IJCIET

INTERNATIONAL JOURNAL OF CIVIL ENGINEERING AND TECHNOLOGY

Journal ID: 6971-8185

IAEME Publication

Chennai, India

editor@iaeme.com/ iaemedu@gmail.com

https://iaeme.com/Home/journal/IJCIET

International Journal of Civil Engineering and Technology (IJCIET)
Volume 17, Issue 4, July-August 2026, pp. 48-69, Article ID: IJCIET_17_04_007
Available online at https://iaeme.com/Home/issue/IJCIET?Volume=17&Issue=4
ISSN Print: 0976-6308; ISSN Online: 0976-6316
Impact Factor (2026): 27.65 (Based on Google Scholar Citation)
Journal ID: 6971-8185; DOI: https://doi.org/10.34218/IJCIET_17_04_007

COMPARATIVE REVIEW OF FLEXURAL BEHAVIOUR AND SERVICEABILITY OF GFRP AND STEEL REINFORCED CONCR ETE BEAMS

M. C. Charapale[1], N. K. Patil[2], A. S. Manjarekar[3]

[1]PG Student, Department of Civil Engineering, Sanjay Ghodawat University, Kolhapur, Maharashtra, India

[2]Professor, Department of Civil Engineering, Sanjay Ghodawat University, Kolhapur, Maharashtra, India

[3]Assistant Professor, Department of Civil Engineering, Sanjay Ghodawat University, Kolhapur, Maharashtra, India

ABSTRACT

Glass Fiber Reinforced Polymer (GFRP) bars have emerged as a practical alternative to conventional steel reinforcement for reinforced concrete members, particularly in structures exposed to corrosive environments. Their high tensile strength, low self-weight, and resistance to corrosion have encouraged researchers to investigate their structural performance under flexural loading. However, the relatively low modulus of elasticity of GFRP influences stiffness, crack development, and deflection, making serviceability an important aspect of design.

This review critically examines recent research on the flexural behaviour and serviceability performance of GFRP-reinforced concrete beams. Published experimental, analytical, and numerical investigations are assessed to compare the structural response of GFRP- and steel-reinforced members.

The discussion focuses on load-carrying capacity, load-deflection response, first cracking load, crack width, reinforcement ratio, bond behaviour, failure mechanisms, durability, and current design recommendations. The review also evaluates the influence of material characteristics on structural performance and highlights the strengths and limitations reported in previous investigations.

The findings indicate that GFRP-reinforced beams are capable of achieving satisfactory flexural strength while providing excellent resistance to corrosion and reduced maintenance requirements. Nevertheless, larger deflections and wider cracks are generally observed because of the lower stiffness of GFRP bars, requiring greater attention to serviceability during design. Existing design standards provide a useful framework for practical applications, although further refinement is required for long-term behaviour, crack prediction, and bond performance. The review concludes by identifying research priorities that may contribute to the wider and more efficient application of GFRP reinforcement in reinforced concrete structures.

Keywords: Glass Fiber Reinforced Polymer (GFRP); Reinforced Concrete Beams; Flexural Behaviour; Serviceability; Load-Deflection Response; Crack Width; Durability.

Cite this Article: M. C. Charapale, N. K. Patil and A. S. Manjarekar. (2026). Comparative Review of Flexural Behaviour and Serviceability of GFRP and Steel Reinforced Concrete Beams. *International Journal of Civil Engineering and Technology (IJCIET)*, 17(4), 113-133. DOI: https://doi.org/10.34218/IJCIET_17_04_007

1. INTRODUCTION

Reinforced concrete (RC) continues to be one of the most extensively used construction materials because it combines the compressive strength of concrete with the tensile resistance provided by internal reinforcement. For several decades, steel has remained the preferred reinforcing material owing to its strength, ductility, and well-established design practices. However, when reinforced concrete structures are exposed to chloride-rich or chemically aggressive environments, steel reinforcement becomes vulnerable to corrosion. The corrosion process gradually weakens the bond between concrete and reinforcement, causes cracking and spalling of the concrete cover, and ultimately reduces both structural performance and service life.

These durability-related concerns have encouraged researchers to investigate alternative reinforcement materials capable of maintaining structural integrity while minimizing maintenance requirements (Alsayed, 1998; Ramachandra Murthy et al., 2020; Tedford & Polak, 2022).

Among the available alternatives, Glass Fiber Reinforced Polymer (GFRP) reinforcement has gained considerable attention because of its excellent resistance to corrosion together with favourable mechanical characteristics. GFRP bars possess high tensile strength, relatively low weight, and non-magnetic behaviour, making them suitable for applications where conventional steel reinforcement is susceptible to deterioration. Compared with other fibre-reinforced polymer systems, GFRP reinforcement is generally more economical while still providing satisfactory structural performance. Consequently, its use has been investigated for bridge decks, marine structures, water-retaining facilities, parking structures, and other infrastructure where long-term durability is a major design consideration (Grace et al., 1998; Alsayed, 1998; Tedford & Polak, 2022).

Despite these advantages, the structural behaviour of GFRP-reinforced concrete differs from that of conventional steel-reinforced members. Unlike steel, GFRP bars do not exhibit yielding before failure and possess a significantly lower modulus of elasticity. As a result, beams reinforced with GFRP generally experience greater deflections and wider cracks under service loads, even though their ultimate flexural capacity can remain satisfactory. These characteristics shift the emphasis of design towards serviceability, requiring careful control of deflection, crack width, and reinforcement ratio to achieve acceptable structural performance (Abdelkarim et al., 2019; El-Nemr et al., 2018; Gouda et al., 2022; Muhammad & Ahmed, 2023).

Over the past two decades, numerous experimental, numerical, and analytical investigations have examined the flexural response of GFRP-reinforced concrete beams. These studies have explored parameters such as load-carrying capacity, load-deflection behaviour, cracking characteristics, reinforcement ratio, bond performance, and failure mechanisms under different loading conditions. Although considerable progress has been made, variations in experimental programmes, reinforcement configurations, and material properties have produced differing observations regarding serviceability behaviour and design recommendations. Bringing these findings together in a systematic manner is therefore important for understanding the present state of knowledge and identifying areas requiring further investigation (Ramachandra Murthy et al., 2020; Ifrahim et al., 2023; Sasikumar & Manju, 2024).

The present review consolidates recent research on the flexural and serviceability behaviour of GFRP-reinforced concrete beams. The discussion covers load-deflection response, cracking behaviour, reinforcement ratio, bond characteristics, durability, and failure modes while also comparing the structural performance of GFRP- and steel-reinforced members. In addition, the review discusses current design approaches, highlights limitations reported in previous investigations, and identifies research opportunities that may support the broader application of GFRP reinforcement in reinforced concrete structures (Gouda et al., 2022; Ramachandra Murthy et al., 2020; Ifrahim et al., 2023; Sasikumar & Manju, 2024).

Figure 1.1: Typical Glass Fiber Reinforced Polymer (GFRP) Reinforcement Bars

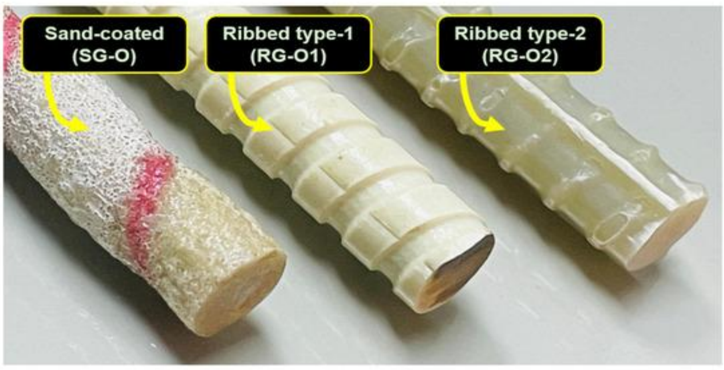

Figure 1.2: Types of bonds in GFRP bars

2. REVIEW METHODOLOGY

2.1. Literature Search Strategy

To prepare this review, a structured literature search was carried out to identify published studies related to the flexural and serviceability behaviour of GFRP-reinforced concrete beams.

Relevant research articles were collected from widely recognized scientific databases, including Scopus, ScienceDirect, SpringerLink, ASCE Library, MDPI, Wiley Online Library, Taylor & Francis Online, and Google Scholar. Different combinations of search terms were used during the literature survey, such as Glass Fiber Reinforced Polymer (GFRP), reinforced concrete beams, flexural behaviour, serviceability, load-deflection response, crack development, bond behaviour, and failure modes. Preference was given to peer-reviewed journal articles that provided experimental, analytical, or numerical investigations directly related to the structural performance of GFRP-reinforced concrete members. This systematic approach ensured that the review was based on relevant and reliable scientific evidence.

2.2. Scope of Reviewed Studies

The present review is based on 30 peer-reviewed research articles that investigate the flexural behaviour and serviceability performance of GFRP-reinforced concrete beams. The selected publications examine a wide range of structural parameters, including reinforcement ratio, flexural strength, stiffness, load-deflection response, crack initiation and propagation, bond characteristics, failure mechanisms, and comparisons between GFRP- and steel-reinforced concrete beams. Only studies published in well-established scientific journals indexed through internationally recognized databases were considered to maintain the quality and credibility of the review.

The selected literature provides a balanced overview of recent developments in GFRP reinforcement, covering both experimental observations and analytical investigations. Collectively, these studies highlight the influence of material properties and reinforcement detailing on structural behaviour while also identifying the advantages and limitations of GFRP reinforcement in comparison with conventional steel reinforcement. A summary of the reviewed publications and their principal findings is presented in Table 2.1.

Table 2.1. Summary of Selected Experimental and Analytical Studies on the Flexural Behaviour of GFRP Reinforced Concrete Beams

Sr. No.	Author(s)	Year	Study Focus	Key Findings
1	Alsayed	1998	Flexural behaviour of GFRP-RC beams	GFRP-reinforced beams exhibited satisfactory flexural performance with higher deflection than steel-reinforced beams due to the lower modulus of elasticity.
2	Grace et al.	1998	Behaviour and ductility of simple and continuous FRP beams	FRP-reinforced beams showed adequate load-carrying capacity but reduced ductility because FRP bars do not yield before failure.

3	Konsta-Gdoutos et al.	1998	Flexural behaviour of FRP-RC beams	FRP reinforcement provided stable flexural behaviour with crack development governed by reinforcement stiffness.
4	Barris et al.	2009	Experimental study and comparison with prediction models	Experimental results agreed reasonably with design models, although serviceability predictions varied among codes.
5	Ascione et al.	2010	Flexural behaviour of GFRP-RC beams	GFRP bars enhanced corrosion resistance while beam behaviour remained primarily controlled by serviceability requirements.
6	El-Mogy et al.	2010	Continuous FRP-reinforced beams	Continuous GFRP beams exhibited satisfactory moment redistribution with larger deflections than conventional RC beams.
7	Adam et al.	2015	Static and impact loading behaviour	GFRP-reinforced beams demonstrated satisfactory behaviour under both static and impact loading conditions.
8	Goldston et al.	2016	Steel vs GFRP reinforced beams	GFRP beams showed higher deflection but stable failure behaviour compared to steel beams.
9	El-Nemr et al.	2018	Flexural strength and serviceability of different GFRP bars	Bar surface configuration significantly influenced crack width, stiffness, and serviceability behaviour.
10	Zhang et al.	2018	Working crack behaviour	Existing cracks influenced stiffness degradation and crack propagation during loading.
11	Baša et al.	2018	Continuous concrete beams with GFRP reinforcement	Continuous GFRP beams exhibited stable flexural response with acceptable crack distribution.
12	Abdelkarim et al.	2019	Deformed GFRP bars	Deformed GFRP bars improved bond behaviour, flexural capacity, and serviceability performance compared with smooth bars.
13	Krall et al.	2019	Arrangement of flexural and shear reinforcement	Proper reinforcement detailing significantly improved structural behaviour and failure characteristics.
14	Liu et al	2019	Lightweight aggregate concrete beams	Fibre-reinforced lightweight concrete enhanced flexural capacity while reducing beam self-weight.
15	Saleh et al.	2019	Appraisal of design-code recommendations	Existing design codes produced conservative predictions for flexural strength and serviceability of GFRP-RC beams.

16	Maranan et al.	2019	Geopolymer concrete with hybrid reinforcement	Hybrid GFRP–steel reinforcement improved structural performance and crack control in geopolymer concrete beams.
17	Ramachandra Murthy et al.	2020	Monotonic loading behaviour	Beams exhibited linear-elastic behaviour until failure, and reinforcement ratio strongly influenced ultimate load capacity.
18	Chellapandian et al.	2020	Macro-synthetic fibres and GFRP ratios	Macro-synthetic fibres enhanced crack control, stiffness, and flexural performance.
19	Xiao et al.	2021	GFRP and steel-fibre composite bars	Composite reinforcement improved crack distribution and delayed failure compared with conventional GFRP reinforcement.
20	Chen et al.	2022	Marine environment and seawater sea sand concrete	GFRP reinforcement maintained excellent durability and structural performance under aggressive marine exposure.
21	Mehany et al.	2022	Lightweight self-consolidating concrete	GFRP-reinforced lightweight beams demonstrated satisfactory flexural strength and serviceability behaviour.
22	Gouda et al.	2022	Ribbed GFRP bars	Ribbed GFRP bars significantly improved bond characteristics, crack control, and serviceability performance.
23	Tedford & Polak	2022	Experimental investigation of GFRP-RC beams	GFRP beams achieved satisfactory flexural capacity while exhibiting greater deflections than steel-reinforced beams.
24	Abbas et al.	2022	Hybrid GFRP and steel reinforcement	Hybrid reinforcement effectively improved ductility, stiffness, and crack control.
25	Ifrahim et al.	2023	Experimental and numerical investigation	Numerical simulations closely agreed with experimental results for flexural response and failure behaviour.
26	Mahaini et al.	2023	UHPC beams reinforced with GFRP	UHPC significantly enhanced flexural capacity, stiffness, and crack resistance of GFRP-reinforced beams.
27	Muhammad et al.	2023	Deflection and flexural performance	Higher concrete strength reduced deflection and improved serviceability performance of GFRP-RC beams.
28	Wei et al.	2024	Hybrid FRP–steel reinforcement	Hybrid reinforcement substantially improved ductility and mitigated brittle failure associated with GFRP bars.
29	Imjai et al.	2024	Recycled aggregate concrete beams	Steel fibres effectively reduced deflection and improved crack resistance in recycled aggregate concrete beams.
30	Sasikumar & Manju	2024	Experimental and analytical investigation	Experimental and analytical results confirmed the effectiveness of GFRP reinforcement in enhancing flexural performance while maintaining acceptable serviceability.

3. MATERIAL PROPERTIES AND COMPARATIVE CHARACTERISTICS

The behaviour of reinforced concrete beams depends not only on the properties of concrete but also on the characteristics of the reinforcement used to resist tensile forces. Replacing conventional steel with Glass Fiber Reinforced Polymer (GFRP) bars introduces significant changes in structural response because the two materials differ considerably in their mechanical and physical properties. GFRP reinforcement combines high tensile strength with low weight, excellent resistance to corrosion, and non-conductive characteristics, whereas its relatively low elastic modulus influences stiffness, crack development, and deflection. Understanding these differences is essential when evaluating the suitability of GFRP bars for reinforced concrete applications and interpreting their structural performance under flexural loading.

3.1. Mechanical Properties of GFRP and Steel Reinforcement

Glass Fiber Reinforced Polymer (GFRP) reinforcement has attracted considerable attention in reinforced concrete construction because it provides an effective solution to durability problems associated with steel corrosion. These bars are manufactured using a pultrusion process in which continuous glass fibres are embedded within a polymer resin matrix, producing a lightweight composite material with high tensile strength and good resistance to aggressive environmental conditions. Since GFRP does not undergo electrochemical corrosion, it is considered particularly suitable for structures located in marine regions, bridge decks, water-retaining facilities, and other environments where conventional steel reinforcement may deteriorate over time (Abdelkarim et al., 2019; El-Nemr et al., 2018; Tedford & Polak, 2022).

Although both steel and GFRP reinforcement are intended to resist tensile forces in reinforced concrete members, their mechanical behaviour differs substantially. Steel possesses a high modulus of elasticity and exhibits yielding before failure, allowing structural members to develop ductile behaviour. In contrast, GFRP reinforcement behaves as a linear-elastic material until rupture and does not experience a yielding stage. While the tensile strength of GFRP bars is generally higher than that of conventional steel, their lower stiffness results in greater beam deflections and wider crack widths under service loads. Consequently, the design of GFRP-reinforced concrete beams requires greater emphasis on serviceability considerations than is normally required for steel-reinforced members (Abdelkarim et al., 2019; El-Nemr et al., 2018; Gouda et al., 2022).

The overall performance of GFRP-reinforced concrete beams is influenced by several interacting parameters, including reinforcement ratio, concrete strength, surface configuration of the bars, and bond quality between the reinforcement and surrounding concrete. Experimental investigations have shown that ribbed or surface-modified GFRP bars improve stress transfer and crack distribution by enhancing the bond with concrete. Although the lower stiffness of GFRP reinforcement cannot be eliminated, appropriate reinforcement detailing together with adequate bond performance enables concrete beams to achieve satisfactory flexural behaviour while maintaining the long-term durability advantages offered by GFRP reinforcement (Krall & Polak, 2019; Gouda et al., 2022; Sasikumar & Manju, 2024).

Table 3.1. Comparison of Mechanical Properties of Steel and GFRP Reinforcement

Sr. No.	Property	Steel Reinforcement	GFRP Reinforcement
1	Density	High (≈7850 kg/m³)	Low (≈1900–2100 kg/m³)
2	Tensile Strength	Moderate	High
3	Modulus of Elasticity	High (≈200 GPa)	Lower (≈40–60 GPa)
4	Corrosion Resistance	Poor in aggressive environments	Excellent
5	Electrical Conductivity	Conductive	Non-conductive
6	Magnetic Property	Magnetic	Non-magnetic
7	Stress–Strain Behaviour	Elastic–plastic	Linear elastic until rupture

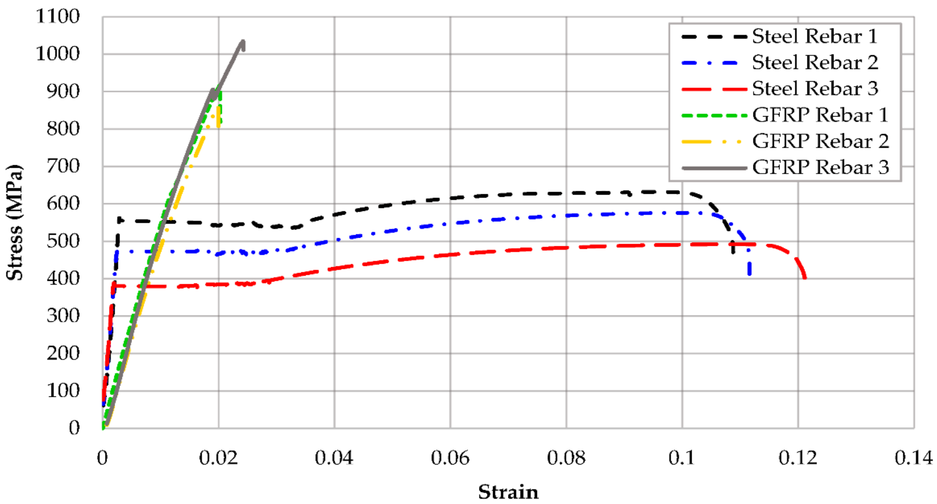

Figure 3.1: Experimental Stress-Strain Curves for Conventional Steel vs. GFRP Reinforcement

3.2. Comparative Characteristics and Design Implications

The differences between GFRP and conventional steel reinforcement extend beyond material properties and directly influence the design philosophy of reinforced concrete structures. While steel reinforcement has traditionally been preferred because of its stiffness and ductile behaviour, GFRP reinforcement offers several advantages in situations where durability is the primary concern. Its high tensile strength, low density, corrosion resistance, and non-magnetic nature make it particularly suitable for bridge decks, coastal structures, marine facilities, retaining walls, water-treatment plants, and other infrastructure exposed to aggressive environmental conditions. In such applications, the use of GFRP reinforcement can significantly reduce the risk of corrosion-related deterioration and prolong the service life of reinforced concrete members (Abdelkarim et al., 2019; Tedford & Polak, 2022; Chen et al., 2022).

Although GFRP reinforcement provides excellent durability, its comparatively low modulus of elasticity has an important influence on structural performance. Numerous experimental investigations have reported larger service-load deflections and wider crack widths in GFRP-reinforced beams than in similar members reinforced with steel. Researchers have also shown that increasing the reinforcement ratio, improving the bond between reinforcement and concrete through ribbed or surface-treated bars, and using higher-strength concrete can effectively enhance stiffness and improve crack control. These measures help to achieve satisfactory serviceability while retaining the durability advantages associated with GFRP reinforcement (Abdelkarim et al., 2019; Gouda et al., 2022; Muhammad & Ahmed, 2023; Sasikumar & Manju, 2024).

These material characteristics have led to a design approach that differs from conventional steel-reinforced concrete. Current design provisions, including ACI 440.1R and CSA S806, place considerable emphasis on serviceability by introducing specific requirements for deflection prediction, crack-width control, and reinforcement detailing. Unlike steel, GFRP reinforcement does not yield before failure, making stiffness and deformation control essential during design. Although the initial cost of GFRP bars is generally higher than that of steel reinforcement, studies have indicated that reduced maintenance requirements and improved durability can provide favourable life-cycle performance, particularly for structures operating in aggressive environments where corrosion-related repairs are costly (Saleh et al., 2019; Tedford & Polak, 2022; Sasikumar & Manju, 2024).

Table 3.2 Comparison of Mechanical Properties of GFRP and Steel Reinforcement

Sr. No.	Properties	Material	
		Steel rebar	GFRP rebar
01	Tensile Strength	360-500 MPa	800 – 1000 MPa
02	Elastic Modulus	200 GPa	40 – 50 GPa
03	Tensile strain	14 – 15 %	1.5 – 2.1 %
04	Shear strength	130 MPa	160 MPa
05	Density	7.0 – 8.0 gms/cc	1.9 – 2.6 gms/cc
06	Compression strength	250 MPa	250 MPa
07	Bond Strength	7.0 – 9.0 MPa	7.0 – 9.0 MPa
08	Thermal Coefficient of expansion	13 – 15 10^{-6}/k	9 – 12 10^{-6}/k
09	Corrosion resistance	No	Yes
10	Chemical resistance	No	Yes
11	Thermal conductivity	Yes	No
12	Electric conductivity	Yes	No
13	Sensitive to Electromagnetic field	Yes	No
14	Life Expectancy	50 – 80 Years	> than 100 Years

4. FLEXURAL BEHAVIOUR AND SERVICEABILITY PERFORMANCE

The flexural response of reinforced concrete beams strengthened with GFRP bars is governed by the interaction between the mechanical properties of the reinforcement, the characteristics of concrete, and the detailing adopted within the member. Although GFRP reinforcement provides high tensile strength together with excellent resistance to corrosion, its lower modulus of elasticity and absence of yielding produce a structural response that differs from conventional steel-reinforced concrete. Consequently, evaluating parameters such as load-deflection behaviour, crack development, reinforcement ratio, and failure mechanisms is essential for understanding the serviceability and overall flexural performance of GFRP-reinforced beams.

4.1. Load–Deflection Response

Under flexural loading, GFRP-reinforced concrete beams generally exhibit three stages of behaviour. The first stage is characterised by an uncracked linear response in which both concrete and reinforcement contribute to member stiffness. Once flexural cracks develop, stiffness decreases and the beam enters a post-cracking stage where deflection increases at a higher rate. The final stage continues until failure, which usually occurs through concrete crushing or rupture of the GFRP bars. Because GFRP reinforcement possesses a lower modulus of elasticity than steel, beams reinforced with GFRP normally experience greater deflections under comparable loading conditions. Nevertheless, studies have shown that satisfactory flexural performance can still be achieved when reinforcement ratio, concrete strength, and bond characteristics are appropriately considered during design. Increasing the reinforcement ratio and improving the bond between concrete and reinforcement enhance post-cracking stiffness, while higher-strength concrete contributes to better resistance against service-load deflection (Abdelkarim et al., 2019; Adam et al., 2015; Tedford & Polak, 2022; Muhammad & Ahmed, 2023; Sasikumar & Manju, 2024)

Figure 4.1 illustrates the general load-deflection behaviour reported in previous investigations. Unlike steel-reinforced beams, which develop a yielding stage before failure, GFRP-reinforced beams continue to respond elastically until ultimate failure.

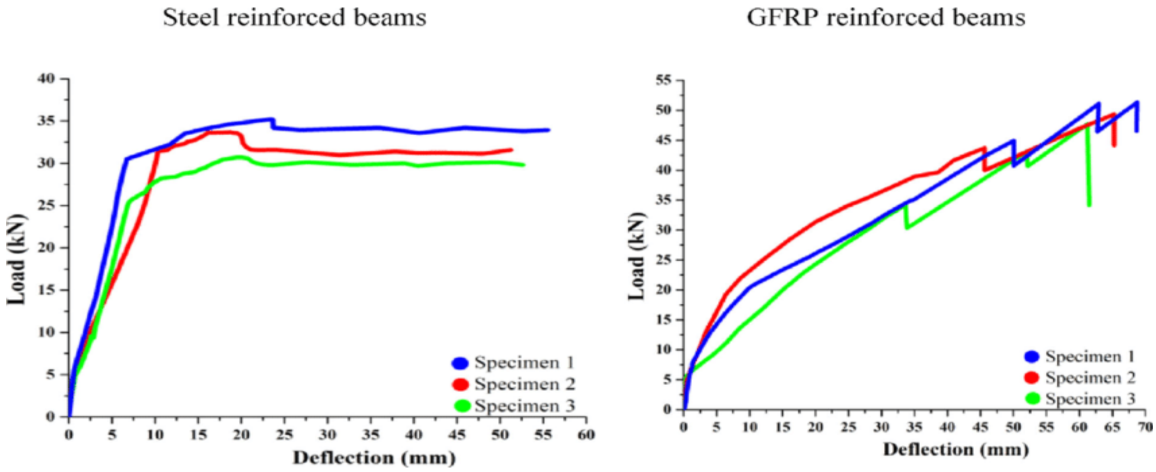

Figure 4.1: Typical load–deflection response of steel- and GFRP-reinforced concrete beams reported in previous studies

4.2. Cracking Behaviour and First Cracking Load

The formation of the first flexural crack is controlled primarily by the tensile strength of concrete. Consequently, beams having similar dimensions and concrete properties generally exhibit comparable first-cracking loads irrespective of whether steel or GFRP reinforcement is used. Differences become more apparent after cracking, where the lower stiffness of GFRP bars leads to larger crack widths than those typically observed in steel-reinforced members. Crack spacing and crack development are influenced by reinforcement ratio, bond quality, and bar surface configuration. Experimental studies have reported that increasing the amount of GFRP reinforcement and improving bond performance promote a more uniform crack pattern and contribute to better serviceability behaviour (Abdelkarim et al., 2019; El-Nemr et al., 2018; Gouda et al., 2022; Zhang et al., 2018).

Researchers have also highlighted the importance of the surface profile of GFRP bars. Ribbed or surface-treated reinforcement provides stronger mechanical interlocking with the surrounding concrete, improving stress transfer and reducing crack spacing. As a result, bond characteristics play an important role in controlling crack width and maintaining satisfactory serviceability performance.

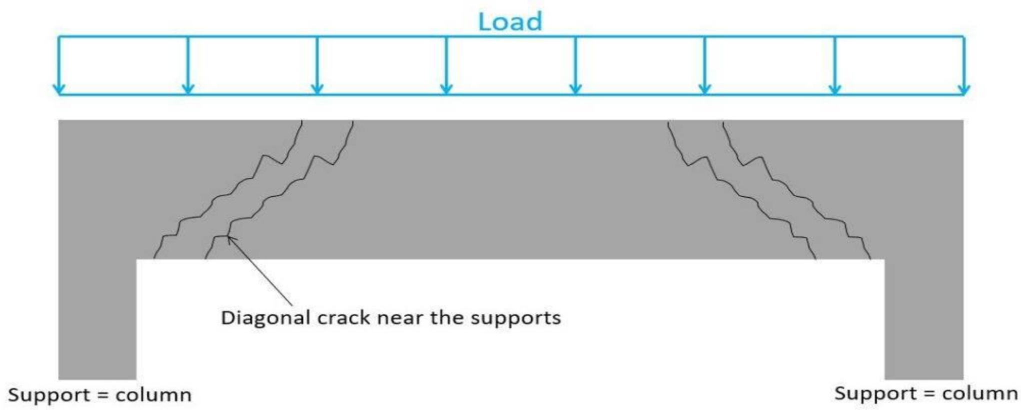

Figure 4.2: Typical flexural crack pattern of reinforced concrete beams subjected to two-point loading

4.3. Influence of Reinforcement Ratio

The reinforcement ratio is one of the most influential parameters governing both the strength and serviceability of GFRP-reinforced concrete beams. Increasing the amount of longitudinal reinforcement enhances the first-cracking load, improves post-cracking stiffness, and increases the ultimate load-carrying capacity. A higher reinforcement ratio also assists in controlling crack widths by distributing tensile stresses more effectively throughout the concrete section. Experimental investigations have consistently shown that properly selected reinforcement ratios improve overall flexural performance while delaying crack propagation (Chellapandian et al., 2020; Gouda et al., 2022; Abbas et al., 2022; Sasikumar & Manju, 2024)

Although increasing the reinforcement ratio improves structural performance, it should be selected carefully to achieve a practical balance between strength, stiffness, serviceability, and economy.

4.4. Failure Modes and Deformability Characteristics

The mode of failure in GFRP-reinforced concrete beams depends on reinforcement detailing, concrete properties, and loading conditions. The most frequently reported failure mechanisms include concrete crushing in the compression zone, rupture of the GFRP reinforcement, and, in some cases, shear failure near the supports. Since GFRP reinforcement does not exhibit yielding before failure, the structural response is generally more brittle than that of steel-reinforced concrete. For this reason, researchers commonly evaluate beam performance using deformability indices and energy absorption capacity instead of conventional ductility measures. Previous investigations have demonstrated that adequate bond performance, suitable reinforcement detailing, and an appropriate reinforcement ratio promote desirable flexural failure while improving the reliability of GFRP-reinforced members (El-Mogy et al., 2010; Xiao et al., 2021; Mahaini et al., 2023; Wei et al., 2024).

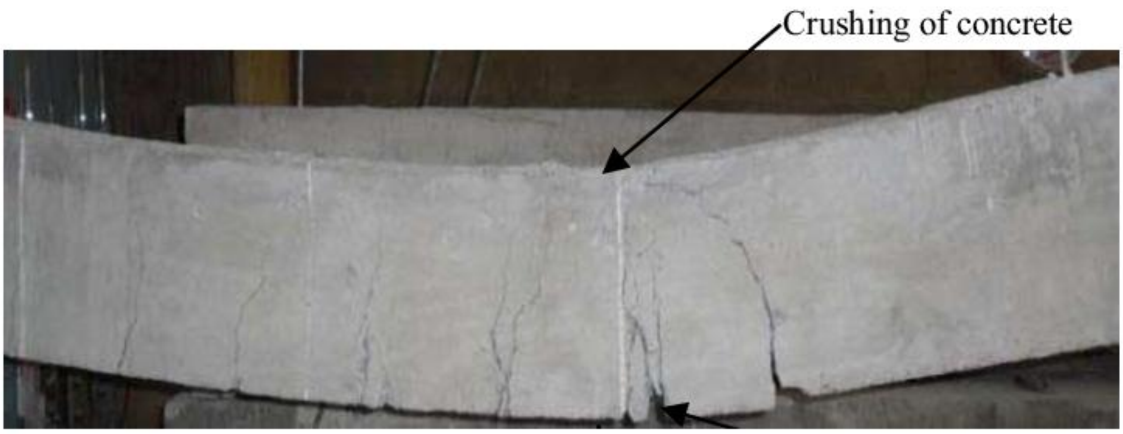

Figure 4.3: Typical flexural failure modes of GFRP-reinforced concrete beams

Table 4. Summary of Key Parameters Affecting Flexural & Serviceability Performance

Parameters	Impact
Failure Mode	Steel beams exhibit warning through ductile yielding. GFRP beams remain linear-elastic until failure, often resulting in sudden, brittle rupture.
Serviceability	GFRP has a significantly lower modulus of elasticity than steel. This leads to larger deflections and wider cracks, meaning serviceability limits usually govern GFRP design.

Reinforcement Ratio	Higher reinforcement ratios in GFRP beams are necessary to improve stiffness and reduce deflection. Over-reinforcing is often preferred as it promotes a more predictable concrete crushing failure.
Durability	GFRP is non-corrosive and non-magnetic. It is technically superior for aggressive environments like marine or coastal regions where steel would corrode and spall.
Bond Interaction	Effective load transfer depends on bars surface (sand coated or ribbed). Improved bond strength helps control crack spacing and enhance overall structural integrity.

Source: Compiled by the authors based on the reviewed literature (Abdelkarim et al., 2019; El-Nemr et al., 2018; Gouda et al., 2022; Tedford & Polak, 2022; Sasikumar & Manju, 2024; Mahaini et al., 2023; Wei et al., 2024).

5. COMPARATIVE EVALUATION OF GFRP AND STEEL REINFORCED BEAMS

Selecting between GFRP and conventional steel reinforcement requires consideration of both structural performance and long-term durability. Steel reinforcement has been used successfully in reinforced concrete construction for many decades because of its high stiffness, ductility, and well-established design procedures. GFRP reinforcement, however, offers advantages that are difficult to achieve with steel, particularly its resistance to corrosion, lower self-weight, and reduced maintenance requirements. As a result, the choice of reinforcement depends on the intended application, environmental exposure, serviceability requirements, and expected service life of the structure.

5.1. Structural Performance Comparison

The structural response of reinforced concrete beams varies according to the type of reinforcement used. Steel-reinforced beams generally exhibit higher stiffness and smaller service-load deflections because steel possesses a much greater modulus of elasticity and undergoes yielding before failure. In comparison, GFRP-reinforced beams remain linearly elastic throughout loading and therefore develop larger deflections and wider flexural cracks before reaching their ultimate capacity. Even with these serviceability differences, many experimental investigations have shown that well-designed GFRP-reinforced beams can achieve flexural strengths comparable with conventional steel-reinforced members. The principal distinction between the two systems is therefore associated with stiffness, crack control, and failure behaviour rather than ultimate load-carrying capacity (El-Nemr et al., 2018; Ramachandra Murthy et al., 2020; Tedford & Polak, 2022; Muhammad & Ahmed, 2023).

Comparative research has also demonstrated that steel reinforcement provides superior ductility because yielding allows considerable deformation before failure. GFRP reinforcement, on the other hand, contributes excellent durability and high tensile strength but offers limited deformation capacity because rupture occurs without yielding. To combine the benefits of both materials, several researchers have investigated hybrid reinforcement systems incorporating steel and GFRP bars. These hybrid arrangements have shown promising improvements in structural behaviour by enhancing ductility while maintaining the durability advantages associated with GFRP reinforcement (Abbas et al., 2022; Wei et al., 2024).

Table 5.1 Comparative Assessment of GFRP and Steel Reinforcement in Concrete Beams

Key Parameters	GFRP Rebar	Steel Rebar
Weight	75% lighter than steel, easy handling and transportation	Heavy, requires more labor and higher transportation costs
Strength	High tensile strength	Good tensile strength (prone to corrosion in some applications)
Resistance to Corrosion	Non-corrosive (suitable for hi-humid and harsh environments)	Corrosive and susceptible to degradation and rust
Thermal Conductivity	Low, reduces heat transfer	High
Cost Efficiency	Higher initial costs but lower long-term expenses due to savings in lifecycle maintenance, labor, and transportation costs	Lower upfront costs but higher long-term expenditures due to maintenance and repair costs
Lifespan	Long-lasting; minimal maintenance; 100+ years	Shorter lifespan in corrosive environments; 50-75 years

Source: Compiled by the authors based on the reviewed literature (El-Nemr et al., 2018; Ramachandra Murthy et al., 2020; Tedford & Polak, 2022; Muhammad & Ahmed, 2023; Chen et al., 2022; Saleh et al., 2019).

5.2. Durability and Life-Cycle Considerations

A major advantage of GFRP reinforcement is its ability to resist corrosion even when exposed to aggressive environmental conditions. Unlike steel reinforcement, GFRP bars are unaffected by chloride-induced corrosion, making them suitable for bridge decks, coastal structures, marine facilities, water-retaining systems, and industrial infrastructure where durability is a primary concern. Although the initial material cost is generally higher than that of steel, the reduced need for maintenance and rehabilitation can significantly lower the overall cost of ownership during the service life of a structure. Several studies have therefore recognised GFRP reinforcement as a practical solution for applications where long-term durability and reduced maintenance are more important than initial construction cost (Chen et al., 2022; Maranan et al., 2019; Saleh et al., 2019; Abdelkarim et al., 2019).

5.3. Design Implications and Serviceability Requirements

The lower stiffness and linear-elastic behaviour of GFRP reinforcement require a different design approach from that adopted for conventional steel-reinforced concrete. Instead of strength alone, greater attention must be given to serviceability parameters such as beam deflection, crack-width control, and reinforcement ratio. Current design recommendations, including ACI 440.1R and CSA S806, incorporate these considerations through modified design provisions developed specifically for FRP reinforcement. Achieving satisfactory structural performance therefore depends on maintaining an appropriate balance between flexural capacity, stiffness, crack control, and long-term serviceability (Saleh et al., 2019; Abdelkarim et al., 2019; El-Nemr et al., 2018).

5.4. Design Codes and Guidelines

The design of GFRP-reinforced concrete members is primarily based on the recommendations provided in **ACI 440.1R** and **CSA S806**. These standards include procedures for flexural design together with methods for evaluating deflection, crack width, and other serviceability requirements. Compared with conventional steel design provisions, these guidelines place greater emphasis on deformation control because GFRP reinforcement does not yield before failure and possesses a lower modulus of elasticity. Although the existing recommendations have supported practical implementation of GFRP reinforcement, published research indicates that further refinement is required for predicting long-term deflection, crack development, and sustained-load behaviour (Saleh et al., 2019; Adam et al., 2015; El-Nemr et al., 2018).

5.5. Sustainability and Economic Considerations

The use of GFRP reinforcement can improve the long-term sustainability of reinforced concrete structures by eliminating corrosion-related deterioration and reducing maintenance requirements throughout the service life of the structure. While the initial investment is generally greater than that required for conventional steel reinforcement, the reduction in repair frequency and rehabilitation work often results in favourable life-cycle performance. Lower maintenance demands also reduce material consumption and associated environmental impacts over time. These advantages make GFRP reinforcement particularly attractive for infrastructure where durability, reliability, and long service life are essential design objectives (Chen et al., 2022; Maranan et al., 2019; Abdelkarim et al., 2019).

6. RESEARCH GAPS AND FUTURE RESEARCH DIRECTIONS

Although substantial progress has been made in understanding the behaviour of GFRP-reinforced concrete beams, several aspects of their structural performance remain insufficiently explored. Most published investigations have concentrated on short-term laboratory testing under monotonic loading, whereas comparatively fewer studies have examined long-term structural behaviour under sustained service conditions. Limited information is currently available regarding creep, fatigue performance, long-term deflection, and the combined influence of environmental factors such as moisture, temperature fluctuations, chloride exposure, and alkaline conditions. In addition, much of the available experimental evidence is based on laboratory-scale specimens, indicating the need for further validation through full-scale structural testing before the findings can be confidently applied to practical engineering structures (Tedford & Polak, 2022; Ifrahim et al., 2023; Chen et al., 2022; Mahaini et al., 2023).

Current design recommendations provide an effective basis for designing GFRP-reinforced concrete members; however, several aspects still require improvement. Researchers have identified limitations in predicting long-term deflection, crack-width development, bond-slip behaviour, and the selection of suitable strength-reduction factors for different reinforcement arrangements. Expanding the available experimental database and developing more reliable analytical models will improve the prediction of serviceability behaviour and contribute to future revisions of existing design provisions (Saleh et al., 2019; Adam et al., 2015; El-Nemr et al., 2018; Mehany et al., 2022).

Future investigations should therefore place greater emphasis on full-scale experimental studies, long-term durability assessment, fatigue and cyclic loading, advanced bond-slip modelling, and refinement of serviceability-based design procedures. Addressing these research needs will strengthen the reliability of current design approaches, support broader acceptance of GFRP reinforcement in structural engineering practice, and encourage the development of reinforced concrete infrastructure that is durable, economical, and sustainable.

Table 5.2 Critical Research Gaps and Future Research Priorities for GFRP-Reinforced Concrete Beams

Sr. No.	Research Area	Current Limitation	Recommended Future Work
1	Long-Term Deflection and Creep	Most studies emphasize short-term monotonic loading, with limited data on creep, shrinkage, and sustained loading effects.	Develop long-term experimental programs and validated prediction models for deflection under sustained service loads.
2	Fatigue and Cyclic Performance	Insufficient information is available on the response of GFRP reinforced beams under repeated and cyclic loading.	Conduct fatigue and cyclic loading studies to establish durability and serviceability limits for practical applications.
3	Environmental Durability	The combined effects of moisture, temperature variation, chlorides, and alkaline exposure are not fully understood.	Investigate long-term mechanical and bond degradation under realistic environmental conditions.
4	Bond–Slip Behaviour	Existing bond models do not fully capture the influence of bar surface treatment, concrete strength, and sustained loading.	Develop improved analytical and numerical models for bond and anchorage performance.
5	Design-Code Refinement	Current provisions for deflection and crack-width prediction remain conservative and may not reflect recent research findings.	Update serviceability models and calibration factors in design guidelines such as American Concrete Institute 440.1R and Canadian Standards Association S806.
6	Sustainability and Life-Cycle Assessment	Relatively few studies quantify long-term economic and environmental benefits compared with conventional steel reinforcement.	Perform comprehensive life-cycle cost and sustainability assessments for large-scale infrastructure applications.

Source: Compiled by the authors based on the reviewed literature (Saleh et al., 2019; El-Nemr et al., 2018; Tedford & Polak, 2022; Ifrahim et al., 2023; Chen et al., 2022; Abbas et al., 2022; Wei et al., 2024; Mahaini et al., 2023).

7. CONCLUSIONS

The present review examined published research concerning the flexural behaviour and serviceability performance of GFRP-reinforced concrete beams. Based on the reviewed literature, the following conclusions can be drawn:

1) Glass Fiber Reinforced Polymer (GFRP) reinforcement possesses high tensile strength, low density, and excellent resistance to corrosion, making it a suitable alternative to conventional steel reinforcement for reinforced concrete structures exposed to aggressive environments.
2) Because of the relatively low modulus of elasticity and linear-elastic behaviour of GFRP bars, reinforced concrete beams generally exhibit larger deflections and wider crack widths than comparable steel-reinforced members. Consequently, serviceability requirements become a governing aspect of design.

3) The flexural behaviour of GFRP-reinforced beams typically progresses through an initial uncracked stage, a post-cracking stage with reduced stiffness, and a final stage ending in either concrete crushing or rupture of the reinforcement.
4) Increasing the reinforcement ratio together with improving bond performance enhances beam stiffness, increases flexural capacity, limits crack development, and improves overall serviceability.
5) The most frequently reported failure modes include concrete crushing, rupture of GFRP reinforcement, and, in some cases, shear failure. Since GFRP reinforcement does not exhibit yielding, deformability and energy absorption provide more meaningful indicators of structural performance than conventional ductility measures.
6) Compared with steel reinforcement, GFRP bars offer superior durability and corrosion resistance while reducing maintenance requirements, making them particularly advantageous for bridge decks, marine structures, coastal infrastructure, and other aggressive service environments.
7) Current design recommendations, including **ACI 440.1R** and **CSA S806**, provide practical guidance for structural design; however, continued refinement is needed for predicting long-term deflection, crack-width development, and bond-related behaviour.
8) Future studies should focus on long-term durability, fatigue performance, full-scale structural testing, and improved serviceability prediction models to support wider implementation of GFRP reinforcement in reinforced concrete construction.

Overall, the reviewed studies demonstrate that GFRP reinforcement is a technically reliable alternative to conventional steel reinforcement, particularly where durability is a primary design requirement. Continued improvements in experimental research, analytical modelling, and design procedures are expected to strengthen confidence in the use of GFRP reinforcement and encourage its broader application in sustainable reinforced concrete infrastructure.

DECLARATIONS

Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

No new data were created or analysed in this study. This article is based exclusively on a review and synthesis of previously published literature.

Funding

Not applicable.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent to publish

Not applicable.

Clinical trial number

Not applicable.

REFERENCES

[1] Konsta-Gdoutos, M., & Karayiannis, C. H. (1998). Flexural Behaviour of Concrete Beams Reinforced with FRP Bars. Advanced Composites Letters, 7(5). https://doi.org/10.1177/096369359800700502

[2] Grace, N. F., Soliman, A. K., Abdel-Sayed, G., & Saleh, K. R. (1998). Behavior and Ductility of Simple and Continuous FRP Reinforced Beams. Journal of Composites for Construction, 2(4), 186–194. https://doi.org/10.1061/(ASCE)1090-0268(1998)2:4(186)

[3] Abdelkarim, O. I., Ahmed, E. A., Mohamed, H. M., & Benmokrane, B. (2019). Flexural Strength and Serviceability Evaluation of Concrete Beams Reinforced with Deformed GFRP Bars. Engineering Structures, 186, 282–296. https://doi.org/10.1016/j.engstruct.2019.02.024

[4] El-Nemr, A., Ahmed, E. A., El-Safty, A., & Benmokrane, B. (2018). Evaluation of the Flexural Strength and Serviceability of Concrete Beams Reinforced with Different Types of GFRP Bars. Engineering Structures, 173, 606–619. https://doi.org/10.1016/j.engstruct.2018.06.089

[5] Tedford, T., & Polak, M. A. (2022). Experimental Investigation of Concrete Beams Reinforced with Glass Fiber–Reinforced Polymer Bars. Journal of Composites for Construction, 26(5). https://doi.org/10.1061/(ASCE)CC.1943-5614.0001254

[6] Ascione, L., Mancusi, G., & Spadea, S. (2010). Flexural Behaviour of Concrete Beams Reinforced with GFRP Bars. Strain, 46(5), 460–469. https://doi.org/10.1111/j.1475-1305.2008.00524.x

[7] Ifrahim, M. S., Sangi, A. J., & Ahmad, S. H. (2023). Experimental and Numerical Investigation of Flexural Behaviour of Concrete Beams Reinforced with GFRP Bars. Structures, 56, 104951. https://doi.org/10.1016/j.istruc.2023.104951

[8] Ramachandra Murthy, A., Pukazhendhi, D. M., Vishnuvardhan, S., Saravanan, M., & Gandhi, P. (2020). Performance of Concrete Beams Reinforced with GFRP Bars under Monotonic Loading. Structures, 27, 1274–1288. https://doi.org/10.1016/j.istruc.2020.07.020

[9] Saleh, Z., Goldston, M., Remennikov, A. M., & Sheikh, M. N. (2019). Flexural Design of GFRP Bar Reinforced Concrete Beams: An Appraisal of Code Recommendations. Journal of Building Engineering, 25, 100794. https://doi.org/10.1016/j.jobe.2019.100794

[10] Gouda, O., Asadian, A., & Galal, K. (2022). Flexural and Serviceability Behavior of Concrete Beams Reinforced with Ribbed GFRP Bars. Journal of Composites for Construction, 26(5). https://doi.org/10.1061/(ASCE)CC.1943-5614.0001253

[11] Muhammad, M. A., & Ahmed, F. R. (2023). Evaluation of Deflection and Flexural Performance of Reinforced Concrete Beams with Glass Fiber Reinforced Polymer Bars. Case Studies in Construction Materials, 18, e01855. https://doi.org/10.1016/j.cscm.2023.e01855

[12] Adam, M. A., Said, M., Mahmoud, A. A., & Shanour, A. S. (2015). Analytical and Experimental Flexural Behavior of Concrete Beams Reinforced with Glass Fiber Reinforced Polymers Bars. Construction and Building Materials, 84, 354–366. https://doi.org/10.1016/j.conbuildmat.2015.03.057

[13] Baša, N., Ulićević, M., & Zejak, R. (2018). Experimental Research of Continuous Concrete Beams with GFRP Reinforcement. Advances in Civil Engineering, 2018, Article ID 1849687. https://doi.org/10.1155/2018/1849687

[14] El-Mogy, M., El-Ragaby, A., & El-Salakawy, E. (2010). Flexural Behavior of Continuous FRP-Reinforced Concrete Beams. Journal of Composites for Construction, 14(6), 669–680. https://doi.org/10.1061/(ASCE)CC.1943-5614.0000127

[15] Abbas, H., Abadel, A., Almusallam, T., & Al-Salloum, Y. (2022). Experimental and Analytical Study of Flexural Performance of Concrete Beams Reinforced with Hybrid of GFRP and Steel Rebars. Engineering Failure Analysis, 138, 106397. https://doi.org/10.1016/j.engfailanal.2022.106397

[16] Sasikumar, P., & Manju, R. (2024). Flexural Behaviour of Reinforced Concrete Beams Reinforced with Glass Fibre Reinforced Polymer (GFRP) Bars: Experimental and Analytical Study. Asian Journal of Civil Engineering, 25(4), 3623–3636. https://doi.org/10.1007/s42107-024-00876-8

[17] Xiao, S., Lin, J., Li, L., Guo, Y., Zeng, J., Wei, F., & Li, M. (2021). Experimental Study on Flexural Behavior of Concrete Beam Reinforced with GFRP and Steel-Fiber Composite Bars. Journal of Building Engineering, 43, 103087. https://doi.org/10.1016/j.jobe.2021.103087

[18] Imjai, T., Aosai, P., Garcia, R., Raman, S. N., & Chaudhary, S. (2024). Deflections of High-Content Recycled Aggregate Concrete Beams Reinforced with GFRP Bars and Steel Fibres. Engineering Structures, 312, 118247. https://doi.org/10.1016/j.engstruct.2024.118247

[19] Wei, B., He, X., Zhou, M., Wang, H., & He, J. (2024). Experimental Study on Flexural Behaviors of FRP and Steel Bars Hybrid Reinforced Concrete Beams. Case Studies in Construction Materials, 20, e02759. https://doi.org/10.1016/j.cscm.2024.e02759

[20] Mahaini, Z., Abed, F., Alhoubi, Y., & Elnassar, Z. (2023). Experimental and Numerical Study of the Flexural Response of Ultra High-Performance Concrete (UHPC) Beams Reinforced with GFRP. Composite Structures, 315, 117017. https://doi.org/10.1016/j.compstruct.2023.117017

[21] Chen, Z., Li, S., Zhou, J., Xu, R., & Dai, S. (2022). Flexural Behavior of GFRP Bars Reinforced Seawater Sea Sand Concrete Beams Exposed to Marine Environment: Experimental and Numerical Study. Construction and Building Materials, 349, 128784. https://doi.org/10.1016/j.conbuildmat.2022.128784

[22] Chellapandian, M., Mani, A., & Suriya Prakash, S. (2020). Effect of Macro-Synthetic Structural Fibers on the Flexural Behavior of Concrete Beams Reinforced with Different Ratios of GFRP Bars. Composite Structures, 254, 112790. https://doi.org/10.1016/j.compstruct.2020.112790

[23] Goldston, M., Remennikov, A. M., & Sheikh, M. N. (2016). Experimental Investigation of the Behaviour of Concrete Beams Reinforced with GFRP Bars under Static and Impact Loading. Engineering Structures, 113, 220–232. https://doi.org/10.1016/j.engstruct.2016.01.048

[24] Maranan, G. B., Manalo, A. C., Benmokrane, B., Karunasena, W., Mendis, P., & Nguyen, T. Q. (2019). Flexural Behavior of Geopolymer-Concrete Beams Longitudinally Reinforced with GFRP and Steel Hybrid Reinforcements. Engineering Structures, 182, 141–152. https://doi.org/10.1016/j.engstruct.2018.12.048

[25] Liu, X., Sun, Y., & Wu, T. (2019). Flexural Capacity and Deflection of Fiber-Reinforced Lightweight Aggregate Concrete Beams Reinforced with GFRP Bars. Sensors, 19(4), 873. https://doi.org/10.3390/s19040873

[26] Krall, M., & Polak, M. A. (2019). Concrete Beams with Different Arrangements of GFRP Flexural and Shear Reinforcement. Engineering Structures, 198, 109333. https://doi.org/10.1016/j.engstruct.2019.109333

[27] Zhang, D., Han, Z., & Dai, L. (2018). Experimental Investigation on Flexural Behavior of Concrete Beams Reinforced with GFRP Bar with Working Cracks. IOP Conference Series: Earth and Environmental Science, 128, 012075. https://doi.org/10.1088/1755-1315/128/1/012075

[28] Barris, C., Torres, L., Turon, A., Baena, M., & Catalan, A. (2009). An Experimental Study of the Flexural Behaviour of GFRP RC Beams and Comparison with Prediction Models. Composite Structures, 91(3), 286–295. https://doi.org/10.1016/j.compstruct.2009.05.005

[29] Mehany, S. S. F., Mohamed, H. M., & Benmokrane, B. (2022). Flexural Strength and Serviceability of GFRP-Reinforced Lightweight Self-Consolidating Concrete Beams. Journal of Composites for Construction, 26(3). https://doi.org/10.1061/(ASCE)CC.1943-5614.0001200

[30] Alsayed, S. H. (1998). Flexural Behaviour of Concrete Beams Reinforced with GFRP Bars. Cement and Concrete Composites, 20(1), 1–11. https://doi.org/10.1016/S0958-9465(97)00061-9

Citation: M. C. Charapale, N. K. Patil and A. S. Manjarekar. (2026). Comparative Review of Flexural Behaviour and Serviceability of GFRP and Steel Reinforced Concrete Beams. International Journal of Civil Engineering and Technology (IJCIET), 17(4), 113-133.

Abstract Link: https://iaeme.com/Home/article_id/IJCIET_17_04_007

Article Link: https://iaeme.com/MasterAdmin/Journal_uploads/IJCIET/VOLUME_17_ISSUE_4/IJCIET_17_04_007.pdf

✉ **editor@iaeme.com**