Supplementing the polypropylene Fibers did not significantly affect the post-cracking characteristics of beams reinforced with GFRP. An analytical equation was employed to predict the load–deflection response for the beams reinforced using GFRP, and predictions were close to the corresponding experimentally observed response.

The response of hybrid-reinforced beams in flexure was studied by **Wenjun Qu.** Eight beams were cast, two using only steel rebars and GFRP, respectively, and the remaining six beams using hybrid reinforcement. The beam length was 1800 mm, and the cross-sectional area was 180 × 250 mm. Steel stirrups with 100 mm spacing and 10 mm diameter bars as shear reinforcement were used.

studies

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 significantly affected the maximum load-bearing capacity and failure pattern of the flexural member. They also found that the flexural strength of beams reinforced with mixed or hybrid reinforcement was higher.

Saikia and P. Kumar experimented with the strength and serviceability performance of beams with GFRP reinforcement. They observed that the serviceability conditions for beams reinforced with GFRP were governed by the maximum crack width. Researchers also studied the influence of reinforcement ratio, surface characteristics, and concrete cover on the width and spacing of cracks in GFRP-reinforced elements.

Table 1 Summary of properties: GFRP reinforcement used in previous

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& 16	1000	60
[54]	9.5	1100	52.5
[55]	13	941	48.1
[46]	4	1200	50
[56]	4& 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

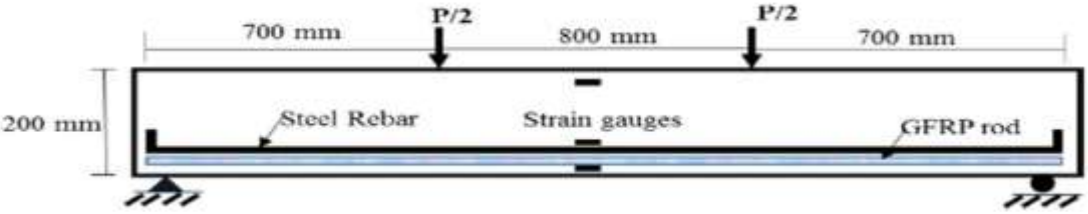


Fig. 3 Test specimen

Load–Deflection Behavior and Crack Pattern:

Lapko and Urbanski presented the following observations on deflections based on different methods and experimental studies of FRP bar-reinforced beams. Unlike traditional beams reinforced with steel bars, basalt fibre-reinforced beams exhibit linear behavior between load and deflection. The values obtained from experimental studies are noticeably higher for the FRP-reinforced beam than for the deflections of the steel-reinforced beam, as shown in Fig. 4 and Fig. 5. This is due to the lower modulus of elasticity in the FRP bar compared to steel bars. as strain-controlled aspects. Figure 5 also shows the comparison . as strain-controlled aspects. Figure 5 also shows the

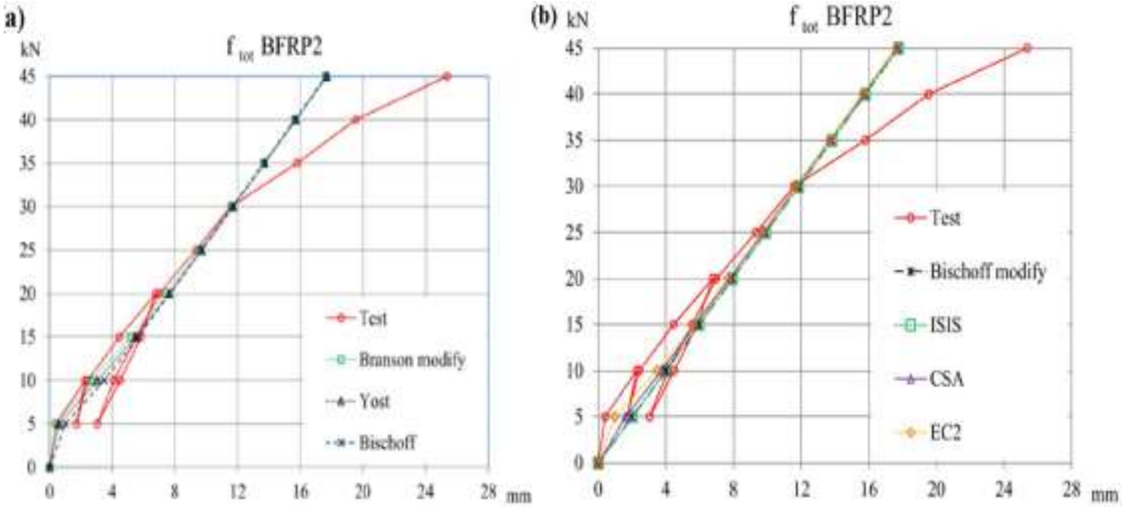


Fig. 4 a Theoretical, b Experimental behavior of load–deflection for FRP-reinforced beam

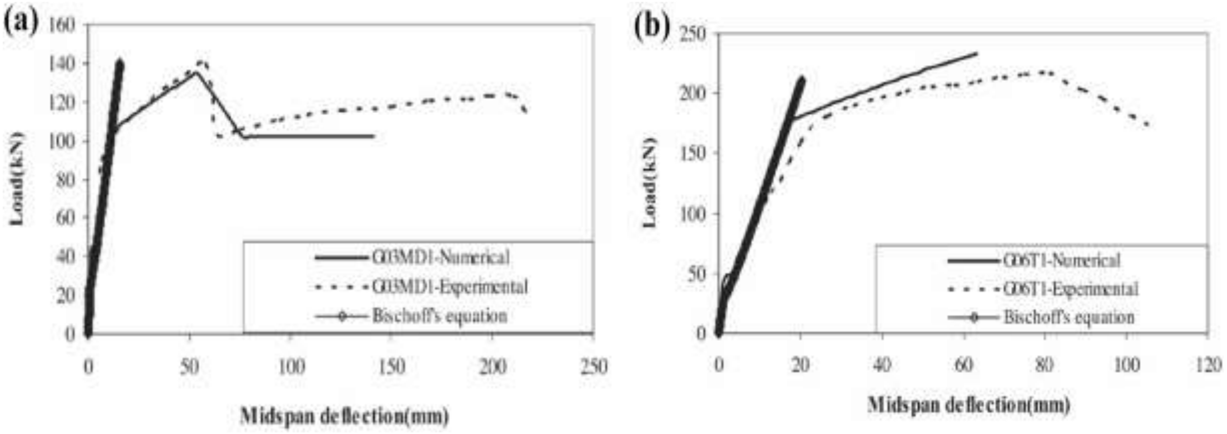


Fig. 5 Load vs deformation relation for concrete beams using hybrid reinforcement (FRP and steel)

Figure 5 also illustrates the comparison of deflection behavior as per the strain-controlled aspects, as assumed by the Bischoff model, both before and after the first load-induced cracking, at lower load levels. M. Issa et al. conducted studies to investigate the influence of Fibers on the flexural behavior of GFRP-reinforced beams [41]. These studies demonstrate that various types of Fibers, such as glass, steel, and polypropylene, improve the ductility of concrete beams reinforced with FRP. Specifically, the use of steel Fibers significantly enhances the ductility of the beam. Therefore, incorporating steel Fibers is one solution to enhance the lower ductility of FRP reinforcement.

Figure 6 displays the load–deflection behavior of lower-strength concrete beams reinforced with GFRP and steel bars. It was observed that the pre-yielding behavior **of** steel (L0) and GFRP-reinforced beams (L2, L5) was identical. Beams reinforced only with GFRP bars (L1) exhibited changes in beam stiffness at a 7 kN load (crack load), and subsequently, the L1 beam specimen displayed an increasing load–deformation behavior until complete deformation. Beams reinforced only with steel (L0) showed typical post-yield horizontal behavior with no notable increase in the load-bearing capacity of the beam. However, after the yielding load of the steel bars, the hybrid-reinforced flexural members (L2 and L5) exhibited an increase in the beam's load-bearing capacity. It was noted that the load–deflection characteristics of L1 and H1 were comparable to those of L2 and H2. The load-resisting capacities of the beams (H2, H5) are higher with higher concrete grades compared to lower-grade concrete (L2, L5).

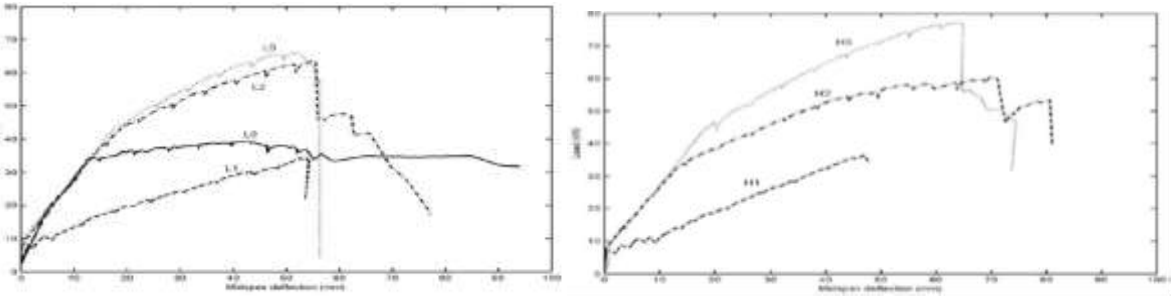
Figure 7 illustrates the load–deformation performance of GFRP-reinforced beams.
In GFRP-reinforced concrete beams, the load–deflection behavior reflects a notable change in the graph at the cracking load. Initially, the slopes of the load vs deformation curves are relatively steep, indicating higher stiffness before cracking, resulting in a gradual increase in deformation as the load is applied. However, the slope decreases after cracking in the tensile zones, leading to a reduction in stiffness. Figure 7(b) illustrates that the deflection in steel-reinforced concrete beams is slower, with a deflection value less thn GaFRP-reinforced concrete beams by only 60%. These outcomes are primarily attributed to the elastic modulus of the reinforcement material; GFRP beams have a lower elastic modulus and thus deform more easily. It also highlights the importance of the reinforcement ratio on the structural deformation capacity of members reinforced with GFRP. It is observed that initially, the beams remain stiff and uncracked. As

the load increases, cracks appear in the pure-bending zone. The load vs deflection behavior of the beams is similar until reaching service loads, indicating the beams' rigidity. The beams were loaded incrementally until experiencing significant deflections. In each load increment, GFRP bars in high-strength concrete outperformed those in standard strength concrete.

Figure 8 illustrates the failure patterns and crack widths on all four sides of the beams made from GFRP-reinforced concrete. Cracks initiate as tensile stress exceeds the concrete's tension capacity. In comparison to plain beams, the rate of crack propagation in GFRP-strengthened beams is slower, and the width of the cracks is less. crack, which

The small crack width corresponding to the ultimate load highlights the higher damage resistance of concrete beams reinforced with GFRP compared to 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 .



1. **Lower strength concrete** (b) **Higher-strength concrete**

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

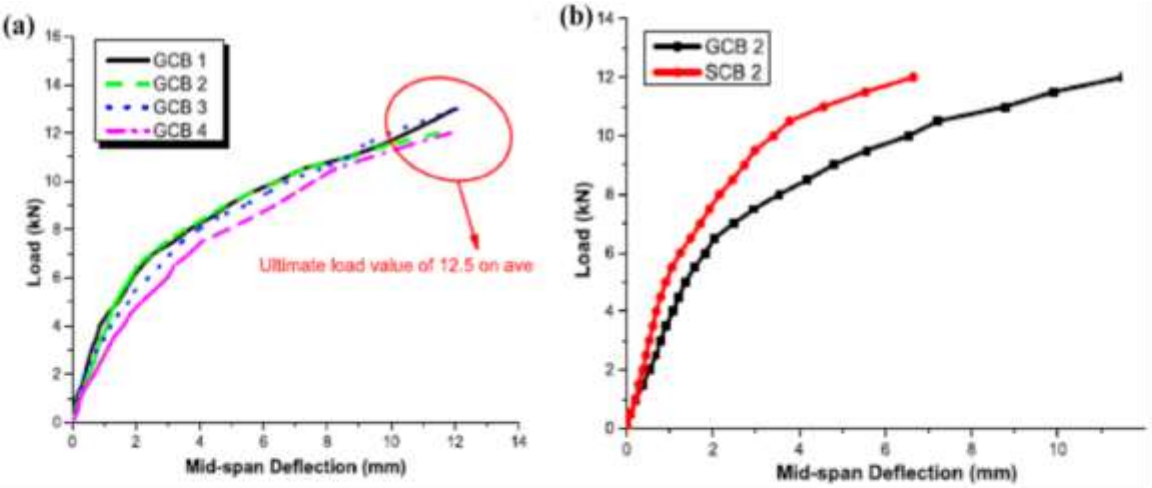


Fig. 7 Load vs deflection plots: a the GFRP-reinforced beams and b the GFRP- and steel-reinforced concrete beams comparison

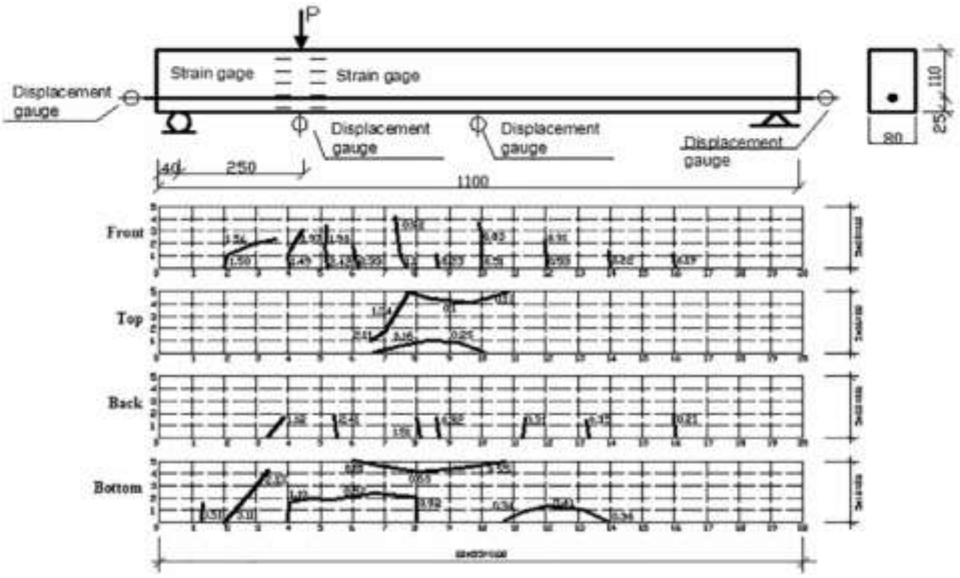


Fig. 8 Cracks on GFRP-reinforced beam after failure

GFRP Concrete Bond Strength:

Researchers conducted tests on FRP-reinforced beams to evaluate bond strength and durability. They also examined the flexural behavior and shear resistance of these specimens. The experimental specimens were prepared following ACI-440-3R regulations and tested according to ASTM standards. Various factors such as concrete strength, cover, bar diameter, and the confinement provided by transverse reinforcement were observed to influence bond strength. The non-homogeneous, anisotropic, and linear elastic characteristics of GFRP bars were crucial factors influencing the bond stress property of glass FRP rods within the concrete. Earlier research has indicated that the alkaline pH of concrete, which ranges from 12.7 to 13.6, can reduce the tensile and bond strengths of GFRP rods reinforced in concrete. Bond stress between the concrete and reinforcing bars plays a vital role in the stability, safety, and deformability characteristics of concrete structures. Bond strength, a common characteristic considered in reinforced concrete, measures the load transmission between reinforcement and concrete. Concrete properties, bar geometry, confinement, development length, and surface conditions of the rebar all affect bond strength. Research has been conducted to understand bond stress in FRP-reinforced concrete structures. Design codes such as the Canadian Highway Bridge Design Code (CHBDC) CSA S6-06 and Canadian Code CSA S806-02 provide equations for the development length of FRP bars in conventional concrete, considering factors such as the surface of a bar, location of the bar, clear cover, and distance between bars. Design codes such as the Canadian Highway Bridge Design Code (CHBDC) CSA S6-06 and Canadian Code CSA S806-02 provide equations for the development length of FRP bars in conventional concrete, considering factors such as the surface of a bar, location of the bar, clear cover, and distance between bars arajli M. and Aboulia studied the ACI 440 guidelines for the bond strength behavior of GFRP bars in tension, conducting 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. Due to the larger concrete cover, the pullout test specimens were observed to fail in pullout mode, as shown in Fig. 12, which also illustrates 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 and suggested an analytical expression predicting the bond stress of headed-end bars-reinforced specimens containing discrete fibers.Fei Yan et al. conducted

682 pullout test specimens to understand the bond performance of GFRP bars. Figure 13 illustrates the bond performance evaluation (BPE) model for concrete and steel reinforcement.The modified bond-slip stress model mBPE, shown in Fig. 14

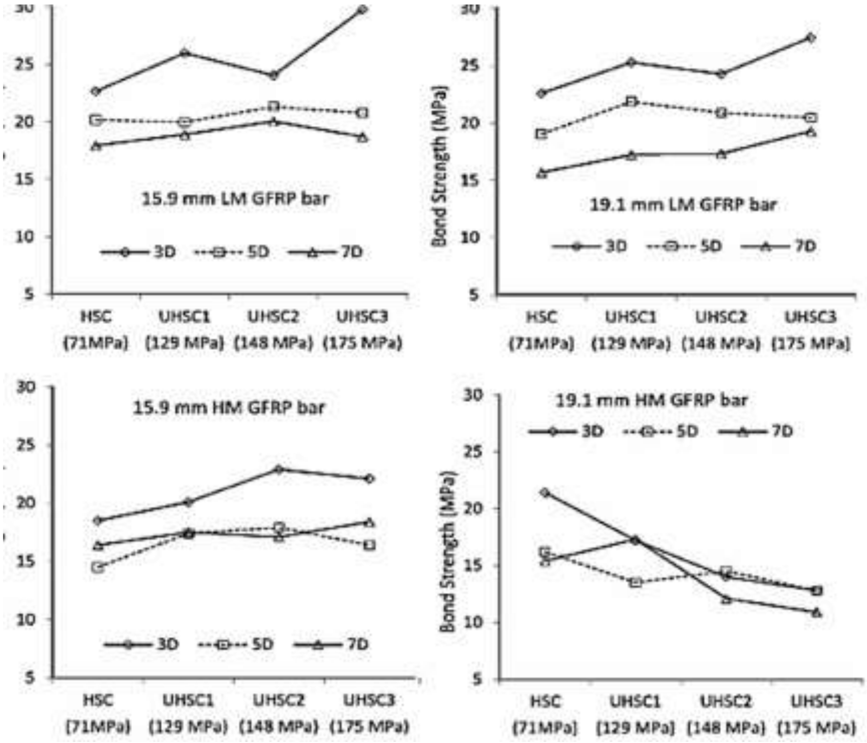


Fig. 10 Effect of rebar type/diameter, concrete compressive stress, and embedment Length on bond stress [94]

In these equations, ss and $\tau\tau$ represent slip and bond stress, while sb and τb denote the extreme slip and its corresponding bond strength. An improved model for FRP bars took into account the treatment of the bond stress surface.Bogachan Basaran et al. conducted a detailed investigation into the effect of development length on the bond strength of FRP bars embedded in concrete. Their research aimed to provide an in-depth analytical study to evaluate the bond stress of FRP reinforcing bars in concrete. The analytical model results were compared with experimental results from the literature. Practical algorithms were developed to predict the strengths of bond and the development lengths of FRP reinforcing bars with different physical properties. Doost Mohamadi et al. evaluated the influence of concrete type on the bond strength of GFRP bars. They observed that increasing compressive strength in both normal-weight and lightweight concrete enhances the bond strength. Due to their shape, surface texture, and mechanical properties, GFRP bars exhibit lower bond strength with concrete. However, by applying an appropriate restraint system, this deficiency can be addressed in the design approach. Sand-coated BFRP bars demonstrated higher adhesion and bond strength to concrete than ribbed bars.

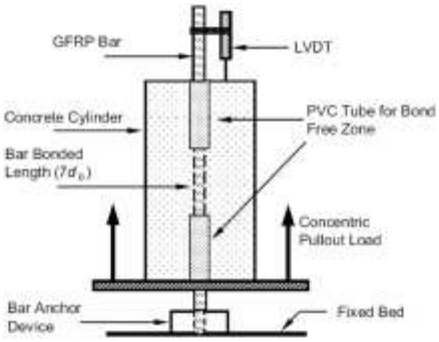


Fig. 11 Test setup for pullout specimens [95]

Fig. 12 Bond failure modes of beam specimens

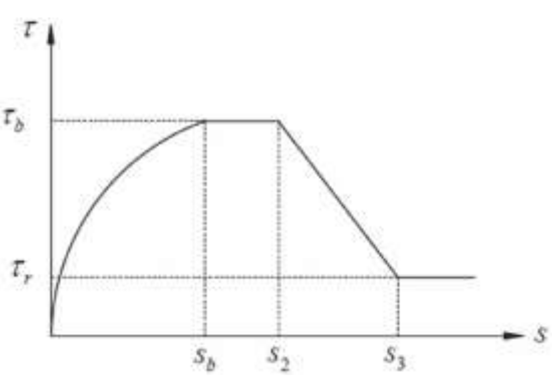


Fig. 13 BPE model for steel rebar [91]

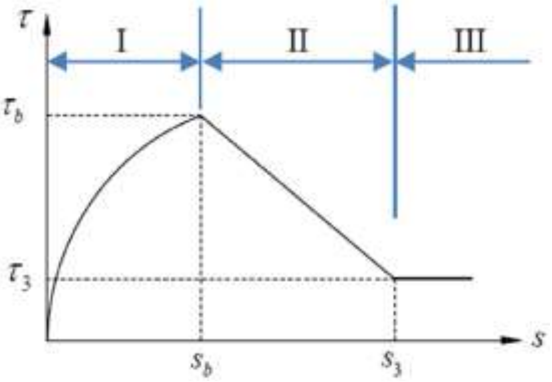


Fig. 14 mBPE model for FRP bar [42]

GFRP bars [43]. The elevated temperature can degrade the bond strength of frp- reinforced concrete

CONCLUSION:

This paper provides a comprehensive review of the behavior of GFRP-reinforced structural members in flexural applications, discussing load–deflection characteristics, bond strength, and crack patterns. The aim of the review is to critically assess the application of GFRP as reinforcing bars in concrete structures, particularly in beams. The key findings from the literature study are summarized as follows:

1) FRP-reinforced concrete elements are typically designed with increased safety factors.

1. Design guidelines provided by ACI and CSA codes are used for designing GFRP-reinforced concrete structures. However, there are no specific design codes available, especially in the Indian context, for such members.
2. The lower elasticity modulus and higher rupture strain of GFRP are the main factors responsible for the higher ultimate strength, lower stiffness, and greater deflection of GFRP-strengthened beams

compared to steel-reinforced beams. GFRP-reinforced members in flexure outperform steel-reinforced beams.

3. The flexural behavior of beams can be improved by using steel rebar in combination with GFRP reinforcement, resulting in increased load-carrying capacity and higher deflection compared to GFRP-reinforced beams. However, in the post-cracking stage, the GFRP bar, along with the steel bar, carries more load, leading to shear failure. Therefore, shear reinforcement needs to be carefully considered.
4. The critical load-carrying capability of hybrid-reinforced concrete beams is higher compared to beams reinforced using only GFRP or steel, respectively.
5. Various investigations on using Fibers in GFRP-reinforced concrete members indicate improvements in the mechanical properties of concrete members. Steel Fibers can resist macro-cracks, while basalt and glass Fibers can resist micro-cracks. The percentage of hybrid Fibers is determined based on test results and cost comparisons of using Fibers in concrete.
6. The maximum load-carrying capability in GFRP-reinforced concrete beams with Fibers is higher than in GFRP-reinforced beams without Fibers.
7. Literature studies have shown that hybrid reinforcement plays a significant role in improving the bending stress of beams, thereby enhancing their flexural strength beams. Load–deflection curves before yielding remain the same for GFRP-reinforced or steel-reinforced flexural members for the same series of compressive strength.
8. GFRP bars become effective for hybrid reinforcement once steel rebars reach their yielding point. Supplementing concrete members reinforced with GFRP with steel Fibers is one technique to mitigate the lower ductility limitation.
9. The effective reinforcement ratios significantly influence the load-carrying capacity of hybrid-reinforced beams more than the axial stiffness ratio between steel and GFRP. As the effective reinforcement ratio increases, the load-carrying capacity also increases.
10. Corrosion and deterioration of steel-reinforced concrete, along with the high costs of rehabilitating and remediating structures, make GFRP bars a practical alternative. Despite some drawbacks such as low elasticity modulus and lower shear strength compared to steel, GFRP bars' greater tensile strength and non-corrosive nature make them a favorable alternative.
11. Experimental and analytical studies are necessary to better understand the flexural behavior of such members. New strength reduction factors for an innovative design approach for GFRP-reinforced concrete members can be developed through further research.
12. Despite previous studies, the proposed equations in various studies have limitations in understanding the behavior of GFRP bars in concrete flexure members. The lack of standard design guidelines addressing the disadvantages of pure GFRP-RC members is notable. Therefore, developing new methodologies or design guidelines is critical for the future use of GFRP rebars in concrete structural members, potential replacing steel reinforcing bars with GFRP bars. This could help avoid corrosion issues in structural elements, resulting in safer and more durable structures.

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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 research.

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 our manuscript does not conflict with the ethical standards required by the journal.

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