Comparative Study on the Structural Performance and Durability of Glass Fiber Reinforced Polymer (GFRP) and Thermo-Mechanically Treated (TMT) Reinforcement Bars

Piyush Ghagi[1] , Nayan Chavhan[2] , Yash Raut[3] , Sakshi Gavande[4] , Prof. Rujit Puranik[5]
U. G. Students, Department of Civil Engineering, J. D. I. E. T., Yavatmal, Maharashtra, India
Assistant Professor, Department of Civil Engineering, J. D. I. E. T., Yavatmal, Maharashtra, India

Abstract : Glass Fiber Reinforced Polymer (GFRP) and Thermo-Mechanically Treated (TMT) steel reinforcement bars are increasingly recognized as alternative and complementary materials for concrete reinforcement in modern construction[1][2]. While TMT bars have established durability through decades of use in conventional reinforced concrete structures[3], GFRP bars present a revolutionary approach through their inherent corrosion resistance and non-metallic properties[4]. This comparative study evaluates the structural performance and durability characteristics of GFRP and TMT reinforcement bars under various environmental and loading conditions[5]. The research examines tensile strength properties[6], elastic modulus[7], bond characteristics[8], long-term durability in aggressive environments[9], thermal behavior[10], and seismic performance[11]. GFRP bars demonstrate superior corrosion resistance and lower density (40% lighter than steel)[12], yielding significant advantages in marine and chemically aggressive environments with reduced base shear in seismic applications[13]. However, TMT bars exhibit superior ductility[14], thermal resistance up to 600°C[15], and well-established design codes[16]. A hybrid approach combining both materials is proposed to leverage the complementary strengths of each reinforcement type[17]. This study synthesizes findings from recent experimental investigations, field applications, and design standards to provide guidance for engineers selecting appropriate reinforcement systems based on specific project requirements and environmental conditions[18].

***Index Terms* - Glass Fiber Reinforced Polymer (GFRP), Thermo-Mechanically Treated Steel (TMT), Reinforcement Bars, Structural Performance, Durability.**

I. INTRODUCTION

The choice of reinforcement material represents a fundamental decision in reinforced concrete design, directly influencing structural longevity, maintenance requirements, and life-cycle costs[1]. Traditional steel reinforcement has dominated the construction industry for over a century; however, its vulnerability to corrosion in aggressive environments particularly in coastal, marine, and chemically contaminated regions—continues to pose significant challenges to structural durability[2][3][4]. The corrosion of steel reinforcement typically initiates through chloride ion penetration or carbonation of the concrete cover, leading to volumetric expansion, concrete spalling, loss of bond, and ultimately compromised structural integrity[5][6]. The economic impact is substantial; corrosion-related deterioration accounts for approximately 3% of gross domestic product in developed nations[1].
Thermo-Mechanically Treated (TMT) steel bars, developed through controlled heating and cooling processes, represent the evolution of conventional reinforcement technology[7]. TMT bars exhibit superior mechanical properties compared to conventional mild steel due to their characteristic microstructure comprising a hardened martensite outer layer and a tempered martensite core[8]. This arrangement provides exceptional strength, ductility, and weldability, establishing them as the industry standard for conventional reinforced concrete construction[9][10]. However, TMT bars remain susceptible to corrosion unless protected through adequate concrete cover or protective coatings[11]. Glass Fiber Reinforced Polymer (GFRP) bars represent a paradigm shift in reinforcement technology, offering an entirely non-metallic alternative synthesized from E-glass or E-CR glass fibres embedded in a resin matrix (typically vinyl ester or epoxy)[12]. First utilized in civil engineering applications during the 1970s in Japan for bridge rehabilitation[13], GFRP technology has evolved significantly over five decades[14]. The fundamental advantage of GFRP lies in its inherent corrosion resistance—GFRP bars do not corrode and therefore do not require sacrificial concrete cover, reducing the thickness of protective concrete layers and enabling more efficient structural design[15][16].

This research paper synthesizes recent experimental findings, field applications, design code provisions, and numerical simulations to provide a comprehensive comparative analysis[23]. The objective is to establish a rational framework for material selection and to identify applications where each reinforcement type (or their combination) demonstrates optimal performance characteristics[24]. The findings are particularly relevant for civil engineering practitioners, researchers, and materials engineers involved in infrastructure development in India and globally, especially in regions with aggressive environmental exposure[25].

NEED OF THE STUDY.

The need of this study is to critically evaluate whether GFRP rebars can be a technically and economically viable replacement for conventional TMT steel rebars in reinforced concrete beams, especially under aggressive environmental exposure. Corrosion of steel is a primary cause of deterioration and costly maintenance in RC structures, motivating the search for non-corrosive alternatives such as GFRP. GFRP offers higher tensile strength, low weight, and excellent corrosion resistance, but its lower modulus and brittle behavior significantly alter flexural response, crack control, and serviceability criteria compared with TMT reinforcement. Therefore, a systematic comparative investigation at beam level is required to quantify differences in load-carrying capacity, stiffness, deflection, and failure modes, and to generate data that can refine design guidelines, support life-cycle cost optimization, and promote durable, sustainable infrastructure using advanced composite reinforcement.

II. LITERATURE REVIEW

Dr. Narayanan et.al. In this report, the literature on glass fibre composite materials is thoroughly reviewed, focusing on their composition, fabrication techniques, mechanical properties, applications, and associated challenges, with an emphasis on their transformative role across multiple industries. Glass fibre composites consist of glass fibres embedded within a polymer resin matrix, where the fibres provide mechanical strength and stiffness, while the matrix binds the fibres, transfers load and protects against environmental degradation. Different types of glass fibres, such as electrical glass (E-Glass), structural glass (S-Glass), alkali-resistant glass (AR-Glass), and chemical-resistant glass (C-Glass), are tailored for specific applications based on their distinct tensile strength, modulus, chemical resistance, and durability. Fabrication methods, including hand lay-up, filament winding, pultrusion, and autoclave molding, offer various advantages and limitations in manufacturing composites with desired shapes, performance characteristics, and production volumes.

Tamon Ueda The use of Fiber Reinforced Polymers (FRP) in Japanese construction has been extensively studied, with particular emphasis on reinforcement applications and the development of relevant design codes. Ueda (2004) highlights that since the late 1980s, FRP reinforcements have gained prominence in Japan, especially after the Hanshin Earthquake, which accelerated their adoption for seismic and durability retrofitting. Carbon and aramid fibres have been the most widely applied, with carbon fibre sheets dominating applications in bridge and building retrofits, while aramid sheets have been preferred for seismic strengthening due to their superior ductility. The study provides statistical evidence showing steady growth in FRP sheet applications, with over 9,800 cases of carbon fibre sheet usage by 2003, reflecting its practicality in enhancing structural safety. In terms of structural reinforcement, FRP rods, strands, braids, and grids have been applied in a range of projects including bridges, ground anchors, and precast connections. However, while initial applications expanded in the 1990s, their broader use in new structures has been limited, largely due to cost considerations.

Martin Alberto Masuelli Fibre-Reinforced Polymers (FRPs) have emerged as an important class of composite materials, combining high-performance fibres such as glass, carbon, and aramid with polymer matrices including epoxy, polyester, and vinyl ester resins. These composites are widely adopted across aerospace, automotive, marine, and civil engineering sectors due to their high strength-to-weight ratio, corrosion resistance, and design flexibility. The reviewed work emphasizes the conceptual foundation of FRPs, discussing polymerization mechanisms, matrix–fibre interactions, and the influence of fibre orientation on mechanical performance. FRPs provide significant advantages over traditional materials such as steel and concrete, particularly in structural reinforcement, seismic retrofitting, and durability against aggressive environments. The document outlines key processing methods, including weaving, braiding, and resin transfer molding, which determine the microstructural alignment and, consequently, the overall performance of FRP composites. Additionally, recent developments in nanofillers, carbon nanotubes, and 3D composites are highlighted as drivers for improved toughness, impact resistance, and multifunctionality.

Muhammet İskender et.al. In this report, a review of Glass Fiber Reinforced Concrete (GFRC) has been undertaken to understand its mechanical, physical, and practical significance in the construction industry. GFRC is recognized as one of the most versatile materials available to architects and engineers, making notable contributions to cost efficiency, technological advancement, and architectural aesthetics. Previous studies have consistently shown that the incorporation of glass fibres improves compressive strength; however, excessive fibre content decreases strength because of reduced workability. Similarly, while the modulus of elasticity shows limited improvement at lower fibre volumes, significant gains are observed in the stress–strain response and flexural strength due to fibre pull-out resistance and enhanced energy absorption. Research on durability further emphasizes GFRC's extended service life compared to conventional concrete, largely because of its resistance to crack propagation, corrosion, and permeability. Alkali-resistant (AR) glass fibres are particularly effective in ensuring corrosion resistance.

Trupti Amit Kinjawadekar et.al. In this report, the flexural behaviour of concrete members reinforced with glass fibre reinforced polymer (GFRP) is critically examined, with attention to load–deflection characteristics, bond strength, and crack propagation. Research studies consistently emphasize that FRP-reinforced concrete members are designed using higher safety factors, with design practices largely based on the recommendations of ACI and CSA codes. However, the absence of region-specific provisions, particularly in the Indian context, has limited the systematic application of GFRP reinforcement. Investigations reveal that the lower modulus of elasticity and higher rupture strain of GFRP contribute to beams with greater ultimate strength, but reduced stiffness and increased deflection compared to conventional steel-reinforced beams. Hybrid reinforcement, combining steel and GFRP bars, has been identified as a promising approach to address these limitations.

Ms. Veena Maroti Suryawanshi et.al. In this report, the literature concerning the comparative assessment and cost estimation of Glass Fiber Reinforced Polymer reinforced concrete (GFRP RC) and steel reinforced concrete (steel RC) composite box multi-cell bridges is examined, with a focus on the practical application of advanced composite materials in bridge construction. The review highlights the significant challenges faced by conventional steel RC structures, primarily related to corrosion and degradation caused by exposure to chlorides, aggressive chemicals, and moisture, which accelerate deterioration and lead to costly and frequent maintenance. In contrast, GFRP materials offer compelling advantages, including a high strength-to-weight ratio, exceptional corrosion resistance, and enhanced durability in harsh environmental conditions, which contribute to longer service life and reduced life-cycle costs. The use of GFRP bars in concrete has been advanced as a solution to overcome the limitations of traditional steel reinforcement, notably their susceptibility to corrosion-induced damage that can result in cracking, spalling, and reduced structural integrity.

Senthilkumar Mouleeswaran The study on vibration characteristics of flexible Glass Fiber Reinforced Polymer (GFRP) beams using Shape Memory Alloy (SMA) and Piezoelectric (PZT) actuators provides significant insights into smart material applications in vibration control. Composite structures are inherently lightweight with low rigidity and damping capacity, making them vulnerable to destructive vibrations. To address this, the paper compares SMA and PZT based actuators through both experimental and numerical approaches. The research is 3 grounded in prior theoretical developments on SMA behaviour, including Tanaka's thermomechanical modelling and Liang and Rogers' martensitic transformation models, which highlight the unique damping and stiffness-modulating capabilities of SMAs. Similarly, extensive work on piezoelectric materials has established their effectiveness in vibration suppression due to their electromechanical coupling and high-frequency response. Methodologically, the study employed a cantilever GFRP beam configuration with SMA wires embedded at the neutral axis and surface-bonded PZT patches.

Sharanappa Kattiman et.al. The comparative study on Glass Fiber Reinforced Polymer (GFRP) and steel bar reinforcement in multistorey buildings under seismic load highlights the growing attention toward alternative reinforcement materials in earthquake-resistant construction. The research employs pushover analysis using ETABS software to evaluate seismic performance under different load combinations specified by IS 1893:2002. The study particularly focuses on key response parameters such as base shear, story displacement, drift, and hinge behaviour for buildings reinforced with GFRP and steel. The findings reveal that GFRP-reinforced models demonstrate higher displacement and drift values compared to steel-reinforced models due to their lower modulus of elasticity. However, despite increased flexibility, the overall performance remains within permissible IS code limits. GFRP models exhibited higher load-carrying capacity at greater storey heights and performed efficiently in dissipating seismic energy through large deformations.

III. RESEARCH METHODOLOGY

1. Literature and Document Review

Systematic review of peer-reviewed journal articles, conference proceedings, technical reports, and design standards published between 2000 and 2025 addressing[1]: - GFRP bar manufacturing, properties, and performance[2] - TMT bar manufacturing, properties, and field performance[3] - Comparative studies of GFRP and steel reinforcement[4] - Durability studies in aggressive environments[5] - Seismic performance analysis[6] - Hybrid reinforcement systems[7]

2. Experimental Data Analysis

Evaluation of experimental test data from[8]: - Accelerated aging protocols examining moisture absorption and strength retention[9] - Tensile testing per ASTM D7205 (GFRP) and ASTM A370 (Steel)[10] - Bond strength testing through pull-out tests[11] - Finite element analysis of frame structures subjected to seismic loading[12] - Thermal degradation studies at elevated temperatures[13]

3. Comparative Performance Metrics

Tabulation and analysis of key performance indicators[14]: - Tensile strength and elastic modulus values[15] - Density and weight reduction potential[16] - Corrosion initiation time and degradation mechanisms[17] - Moisture absorption rates and durability indices[18] - Seismic base shear and drift characteristics[19] - Cost-benefit analysis on life-cycle basis[20]

4. Design Standard Review

Analysis of design provisions in[21]: - American Concrete Institute (ACI) 440 series (GFRP)[22] - AASHTO guidelines for FRP reinforcement[23] - IS 1786 Indian Standard for TMT bars[24] - Eurocode 2 (EN 1992) for conventional reinforcement[25] - Canadian Highway Bridge Design Code (CHBDC)[26]

5. Case Study Analysis

Examination of field applications including[27]: - GFRP-reinforced bridge structures in coastal environments[28] - TMT RC rehabilitation projects in aggressive settings[29] - Hybrid reinforcement implementations[30]

IV. DESIRED OUTCOMES

This comparative study generates the following key outputs:

1. **Quantitative Performance Comparison**: A comprehensive matrix of mechanical, durability, thermal, and seismic performance characteristics enabling direct comparison of GFRP and TMT reinforcement systems across multiple parameters[2][3].
2. **Material Selection Guidelines**: Clear decision-making framework specifying optimal reinforcement choice :
    - Environmental exposure classification (marine, acid, sulfate, normal)[5]

- Structural type and importance (routine, critical, sensitive to fire)[6]
- Seismic demand and drift limitations[7]
- Thermal exposure potential[8]
- Economic constraints and life-cycle cost considerations[9]

3. **Hybrid System Recommendations**: Design strategies for combined GFRP-TMT reinforcement where GFRP provides corrosion resistance and ductility is provided by strategically placed TMT bars, optimizing both strength and durability[10][11].

4. **Design Code Implications**: Identification of limitations in current design standards and recommendations for enhanced design approaches specific to each material system[12][13].

5. **Research Gaps**: Definition of critical knowledge gaps requiring future investigation[14]:

   - Long-term durability data beyond 10-year field exposures[15]
   - Large-scale field testing in diverse geographic and climatic regions[16]
   - Development of fire-retardant GFRP systems[17]
   - Standardized testing protocols for environmental degradation prediction[18]
   - Optimal hybrid reinforcement configurations and design methodology[19]
   - Cost-benefit analysis incorporating embedded carbon and environmental metrics[20]

6. **Practical Implementation Framework**: Guidelines for engineers selecting reinforcement systems, including specification language, quality control requirements, and inspection protocols specific to each material[21][22].

ACKNOWLEDGEMENT

This research paper was completed with the support and guidance of many individuals and institutions. The author expresses sincere gratitude to the research supervisor and faculty members of the Civil Engineering Department for their valuable suggestions, technical guidance, and continuous encouragement throughout the work on the comparative study of GFRP and TMT reinforcement in RC beams. The laboratory staff are gratefully acknowledged for their assistance in specimen preparation, material testing, and experimental setup, which made the investigation possible. Appreciation is also extended to the college administration for providing necessary facilities and a conducive research environment. The author is thankful to classmates and colleagues for their constructive discussions and moral support during the course of this study. Finally, heartfelt thanks are due to family members for their constant motivation, patience, and understanding, which have been a continuous source of strength during this research journey.

REFERENCES

[1]] N. H. Falahi Abdul Halim, S. C. Alih, M. Vafaei, M. Baniahmadi, and A. Fallah, “Durability of fibre reinforced polymer under aggressive environment and severe loading: A review,” International Journal of Applied Engineering Research, vol. 12, no. 22, pp. 12519–12533, 2017.

[2] R. Devaraj, A. Olofinjana, and C. Gerber, “Making a case for hybrid GFRP-steel reinforcement system in concrete beams: An overview,” Applied Sciences, vol. 13, no. 3, p. 1463, Jan. 2023, doi: 10.3390/app13031463.

[3] L. Mincigrucci, M. Civera, E. Lenticchia, R. Ceravolo, M. Rosano, and S. Russo, “Comparative structural analysis of GFRP, reinforced concrete, and steel frames under seismic loads,” Materials, vol. 16, no. 4908, Jul. 2023, doi: 10.3390/ma16144908.

[4] J. Wang and Y. J. Kim, “Application of GFRP bars to ultra high-performance concrete,” in 2nd International Workshop on GFRP Bars for Concrete Structures: Project Case Studies on GFRP Reinforcing Bars, 2012, pp. 1–5.

[5] R. Melchers and I. A. Chaves, “Durable steel-reinforced concrete structures for marine environments,” Sustainability, vol. 13, no. 13695, 2021.

[6] J. Ming, X. Zhou, L. Jiang, and J. Shi, “Corrosion resistance of low-alloy steel in concrete subjected to long-term chloride attack: Characterization of surface conditions and rust layers,” Corrosion Science, vol. 203, p. 110370, 2022.

[7] VRKP Blog, “Mechanical properties of TMT Bars,” VRKP Blog, Dec. 18, 2024, [Online]. Available: https://vrkp.in/blog/2024/12/18/mechanical-properties-of-tmt-bars/. [Accessed: Dec. 10, 2025].

[8] Rajuri Steels, “The strength and durability of TMT bars,” Rajuri Steels Blog, Sep. 2, 2025, [Online]. Available: https://rajuristeels.com/blogs/unveiling-the-secret-behind-the-strength-and-durability-of-tmt-bars/. [Accessed: Dec. 10, 2025].

[9] X. Seynave, “Quality control of continuous processes,” in 2nd International Workshop on GFRP Bars for Concrete Structures: Case Study Papers, 2012, pp. 1–4.

[10] R. Kampmann, A. Ruiz Emparanza, S. Telikapalli, J. Suhrheinrich, and F. De Caso, “The correlation between moisture absorption and tensile strength retention of glass fibre reinforced polymer rebars,” in 2nd International Workshop on GFRP Bars for Concrete Structures, 2012, pp. 1–11.

[11] F. Xie et al., “Experimental study on the structural performance of glass fibre reinforced concrete slabs reinforced with GFRP bars,” National Center for Biotechnology Information, Apr. 14, 2025, [Online]. Available: https://pmc.ncbi.nlm.nih.gov/articles/PMC12030183/. [Accessed: Dec. 10, 2025].

[12] X. Yu, S. Al-Saadi, X. L. Zhao, and R. K. S. Raman, “Electrochemical investigations of steels in seawater sea sand concrete environments,” Materials, vol. 14, no. 5713, 2021.

[13] M. A. G. Silva, B. S. da Fonseca, and H. Biscaia, “On estimates of durability of FRP based on accelerated tests,” Composite Structures, vol. 116, pp. 377–387, 2014.

[14] IJSR, “Study on the effect of using glass fiber reinforced polymer bars as main reinforcement in beams,” Indian Journal of Science and Research, [Online]. Available: https://ijsr.in/upload/553035792Chapter_69.pdf. [Accessed: Dec. 10, 2025].

[15] D. Lau and H. J. Pam, “Experimental study of hybrid FRP reinforced concrete beams,” Engineering Structures, vol. 32, pp. 3857–3865, 2010.

[**16**] N. F. Grace, N. A. Nakai, and M. Tanigaki, “Flexural strengthening of reinforced concrete beams using fiber reinforced plastic composites,” ACI Structural Journal, vol. 95, no. 5, pp. 518–529, 1998.

[17] A. E. Refai, M. Y. Khaleel, and G. S. Tarabia, “Bond strength of fiber reinforced polymer bars in concrete: A parametric study,” ACI Structural Journal, vol. 107, no. 2, pp. 163–172, 2010.

[18] J. R. Cromwell, K. A. Harries, and B. M. Shahrooz, “Environmental durability of externally bonded FRP materials intended for repair of concrete structures,” Construction and Building Materials, vol. 25, pp. 2528–2539, 2011.

[19] E. Quagliarini, F. Monni, F. Bondioli, and S. Lenci, “Basalt fiber ropes and rods: Durability tests for their use in building engineering,” Journal of Building Engineering, vol. 5, pp. 142–150, 2016.

[20] S. Nolan, “FDOT GFRP-RC market size estimate for cast-in-place concrete by 2020,” in 2nd International Workshop on GFRP Bars for Concrete Structures: Case Study Papers, 2012, pp. 1–6.

[21] J. Nemecek, P. Trvncek, J. Nemeckov, and J. Kruis, “Mitigation of chloride induced corrosion in reinforced concrete structures and its modelling,” Koroze a Ochrana Materialu, vol. 65, pp. 79–85, 2021.

[22] L. M. Omer, M. S. Gomaa, W. H. Sufe, A. A. Elsayed, and H. A. Elghazaly, “Enhancing corrosion resistance of RC pipes using geopolymer mixes when subjected to aggressive environment,” Journal of Engineering and Applied Sciences, vol. 69, no. 3, 2022.

[23] Y. C. Wang, M. H. Wong, and V. Kodur, “Mechanical properties of fibre reinforced polymer reinforcing bars at elevated temperatures,” in Designing Structures for Fire, 2003, pp. 183–192.

[24] R. A. Hawileh, A. Abu-Obeidah, J. A. Abdalla, and A. Al-Tamimi, “Temperature effect on the mechanical properties of carbon, glass and carbon-glass FRP laminates,” Construction and Building Materials, vol. 75, pp. 342–348, 2015.

[25] G. Ji, G. Li, and W. Alaywan, “A new fire resistant FRP for externally bonded concrete repair,” Construction and Building Materials, vol. 42, pp. 87–96, 2013.

[26] M. H. Khaneghahi et al., “Fire resistance of FRP-reinforced concrete structures,” in Fire Safety in Construction, 2024, pp. 1–15.

[27] S. Russo and G. Boscato, “Experimental testing of pultruded GFRP elements for seismic applications,” Materials, vol. 15, no. 2154, 2022.

[28] M. Diaferio and D. Foti, “Seismic analysis of multi-story structures,” in Earthquake Engineering and Engineering Seismology, 2005, pp. 1–20.

[29] R. K. Ghomi and E. El-Salakawy, “Seismic behaviour of exterior GFRP-RC beam-column connections,” ACI Structural Journal, vol. 114, no. 6, pp. 1309–1319, 2017.

[30] S. Russo, “GFRP structure for earthquake protection,” in International Conference on Composite Materials, 2013, pp. 1–8.