

A Review of the Mechanical Properties and Applications of Fiberglass Reinforced Polymer Composite



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ABSTRACT

Fiberglass reinforced polymer (FRP) composites have emerged as important engineering materials due to their high strength-to-weight ratio, corrosion resistance, design flexibility, and cost-effectiveness. These attributes have enabled their widespread adoption across numerous industries, including construction, transportation, aerospace, marine, energy, and consumer manufacturing. This review provides a comprehensive assessment of the composition, manufacturing processes, mechanical properties, and practical applications of fiberglass FRP composites. The roles of glass fibers, polymer matrices, and interfacial bonding in determining composite performance are examined, together with commonly used fabrication techniques and material classifications. Particular attention is given to key mechanical characteristics, including tensile, compressive, flexural, impact, and fatigue properties, as well as the factors influencing their performance under service conditions. The review further evaluates the long-term reliability of fiberglass composites by discussing the effects of environmental exposure, such as moisture absorption, temperature fluctuations, ultraviolet radiation, and chemical degradation. Major engineering applications are highlighted to demonstrate the versatility of these materials in lightweight structural and non-structural components. In addition, current challenges associated with durability, recyclability, and sustainability are critically discussed alongside emerging developments aimed at improving performance and environmental compatibility. The findings indicate that fiberglass FRP composites continue to offer significant advantages over conventional materials, while ongoing advances in material design, processing technologies, and sustainable manufacturing are expected to further expand their application potential in modern engineering systems.

Keywords: Fiberglass reinforced polymer, Composite materials, Mechanical properties, Durability, Structural applications and Sustainability.

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Introduction

Fiberglass reinforced polymer (FRP) composites have emerged as one of the most important classes of advanced engineering materials because of their exceptional combination of low density, high strength, corrosion resistance, and design flexibility [1]. These composites are composed of glass fibers embedded within a polymer matrix, creating a material system that effectively combines the load-bearing capability of fibers with the protective and binding functions of the matrix [2]. Unlike conventional materials such as steel, aluminum, and wood, fiberglass composites offer superior resistance to environmental degradation while maintaining favorable mechanical performance [3]. Their ability to deliver high specific strength and stiffness has contributed to their growing adoption in sectors where lightweight structures and long-term durability are essential [4]. Consequently, fiberglass reinforced polymer composites have become increasingly significant in addressing modern engineering challenges associated with efficiency, sustainability, and structural reliability [5].

The mechanical performance of fiberglass reinforced polymer composites is primarily determined by the characteristics of the constituent materials and the quality of the fiber–matrix interface [6]. Glass fibers provide the composite with strength and stiffness, while the polymer matrix facilitates load transfer and protects the fibers from mechanical and environmental damage [7]. Factors such as fiber orientation, fiber volume fraction, matrix composition, and manufacturing technique significantly influence the resulting mechanical properties of the composite [8]. Advances in fabrication technologies have enabled improved control of composite architecture, resulting in enhanced structural efficiency and reliability [9]. As a result, significant research efforts have focused on optimizing material design and processing parameters to maximize composite performance across a wide range of applications [10].

Mechanical properties are widely recognized as the primary indicators of the suitability of fiberglass composites for engineering applications [11]. Tensile strength, compressive strength, flexural strength, impact resistance, fracture toughness, and fatigue performance collectively determine the ability of these materials to withstand service loads and environmental stresses [12]. Studies have shown that fiberglass composites can achieve excellent strength-to-weight ratios while maintaining desirable levels of stiffness and structural integrity [13]. However, exposure to moisture, ultraviolet radiation, temperature fluctuations, and aggressive chemical environments may gradually affect their mechanical behavior and durability [14]. Recent investigations employing multiscale mechanics and molecular dynamics simulations have provided deeper insights into the mechanisms governing degradation and long-term performance in fiber-reinforced polymer system [15]. Understanding these factors is essential for predicting service life and ensuring the safe utilization of fiberglass composites in demanding operating conditions [16].

The expanding use of fiberglass reinforced polymer composites across diverse industries reflects their versatility and engineering value [17]. In civil infrastructure, these materials are increasingly utilized for structural strengthening, bridge rehabilitation, reinforcing bars, and corrosion-resistant construction systems because of their favorable mechanical and durability characteristics [18]. The automotive and aerospace industries employ fiberglass composites to reduce structural weight, improve fuel efficiency, and enhance overall performance [19]. Similarly, marine applications benefit from their excellent resistance to corrosion and harsh environmental exposure, while renewable energy technologies rely on fiberglass composites for wind turbine blades and other critical components [20].

The continued expansion of these applications demonstrates the growing importance of fiberglass composites in the development of sustainable and high-performance engineering systems [21].

This review provides a comprehensive assessment of fiberglass reinforced polymer composites with a particular focus on their mechanical properties and practical applications. The review begins by examining the fundamental constituents of fiberglass composites, including glass fibers, polymer matrices, and interfacial bonding mechanisms that govern material behavior. It subsequently discusses the major classification systems and manufacturing techniques employed in the production of these materials, highlighting the influence of processing conditions on performance. Particular attention is devoted to the analysis of key mechanical properties, including tensile, compressive, flexural, impact, fracture, and fatigue behavior. The review further explores the effects of environmental exposure and aging on long-term durability and reliability. In addition, major engineering applications across civil infrastructure, transportation, aerospace, marine, and energy sectors are critically evaluated to demonstrate the versatility of fiberglass composites. Finally, current challenges, sustainability concerns, recycling opportunities, emerging technological developments, and future research directions are discussed. Through the synthesis of recent advances and existing knowledge, this review aims to provide researchers, engineers, and industry professionals with a clear and comprehensive understanding of the capabilities, limitations, and prospects of fiberglass reinforced polymer composites in modern engineering practice.

Composition, Manufacturing, and Classification of Fiberglass Reinforced Polymer Composites

Fiberglass reinforced polymer (FRP) composites are multifunctional materials whose performance is governed by the combined effects of constituent materials, processing techniques, and structural design configurations [22]. The remarkable mechanical properties and durability exhibited by these composites arise from the synergistic interaction between glass fibers and polymer matrices, which can be tailored to meet specific engineering requirements [23]. Continuous advancements in material science, nanotechnology, and manufacturing technologies have further expanded the capabilities and application scope of fiberglass composites across infrastructure, transportation, aerospace, marine, energy, and defense sectors [24]. Understanding the composition, manufacturing processes, and classification systems of fiberglass reinforced polymer composites is therefore fundamental to evaluating their mechanical behavior and practical applications.

Table 1. Major constituents and classification categories of Fiberglass Reinforced Polymer (FRP) composites

Components/Category	Types
Glass Fiber Reinforcement	E-glass, S-glass, C-glass, AR-glass
Polymer Matrix	Epoxy, polyester, Vinyl Ester, Thermoplastics (PP, PE, PA)
Classification by Matrix	Thermoset FRP, Thermoplastic FRP
Classification by Reinforcement Architecture	Continuous Fiber Composites, Discontinuous/Short Fiber Composites, Woven Fiber Composites
Classification by Structural Design	Laminated Composites, Sandwich Composites, Hybrid Composites

Constituents of Fiberglass Reinforced Polymer Composites

The fundamental architecture of fiberglass reinforced polymer composites consists of reinforcing glass fibers embedded within a continuous polymer matrix [25]. This combination enables the development of lightweight materials capable of exhibiting high strength, stiffness, corrosion resistance, and dimensional stability under demanding service conditions [26]. The reinforcing fibers primarily carry external loads, while the matrix binds the fibers together, transfers stresses, and protects the reinforcement from environmental and mechanical damage [27]. The effectiveness of this composite system depends largely on the individual properties of its constituents and the quality of the fiber-matrix interface. Glass fibers are among the most widely used reinforcement materials in polymer composites because they provide an excellent balance of performance, availability, and cost-effectiveness [28]. E-glass fibers dominate commercial applications owing to their high tensile strength, electrical insulation properties, and favorable economic characteristics [29]. S-glass fibers offer higher strength and stiffness, making them suitable for high-performance structural applications, while C-glass fibers are preferred in chemically aggressive environments because of their enhanced corrosion resistance [30]. Alkali-resistant (AR) glass fibers have also been developed for cement-based and civil engineering applications where exposure to alkaline environments is unavoidable [31]. The mechanical contribution of glass fibers is strongly influenced by their orientation, aspect ratio, volume fraction, and distribution within the composite structure [32].

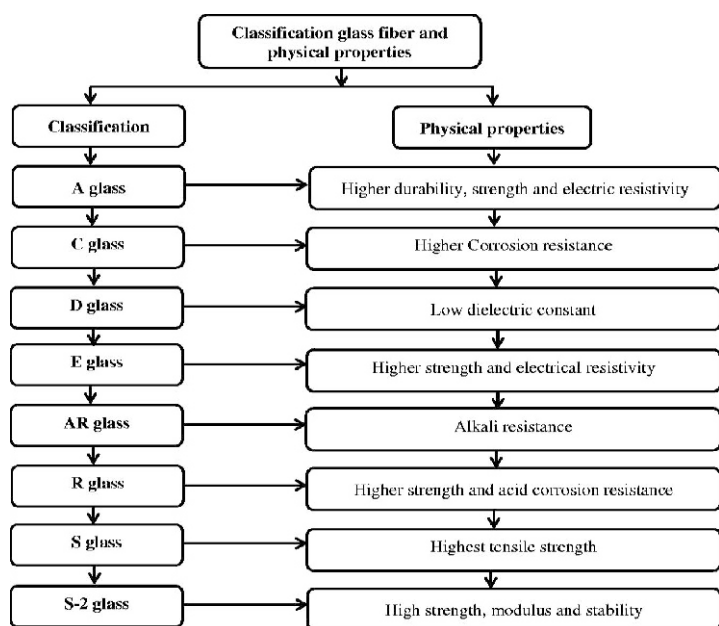


Figure 1. Classification and physical properties of glass fibers. This chart outlines the classification and key physical properties of glass fibers commonly used in fiber-reinforced polymer composites. It highlights the distinguishing characteristics of different glass fiber types and their suitability for specific industrial and engineering applications.
Source: [28]

The polymer matrix serves as the continuous phase that maintains the structural integrity of the composite and facilitates efficient stress transfer between reinforcing fibers [33]. Thermosetting polymers, including epoxy, polyester, and vinyl ester resins, remain the most widely utilized matrices because of their excellent mechanical performance, chemical resistance, and dimensional stability [32].

Epoxy resins are particularly valued for their superior adhesion and strong fiber-matrix bonding characteristics, which contribute significantly to mechanical reliability and durability [31]. In contrast, thermoplastic polymers such as polypropylene, polyethylene, and polyamide are increasingly being adopted because of their recyclability, impact resistance, and shorter manufacturing cycles [12]. The selection of matrix material plays a critical role in determining the composite's mechanical response, environmental resistance, and service life. Modern fiberglass composites frequently incorporate secondary additives to enhance specific performance characteristics [13]. Fillers, flame retardants, ultraviolet stabilizers, coupling agents, and toughening modifiers are commonly introduced to improve durability and functionality. Surface treatments such as silane coupling agents improve interfacial adhesion between fibers and matrices, thereby enhancing stress transfer efficiency and mechanical performance [14]. Furthermore, the emergence of fiber-reinforced polymer nanocomposites has introduced new opportunities for performance enhancement through the incorporation of nanoscale reinforcements such as graphene nanoplatelets, carbon nanotubes, nanoclays, and metal oxide nanoparticles [15]. These nanomaterials can significantly improve stiffness, fracture resistance, thermal stability, and multifunctional properties, thereby broadening the application potential of fiberglass composite systems.

Manufacturing Techniques

The manufacturing process is a critical determinant of the quality and performance of fiberglass reinforced polymer composites because it directly influences fiber alignment, resin impregnation, porosity, interfacial bonding, and dimensional accuracy [16]. Appropriate process selection is therefore essential for achieving the desired mechanical properties and ensuring structural reliability in service [17]. Hand lay-up remains one of the most established fabrication techniques due to its simplicity, flexibility, and low equipment requirements [18]. In this process, layers of fiberglass reinforcement are manually placed into a mold and impregnated with resin before curing. The technique is particularly suitable for large structures and low-volume production; however, variations in workmanship can lead to inconsistent fiber distribution and elevated void content, which may adversely affect mechanical performance [19]. Closed-mold manufacturing methods such as resin transfer molding (RTM) and vacuum-assisted resin transfer molding (VARTM) have gained widespread acceptance because they provide superior process control and product quality [20]. These techniques facilitate improved fiber wetting, reduced porosity, enhanced dimensional accuracy, and more uniform mechanical properties throughout the composite structure. Consequently, RTM and VARTM are extensively employed in aerospace, transportation, marine, and infrastructure applications where high performance and consistency are required [21].

Pultrusion is another important manufacturing method used for the continuous production of structural profiles with constant cross-sections, including reinforcing bars, beams, channels, and bridge components [22]. The process involves pulling continuous fiber reinforcements through a resin bath and heated die, producing components with excellent fiber alignment and superior longitudinal mechanical properties [23].

Additional manufacturing techniques such as filament winding, compression molding, injection molding, and automated fiber placement further expand the versatility of fiberglass composite production [23]. Recent developments in automation, digital process monitoring, and precision manufacturing have enabled the production of advanced FRP structures with improved quality control, reduced waste generation, and enhanced performance for aerospace and defense applications [24].

Classification of Fiberglass Reinforced Polymer Composites

Fiberglass reinforced polymer composites can be classified according to matrix type, reinforcement architecture, and structural configuration, with each classification influencing the resulting mechanical and functional properties of the material [25]. These classification systems provide a framework for selecting appropriate composite designs for specific engineering applications. Based on matrix composition, fiberglass composites are broadly categorized into thermoset and thermoplastic systems [26]. Thermoset composites generally exhibit superior stiffness, thermal stability, and chemical resistance, making them suitable for structural applications. Conversely, thermoplastic composites offer advantages such as enhanced toughness, recyclability, and rapid processing, which have increased their attractiveness in sustainable manufacturing initiatives [27]. Classification according to reinforcement architecture includes continuous fiber composites, short-fiber composites, woven fabric composites, stitched-fabric composites, and multidirectional laminates [28]. Continuous fiber systems generally exhibit superior load-carrying capacity and mechanical efficiency because stresses can be effectively transferred along the fiber length [29]. In contrast, short-fiber composites offer lower production costs and greater flexibility for manufacturing complex geometries.

Fiberglass composites may also be categorized according to structural design. Laminated composites consist of multiple layers arranged in specific orientations to optimize strength and stiffness under multidirectional loading conditions [30]. Sandwich composites combine fiberglass-reinforced face sheets with lightweight core materials to achieve exceptional stiffness-to-weight ratios and energy absorption capabilities [31]. More recently, hybrid composites incorporating glass fibers with carbon fibers, basalt fibers, natural fibers, or nanomaterials have attracted considerable attention because they enable the simultaneous optimization of performance, cost, and sustainability objectives [33]. The development of advanced hybrid and multifunctional composite systems is also creating new opportunities for aerospace, defense, and high-performance engineering applications where superior mechanical performance and operational reliability are required [34].

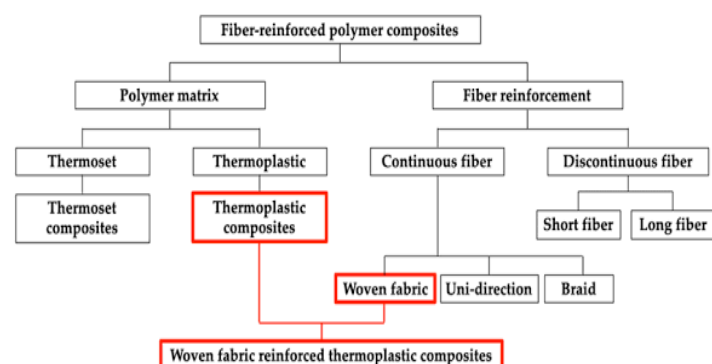


Figure 2. Classification of Fiber-Reinforced Polymer (FRP) composites. The flowchart illustrates the classification of fiber-reinforced polymer (FRP) composites according to the type of reinforcing fibers and polymer matrices. It highlights the hierarchical relationships among various FRP systems and provides a framework for understanding their structural diversity and engineering applications.

Source: [16]

Mechanical Properties of Fiberglass FRP Composites

The widespread adoption of fiberglass fiber-reinforced polymer (FRP) composites in structural and industrial applications is largely attributed to their favorable mechanical properties, including high specific strength, excellent stiffness-to-weight ratio, impact tolerance, and long-term durability. These properties arise from the synergistic interaction between glass fibers and polymer matrices, which enables efficient load transfer and damage resistance under various service conditions [17]. However, the mechanical behavior of fiberglass composites is influenced by several factors, including fiber architecture, interfacial bonding, manufacturing processes, environmental exposure, and loading conditions [18]. Understanding these properties is essential for optimizing composite design and ensuring reliable performance in engineering applications.

Tensile Properties

Tensile properties are among the most important indicators of the structural performance of fiberglass FRP composites because they reflect the material's ability to resist axial loading without failure. Glass fibers serve as the primary load-carrying constituents, while the polymer matrix facilitates stress transfer between adjacent fibers and maintains structural integrity [19]. Consequently, tensile strength and tensile modulus depend strongly on the quality of the fiber-matrix interface and the effectiveness of load transfer mechanisms. The tensile behavior of fiberglass composites is influenced by fiber orientation, fiber volume fraction, and manufacturing quality. Unidirectional fiber arrangements generally exhibit superior tensile strength because the applied load is transferred directly along the fiber axis, whereas randomly oriented fibers result in lower mechanical efficiency [20]. Manufacturing methods also play a significant role, as defects such as voids, poor resin impregnation, and fiber misalignment can reduce tensile performance [21]. Advanced processing techniques, including injection molding and controlled impregnation methods, have demonstrated improved fiber distribution and enhanced mechanical consistency in reinforced polymer composites [21]. Recent studies have further emphasized the importance of interfacial adhesion in determining tensile performance. Strong bonding between glass fibers and the polymer matrix promotes efficient stress transfer and delays crack initiation under tensile loading [22]. Additionally, tensile behavior may vary with strain rate and temperature, with higher strain rates generally resulting in increased strength and stiffness, while elevated temperatures can reduce mechanical performance because of matrix softening effects [23].

Compressive and Flexural Properties

Compressive and flexural properties are critical for applications where fiberglass composites are subjected to bending, buckling, or multidirectional loading. Unlike tensile loading, compressive loading often induces complex failure mechanisms such as fiber microbuckling, matrix yielding, shear instability, and interlaminar delamination [24]. As a result, compressive strength is frequently lower than the corresponding tensile strength despite the high inherent strength of glass fibers.

Flexural performance represents the combined response of tensile, compressive, and shear stresses acting simultaneously within the composite structure. Fiberglass composites generally exhibit excellent flexural strength and stiffness, making them suitable for bridge decks, structural panels, transportation components, and marine structures [25]. The flexural behavior of these materials is strongly affected by laminate configuration, fiber orientation, and reinforcement architecture. Continuous fiber systems and woven reinforcements typically provide superior load distribution and greater resistance to bending-induced damage [26]. Recent structural investigations have demonstrated the effectiveness of glass-fiber-based composite systems in enhancing the load-carrying capacity of hybrid structural members. For example, the incorporation of glass roving-tied GFRP shear connectors significantly improved structural efficiency and delayed failure in composite beam systems subjected to flexural loading [27]. Such findings highlight the importance of reinforcement design and structural configuration in maximizing compressive and flexural performance.

Impact Resistance and Fracture Behavior

Impact resistance is a key mechanical characteristic of fiberglass FRP composites because many engineering structures experience accidental impacts, dynamic loads, or shock events during service. The ability of a composite to absorb and dissipate impact energy depends on multiple damage mechanisms operating simultaneously, including matrix cracking, fiber breakage, interfacial debonding, fiber pull-out, and delamination [28]. These mechanisms enable the material to dissipate energy progressively rather than failing catastrophically. Fracture behavior in fiberglass composites is inherently complex because damage evolves across multiple structural scales. Crack initiation generally occurs within the polymer matrix before propagating along fiber-matrix interfaces or through reinforcing fibers [29]. The extent and progression of fracture are strongly influenced by fiber architecture, interfacial strength, and laminate design. Improved interfacial bonding can suppress crack propagation and enhance fracture toughness by facilitating more effective stress redistribution throughout the composite structure [30]. Recent advances in nanotechnology have further improved the impact and fracture performance of FRP composites. The incorporation of nanofillers such as graphene nanoplatelets, carbon nanotubes, and nanoclays has been shown to increase fracture toughness, delay crack growth, and enhance energy absorption capabilities [31]. These improvements contribute to greater structural reliability in demanding applications where impact resistance is a critical design requirement.

Fatigue Performance and Durability

The long-term performance of fiberglass FRP composites is largely determined by their resistance to fatigue damage and environmental degradation. Fatigue failure occurs when repeated cyclic loading progressively accumulates damage within the composite, leading to stiffness reduction, crack propagation, and eventual structural failure [1]. Unlike static loading, fatigue damage develops gradually and may remain undetected until significant degradation has occurred. The fatigue life of fiberglass composites is influenced by stress amplitude, loading frequency, fiber orientation, matrix properties, and manufacturing quality.

Repeated loading can initiate matrix microcracks, interfacial debonding, and fiber fracture, which collectively reduce the load-bearing capability of the material [2]. Composite architectures with optimized fiber alignment and strong interfacial bonding generally demonstrate superior fatigue resistance and slower damage accumulation. Environmental conditions further influence the durability of fiberglass composites. Exposure to moisture, ultraviolet radiation, temperature fluctuations, and aggressive chemical environments can degrade the fiber-matrix interface and accelerate mechanical deterioration [25]. Such degradation may reduce tensile, compressive, and flexural properties over prolonged service periods. Nevertheless, advancements in matrix modification, surface treatment technologies, and nano-enhanced reinforcement systems have significantly improved the environmental stability and service life of modern FRP composites [25]. Consequently, the overall mechanical performance of fiberglass composites depends not only on their intrinsic material properties but also on the interaction of manufacturing quality, interfacial characteristics, structural design, and environmental exposure throughout their operational lifespan. A summary of the representative mechanical properties reported for GFRP composites is presented in **Table 2**. The data highlight the strong tensile and flexural performance, favorable stiffness characteristics, and durability that have contributed to the widespread adoption of GFRP materials in engineering applications.

Environmental Performance and Long-Term Reliability

The long-term performance of fiberglass fiber-reinforced polymer (FRP) composites is strongly influenced by their interaction with environmental conditions throughout service life. Although these materials exhibit excellent corrosion resistance, high specific strength, and favorable durability compared with conventional metallic materials, prolonged exposure to environmental stressors can gradually alter their physical, chemical, and mechanical characteristics [14]. Consequently, understanding the mechanisms governing environmental degradation is essential for predicting service life and ensuring the reliability of fiberglass composites in civil infrastructure, transportation, marine, and industrial applications. Environmental exposure can significantly affect the structural integrity of fiberglass composites. Moisture is among the most critical degradation agents because water molecules can diffuse into the polymer matrix and accumulate at the fiber-matrix interface, causing matrix plasticization, swelling, and interfacial weakening [20]. Elevated temperatures further accelerate these processes by increasing molecular mobility and promoting thermo-oxidative reactions within the polymer network. Ultraviolet (UV) radiation can induce photo-oxidative degradation, resulting in surface embrittlement, discoloration, and reductions in mechanical performance, particularly in outdoor applications [14]. Chemical exposure to saline environments, acids, alkalis, and industrial contaminants may also compromise matrix integrity and weaken fiber-matrix adhesion, leading to progressive deterioration of structural performance [15].

In addition to environmental attack, fiberglass composites are susceptible to creep and aging phenomena during long-term service. Creep refers to the gradual time-dependent deformation that occurs when a material is subjected to sustained loading.

This behavior is primarily associated with the viscoelastic nature of the polymer matrix and becomes more pronounced under elevated temperatures and high stress levels [13]. Aging processes involve cumulative physical and chemical changes within the composite structure, including oxidation, molecular rearrangement, and interfacial deterioration. Over time, these changes can reduce stiffness, strength, and fatigue resistance, ultimately affecting structural reliability [28]. The rate and extent of aging are influenced by environmental conditions, loading history, and constituent material properties. The degradation of fiberglass FRP composites typically results from multiple interacting mechanisms rather than a single process. Moisture ingress, thermal stresses, UV exposure, and chemical attack often initiate matrix microcracking and interfacial debonding, creating pathways for further environmental penetration [29]. As damage accumulates, delamination, fiber–matrix separation, and localized crack propagation may occur, reducing the effectiveness of load transfer within the composite structure. These degradation mechanisms can progressively diminish tensile, compressive, and flexural performance, particularly in aggressive service environments [30]. The complexity of these interactions highlights the importance of comprehensive durability assessments when designing FRP components for long-term applications.

Various strategies have been developed to improve the environmental durability and long-term reliability of fiberglass composites. Advances in resin formulation have produced matrices with enhanced thermal stability, moisture resistance, and chemical durability [31]. Surface treatments and coupling agents are widely employed to strengthen fiber–matrix interfacial bonding and reduce susceptibility to moisture-induced degradation. Protective coatings and UV-resistant surface layers further mitigate environmental damage in outdoor environments [32]. More recently, nanotechnology-based modifications have emerged as promising approaches for enhancing durability. The incorporation of nanofillers such as graphene nanoplatelets, carbon nanotubes, and nanoclays can improve barrier properties, reduce permeability, and retard crack propagation, thereby extending service life while maintaining mechanical performance [33]. These developments are contributing to the increased adoption of fiberglass FRP composites in applications where long-term structural reliability is a critical requirement.

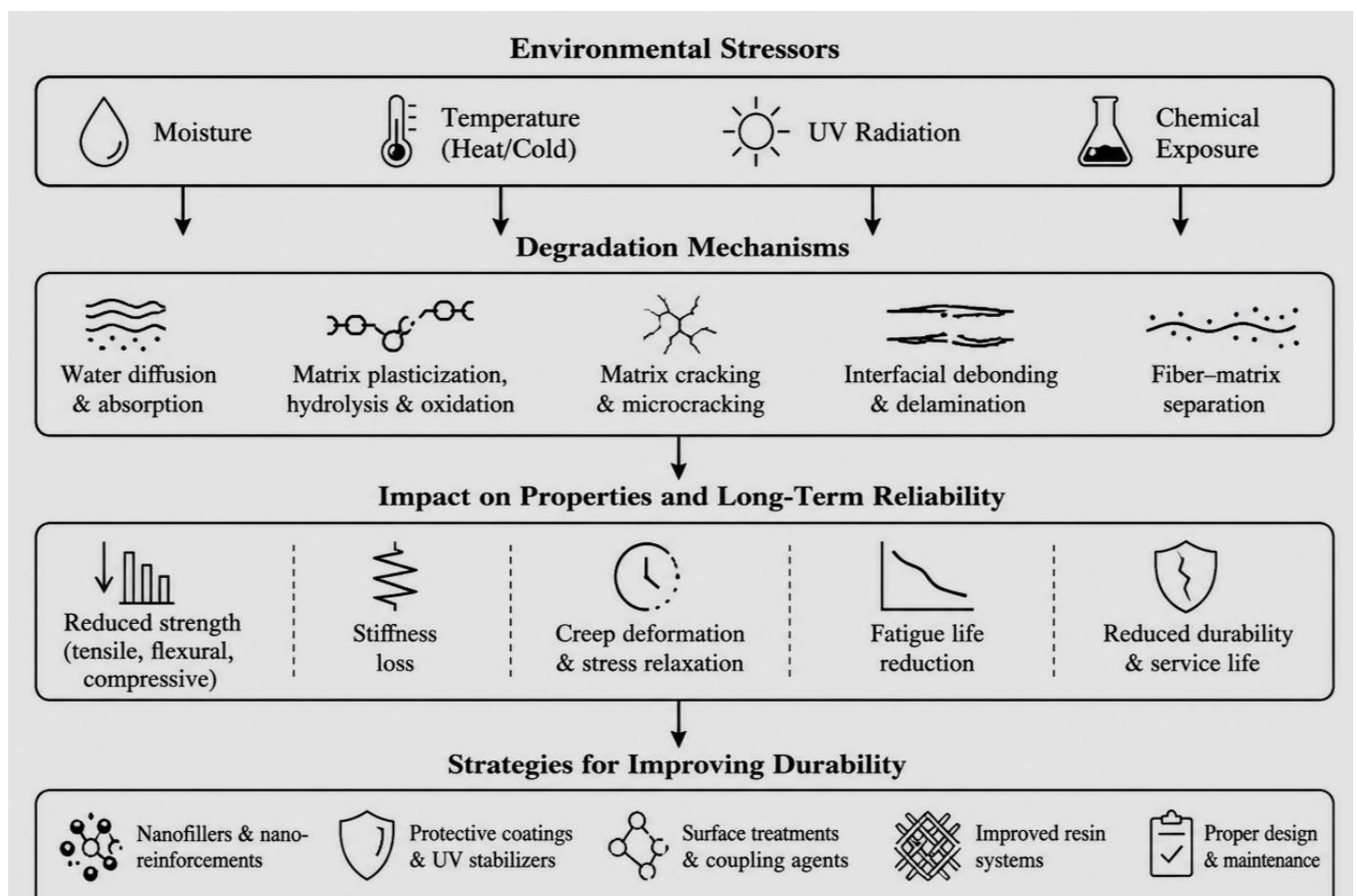


Figure 3. Environmental degradation pathways and durability enhancement strategies in Fiberglass Reinforced Polymer (FRP) composites. This figure illustrates the major environmental stressors affecting fiberglass FRP composites, including moisture, temperature variations, ultraviolet radiation, and chemical exposure. It highlights the associated degradation mechanisms and their effects on mechanical performance, durability, and service life, while summarizing key strategies employed to enhance long-term reliability and environmental resistance.

Source: [14]

Engineering and Industrial Applications

The exceptional strength-to-weight ratio, corrosion resistance, design flexibility, and long-term durability of fiberglass fiber-reinforced polymer (FRP) composites have enabled their widespread adoption across numerous engineering and industrial sectors. Compared with conventional materials such as steel, aluminum, and timber, fiberglass composites offer significant advantages in terms of lightweight construction, reduced maintenance requirements, and enhanced environmental resistance [14]. Advances in manufacturing technologies, material design, and structural optimization have further expanded their application range, making fiberglass FRP composites important materials for modern infrastructure, transportation, energy systems, and advanced engineering solutions.

Aerospace and Automotive Sectors

The aerospace and automotive industries were among the earliest adopters of fiberglass composites because of the continuous demand for lightweight materials capable of maintaining high structural performance. In aerospace applications, fiberglass FRP composites are used in radomes, interior cabin components, fairings, secondary structural elements, and insulation systems due to their excellent specific strength, fatigue resistance, and electromagnetic transparency [15]. The reduction in structural weight contributes directly to improved fuel efficiency and lower operational costs. Similarly, the automotive sector utilizes fiberglass composites in body panels, bumpers, leaf springs, roof structures, and interior components to reduce vehicle mass while maintaining safety and durability requirements [16]. The growing emphasis on electric vehicles has further increased interest in fiberglass composites because lightweight structures improve battery efficiency and vehicle range.

Civil and Construction Engineering

Fiberglass FRP composites have become increasingly important in civil infrastructure because of their resistance to corrosion, high durability, and favorable mechanical properties. Traditional steel-reinforced structures often experience deterioration due to corrosion, particularly in aggressive environments, leading to significant maintenance and replacement costs. Fiberglass composites provide an attractive alternative for reinforcing concrete structures, bridge decks, strengthening systems, and prefabricated structural components [17]. Glass fiber-reinforced polymer bars, sheets, and laminates are widely employed in structural rehabilitation projects to enhance load-carrying capacity and extend service life. In addition, pultruded GFRP profiles are increasingly used in pedestrian bridges, utility structures, and modular construction systems because of their lightweight nature and ease of installation [18]. These advantages have contributed to the growing acceptance of FRP-based solutions in sustainable infrastructure development.

Marine and Offshore Structures

Marine and offshore environments present severe challenges to conventional materials because of continuous exposure to moisture, saltwater, and corrosive conditions.

Fiberglass composites exhibit excellent resistance to seawater corrosion and biological degradation, making them particularly suitable for marine applications [14].

Consequently, fiberglass FRP composites are widely utilized in boat hulls, decks, superstructures, docks, pipelines, and offshore platforms. Their lightweight characteristics improve vessel efficiency and reduce fuel consumption, while their durability minimizes maintenance requirements throughout service life. In offshore energy systems, fiberglass composites are increasingly used in structural components exposed to aggressive marine environments where corrosion resistance and long-term reliability are essential performance requirements [15].

Electrical, Energy, and Consumer Products

The excellent electrical insulation properties of fiberglass composites have supported their extensive use in electrical and energy-related applications. Fiberglass FRP materials are commonly employed in insulators, cable trays, switchgear enclosures, transformer components, and electrical support structures because they combine high mechanical strength with low electrical conductivity [17]. In the renewable energy sector, fiberglass composites play a vital role in the manufacture of wind turbine blades, where lightweight construction, fatigue resistance, and environmental durability are critical for long-term operation [18]. Beyond industrial applications, fiberglass composites are increasingly incorporated into consumer products, including sporting goods, recreational equipment, storage tanks, furniture, and electronic device housings, owing to their versatility, aesthetic adaptability, and cost-effectiveness.

Emerging and Advanced Applications

Recent advances in materials engineering, nanotechnology, and smart manufacturing are creating new opportunities for fiberglass FRP composites in emerging applications. The incorporation of nanoscale reinforcements has enabled the development of multifunctional composites with enhanced mechanical, thermal, and environmental performance characteristics [19]. Furthermore, hybrid composite systems that combine glass fibers with carbon, aramid, or natural fibers are being explored to achieve optimized combinations of strength, weight reduction, and cost efficiency [20]. Additive manufacturing and advanced processing technologies are also expanding the design possibilities for complex composite structures while improving manufacturing efficiency and material utilization [21]. Emerging applications extend beyond traditional engineering sectors into areas such as defense, biomedical devices, smart infrastructure, and sustainable energy systems. Advanced fiberglass composite materials are increasingly being integrated into sensor-enabled structures capable of real-time health monitoring and predictive maintenance, supporting the development of intelligent infrastructure systems [22]. As research continues to improve durability, sustainability, and multifunctionality, fiberglass FRP composites are expected to play an increasingly important role in next-generation engineering technologies and high-performance industrial applications.

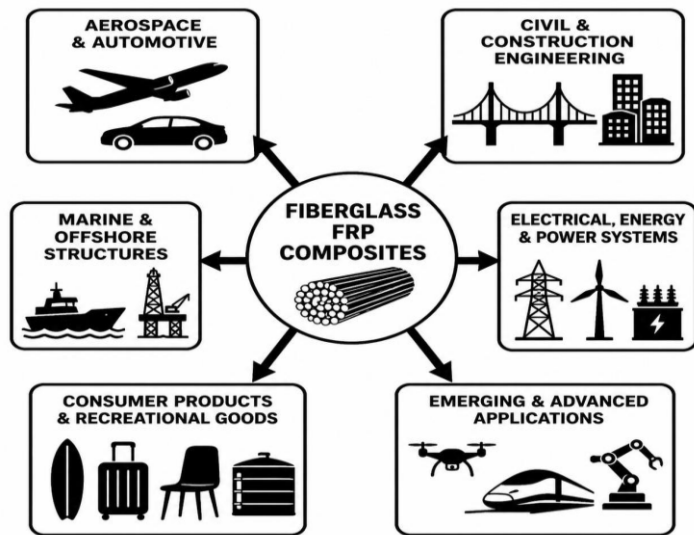


Figure 4. Major engineering and industrial applications of Fiberglass Reinforced Polymer (FRP) composites. This figure presents a concise overview of the principal application domains of fiberglass FRP composites, including aerospace and automotive systems, civil and construction engineering, marine and offshore structures, electrical and energy infrastructure, consumer products, and emerging advanced technologies. The widespread adoption of these materials is driven by their high strength-to-weight ratio, corrosion resistance, durability, and design flexibility, which make them suitable for both traditional and next-generation engineering applications.

Source: [6]

Challenges and Future Perspectives

The continued advancement and large-scale adoption of fiberglass fiber-reinforced polymer (FRP) composites are accompanied by several technical, environmental, and economic challenges that must be addressed to fully realize their potential in engineering applications. Although these materials offer excellent strength-to-weight ratios, corrosion resistance, and design flexibility, their performance is still constrained by issues related to recyclability, interfacial durability, manufacturing complexity, and long-term sustainability [14]. Consequently, ongoing research is increasingly focused on overcoming these limitations through material innovation, process optimization, and the development of sustainable lifecycle management strategies. One of the primary technical challenges associated with fiberglass FRP composites is their inherent heterogeneity and anisotropy, which can lead to complex failure mechanisms under service loading. Interfacial degradation between fiber and matrix remains a critical concern, particularly under cyclic loading, moisture exposure, and thermal fluctuations, which collectively contribute to progressive damage accumulation and reduced structural integrity [15]. Additionally, manufacturing defects such as voids, fiber misalignment, and inconsistent resin impregnation can significantly affect mechanical performance and reduce reliability in large-scale structural applications. These limitations highlight the need for improved quality control and advanced processing techniques to ensure consistency in composite performance.

Sustainability and end-of-life management represent another major challenge in the FRP industry. Thermoset-based fiberglass composites, which dominate structural applications, are particularly difficult to recycle due to their cross-linked polymer networks. As a result, large volumes of composite waste are generated from wind turbine blades, marine structures, and construction materials, raising environmental concerns [30].

Recycling technologies for fiber-reinforced polymers are still developing, with current approaches including mechanical grinding, thermal pyrolysis, and chemical recycling; however, each method has limitations in terms of cost, fiber degradation, and material recovery efficiency [33]. In response, research is increasingly exploring circular economy strategies, including recyclable thermoplastic matrices and reprocessable composite systems. Recent innovations in hybridization and multifunctional composites offer promising pathways to overcome existing limitations. Hybrid fiber systems combining glass fibers with carbon, aramid, or natural fibers have demonstrated improved mechanical balance, enhanced crack resistance, and optimized cost-performance ratios [1]. Similarly, advances in nanotechnology have enabled the development of nano-modified FRP composites with improved interfacial bonding, barrier properties, and damage resistance, thereby enhancing both mechanical and environmental performance [27]. These innovations are also facilitating the development of smart composites capable of self-sensing, damage detection, and real-time structural health monitoring.

From a future perspective, the integration of advanced manufacturing technologies such as automated fiber placement, additive manufacturing, and digital design optimization is expected to significantly improve the efficiency and precision of FRP composite production. Furthermore, the adoption of life-cycle assessment (LCA) methodologies and sustainability-driven design principles will play an increasingly important role in guiding material selection and engineering decisions [6]. Emerging trends also indicate a shift toward bio-based resins, recyclable thermoplastics, and eco-friendly reinforcement strategies aimed at reducing the environmental footprint of composite systems. Overall, the future of fiberglass FRP composites lies in balancing high-performance engineering requirements with sustainability and circular economy principles. Continued interdisciplinary research combining materials science, mechanical engineering, nanotechnology, and environmental science will be essential in addressing current limitations and unlocking new opportunities for next-generation composite systems.

Conclusion

Fiberglass reinforced polymer composites have established themselves as versatile engineering materials due to their combination of high specific strength, corrosion resistance, and adaptable manufacturing potential. Their mechanical performance is governed by fiber-matrix interactions, structural architecture, and processing methods, while environmental exposure and long-term loading remain key considerations in service reliability. Continuous advancements in material design, nanomodification, and hybrid systems are further enhancing their durability and expanding their applicability across aerospace, civil infrastructure, marine, energy, and emerging technological fields. Overall, fiberglass FRP composites represent a sustainable and high-performance class of materials with strong potential for future structural and multifunctional applications in modern engineering systems.

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