Flexural Behavior of GFRP Reinforced Concrete Beams

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ABSTRACT: Glass fiber-reinforced polymer (GFRP) rebar is a composite material with the potential to replace steel rebars, which are often employed in RCC constructions. GFRP rebar greatly increases the lifespan of structures and is corrosion-resistant, lightweight, stronger, non-conductive, and long-lasting. Steel's vulnerability to corrosion, increased maintenance costs, weight, and short lifespan are the primary reasons for the switch from standard steel rebars to Glass Fiber Reinforced Polymer (GFRP). In severe conditions, steel rebars are prone to rust, which gradually reduces structural integrity. In contrast, GFRP is lighter, more durable, and resistant to corrosion. To find out how flexural members reinforced with GFRP will respond to shear and bending, the researchers employed a variety of design philosophies; investigated alternative codal provisions, reinforcement ratios and examined the characteristics of GFRP rebar. This paper critically examines the reaction of flexural members reinforced with glass fiber-reinforced polymer (FRP) bars, with an emphasis on studies carried out in the last decade. To guarantee structural safety, optimize design, and comprehend load-bearing capacity, it is essential to investigate the flexural behavior of concrete beams reinforced with GFRP rebars. In contrast to steel, GFRP exhibits a lower stiffness and a higher tensile strength. By evaluating deflection, crack patterns, and failure modes, flexural performance research ensures dependable and durable construction. As a result, a careful examination is necessary to comprehend the behavior of these structures. This study examines a range of GFRP-reinforced beam characteristics to understand how GFRP reinforcement is used in flexural members.

Keywords: GFRP rebars, Reinforced concrete, Design philosophy, Flexural behavior.

INTRODUCTION

The demand for durable, corrosion-resistant, and high-performance construction materials has become increasingly important in modern civil engineering. Traditional steel reinforcement, while widely used in concrete structures, poses several challenges particularly in aggressive environments such as coastal regions, industrial zones, and areas with high humidity or exposure to de-icing salts. Corrosion of steel reinforcement not only compromises structural integrity but also leads to increased maintenance costs and a reduced lifespan of structures. As a result, researchers and engineers have been exploring alternative materials that can address these limitations while maintaining or improving structural performance. Glass Fiber Reinforced Polymer (GFRP) has emerged as a promising substitute for steel reinforcement in concrete structures. Composed of high-strength glass fibers embedded in a polymer matrix, GFRP bars exhibit exceptional resistance to corrosion, high tensile strength-to-weight ratios, electromagnetic neutrality, and non-magnetic properties. These characteristics make GFRP particularly attractive for use in infrastructures such as bridges, marine structures, tunnels, water treatment plants, and buildings exposed to harsh environmental conditions.

Despite the many benefits of GFRP reinforcement, its behavior in concrete structures is fundamentally different from that of traditional steel. GFRP bars exhibit linear-elastic behavior until failure, without yielding, which influences the ductility and failure mechanisms of reinforced concrete members. Furthermore, the bond characteristics, crack control, deflection behavior, and long-term performance of GFRP-reinforced concrete beams demand a detailed understanding to ensure safe and effective design practices. Existing design codes are still evolving to fully accommodate the unique mechanical and physical properties of GFRP

This research focuses on the structural performance of GFRP-reinforced concrete beams, with an emphasis on flexural behavior, failure modes, and the influence of reinforcement ratios. The study aims to contribute to the growing body of knowledge by providing experimental evidence, comparative analysis with steel-reinforced beams, and recommendations for design improvements. Through this investigation, the potential of GFRP as a viable and sustainable alternative to conventional reinforcement in concrete beams is critically evaluated, supporting its integration into future construction practices.

LITERATURE REVIEW

Flexural Behavior of Beams was examined by Omar Gouda et al.(2022) where, Eleven GFRP-reinforced concrete beams measuring 4,350 x 400 x 200 mm (length x height x breadth) casted and tested under 4 point loading. The distance between the centers of beam supports was 3,750 mm, while the gap between the centers of the loading points on the beams was 1,000 mm. In order to measure the load values, a 500kN load cell was used with an accuracy of ±0.05kN. The beams were having the unique nomenclature Beams 3#5-c50-s317, 3#5-c50-s200, and 3#5-c50-s100 here, B is the size of the reinforcement, c is the transparent concrete cover, and a is the total number of tensile reinforcements made of GFRP. Each GFRP reinforcement had at least two strain gauges are installed, each measuring 2 mm in gauge length. During the experiment, the widths of the initial 3 flexural cracks were recorded up to the point of failure. The initial widths of these cracks were first measured using a portable microscope and subsequently with the LVDT. In this study researchers achieved the cracking Moment Mcr by experimental investigation which is validated with previously calculated cracking moment by CSA-S806-12 (Canadian Standard Association-2012), ACI440.1R-15 (American Concrete

Institute-2015) and by CSAS6-14 (Canadian Standard Association-2014).

The highest cracking moment capacity was theoretically calculated for beam 2#5-c30, c38, c50 which means beam with 2 GFRP bars and 15mm diameter of bars at tension side with clear concrete cover (30, 38, and 50) mm respectively. The calculated moment was 20.2kN.m, 20.9kN.m, and 13.5kN.m by the CSAS806-12, ACI440.1R-15, and CSAS6-14 design provisions respectively. But experimentally the highest critical moment was achieved by 2#8-c50 which means 2 GFRP rebars 25mm diameter of bars with 50mm clear concrete cover which is 19kN.m. While talking about the failure modes that all beams failed due to the crushing of top concrete fibers which were already expected by the researchers. As the reinforcing ratio rose, so did the depth of crushed compression concrete blocks. As per the researcher this happened because of the extensive separation between the stirrups particularly in the intermediate bending zone, the lateral support for compression reinforcements is insufficient. Ultimately, it is determined that the concrete crushing at the intense compression fibers caused the tested beams to collapse. Beams with a lower reinforcement ratio (≤0.85%) showed bilinear load-deflection behavior, whereas trilinear behavior was displayed by individuals with a greater reinforcement ratio. Moment capacity predictions from the CSAS806-12 (CSA 2012) and ACI440.1R-15 (ACI 2015) were in close agreement with the experimental findings.

GFRP rebars can be the perfect alternative for the traditional steel rebars for this the research has been made by the Shahad AbdulAdheem Jabbar and Saad B.H. Farid (2018) where the research work focuses on substitution of GFRP rebars for steel rebars in concrete buildings. In this study, researcher's main aim was to manufacture the GFRP rebar made of unsaturated polyester resin and glass fibers, cast the cube samples and beams and then test under three point loading test. The test results highlights the tensile strength of GFRP rebar, bond behavior, bending strength and flexural strength of beam specimens. The manufactured GFRP rebar contains 86 fibers with resin to create a 1.25 cm diameter rebar. Unsaturated polyester resin made by Iran Company, Methyl ethyl ketone peroxide by a Turkey company. Iraqi specifications were met by the necessary fibers, fine aggregates, and qualities such as density, specific gravity, sulfate content, and sieve analysis. Ultimately, a 12.5 mm diameter bar, typical for construction applications, was produced, with an 80% fiber volume fraction and a 20% polyester volume fraction. Ultimately, a 12.5 mm diameter bar, typical for construction applications, was produced, with an 80% fiber volume fraction and a 20% polyester volume fraction. The test results showed that the tensile strength of GFRP rebars (593 MPa) was approximately 13% higher than that of steel rebars, and the flexural strength of sand-coated GFRP reinforced concrete reached 13.5 MPa at 28 days, which was close to steel-reinforced concrete (17.5 MPa). Moreover, GFRP RC exhibited higher strain and more ductile behavior before failure, providing a better failure warning compared to traditional steel RC. While GFRP bars had lower flexural modulus, the bond performance was significantly enhanced through sand coating, leading to reduced crack widths and improved energy absorption. The study concluded that GFRP rebars particularly with surface modification can serve as a highly effective and durable replacement for steel in reinforced concrete, especially in aggressive environments where corrosion resistance and ductility are critical.

The study of bending behavior of RC beams with regular web openings by GFRP reinforcement is studied by Saruhan Kartal and Emin Kısıklı (2024). Eight RC beams in all were put through four-point bending testing, consisting of two reference beams devoid of web apertures. Each stirrup was created by joining four separate FRP bars considering that GFRP stirrups are difficult to bend. The current studies showed that the RC beams' flexural behavior is greatly impacted by the diagonal reinforcement that surrounds the apertures. Eight RC beams in all were prepared in which each beam measured 200 mm in width, 336 mm in height, and 3000 mm in total length, with a clear span of 2800 mm. Reference specimens without openings are denoted by "R," whereas RC beams with circular openings are denoted by "C." Only GFRP materials are used to reinforce the specimens, as indicated by the second capital letter "G." The lowercase "x" and "s" indicate the usage of diagonal reinforcement between the short stirrups and the apertures of the posts, respectively, In contrast, "m" and "h" indicate ratios that are moderately and highly reinforced, respectively. Ten circular openings (Ø160 mm) were present along the span of the remaining RC beams, while reference beams without holes were included in each experimental group. For the sections that were moderately and severely reinforced, respectively, five and six GFRP (Ø12) rebars were utilized as tension reinforcement. It was made sure that RC beams were over-reinforced (ACI 440.1R-15-2015), which means that the concrete crushed before the FRP reinforcement ruptured. The load points and support points were positioned 250 mm from the beam's midpoint and 100 mm from its ends, respectively. Debonding failure was seen between the beam type and tensile reinforced concrete. Individual short stirrups, the insufficient dowel action effect of GFRP longitudinal reinforcement, and the vital role of web apertures are the causes of this kind of failure. While the failure mode in reference specimens changed from bending to bond + shear failure, there was no change in the failure modes of RC beams with apertures when the longitudinal reinforcement ratio was increased.

At the end it is found that about 90% of the theoretical capacity was attained by RGh regarding load, 85% regarding curvature, and 85% regarding FRP strain. When the reinforcement ratio improved in RC beams with openings, the load capacitance is increased by a maximum of about 11%, but the curvature and FRP strain values decreased by a maximum of about 20% and 19%, respectively. The FRP strain value is dropped by roughly 8% and the bending capacity is improved by roughly 9% with a 15% increase in the reinforcement ratio for RGh*t/RGm* specimens. Regular web holes in GFRP-RC beams demonstrated bond failure at the openings and diagonal concrete crushing. The lower and upper chords both experience shear zones at the same time. In comparison to other beams with apertures, RC beams with diagonal reinforcement have greater strength and strain capacity.

The design of flexural members reinforced with GFRP bars by Indian Standard code parameters are studied by Abinash Kumar Sethi, et al (2020). In this research they have derived design philosophy to design the RC beam reinforced with GFRP rebars as per the Indian Standard code parameters. IS codes regarding design of GFRP reinforced rebar are yet to be published by Bureau of Indian Standards. Therefore, after examining the many codes and criteria for flexural members, the investigation of design guidelines is established. Within the elastic range, the slope of the stress-strain curve represents the modulus of elasticity (E) of FRP. For GFRP bars, the ultimate rupture strain is calculated to be between 0.012 and 0.015. Position of neutral axis is derived by the formula of Maximum depth of Neutral Axis i.e. Xu limiting, where Xu limiting is given by Xu limit=$(0.0035/0.0035 + 0.0128)$d. Total tensile and compressive force can be expressed as, T=$AfEf$ $\mathcal{E}f$, C =0.542 $fckxub$. Xu =Actual depth of Neutral Axis b =width of beam), $\mathcal{E}f$ = Modulus of elasticity of GFRP bars, Af =Area of GFRP reinforcement, fck = Characteristic Compressive strength of concrete. By using the above design philosophy the GFRP reinforced RC beam of size 1200mm x 150mm x 100mm is casted. The beam is tested under 2 point bending test measuring 366.66mm distance from 2 point loads. According to the experimental findings, the specimen was flexure critical, which caused the top layer of concrete to crush as a result of the bottom layer being over-reinforced. Increasing reinforcement percentage leads to higher load bearing capacity. Whereas the theoretical load was 26.88 kN and 35.216 kN was the experimental ultimate load. The theoretical maximum load differs from the experimental load by 23.67%. Analytical investigation suggests that increasing the reinforcement ratio in flexural members improves load carrying capability. Consequently, designing GFRP RC structures as over-reinforced is advised.The range of discrepancies between experimental and theoretical results is 18% to 25%. Superior performance for high strength and ultra-high strength concrete is offered by GFRP reinforced concrete. A higher concrete grade results in a higher ultimate load capability.

The flexural behavior of deep beams made of high concrete reinforced with locally made GFRP rebars is examined by Mona K. Nassif et al (2021). Eight beams (1800 mm in length, 500 mm in depth, and 150 mm in width) with shear reinforcement of 7Ø8/m were cast and subjected via a two-point loading test until it failed. 50 and 60 MPa concrete compressive strengths were employed. Furthermore, various steel reinforcement ratios of 0.0033 and balanced condition ratios of 0.8, 1.0, and 1.2 were employed. To cut costs, GFRP rebars with diameters of 8 mm, 10 mm, and 12 mm are made locally for this study. Following tensile testing, the resulting tensile strengths were 650 MPa, 740 MPa, and 1075 MPa, respectively. The a/d ratio of the beams was 1.33, where d is depth and an is distance from the applied load. The 8 beams were categorized in 2 groups. In group 1 - beams naming SP1, SP3, SP4, and SP5 with 50Mpa compressive strength having reinforcement ratios of 0.83 µbs, 0.80 µb, 1.00 µb, 1.20 µb respectively. In group 2- Beams naming SP2,SP6, SP7, SP8 with 60Mpa compressive strength having reinforcement ratios of 0.83 µbs, 0.80 µb, 1.00 µb, 1.20 µb respectively. Beams SP1 and SP2 are reference beams casted with steel rebars where other beams are reinforced with GFRP rebars. In group 1 SP1 reached failure load of 658.69kN where failure load was lower for other beams than for the control specimen. SP5 reached the failure load of 675.3 kN surpassing control specimen SP1 by 2.5%. In group 2 SP8 reached failure load of 720.4 kN surpassing control specimen SP2 by 4%. In accordance with the crack patterns, about group 1 the initial flexural fracture was caused by a force of 110kN, 117kN, 120kN for SP3, SP4 and SP5 respectively. The initial flexural crack for group 2 developed at a load of 115kN, 118kN, 130kN for SP6, SP7 and SP8 respectively. Higher deflection was the result of lowering the beams' stiffness more quickly, especially the GFRP RC beams. This might be as a result of GFRP bars' lower elastic modulus when contrasted with reinforcing steel bars. Non-linear finite element analysis (NLFEA) of deep beams carried out with the ANSYS-2019-R1 software. All models have a maximum meshing dimension of 25 × 25 mm. The deflection ratios are calculated from the results obtained from NLFEA and experimental work. With an average of 88.0%, the load-deflection curves for every specimen under examination and the numerical results showed good agreement.

Sayan Sirimontree, et al (2021) conducted a conduct an inquiry of flexural behavior of concrete beam. It involves casting and testing six full-scale beams measuring 150x250x2500 mm and strengthened with steel or GFRP bars using a four-point loading test. For Grades SD30 and SD40, the steel reinforcements' nominal yield strengths were 300 and 400 MPa, respectively. All the rebars used are of diameter 12mm. Beams B-30(A) & B-30(B), B-40(A) and B-40(B), B-FRP(A) and B-FRP(B) are casted by steel SD30, steel SD40 and GFRP rebars respectively. Shear failure is avoided by using 9 mm (RB9) stirrups spaced 100 mm apart. Testing of beams is conducted under simply supported boundary conditions by two steel rollers. LVDTs were used to measure deflections at two loading locations at the mid-span position. For all beams, the initial cracking load of 10kN was identical. Because GFRP bars have a lower elastic modulus than steel rebars, when concrete was reinforced with GFRP bars, it was less rigid than when steel bars were used. The test results are mentioned in the table below. When concrete beams were reinforced with GFRP bars, their maximum load was 98% greater than that of concrete beams reinforced with steel bars (grades SD30 and SD40), respectively. With maximum and average loads of about 35.6 kN and an average deflection of 55 mm, beams bearing the B30 mark have lower load capabilities. Better performance is demonstrated by beams designated as B-40, which can support loads up to 62.2 kN and have an average deflection of 51 mm. With an average deflection of 52.3 mm, the best-performing beams, designated B GFRP, can support maximum loads surpassing 70.5 kN. These findings show an improvement in deflection control and load-bearing capability, most likely due to improvements in structural and material design.

Performance of concrete beams including holes reinforced with GFRP rebar is studied by Hasan Hussein Ali and Abdulmuttailb I. Said (2023). The flexure behavior of simply supported RC beams with holes in both vertical and transverse directions is investigated in this study. Five beams with dimensions of 2700 mm by 180 mm by 260 mm were cast and put through a two-point loading test. Out of 5 beams one beam is casted with devoid opening as a reference beam. Two beams are casted 2 adjacent openings with vertical and horizontal opening in the mid-width. Remaining two beams are casted with opening of 89mm diameter. The beams casted with 2ø12 mm GFRP tensile reinforcement, 2 ø8 mm GFRP compression reinforcement and 6@120 mm of GFRP stirrups. 36 MPa was the average compressive strength of the concrete, whereas the tensile strength of 12 mm diameter GFRP bars was 1380 MPa. Two point loading tests are performed using hydraulic testing apparatus with a 600 kN capability. The mid-span section used LVDTs, and the load increased by 5 kN. Cracks were discovered to occur at random locations and were usually vertical after the beams were tested. The mid-span displacement increases and the ultimate strength decreases more as a result of the vertical holes. This is because the concrete at the crucial area is significantly reduced by the vertical opening. The percentage decrease in ultimate strength for beams with a single opening in comparison to the reference beam was roughly 22% for horizontal openings and 27.8% for vertical openings. In contrast with the control beam, double-opening beams had an ultimate load reduction of 11% for vertical openings and 8.6% for horizontal openings. For beams with one or two horizontal apertures, the ultimate load was reduced by 22% and 8.6%, respectively. The mid-span deflection increases by 32% and 21%, respectively, when the apertures are increased from single to double. By decreasing ultimate strength, increasing mid-span displacement, and reinforcing strain, openings in RC beams affect overall performance. Beams reinforced with GFRP with flexure zone apertures showed the largest reduction in ultimate load, around 27.8%. Approximately 34.85% more tension GFRP reinforcement strain was seen in the specimen with a single vertical opening in the flexural area at the same load level.

Pham Thi Loan et al (2021) studied flexural behavior of beams made of GFRP reinforced concrete under 3 point bending test. 3 beams with different GFRP ratios are designed by ACI-440 1R provisions. The beams of size 1600mmx100mmx180mm are casted with B20 grade of concrete. The beams are designed in such manner to fail either by rupture of GFRP rebars at tension zone or pulverizing. All the beams are having 2#8mm diameter of GFRP rebars as top reinforcement. Beams B1, B2, B3 are with 2, 3 and 4 number of GFRP rebars at bottom having 8mm diameter. Mn is the nominal flexural strength after finding ρf FRP reinforcement ratio. The design ultimate load calculated for the beams B1, B2 and B3 is (11.4, 14 and 14.4) kN respectively. The values obtained after testing the beams are (11.46, 14.38 and 14.4) kN with the difference of 0.5, 2.7,0 w.r.t design load respectively. FRP reinforcement ratio producing balanced strain conditions- ρfb was 0.46 for all the beams. For beams B1, B2, and B3 FRP reinforcement ratio- ρf was 0.43, 0.64 and 0.90 respectively. The beams' cracks were visually examined throughout the test, from the initial crack to failure, and the loads that accompanied them were noted. The first cracking appeared with the load values of cracking curves being 1.6 kN, 1.8 kN, and 3.8 kN in the sequence of beam B1, B2, and B3, respectively. Vertical flexural cracks are concentrated near the load point, whereas fractures spreading to the sides of the supports tend to incline and it is observed that concrete in the compression zone of GFRP reinforced beams was severely crushed. For concrete crushing failure, the strength reduction factor φ was set at 0.65, while for FRP rupture failure; it was set at 0.55 as per ACI-440 1R provisions. A linear branch and two major linear segments comprise the load-deflection curves of the RC beams with GFRP bars that represents the beam's cracked response and linear segments with a lower slope that indicate the stiffness degradation and cracked response of the beam. To guarantee beam resistance and prevent FRP rupture and concrete crushing failure during the service stage, it is essential that the strength reduction factor for flexural strength fall between 0.55 and 0.65. For GFRP reinforced concrete beams, the plane section assumption has remained valid.

Performance of doubly reinforced concrete beams with GFRP bars is examined by Musa AbdulMuttalib Issa et al (2024) to assess their performance in relation to their deflection, load-bearing capability, and other mechanical attributes. A total of six beams with a rectangular form measuring 300 mm in width by 250 mm in depth, 2,400 mm in total length, and 2,100 mm in clear span were cast in this study. The testing of beams is done under static actuator having capacity of 150 metric-tons. Four long bars, each with a diameter of 15 mm, were used to singly strengthen the reference beam (R-1) in the tension zone with GFRP tension reinforcment ratio ρf= 1.885, ρfb (FRP reinforcement ratio producing balanced strain conditions). There were 2 Ø 8 mm longitudinal steel bars installed in the compression zone.. Out of two groups the first group with 3 beams- G1GS1, G1GS2, and G1GS3 reinforced with GFRP bars. Here, constant reinforcement ratio for tension zone was 1.885 ρfb, where for compression zone reinforcement ratios varied by 0.5, 0.75, and 1.0. Two beams (G1 GS4 and G1 GS5) strengthened with GFRP bars make up the second group. Here, constant reinforcement ratio for tension zone was 2.357 ρfb, where for compression zone reinforcement ratios varied by 0.4 and 0.6. Because the fibers of GFRP bars will break if it is clamped straight onto their ends, testing them in direct uniaxial tension is challenging. So, The ends of steel couplers were epoxy-bonded to GFRP bars. Applying a test for load control, the beams were subjected to a 5 kN loading step that increased monotonically until failure. In comparison to beam (G1GS1) with 2Ø15mm, specimens (G1GS2) and (G1GS3) have respective diameter specifications of 3Ø15mm and 4Ø15mm, achieved 9.29 and 6.29% increases in load capacity. It is clear that the entire service load that corresponded to an 8.75mm midspan deflection varied from 32.9 to 40.6% of the failure load. It has been confirmed that expanding the compression GFRP bar's area boosts the beam's stiffness and resistance to displacement when the load is at its highest. The examined beams had an average crack spacing of 100.7 to 150.7 mm. Ultimately, it is determined that when the compression GFRP-reinforcement ratio rises, the crack width falls under service stress. For sections intended to fail in concrete crushing, the service load that meets serviceability norms at the cross section level is between 27 and 50% higher than the ultimate load.

Naganna et al (2024) completed an experimental investigation on steel and GFRP RC beams using polypropylene fiber. In this study 11 beams of size 100 × 150mm and a 1500-mm casted with M20 grade of concrete. The beams are casted by changing the percentage and type of reinforcement at tension-compression side. In this research the beam specimens varied with use of different combinations and proportions of steel reinforcement, GFRP bars, polypropylene fiber. B1-CB beams casted with 4 steel rebars of 10mm diameter at top and bottom. B2-SP beams casted same as per B1 but replacing one percent of concrete's fine aggregate volume which is composed of polypropylene fibers.

B3-GP casted as per B1 just by changing steel rebars by GFRP rebars. B4-GP-T casted with 2 steel bars at top while 2 GFRP rebars at bottom of 10mm diameter in addition of one percent of concrete's fine aggregate volume which is composed of polypropylene fibers. B5-GP-C casted as per the same phenomenon used while casting B4 just by reversing both steel and GFRP rebars both at top and bottom. PFRC beams considered as polypropylene fiber reinforced concrete beams which involves beams B1, B2, B3. At the end it is concluded that when using GFRP in the compression zone, PFRC's ultimate load carrying capacity and first fracture load are both raised by 0.11% and reduced by 7.5%, respectively, in comparison to conventional beams, while there is a 125.5% increase in deflection at the initial crack.

RESULTS & DISCUSSION

Jabbar & Farid (2018): Improved GFRP-concrete bond using sand-coated rebars, boosting flexural strength.

Kartal & Kısıklı (2024): Introduced diagonal GFRP reinforcement around openings to recover flexural capacity.

Sirimontree et al. (2021): Showed GFRP RC beams can exceed steel RC load capacity by up to 98%.

Ali & Said (2023): Identified vertical openings as more detrimental than horizontal in GFRP RC beams.

Issa et al. (2023): Proved GFRP in compression zone adds minimal benefit in doubly reinforced beams.

Naganna et al. (2024): Combined GFRP bars with polypropylene fibers for enhanced ductility and crack control

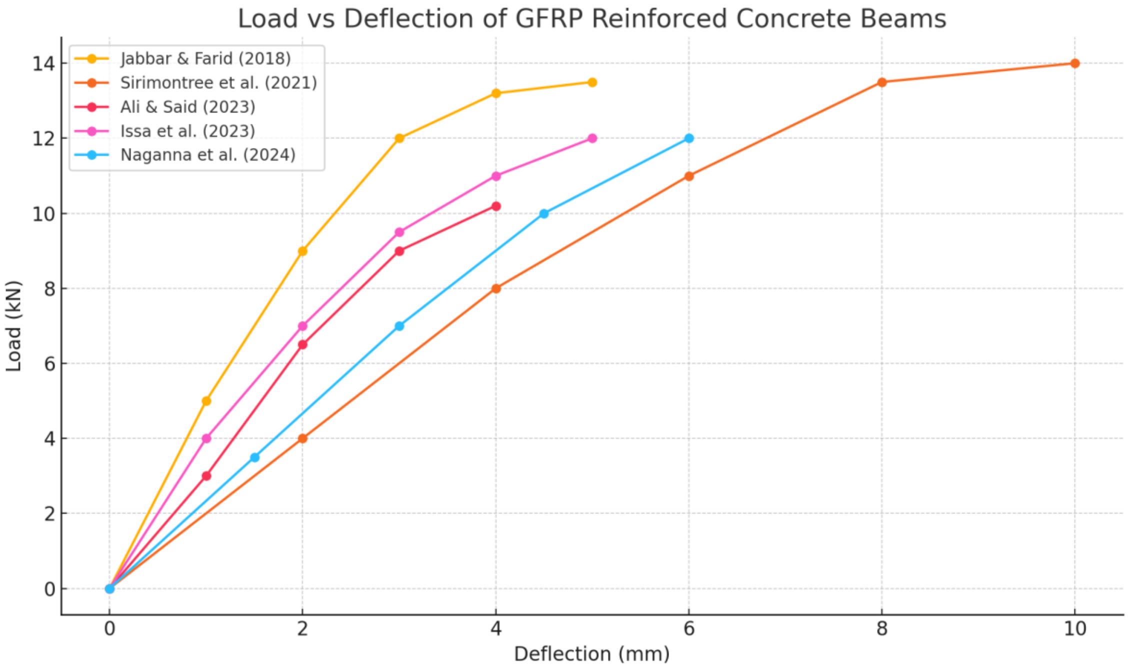

Fig: Load vs Deflection Graph

CONCLUSION

The adoption of Glass Fiber Reinforced Polymer (GFRP) rebars is gaining serious momentum in civil infrastructure due to their corrosion resistance, high tensile strength, and lightweight characteristics. With steel rebars facing durability issues, especially in marine and chemically aggressive environments, GFRP has emerged as a viable alternative. However, despite increasing global usage, India **still lacks standardized codal guidelines** for the design of GFRP-reinforced concrete beams, resulting in a heavy reliance on international codes such as **ACI 440.1R and CSA S806**. Additionally, **long-term environmental durability data**, especially under Indian climate and service conditions, remains sparse and must be addressed to boost confidence in real-world applications.

From the reviewed literature, several critical insights emerge that can inform future design:

Over-reinforcement in GFRP beams (as per ACI 440.1R) is consistently recommended to ensure concrete crushing occurs before GFRP rupture, as observed in Kartal & Kısıklı (2024), Pham Thi Loan et al. (2021), and Sethi et al. (2020).

Use of diagonal GFRP reinforcement around web openings (Kartal & Kısıklı, 2024) effectively mitigates stress concentration and enhances flexural strength, outperforming standard horizontal layouts in beams with voids.

Sand-coated GFRP rebars developed by Jabbar & Farid (2018) significantly improved bond strength and reduced crack width, proving beneficial in achieving better load-deflection performance.

Increased GFRP tension reinforcement ratio leads to enhanced flexural capacity but may reduce ductility and increase brittle failure modes (Sirimontree et al., 2021; Pham Thi Loan et al., 2021). A careful balance in ratio selection is essential.

Hybrid arrangements (steel in compression and GFRP in tension, or combined with polypropylene fibers) used by Naganna et al. (2024) demonstrated improved ductility and energy absorption, highlighting potential for hybrid-reinforcement systems in seismic zones.

Failure modes vary depending on reinforcement layout, presence of openings, and load type. Modes such as **concrete crushing, GFRP rupture, bond failure**, and **diagonal shear cracking** were observed, indicating that more experimental work is needed to understand influencing factors.

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