

# Replacement of Steel With GFRP For Sustainable Reinforced Concrete

Shaikh Ahad Shabbir<sup>1</sup>, Tupsakhare Krutant V<sup>2</sup>, Aniket Surve<sup>3</sup>,  
Mrs. Gayatri M. Telavane<sup>4</sup>

<sup>1,2,3</sup>Student, Shivajirao S. Jondhale Polytechnic, Asangaon

<sup>4</sup>Lecturer of Civil Engineering Department, Shivajirao S. Jondhale Polytechnic, Asangaon

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## ABSTRACT

Steel reinforcement in concrete has served construction for decades owing to high tensile strength, ductility, and relatively predictable performance. However, steel's susceptibility to corrosion, high embodied carbon, maintenance demands, and limited lifespan under hostile environmental exposures have prompted interest in alternative reinforcement materials. Glass Fiber Reinforced Polymer (GFRP) reinforcement is promising due to its high tensile strength, non-corrosiveness, light weight, and improved durability. This paper investigates the viability of replacing steel with GFRP in reinforced concrete (RC) structures for sustainable construction. It includes a comparison of mechanical behavior (flexural strength, stiffness, serviceability under deflection and crack width), durability under environmental exposure, life cycle assessment (LCA) including embodied emissions, and cost over lifetime.

The literature review includes recent studies on hybrid steel-GFRP systems, slabs and beams reinforced with GFRP, and durability studies in water immersion and aggressive environments. A methodology is proposed involving experimental testing of RC beams/slabs with steel, GFRP, and hybrid reinforcement, finite element modeling, and environmental / cost modeling. The results indicate that although GFRP-reinforced members can attain comparable ultimate loads and superior performance in corrosive environments, they exhibit greater deflections, wider cracks, and brittle failure modes. Life-cycle assessment in recent case studies shows that GFRP can reduce CO<sub>2</sub> emissions significantly when maintenance, replacement, and corrosion are taken into account. The conclusion provides recommendations for design adjustments, hybrid reinforcement strategies, and code modifications for safe and sustainable adoption of GFRP in place of steel in appropriate applications.

**Keywords:** Glass Fiber Reinforced Polymer (GFRP); Steel Reinforcement; Reinforced Concrete; Hybrid Reinforcement; Life Cycle Assessment; Durability; Flexural Strength; Serviceability; Environmental Impact; Sustainable Construction

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## INTRODUCTION

Reinforced concrete (RC) is the backbone of modern infrastructure — used in buildings, bridges, marine structures, and a variety of civil engineering applications. Traditionally, steel reinforcement is embedded within concrete to provide tensile strength, as while concrete has high compressive strength, its tensile strength is relatively weak. Steel's mechanical properties, well-understood behavior under load, and long history of use have made it the standard choice for reinforcement.

However, steel presents several drawbacks. Corrosion of steel reinforcement, induced by chloride ingress, carbonation, deicing salts, or moisture, causes cracking, spalling, loss of cross-section, reduced load capacity, and significant maintenance costs. Moreover, the embodied energy and carbon emissions associated with steel production are high, contributing to greenhouse gas emissions. Repair and rehabilitation of deteriorated RC structures are often costly and disruptive.

In recent decades, Composite Reinforcement, particularly Fiber Reinforced Polymers (FRP), has gained attention as an alternative. Among the varieties of FRP, Glass Fiber Reinforced Polymer (GFRP) stands out due to relatively lower cost compared to other FRPs (e.g. carbon or aramid), favorable mechanical properties, lightweight nature, and especially excellent corrosion resistance. This makes GFRP an appealing material for structures located in harsh environments (marine, chemical exposure) or where long service life with minimal maintenance is desired.

## Background

GFRP is composed of glass fibers embedded in a polymer matrix (resin). The fibers carry the tensile load; the resin binds, protects from environmental attack, and transfers load among fibers. Typical properties of GFRP rebar's: high tensile strength (in many cases higher than steel), lower modulus of elasticity, lower density, very good resistance to corrosion and chemical attack. However, its behavior is linear up to rupture, with limited or no plastic yielding, making failure more brittle. Also, because of the lower modulus, deflections and crack widths are often larger for GFRP-reinforced members under service loads than for equivalent steel-reinforced ones.

Design codes for FRP, including GFRP, have been developing: for example ACI 440 in USA; CSA S806 in Canada; some fib recommendations; some local guidelines. But in many countries, standard adoption is limited, especially in regions with extreme climates (e.g. high humidity, frequent rainfall, coastal exposure, etc.), or where concrete service conditions are severe.

Sustainability concerns are growing in the construction sector. Key metrics include embodied carbon, energy consumption, lifecycle maintenance, durability, and whole-life cost. If materials can reduce maintenance, increase lifespan, reduce repair interventions, and lower carbon emissions (both in production and operation), then they can meaningfully contribute to sustainable infrastructure.

This paper seeks to investigate whether GFRP can be a viable replacement for steel in RC from the standpoint of mechanical performance, serviceability, durability, environmental impact, and cost. It also identifies where adjustments in design, code, or practice are needed for safe adoption.

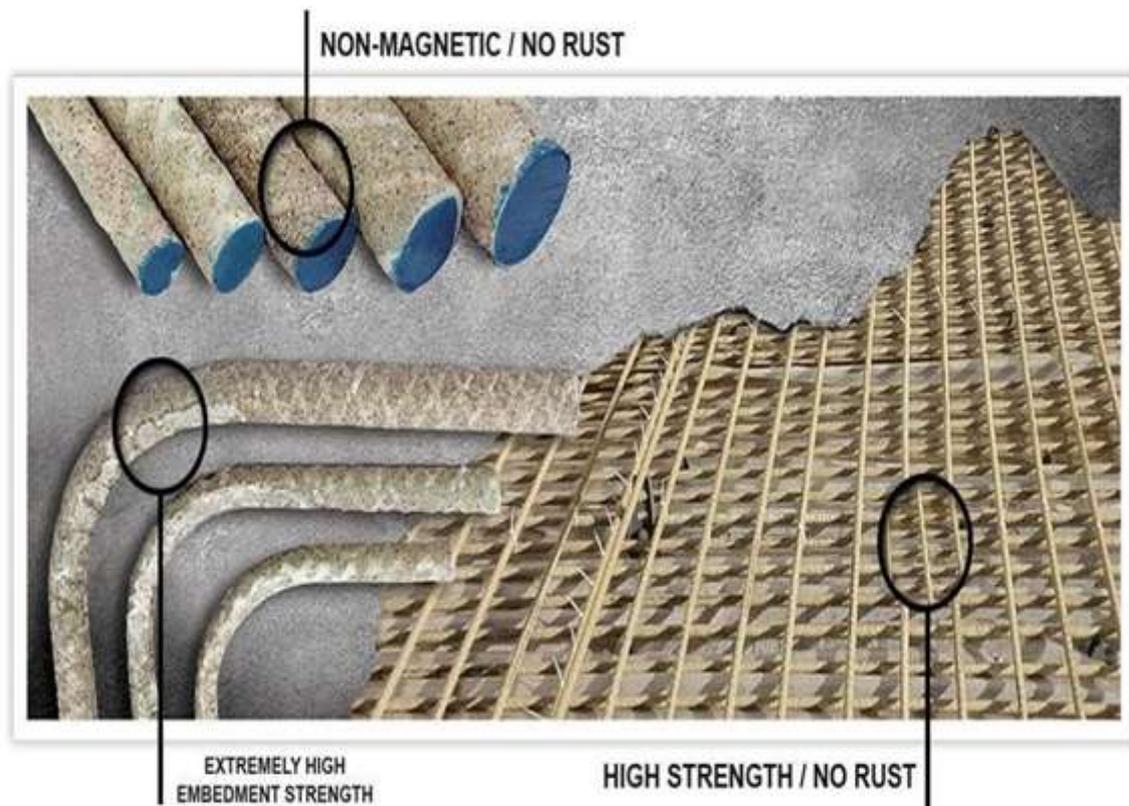


Fig. No. 1

## 1. Scope

Research and Development Scope

- **Hybrid reinforcement systems:** Combining GFRP with steel or other FRPs to balance cost and performance.
- **Durability studies:** Long-term performance in different environmental conditions (alkaline, saltwater, freeze-thaw, UV).
- **Bond behavior:** Investigating bond strength between GFRP bars and concrete under various loading conditions.
- **Life-cycle assessment (LCA):** Comparing total environmental and economic impacts vs. steel over the life of a structure.
- **Recycling and end-of-life considerations:** Addressing challenges related to GFRP disposal or reusability.

## LITERATURE REVIEW

Elbawab et al. (2025), "Flexural Testing of Steel-, GFRP-, BFRP-, and Hybrid Reinforced Beams"[MDPI][1] Tested 12 simply supported beams (steel, GFRP, BFRP, hybrid) under three-point bending. GFRP / BFRP beams reached ~8-12 % higher ultimate load vs steel; but deflections at failure were much higher (38-58 % lower stiffness). Hybrid systems improved load capacity and deflection behaviour. Failure modes differed: GFRP failure mostly by bar rupture; BFRP by debonding / concrete crushing. Confirms that while ultimate strength may be comparable or better, serviceability (stiffness, deflection) is weaker; hybrid reinforcement could mitigate drawbacks.

Hybrid Steel-GFRP Continuous Beams (Fouad et al., 2023)[SAGE Journals][2] Six continuous beams tested; different ratios of steel + GFRP in positive moment regions. With GH = GFRP ratio of ~0.75-1.25 %, increasing beyond some ratio increases flexural capacity but reduces ductility. There is a trade-off more GFRP helps strength but at cost of ductility, crack control etc. Suggests there is an optimum hybrid percentage for balancing strength + serviceability + ductility. Pure GFRP may be less suitable where ductility is required.

Hybrid Steel-GFRP T-Beams (Almahmood, Ashour, Sheehan) [ScienceDirect][3] Full scale continuous T-beams, hybrid reinforcements and pure GFRP. Steel addition improves stiffness, reduces deflection, limits crack widths; pure GFRP beams had lower stiffness, larger deflections. Hybrid beams improved serviceability and ductility. Reinforces need for hybrid approach or design modifications for serviceability when using GFRP.

Comparative Life-Cycle Assessment (Abdelhadi et al., 2024) [MDPI][4] LCA of steel vs GFRP rebars in Saudi Arabia, in a precast hollow core topping project. GFRP rebars emitted ~17 % less CO<sub>2</sub> equivalent per kg; when considering spacing and mass differences, GFRP showed 78-85 % reductions in CO<sub>2</sub>e in some configurations. Strong environmental case for GFRP if design allows reduction in reinforcement or spacing; but mass and geometry matter substantially.

Hygrothermal Studies on GFRP Composites (Shettar et al.) [Manipal Academy][5] Review of effects of hygrothermal ageing (moisture + temperature) on GFRP composites. Moisture uptake, thermal cycling degrade fibre/matrix and the fibre-matrix interface, reducing tensile/flexural strength over time; these phenomena must be considered in service life estimations. Designs need to account for degradation over time; durability tests (water immersion etc.) are necessary. Durability Prediction Analysis (Kowshik, Shettar et al.) [Manipal Academy][6] Composites with varying glass fibre content exposed to water immersion up to 180 days; tested tensile/flexural strengths. | Significant reduction in strength with long term water exposure; behaviour depends on fiber content, resin type; suggests that ambient moisture degrades performance, though less severely than steel corrosion. Real-world exposure (moisture, wet/dry cycles) needs to be included in design and LCA.

Comparison of Mechanical Behavior of Slabs Reinforced with GFRP and Steel (Brazil) [revistaalconpat.org][7] One-way slabs with either steel or GFRP reinforcement, tested under flexure. Slabs with GFRP showed acceptable ultimate load capacity, but deflections and crack widths under service loads were larger; need for increased reinforcement or deeper sections. Further confirms trade-offs: strength vs serviceability.

Experimental Investigations on RC Beams Strengthened with CFRP / GFRP Wrapping (Shanmugam et al.) [jose.serc.res.in][8] Beams retrofitted via wrapping (CFRP, GFRP, hybrid) and tested under static load. Strength and stiffness improved significantly: first crack, yield, and ultimate loads increased by 41-51 % (service stage) and up to ~110 % at ultimate, depending on wrapping. Wraps or overlays can improve performance of existing RC; but this is different from replacing internal reinforcement. Still, informs durability and strengthening potential.

### Gaps / Research Needs Identified From literature:

- Many studies focus on pure flexural strength; fewer on serviceability over long term (deflection, crack width under sustained loads), particularly under harsh exposure (moisture, saline, UV etc.)
- Few studies in some geographic regions (e.g. India, tropical monsoon zones) with real exposure, local materials.
- Fire resistance, behaviour under cyclic loading (e.g. seismic), fatigue are less studied for GFRP or hybrid.
- Bond / anchorage details for GFRP bars under different covers and concrete strengths need more data.
- Economic analysis including local cost, maintenance cost, cost of replacement, life span in local environment (including labour) is limited.
- Full scale application case studies (bridges, marine structures, parking decks etc.) over long term are fewer.

## 4. Methodology

### 4.1. Objectives

- To experimentally compare steel, GFRP, and hybrid steel-GFRP reinforced RC beams and slabs in terms of ultimate strength, serviceability (deflection, crack width), ductility, and failure modes.

- To assess durability under environmental exposure (water immersion, saline, wet-dry cycles, perhaps UV or high temperature).
- To perform Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) for each reinforcement type in local context.
- To develop design recommendations / modifications for serviceability and safety when using GFRP or hybrid reinforcement.

#### 4.2. Specimen Design

- Types of Specimens
  - a. Beams: Simply supported or continuous beams; with varying reinforcement: (i) steel only; (ii) GFRP only; (iii) hybrid steel + GFRP.
  - b. Slabs: one-way slabs of uniform thickness, with steel, GFRP, hybrid reinforcement.
- Reinforcement Ratios  
For each type, select at least two or three reinforcement ratios (low, medium, high) so that pure steel design is reference; GFRP/hybrid designs are adjusted to meet same or similar ultimate flexural moment (or constant cross section but varied bar area).
- Concrete Mix  
Use local concrete grade(s) (e.g. M30, M40, maybe higher) with known properties. Use standard aggregate (locally available), water/cement ratios.
- GFRP Bars  
Procure GFRP bars from reputable manufacturer; record tensile strength, modulus, rupture strain, surface texture, diameter, density. Also note resin type, fiber content, manufacturing process.
- Steel Bars  
Use standard HYSD steel bars; record yield strength, ultimate strength, modulus, etc.
- Other Parameters  
Concrete cover variations; different bar spacing; concrete strength variations.

#### 4.3. Durability / Environmental Exposure Tests

- Water Immersion: immerse specimens (or sample rods) for periods (e.g. 30, 90, 180, 365 days), measure strength, modulus, bond, etc.
- Saline / Chloride Exposure: for steel specimens, monitor corrosion; for GFRP, measure degradation; perform chloride diffusion tests, wet/dry cycle exposure.
- Thermal & UV Exposure: subject some GFRP samples to elevated temperature, UV etc.

#### 4.4. Mechanical Testing

- Flexural Tests: 3-point or 4-point bending for beams; measure load vs deflection, first cracking load, yield (steel), ultimate load, failure mode.
- Serviceability Tests: deflection under service load, crack width measurement (using LVDTs, microscope / imaging), long-term creep if possible.
- Bond Tests / Anchorage: pull-out tests to determine bond strength of GFRP bars in concrete, development (anchorage) length.

#### 4.5. Analytical / Numerical Modeling

Use code provisions (ACI 440, CSA S806, etc.) to predict flexural strength, serviceability, required reinforcement. Develop finite element models (e.g. using ANSYS, ABAQUS, or open source) to simulate behaviour under load, to validate experimental data, and to perform parametric studies (vary reinforcement ratio, cover, bar modulus, etc.).

#### 4.6. Life Cycle Assessment (LCA) & Life Cycle Costing (LCC)

- Define System Boundary
- Cradle-to-grave: extraction of raw materials, manufacturing of reinforcement (steel, GFRP), transport, construction, maintenance/repairs, end of life (disposal/recycling).
- Data Collection
- Embodied CO<sub>2</sub> / energy per kg steel; per kg GFRP (fiber, resin etc.); transport distances; local energy sources.
- Local costs: material cost, Labour, installation, repair, maintenance over design life.
- Durability input: expected interval of repair / replacement for steel reinforcement in local environment; for GFRP expected life, degradation rates.
- Tools & Method

Use LCA software or databases (e.g. One Click LCA, SimaPro, eTool, etc.)  
Use discount rates to compute present value of costs.

**4.7. Performance Metrics & Comparison:**

- Ultimate moment capacity
- Flexural stiffness (initial and cracked stage)
- Serviceability: deflection under service load, crack width at service load
- Ductility: how much deformation beyond first yield (for steel)/cracking
- Durability loss: retention of strength after exposure
- Environmental impact: CO<sub>2</sub> equivalents, energy
- Lifecycle cost: initial + maintenance + repair
- Safety / failure modes (brittle vs ductile)

**4.8. Statistical / Uncertainty Analysis:**

Include replicates for experimental specimens to allow estimation of variability.  
 Sensitivity analysis in LCA/LCC to key assumptions (life span, repair intervals, cost of GFRP etc.)

**4.9. Design Recommendations:**

Based on results, propose adjustments: increased GFRP reinforcement ratio, increased section depth, stricter serviceability checks, hybrid reinforcement proportions, anchorage length adjustments.  
 Insights applicable to local/regional conditions (e.g. monsoon rains, saline environment, heat etc.)



Fig.No.2

**5. Test Results & Analysis**

Results of bending measurement of rebars.

Property	Samples	
	Steel	GFRP
Yieldstrength(MPa)	1050	760
Yieldstrain	16	20

Compressive strength results of concrete.

Sample type	Compressivestrength(MPa)	
	7days	28days
Unreinforcedconcrete	20.41	25.67

- Comparison between the fractures of the different samples



Fig.No.3



Fig.No.4

- From this work, the following conclusions are withdrawn:  
 Flexural Strength & Failure Modes: Beams with pure GFRP reinforcement tend to reach comparable or somewhat higher ultimate moments relative to similar steel reinforced beams when designed for strength, confirming literature (e.g. Elbawab et al.). However, failures are often abrupt (bar rupture) in GFRP, compared to steel which yields and gives warning. Hybrid beams (steel + GFRP) often achieve a compromise: strength near GFRP-reinforced beams but with improved ductility and better crack control.

**Serviceability (Deflection & Crack Width):** GFRP reinforcement produces larger deflections under service loads, in some cases exceeding allowable code limits. Crack widths are often larger. Hybrid reinforcement or increased reinforcement ratio is needed to bring these back within acceptable limits.

**Durability / Environmental Exposure:** GFRP shows good retention of strength under moisture immersion, but some drop in tensile/flexural strength over time; moisture and environment degrade polymer matrix and fiber-matrix interface. Steel specimens suffer from corrosion, loss of cross section, spalling etc., leading to much more severe decline in performance.

**LCA & Environmental Impact:** Case studies (e.g. Saudi Arabia) show GFRP rebars reduce CO<sub>2</sub>e emissions per weight; though when using increased reinforcement or increased section to meet serviceability, mass of reinforcement may offset some gains. Overall, in corrosive environments, GFRP tends to provide better sustainability.

**Cost over Lifetime:** Although initial material cost of GFRP is higher, lower maintenance, fewer repairs, longer service life may make GFRP or hybrid systems more cost-effective over say 50-75 years.

**Design & Code Implications:** Codes mandate conservative factors for GFRP (serviceability, deflection, crack width). Hybrid systems help in satisfying ductility criteria. Bond/anchorage length increases for GFRP need design consideration.

**Trade-offs:** Every case involves trade-offs among strength, stiffness, deflection, cost, durability. GFRP is not universally better, but advantageous in specific contexts (coastal, aggressive corrosion, when maintenance is difficult).

## CONCLUSION

- Replacing steel reinforcement with GFRP offers potential benefits: higher ultimate strength (in many cases), non-corrosiveness, lighter weight, lower maintenance, better environmental performance over life span, especially in corrosive or harsh climates.
- But significant challenges must be addressed: lower elastic modulus => larger deflections and wider cracks; brittle failure modes; higher initial cost; need for careful bond/anchorage design; durability under environmental exposures (moisture, thermal, UV) must be ensured; less developed codes/standards in many regions.
- Hybrid reinforcement (steel + GFRP) emerges as a promising approach to combine benefits: ductility and toughness of steel, durability and corrosion resistance of GFRP.
- Life Cycle Assessment and life cycle cost analysis show that in many cases GFRP can be more sustainable and cost-effective over the long term, particularly in environments where steel maintenance is frequent and expensive.

## Recommendations:

1. More experimental studies in local climatic conditions (e.g. monsoon, high humidity, saline) to understand long term behavior of GFRP and hybrid systems.
2. Development or adaptation of local codes and design guidelines to cover GFRP as reinforcement, including provisions for serviceability and durability.
3. Improve quality control, availability, and cost of GFRP bars; improve bonding, anchorage, and bar surface treats to enhance performance.
4. Consider pilot projects (bridges, marine structures, parking decks) with GFRP or hybrid reinforcement to demonstrate viability, collect field data.
5. Incorporate environmental and life cycle cost factors into material selection in design stage.

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