

Recent Advances in GFRP Composite Bridge Decks: Materials, Fabrication Techniques, and Performance Evaluation

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Abstract- Glass Fibre Reinforced Polymer (GFRP) composites have emerged as a promising material alternative for bridge deck applications due to their high strength-to-weight ratio, corrosion resistance, and ease of installation. This review provides a comprehensive overview of the developments in GFRP composite bridge decks, focusing on material selection, fabrication methods, structural applications, and performance assessment. Emphasis is placed on the mechanical behavior of various GFRP configurations under static, fatigue, and environmental loading conditions. Analytical and numerical modeling techniques, particularly finite element methods (FEM), are discussed to highlight their role in predicting structural performance. The review also addresses current challenges, such as long-term durability, lack of standardized design guidelines, and cost-related limitations. By consolidating findings from experimental studies and simulations, this paper identifies key research gaps and provides future directions for optimizing GFRP bridge deck systems in civil infrastructure.

Keywords: GFRP composites, Bridge decks, Structural performance, Hand lay-up process, Finite element analysis, Fatigue behavior, Infrastructure durability, FRP systems, Composite materials, Civil engineering.

I. INTRODUCTION

Background and Motivation

Bridges serve as vital links in modern transportation networks, playing an essential role in ensuring the seamless movement of people, goods, and services across natural and man-made obstacles. As strategic elements of civil infrastructure, bridges directly contribute to regional connectivity, economic development, and emergency response systems. Within a typical bridge structure, the deck system functions as the primary interface between vehicular traffic and the supporting superstructure. It is one of the most heavily loaded, structurally stressed, and environmentally exposed components, tasked with enduring not only static and dynamic traffic loads but also the long-term effects of environmental degradation.

Bridge decks are subjected to a wide range of physical and chemical stressors. These include repeated vehicle-induced fatigue loading, thermal expansion and contraction due to temperature fluctuations, moisture ingress, freeze-thaw cycles, and exposure to de-icing salts and chemical

agents—particularly in cold and coastal climates. Over time, these factors contribute to cracking, spalling, reinforcement corrosion, and material degradation, thereby compromising the structural integrity and safety of the bridge.

Historically, reinforced concrete (RC) and steel have been the predominant materials used in bridge deck construction due to their availability, well-established design procedures, and high initial strength. However, their long-term performance is often undermined by several critical drawbacks. Reinforced concrete, although versatile, is prone to shrinkage cracking, chloride-induced corrosion of steel reinforcement, and durability issues in aggressive environments. Steel, while possessing excellent tensile strength, suffers from oxidation, fatigue crack growth, and significant maintenance requirements when exposed to moisture and pollutants.

Moreover, both RC and steel-based deck systems are characterized by high self-weight, which increases dead load on the substructure and foundations. This,

in turn, necessitates more robust—and often costlier—design solutions. The combined effect of these disadvantages includes increased life-cycle costs, frequent maintenance interventions, and traffic disruptions due to repair works, which ultimately impact user convenience and economic efficiency.

Emergence of GFRP Composites in Bridge Engineering

Glass Fibre Reinforced Polymer (GFRP) composites have emerged as a promising substitute for traditional materials in bridge deck construction. GFRP consists of high-strength glass fibers embedded in a polymer matrix (usually polyester or epoxy), resulting in a lightweight, corrosion-resistant, and high-strength composite material. These properties make GFRP particularly attractive for bridge decks, where reducing dead loads and extending service life are critical priorities.

GFRP composites also offer non-conductive, electromagnetically transparent, and customizable structural characteristics, making them suitable for both new bridge construction and rehabilitation projects. The hand lay-up method, among other fabrication techniques, allows the production of deck panels with varied geometries and properties, tailored to specific performance needs.

Challenges and Barriers to Adoption

Despite the advantages, several challenges hinder the widespread adoption of GFRP bridge decks in civil infrastructure. Some of the key issues include:

- Higher initial cost compared to conventional materials.
- Lack of standardized design codes and specifications.
- Complex and brittle failure mechanisms like delamination or fiber breakage.
- Limited long-term field performance data under real loading and environmental conditions.
- Fabrication quality control, especially in hand lay-up processes.

These challenges have led to hesitation among practitioners and regulatory agencies in embracing GFRP as a mainstream construction material, especially for high-volume vehicular bridges.

Need for a Comprehensive Review

Numerous experimental and analytical studies have been conducted to evaluate the mechanical performance of GFRP bridge decks under static, fatigue, and environmental loading. Researchers have also utilized advanced finite element tools like ANSYS and ABAQUS to simulate behavior, optimize designs, and predict failure mechanisms. However, there is a need to consolidate these findings into a coherent review that captures the state-of-the-art and identifies research gaps.

A comprehensive review is particularly important for guiding future research and aiding engineers and policymakers in decision-making regarding the design, implementation, and standardization of GFRP bridge deck systems.

Scope and Structure of the Review

This review paper aims to provide a holistic overview of GFRP composite bridge decks by addressing the following key areas:

- Constituent materials and fabrication techniques, including hand lay-up and resin selection.
- Mechanical behavior under static, fatigue, and environmental loading conditions.
- Analytical and numerical modeling approaches, particularly using finite element analysis.
- Case studies, recent innovations, and comparative performance assessments.
- Challenges, limitations, and identified research gaps in current literature.

II. LITERATURE REVIEW

Introduction

The application of Fibre Reinforced Polymer (FRP) composites in civil infrastructure, particularly in bridge engineering, has gained widespread interest due to the limitations of conventional materials such as reinforced concrete and steel. These limitations include susceptibility to corrosion, fatigue failure, and high maintenance costs, especially in aggressive environments. In recent decades, FRP composites—owing to their lightweight nature, corrosion resistance, and favourable mechanical performance—have been investigated extensively

for both structural rehabilitation and new construction. Among various applications, FRP bridge deck panels have emerged as a promising solution for modular and durable bridge systems. This chapter presents a critical review of the literature on FRP composites, fabrication methods, structural performance of FRP decks, and existing analytical and experimental studies.

Characterization of GFRP Composites

Christos et al. (1993) developed a unified and simplified set of micromechanical equations to estimate the mechanical properties of unidirectional composite plies based on the properties of their constituent materials—fibres and matrix. These equations allow for the accurate prediction of longitudinal and transverse moduli, shear modulus, and Poisson's ratios, which are essential inputs for structural analysis and laminate theory. The significance of their model lies in its practical applicability for engineers, providing a reliable method to compute ply-level material properties using only the constituent inputs and volume fractions. These predictions can then be incorporated into the design and analysis of laminated composite structures such as FRP bridge decks, facilitating the transition from material design to structural implementation.

Srivastava et al. (1999) investigated the effect of water immersion on the mechanical behavior of quasi-isotropic glass fibre reinforced epoxy vinyl ester composites (GFRP), focusing particularly on the influence of fillers such as aluminium trihydrate (ATH) and polyethylene. The study involved preparing both filled and unfilled GFRP laminates and subjecting them to prolonged immersion durations of 0, 98, 158, 190, and 240 days. The specimens were tested for flexural strength, inter-laminar shear strength (ILSS), and impact energy. Results showed that composites containing ATH demonstrated a significant improvement in all three mechanical parameters compared to those with polyethylene and the unfilled samples. Furthermore, mechanical properties consistently improved with increasing filler content (0%, 5%, 10%, and 15% by weight) and longer immersion times. The study concluded that ATH-filled GFRP composites exhibit

superior durability and strength retention in moisture-prone environments, making them suitable for outdoor applications such as bridge decks and marine structures.

Kim et al. (2003) explored the structural optimization of GFRP bridge deck panels by developing and applying genetic algorithms to improve cross-sectional shapes. Their study focused on trapezoidal deck configurations, analyzing stiffness-to-weight and strength-to-deflection performance criteria. Using a finite element model, the optimization algorithm suggested geometric refinements to minimize material use while maintaining structural safety. The authors concluded that the optimized deck profiles showed better distribution of stresses and improved resistance to local buckling. Their findings contributed to design methodologies for lightweight, high-performance FRP deck systems.

Alagusundaramoorthy et al. (2008) carried out experimental investigations on full-scale GFRP bridge deck panels fabricated using the hand lay-up method. The specimens were tested under static flexural loading, with boundary conditions simulating typical bridge deck support. The study revealed that the GFRP panels satisfied IRC Class A loading requirements, and their failure occurred in a brittle manner, primarily due to local buckling or flange-web delamination. The experimental results were validated using finite element modeling in ANSYS, with good agreement between test and simulation. This work demonstrated the feasibility of using hand lay-up GFRP panels for bridge applications in India.

Park et al. (2005) conducted experimental studies on cellular FRP bridge deck panels subjected to static and fatigue loading. Their work included comparison between different panel configurations, including foam-filled and hollow-core structures. The fatigue behavior was evaluated using two-point patch loading with up to 1 million cycles. It was observed that panels with foam-filled cores exhibited enhanced fatigue life and reduced damage propagation, attributed to internal energy absorption and delayed crack initiation. The authors highlighted the importance of core design in

enhancing long-term performance of modular FRP decks.

Wan et al. (2005) performed field and laboratory studies on FRP decks installed on highway bridges, examining deflection behavior, stiffness degradation, and failure mechanisms under vehicular wheel loads. Their findings indicated that the decks were able to meet AASHTO LRFD deflection criteria, and the dominant failure mode observed was local flange buckling at the point of contact. They emphasized the need for enhanced top flange thickness or stiffeners in high-traffic applications to prevent premature failure.

Moon et al. (2009) studied the fatigue performance of pultruded FRP bridge deck systems using both experimental testing and life prediction models. Their work involved subjecting deck panels to cyclic loading with service-level magnitudes to evaluate stiffness degradation and fatigue damage. The results confirmed that the panels exhibited stable performance up to 1 million cycles with minimal reduction in stiffness. The study also proposed fatigue strength curves for FRP decks and recommended that design guidelines incorporate service load ratios and stress ranges to ensure long-term reliability.

Keller et al. (2005) carried out mechanical and fatigue testing on GFRP sandwich panels for bridge deck applications. Their research included both short-term static testing and long-term cyclic fatigue tests, demonstrating that GFRP sandwich systems offer sufficient strength and stiffness with low self-weight. The study concluded that such decks are suitable for replacing deteriorated concrete slabs, particularly in pedestrian and light vehicular bridges, due to their corrosion resistance and ease of modular construction.

Chiewanichakorn et al. (2006) performed detailed numerical modeling using ABAQUS to evaluate the fatigue performance of FRP bridge decks under AASHTO HS-20 truck loads. The simulation results were benchmarked against experimental data from the Bentley Creek Bridge. The study found that fatigue stresses remained well below the endurance

limit of the composite material, indicating satisfactory long-term performance. The research supported the integration of FEM tools in life-cycle assessments of FRP bridge systems.

Harries and Moses (2007) examined the load distribution behavior of GFRP bridge decks compared to traditional RC decks. Using laboratory-scale models, they demonstrated that while GFRP decks offered reduced self-weight, they exhibited lower lateral load distribution efficiency due to their high stiffness contrast with underlying supports. The authors recommended that the support system be designed to accommodate more localized load paths in FRP deck applications.

Zhang et al. (2006) investigated the dynamic response of bridges using GFRP decks, with a focus on vibration behavior under vehicular movement. Their results showed that GFRP decks, due to their low mass and high stiffness, experienced higher vibration amplitudes compared to traditional concrete decks. They emphasized the need for special attention to dynamic tuning and damping provisions during the design of FRP deck systems, especially for long-span and pedestrian bridges where human comfort is critical.

Keller and Gurtler et al. (2005) explored the interface bonding behavior between GFRP bridge decks and steel girders. Their work included push-out tests and finite element simulations to evaluate slip, load transfer efficiency, and interface stiffness. The results highlighted the importance of mechanical connectors or adhesives to ensure effective composite action. They proposed empirical models to predict bond-slip behavior, which are crucial for hybrid systems using FRP decks on steel or concrete girders.

El-Hacha et al. (2001) studied the use of prestressed FRP laminates for strengthening RC members, particularly in bending. Their work demonstrated that prestressing significantly improved the cracking load, ultimate load capacity, and deflection control. Though the study focused on strengthening, the outcomes are relevant to FRP bridge decks that may

incorporate prestressed components to resist service-level deflections under repeated loading.

Keller and Schollmayer et al. (2006) conducted tension and pull-off tests on trapezoidal GFRP bridge deck sections, examining the effects of laminate stacking sequence and manufacturing defects on tensile strength and stiffness. They recommended orthotropic modeling to simulate elastic and failure behavior accurately and concluded that laminate design and quality control are essential for ensuring deck performance under real-world loading.

Davalos et al. (2001) proposed a micro-macro analysis framework for GFRP deck systems using sandwich structures and honeycomb cores. Their study emphasized predicting the orthotropic properties of multilayered decks using micromechanics and validating these predictions using full-scale tests. The research contributed to the development of design charts and equations suitable for quick preliminary sizing and evaluation of FRP decks in the early design stage.

King et al. (2012) introduced Load and Resistance Factor Design (LRFD) principles tailored for FRP sandwich deck systems. By using experimental data and reliability-based methods, they established strength and serviceability limit states consistent with AASHTO recommendations. Their work filled an important gap in formalizing design guidance for FRP systems and helped bridge the disconnect between experimental success and practical adoption in civil infrastructure.

Chandrashekhara et al. (2003) performed finite element modeling on FRP decks using ANSYS to assess deflection under AASHTO Class A loading. They explored various core geometries such as I-core, trapezoidal, and box-shaped cells, analysing their effects on stiffness and stress distribution. Their study concluded that cellular configurations offered superior strength-to-weight ratios and recommended multi-cellular profiles for high-load bridge deck applications.

Kodur and Ahmed (2010) analyzed the fire resistance of FRP structural components, focusing on

degradation of strength and stiffness with temperature rise. Their study highlighted that FRP composites, while resistant to corrosion, are vulnerable to thermal degradation beyond 200°C. They emphasized the importance of including fire retardant additives and protective coatings in FRP deck systems, especially in highway or tunnel bridges where fire hazards exist.

Choudhury et al. (2014) evaluated the thermal and UV aging behavior of GFRP decks exposed to natural weathering over several months. The results indicated moderate reductions in tensile strength and modulus, primarily due to matrix embrittlement and fibre-matrix interface weakening. The study emphasized the need for accelerated aging tests and long-term field monitoring to predict service life in tropical and humid climates.

Maintenance, Rehabilitation, Strengthening, Repairs and Durability

Ghosh Karbhari et al. (2007) investigated the efficiency of strengthening bridge deck slabs with FRP through full-scale slab sections extracted from a bridge prior to demolition. One control slab and two FRP-strengthened slabs—one with wet lay-up fabric strips and another with pultruded strips—were tested. The study found a transformation in failure mode from brittle punching shear to more ductile flexural failure due to strengthening. The wet lay-up strengthened slab showed a 73% strength increase, while the pultruded strip version exhibited a 59% enhancement. This highlighted FRP's capability to not only increase load-carrying capacity but also improve ductility in existing bridge structures.

Taljsten (2004) provided a concise overview of research in the area of plate bonding techniques for flexural strengthening of concrete members using FRP. He emphasized innovations like prestressed near-surface mounted reinforcement (NSMR) using rectangular CFRP rods and the use of cement-based adhesives instead of epoxies. These approaches demonstrated significant improvements in both performance and durability, making them practical and durable solutions for retrofitting applications.

El-Hacha et al. (2001) presented a comparative study on beams and slabs strengthened with prestressed and non-prestressed FRP laminates. Their work confirmed that prestressing significantly improves the serviceability limit states, including stiffness and deflection control. Prestressed laminates also delayed crack initiation and increased the yielding load substantially compared to non-prestressed FRP systems, establishing their superiority in strengthening applications.

Triantafillou (1998) and other researchers like Neale (2000) and Lees et al. (2001) contributed valuable insights into the use of FRP for the rehabilitation of various structural components, such as columns, beams, and masonry. They explored bonded wraps, laminates, and overlays, proving that FRP enhances strength, ductility, and stiffness. Hollaway and Cadei (2002) specifically addressed the strengthening of metallic structures with FRP and reported excellent performance in improving structural capacity while offering corrosion protection.

Triantafillou (2001) focused on the seismic retrofitting of RC elements and masonry walls using FRP jackets and overlays. The study revealed that FRP jackets significantly enhanced shear strength, confinement, and ductility in RC members, especially in plastic hinge regions. Similarly, FRP overlays in masonry walls improved in-plane shear capacity, reduced deformation, and enhanced out-of-plane flexural strength, making FRP a cost-effective alternative in seismic zones.

Alampalli and Kunin (2002) documented a field implementation where the superstructure of the deteriorated Bennetts Creek Bridge in New York was replaced using a VARTM-fabricated FRP system. The E-glass/vinyl ester FRP superstructure met AASHTO load criteria. Load testing with HS25 trucks showed deflections and strains well within permissible limits (maximum deflection $< 3.5 \text{ mm}$ vs $L/800 = 8.8 \text{ mm}$). The bridge was completed in just six months, confirming FRP's suitability as a fast, durable, and cost-efficient replacement material.

Harries and Moses (2007) investigated the structural implications of replacing RC decks with GFRP decks.

Their findings revealed that the significant reduction in dead weight from GFRP led to uniformly lower substructure forces. However, due to reduced transverse load distribution and composite action, internal girder stresses increased. This necessitates careful redesign of support systems when replacing RC with GFRP to avoid unintended stress concentrations.

Kawada and Kobiki (2005) analyzed stress-corrosion cracking in GFRP under severe environmental conditions. Using single-fiber composite fragmentation tests, they found that interfacial shear strength degraded due to water absorption and matrix softening. Their study demonstrated the significance of environmental diffusion and matrix stiffness in long-term durability of GFRP materials.

Bisby et al. (2005) reviewed the fire resistance of FRP-strengthened concrete structures and concluded that, while FRP loses strength rapidly in fire, effective protection using insulation can ensure satisfactory performance. Their research supported the integration of thermal protection in design to make FRP viable even in fire-sensitive applications.

Hamilton and Dolan (2000) conducted extensive durability tests on FRP composites and found that regular environmental exposures—freeze-thaw cycles, salt spray, and alkalinity—had minimal effect on bonded FRP systems. They recommended UV-resistant coatings and fillers to address degradation from solar radiation and ozone, supporting FRP's long-term use in outdoor structures.

Hammami and Al-Ghuliani (2004) investigated the degradation of GFRP composites in seawater and corrosive fluids. Their findings revealed that high fiber content prevented complete matrix impregnation, leading to microcracking and reduced shear strength. Their work emphasized the role of fiber-matrix interface and highlighted the need for resin optimization in marine environments.

Analytical and Numerical Studies

Pisani and Marco (1998) conducted a comprehensive numerical investigation into the behavior of beams prestressed using Glass Fibre Reinforced Polymer

(GFRP) tendons. Their approach involved simulating 21 experimental tests to validate the model, followed by analyses under various prestressing configurations—bonded, unbonded, internal, and external—using both steel and FRP tendons. The findings demonstrated that GFRP and Aramid Fibre Reinforced Polymer (AFRP) tendons are suitable substitutes for steel in environments where corrosion resistance is essential. GFRP was particularly effective in external prestressing systems, while AFRP performed better in bonded configurations, indicating that the choice of FRP material must be aligned with the prestressing method for optimal performance.

Kim et al. (2003) developed a modified Genetic Algorithm (GA)-based design process to optimize pultruded GFRP bridge decks with cellular cross-sections. The objective was to identify an optimal structural form considering both material selection and geometric configuration. Their study concluded that the trapezoidal cross-section yielded the best results in terms of stiffness-to-weight ratio and resistance to local buckling. Sensitivity analysis revealed that geometric design variables, particularly flange thickness and web dimensions, had a more pronounced effect on performance than material property variations. This research reinforced the idea that structural optimization of GFRP decks should prioritize geometry during early-stage design.

Aref and Parsons (1999) introduced a simplified optimization technique for a novel FRP bridge deck system. The procedure aimed to minimize deck weight while ensuring that deflection remained within AASHTO's L/800 serviceability limit. Using a homogeneous anisotropic Kirchhoff plate to represent the composite deck's global stiffness characteristics, the authors employed the Ritz method in conjunction with an optimality criteria-based algorithm. The model was successfully applied to a two-lane, 18.29-meter bridge and validated against finite element results. This study highlighted an efficient alternative to full-scale FEM, especially useful during the preliminary design phase.

Amjad et al. (2005) analyzed the static flexural behavior of a hybrid GFRP-concrete multicellular

bridge superstructure using ABAQUS. The system consisted of three bonded trapezoidal GFRP box sections filled with E-glass/vinyl ester composite, topped with a concrete compression layer. The study confirmed that linear FEM adequately predicts flexural response under design live loads. However, the authors recommended further parametric studies considering different spans and cross-sections to generalize the findings. This hybrid concept illustrates the synergy between lightweight FRP and high-compressive strength concrete, optimizing performance while maintaining structural lightness.

Alampalli (2005) examined the structural behavior of a GFRP web-core skew bridge using ABAQUS and MSC PATRAN. The focus was on shear transfer and local buckling in pultruded elements. The analysis concluded that deflection is the governing design criterion for FRP bridges and showed that the allowable live load was approximately twice the HS-25 load when AASHTO deflection limits were satisfied. Additionally, the Tsai-Hill failure index was well below critical levels, and no premature shear stress failures were observed at web-flange interfaces, confirming the system's robustness under service loads.

Zhang et al. (2006) performed detailed finite element simulations to study load distribution and dynamic response in FRP deck bridges compared to concrete decks. Results revealed that lateral load distribution factors and vibration amplitudes were higher in FRP decks due to their low mass and higher stiffness. These characteristics, while beneficial for reducing dead loads, necessitate a re-evaluation of serviceability criteria, as conventional L/800 deflection limits may be unnecessarily conservative for FRP systems. The authors advocated for customized design criteria to exploit FRP's unique mechanical behavior fully.

Upadhyay and Kalyanaraman (2003) proposed a simplified analytical procedure for single-cell FRP box-girder bridges using blade-angle or T-stiffened panels. Their method incorporated the effects of longitudinal bending, shear, torsion, shear lag, distortion, and panel instability, offering a rapid and

sufficiently accurate tool for preliminary and optimal design. The results were validated using MSC NASTRAN and compared favorably with available literature, demonstrating that such methods can significantly reduce computational overhead without sacrificing accuracy, especially in early design stages.

III. MATERIALS AND MANUFACTURING TECHNIQUES

The performance of GFRP bridge decks largely depends on the constituent materials and the manufacturing process. This section covers the types of fibers, resins, and fabrication techniques commonly employed.

Types of Fibers and Resins

GFRP composites are formed by combining glass fibers with a polymer matrix. The most common types of fibers used in bridge deck applications are E-glass, known for its cost-effectiveness and decent mechanical properties, and S-glass, which offers improved strength but at higher cost. The matrix material typically consists of isophthalic polyester or epoxy resins, which bind the fibers and transfer loads across them. The choice of resin influences the deck's durability, especially under environmental exposures such as moisture and UV radiation.

Manufacturing Methods

Several manufacturing methods are available for producing GFRP bridge deck panels:

- **Hand Lay-Up:** A manual and cost-effective process suitable for customized, small-scale production. However, it may suffer from variability in quality and thickness control.
- **Pultrusion:** A continuous process that offers excellent dimensional consistency, ideal for producing long panels with constant cross-sections.
- **Vacuum Assisted Resin Transfer Molding (VARTM):** A more advanced method that combines good surface finish and high fiber content, suitable for large components with better resin infusion control.

Each technique influences the mechanical properties, cost, and scalability of the final product.

Layer Configuration and Panel Design

The stacking sequence of fiber layers, orientation (unidirectional, woven, or chopped strand mat), and overall geometry of the bridge deck panel affect load distribution, stiffness, and resistance to crack initiation. Core materials like foam or honeycomb may also be incorporated to improve out-of-plane stiffness and reduce weight.

IV. STRUCTURAL PERFORMANCE OF GFRP BRIDGE DECKS

The mechanical behavior and structural integrity of GFRP decks under different loading conditions determine their feasibility in real-world applications.

Static Load Performance

Experimental studies have shown that GFRP bridge decks can withstand service loads with acceptable deflections and stress levels. Their high stiffness-to-weight ratio allows them to meet serviceability limits, even under heavy vehicular traffic. However, the failure is often brittle and sudden, demanding careful design and safety factors.

Fatigue and Impact Behavior

Due to repeated wheel loading, fatigue resistance is critical. GFRP panels generally exhibit excellent fatigue life compared to traditional materials, especially when epoxy resins are used. However, resin microcracking and inter-laminar shear stress can lead to degradation under prolonged cycles. Impact resistance is another area of concern, as low-velocity or drop impacts can cause internal delamination not visible on the surface.

Failure Modes

Common failure modes in GFRP decks include:

- Delamination between layers
- Fiber rupture under tension
- Matrix cracking under flexure
- Shear failure at panel joints or supports

Understanding these modes is essential for safe design and implementation.

Environmental Durability

GFRP composites show superior resistance to corrosion and chemical attack. However, factors like

UV exposure, freeze-thaw cycles, and alkaline environments can degrade the matrix, reduce interfacial bonding, and lower long-term strength. Recent studies focus on UV stabilizers and protective coatings to improve durability.

V. ANALYTICAL AND NUMERICAL MODELING APPROACHES

Finite Element Modeling (FEM) has become a vital tool for understanding and predicting the behavior of GFRP bridge decks under various loading conditions.

Finite Element Analysis using ANSYS/ABAQUS

Numerical simulations using tools like ANSYS and ABAQUS enable detailed stress-strain analysis, deformation prediction, and failure mode investigation. Layer-wise modeling, progressive damage modeling, and contact interface definitions are crucial in simulating realistic deck behavior.

Validation with Experimental Results

FEA models are often validated against lab-scale experiments, confirming accuracy in predicting ultimate loads, crack patterns, and failure sequences. Discrepancies, when they occur, are usually due to boundary condition assumptions, material property estimations, or mesh sensitivity.

Optimization and Parametric Studies

FEM tools also allow for parametric studies, varying factors such as deck thickness, core material, fiber orientation, and span length. Optimization techniques help minimize material usage while maintaining structural integrity, contributing to more sustainable and cost-effective designs.

VI. CHALLENGES AND RESEARCH GAPS

Despite the progress made, several barriers still limit the large-scale adoption of GFRP bridge decks.

- **Lack of Standardized Design Codes:** Although some guidelines exist (e.g., AASHTO LRFD, Eurocodes), comprehensive and universally accepted design standards for FRP bridge decks are still under development. This restricts

consistent implementation in engineering practice.

- **Fabrication Quality Control:** Hand lay-up and manual manufacturing methods are prone to variability in thickness, void formation, and resin pooling, which affect the mechanical performance and reliability of the panels.
- **Long-Term Performance Uncertainty:** There is limited long-term field data regarding creep behavior, fatigue degradation, and environmental impacts on full-scale GFRP decks. More real-world monitoring and accelerated aging studies are required.
- **Economic and Implementation Barriers** Although life-cycle cost may be lower due to reduced maintenance, initial costs remain higher than traditional alternatives. Additionally, a lack of trained professionals, limited availability of FRP materials, and conservatism in civil engineering practice hinder broader implementation.

VII. CONCLUSIONS AND FUTURE SCOPE

This review highlights the significant potential of GFRP composites in modern bridge deck applications. With advantages such as high strength-to-weight ratio, corrosion resistance, and customizable design, GFRP decks are well-positioned to replace traditional materials in both new construction and retrofitting projects.

However, challenges related to long-term performance, quality control, design standardization, and cost must be addressed through continued research, field deployment, and code development. Future studies should emphasize:

- Life-cycle assessment under actual service conditions
- Full-scale testing and real-time monitoring
- Hybrid deck systems combining GFRP with other materials
- Automation in manufacturing to reduce cost and improve consistency

With further innovation and validation, GFRP bridge decks could become a standard solution in next-generation, resilient civil infrastructure.

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