

Interfacial Bonding and Performance of Polymer-Based CFRP Composites in Externally Applied Configurations

A. Avaneesh Pushpasai¹, M. HemaPriya², A. Arivumangai³ and J. Faney^{4,*}

Abstract

Polymer-based carbon fiber reinforced polymer (CFRP) composites are widely used for externally bonded strengthening and retrofitting applications due to their high strength-to-weight ratio and adaptability to existing structures. In such systems, overall performance is governed not only by the fiber–matrix interaction within the laminate, but more critically by the polymer adhesive layer and its interaction with the substrate. Polymer chemistry, interfacial bonding mechanisms, processing conditions, and environmental exposure collectively influence load transfer efficiency, mechanical performance, durability, and long-term service reliability. This review provides a comprehensive assessment of interfacial bonding in polymer-based CFRP systems with a specific focus on externally applied configurations. Key interfacial mechanisms, including mechanical interlocking, physical interactions, and chemical bonding, are critically examined alongside the role of adhesive polymer systems and curing processes. The effects of environmental exposure on durability and service life are discussed, with particular emphasis on degradation at the adhesive–substrate interface. Emerging sustainable polymer systems, including bio-based, recyclable, and reprocess able matrices, are also evaluated in terms of their applicability and limitations for externally bonded CFRP applications. Unlike prior reviews that primarily address fiber–matrix interphases in bulk composites, this work emphasizes polymer–adhesive–substrate interactions and integrates polymer chemistry, interfacial mechanisms, processing, durability, modeling, and sustainability within a unified, design-oriented framework for externally bonded CFRP systems.

Keywords: Polymer-based composites, CFRP, interfacial bonding, adhesive polymers, externally applied configurations, polymer matrices, composite performance, durability

INTRODUCTION

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Carbon fiber reinforced polymer (CFRP) composites are high-performance materials consisting of strong, stiff carbon fibers embedded within a polymer matrix. Owing to their excellent strength-to-weight ratio, corrosion resistance, and design flexibility, CFRP systems are widely used across aerospace, automotive, marine, and civil engineering applications. The versatility of CFRP composites arises primarily from the tunability of polymer chemistry, fiber architecture, and interfacial characteristics, which together enable tailored mechanical and functional performance for diverse service conditions.

In recent years, externally bonded CFRP systems have gained significant attention for the strengthening and retrofitting of existing structures. In these configurations, prefabricated CFRP

laminates or fabrics are bonded to substrates such as concrete or steel using polymer-based adhesives. Unlike traditional bulk CFRP composites, externally bonded systems rely on adhesive-mediated load transfer between the composite and the substrate, making interfacial bonding a critical factor governing structural performance, failure behavior, and long-term reliability.

The performance of externally bonded CFRP systems differs fundamentally from that of bulk composites due to the presence of multiple interfaces, including the fiber–matrix interface within the laminate and the adhesive–substrate interface at the structural surface. Factors such as surface preparation, polymer chemistry, curing conditions, and environmental exposure strongly influence interfacial adhesion, stress distribution, and damage evolution. As a result, failure in externally bonded CFRP systems is often controlled by interfacial debonding or substrate-related mechanisms rather than fiber rupture, underscoring the dominant role of polymer interfaces [1].

From a polymer and composite materials perspective, thermosetting polymers—particularly epoxy, vinyl ester, and polyester resins—remain the most widely used matrices and adhesives for externally bonded CFRP applications. Their favorable adhesion characteristics, mechanical stability, and processability make them suitable for on-site application. However, reported performance varies significantly across studies due to differences in polymer molecular architecture, curing protocols, surface treatment methods, and environmental exposure conditions. These variations highlight the need for a deeper understanding of polymer-controlled interphase formation and durability in externally applied systems.

While numerous studies and review articles have examined interfacial bonding in CFRP composites, most focus primarily on fiber–matrix interphases within bulk or factory-manufactured laminates. In contrast, externally applied CFRP systems introduce additional complexities, including substrate variability, field-controlled processing, adhesive layer thickness sensitivity, and direct exposure to aggressive environments. These factors create distinct interfacial challenges that are not adequately addressed by conventional bulk CFRP design assumptions.

This review addresses these gaps by providing a polymer-centric analysis of interfacial bonding and performance in externally bonded CFRP systems. Polymer molecular architecture is systematically linked to interphase formation, interfacial chemistry, processing conditions, mechanical response, durability, and sustainability considerations. In addition, emerging data-driven modeling approaches and sustainable polymer systems are discussed within the context of externally applied configurations. By integrating these aspects into a unified, design-oriented framework, this review aims to provide practical insights for improving the long-term performance and reliability of externally bonded CFRP strengthening systems [2].

Polymer Matrices in CFRP Composites

The polymer matrix is a fundamental component of CFRP composites and performs functions that extend beyond simply binding carbon fibers. In externally bonded CFRP systems, the polymer matrix contributes to stress transfer between the laminate and the substrate, protects fibers from environmental exposure, and plays a critical role in interfacial adhesion and long-term durability. Consequently, the selection and design of polymer matrices have a direct and significant influence on the mechanical performance and service life of externally applied CFRP systems.

Unlike bulk CFRP laminates manufactured under controlled factory conditions, externally bonded systems are applied on-site, where polymer matrices must accommodate variations in substrate properties, curing environments, and workmanship [3]. As a result, polymer behavior at the adhesive–substrate interface often governs system performance more strongly than intrinsic laminate properties.

This section therefore emphasizes polymer matrix characteristics that are particularly relevant to externally bonded CFRP applications, including adhesion, environmental resistance, and compatibility with different substrates.

Thermosetting Polymer Systems

Thermosetting polymers are the most widely used matrices and adhesives in CFRP composites due to their high stiffness, dimensional stability, and strong bonding capability. Among them, epoxy resins are the most commonly employed because of their favorable mechanical properties, chemical resistance, and excellent adhesion to both carbon fibers and structural substrates. During curing, reactive epoxide groups form highly crosslinked polymer networks, resulting in strong interfacial bonding and efficient load transfer.

Despite their widespread use, epoxy-based systems exhibit notable variability in long-term performance. Several studies report improved interfacial strength and stiffness associated with high crosslink density, while others highlight increased brittleness and susceptibility to moisture-induced degradation. Under hygrothermal exposure, reductions in bond strength of up to 30% have been reported, indicating that high initial stiffness does not necessarily translate to superior durability. These contrasting observations suggest an inherent trade-off between mechanical performance and environmental resistance [4].

Alternative thermosetting systems, such as vinyl ester and polyurethane matrices, offer different performance balances. Vinyl ester systems generally exhibit lower stiffness than epoxies but provide improved toughness and resistance to chemical attack, while polyurethane systems offer enhanced flexibility and strain compatibility. These differences indicate that no single thermosetting polymer is universally optimal for all externally bonded CFRP applications, and that polymer selection must be guided by service temperature, loading conditions, and environmental exposure rather than initial strength alone. Figure 1 schematically summarizes the polymer-based CFRP composite system, highlighting recent advances and key challenges related to polymer matrices, interfacial bonding, processing, durability, and sustainability.

Relationship of Polymer Matrices

Quantitative studies demonstrate that the mechanical performance of CFRP composites is strongly influenced by polymer molecular architecture and curing conditions. Increases in crosslink density typically lead to higher elastic modulus but reduced fracture toughness, with reported toughness reductions of 20–40%.

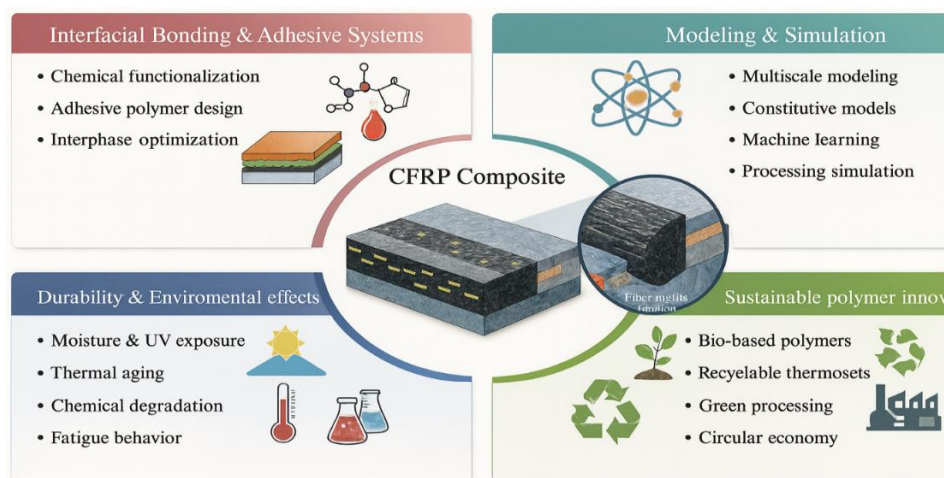


Figure 1. Polymer-based CFRP Composite system: Advances and challenges (adapted from Zhang et al., 2022; Joo et al., 2025).

In contrast, toughening strategies such as rubber modification or thermoplastic blending enhance energy dissipation and crack resistance but often at the expense of stiffness and processing simplicity. These competing effects highlight the need for balanced polymer design strategies in externally bonded CFRP systems [5]. In externally bonded configurations, the effectiveness of polymer matrices is further governed by substrate characteristics, including concrete porosity and alkalinity or steel surface chemistry. Polymer chain architecture, functional group availability, and curing behavior influence wetting, chemical affinity, and interphase formation at the adhesive–substrate interface. As a result, polymer matrices play a central role in controlling interfacial durability, stress redistribution, and long-term performance, reinforcing the importance of substrate-specific polymer selection and design. A comparative summary of commonly used polymer systems and their relative interfacial performance and durability is provided in Table 1.

Interfacial Bonding Mechanisms and Adhesive Polymer Systems

Interfacial bonding is the defining factor governing the performance of externally bonded CFRP systems, as load transfer between the composite and the substrate occurs almost entirely through the adhesive layer. Unlike bulk CFRP laminates, where fiber–matrix interactions dominate, externally applied configurations depend on polymer-controlled interphases formed at the adhesive–substrate boundary. Consequently, interfacial chemistry, surface condition, curing behavior, and environmental exposure collectively determine mechanical efficiency, failure modes, and long-term durability [6]. Reported degradation ranges of interfacial and mechanical properties under different environmental exposure conditions are summarized in Table 2.

Fundamentals of Interfacial Bonding in CFRP Composites

Interfacial bonding in CFRP composites arises from a combination of mechanical interlocking, physical interactions, and chemical bonding. Mechanical interlocking occurs when polymer adhesives penetrate surface asperities or pores, while physical interactions include van der Waals forces and surface energy effects. Chemical bonding results from covalent or hydrogen bonding between functional groups in the polymer and reactive sites on the substrate surface.

In externally bonded CFRP systems, the relative contribution of these mechanisms depends strongly on substrate type. For concrete substrates, mechanical interlocking dominates due to surface roughness and porosity, whereas for steel substrates, adhesion is governed primarily by surface energy, oxide chemistry, and chemical affinity. This substrate dependence distinguishes externally bonded systems from bulk CFRP composites, where interfacial conditions are comparatively uniform and factory-controlled.

Table 1. Relative interfacial performance.

Polymer system	Key feature	Durability	Relative interfacial performance
Epoxy	High stiffness	Moderate	High
Vinyl ester	Tougher	Moderate	Medium
Polyurethane	Flexible	High	Medium–High

Table 2. Reported durability degradation ranges in polymer-based CFRP system.

Exposure Condition	Typical Duration	Property Affected	Reported Degradation Range
Moisture immersion	500–2000 h	Interfacial shear strength	10–35% reduction
Hygrothermal aging	60–80 °C + RH	Bond strength	15–40% reduction
UV exposure	1000–3000 h	Surface adhesion	5–25% reduction
Freeze–thaw cycling	50–300 cycles	Interfacial stiffness	10–30% reduction
Thermal cycling	–20 to 60 °C	Fatigue life	20–45% reduction

Although chemical bonding is considered the leading mechanism of adhesion, the experimental findings relating chemical functionality to the strength of the interface are contradictory. Several studies claim improvements in interfacial shear strength of more than 40 % by chemical surface treatments, others find similar results but mechanical interlocking proves to be the main source of the strength. These contradictions indicate that the relative importance of the bonding mechanisms is highly surface morphology, polymer chemistry and processing dependent and not governed by a single dominant adhesion mechanism. The dominance of a given bonding mechanism is ultimately dictated by polymer chain mobility, functional group availability, and cure-induced network structure, which collectively define the molecular-scale structure of the interphase.

Environmental exposure further modifies interfacial bonding behavior over time. Moisture ingress, thermal cycling, and chemical attack can weaken physical and chemical interactions, leading to progressive bond degradation. These effects are particularly pronounced in externally bonded CFRP systems due to direct exposure of the adhesive–substrate interface to service environments [7].

Adhesive Polymer Systems for Externally Applied Configurations

Adhesive polymer systems serve as the primary load-transfer medium in externally bonded CFRP strengthening applications. Epoxy-based adhesives are most widely used due to their high stiffness, strong adhesion, and compatibility with carbon fibers and structural substrates. Their curing reactions create rigid crosslinked networks capable of efficiently transferring stresses between the CFRP laminate and the substrate.

However, the mechanical behavior of adhesives differs fundamentally from that of structural laminates. Adhesive thickness, curing temperature, and application quality significantly influence stress distribution and debonding resistance. Excessively stiff adhesives may induce stress concentrations, while overly flexible adhesives may reduce load transfer efficiency. The typical strength levels, dominant failure mode tendencies, and service environment suitability of common adhesive systems are outlined in Table 3.

Comparative analysis of different adhesive systems has shown a considerable variation in their performance. Epoxide adhesives generally offer higher bond strength, with interface shear strengths reported in the range of 12 to 25 MPa, whereas the strength of polyurethane systems is lower, but they are able to undergo higher strains and have better impact resistance. The vinyl ester adhesives have intermediate performances and exhibit reduced thermal stability. These compromises indicate that the choice of adhesive should be based on the service temperature, the magnitude of the load, and the exposure to the environment, rather than on the highest achievable bond strength. Thus, adhesive molecular architecture controls not only bond strength but also interphase compliance and damage evolution, which directly influence failure mode transition and long-term durability.

Recent data-driven studies have employed regression-based ML models to predict adhesive performance envelopes by linking adhesive chemistry, modulus, glass transition temperature, and environmental exposure conditions to failure mode transitions. While promising, model accuracy remains highly sensitive to dataset size and testing consistency. Unlike bulk CFRP composites, adhesives in externally bonded systems function as the primary structural medium for load transfer and crack arrest, with their thickness, curing conditions, and field application quality significantly affecting system performance [8]. A detailed overview of adhesive polymer systems commonly employed in externally applied CFRP configurations, along with their key properties and limitations, is presented in Table 4.

Table 3. Failure mode tendency and service environment suitability.

Adhesive	Strength	Failure mode tendency	Service suitability
Epoxy	High	Interfacial → cohesive	Dry / moderate
PU	Medium	Cohesive	Moist / cyclic

Table 4. Adhesive polymer systems commonly used in externally applied cfrp composite configurations.

Adhesive Polymer Type	Typical Polymer Chemistry	Key Properties	Advantages	Limitations
Epoxy-based adhesives	Di glycidyl ether-based thermosets with amine or anhydride curing agents	High stiffness, strong adhesion, low shrinkage	Excellent interfacial bonding, good chemical resistance, wide use	Brittle behavior, moisture sensitivity
Vinyl ester adhesives	Epoxy-modified unsaturated polyester systems	Moderate stiffness, good chemical resistance	Improved toughness compared to polyester, cost-effective	Lower glass transition temperature
Polyester adhesives	Unsaturated polyester resins	Easy processing, low cost	Fast curing, simple application	Higher shrinkage, limited adhesion strength
Polyurethane adhesives	Segmented elastomeric polymers	High flexibility, good impact resistance	Enhanced toughness, accommodates deformation	Lower stiffness, limited thermal resistance

Surface Preparation and Curing Effects on Interfacial Bonding

Surface preparation is a critical step in achieving reliable interfacial bonding in externally applied CFRP systems. Mechanical roughening, grinding, sandblasting, and chemical treatments are commonly used to remove contaminants and increase surface roughness. Proper surface preparation enhances wetting, mechanical interlocking, and chemical interaction between the adhesive and substrate.

When are currently reported advantages of aggressive surface preparation techniques are, but overly roughening or improper drying can lead to stress concentrations and early interfacial cracking. Investigations have shown that undercuring leads to a decrease in bond strength up to 35%, and overcuring might generate an increase of residual stresses and brittleness. This paradox illustrates the need for the optimal, not the maximum, surface treatment and curing protocols. Surface treatment and curing conditions regulate polymer chain diffusion, crosslink development, and residual stress formation at the interphase, thereby linking processing-induced molecular structure to interfacial stability and durability.

Interfacial Failure Modes and Degradation Mechanisms

The interface debonding in the solid polymer matrix based CFRP system is then the result of adhesive failure at the interface of the polymer and the substrate, cohesive failure within the adhesive, and damage of the laminate ply or interlaminar failure in the composite laminate. The dominant mode of failure is a function of polymer chemistry, adhesion strength and exposure to environment. Degradation is accelerated by various conditions such as moisture, temperature change, and chemical attack etc. by plasticizing polymers and weakening interfacial bonds stressing the importance of robust adhesive systems.

The dominant modes of failure that are reported vary widely among studies, as a function of the chemistry of the adhesive, the condition of the substrates, and the environmental exposure. Although debonding between the adhesive and adherends is a commonly reported failure mode under moisture exposure, cohesive failure within the adhesive layer prevails under monotonic loading in the absence of moisture. These differences indicate that the failure micromechanisms are not universal and need to be understood in terms of the service environment and the polymer system involved. Observed failure

modes reflect the underlying polymer network architecture, where brittle, highly crosslinked systems favor adhesive or interfacial failure, while tougher, more mobile networks promote cohesive failure within the adhesive layer. The relationship between interfacial failure modes, polymer-related causes, and influencing factors is summarized in Table 5.

Emerging Strategies for Interface Enhancement

Several strategies have been proposed to enhance interfacial bonding in externally bonded CFRP systems. These include surface functionalization, nano-modification of adhesives, and incorporation of coupling agents to improve chemical affinity. Such approaches aim to strengthen interphase formation and increase resistance to environmental degradation.

Nanomaterials such as carbon nanotubes, graphene, and silica nanoparticles have been incorporated into adhesive systems to improve toughness and crack resistance. These fillers promote energy dissipation and delay crack propagation at the interface. However, challenges remain related to dispersion, processing complexity, and cost.

Bio-based and recyclable polymer systems have also gained attention as sustainable alternatives. While these materials show promise in reducing environmental impact, their interfacial performance and long-term durability in externally bonded configurations remain under investigation. Further research is needed to validate their suitability for structural applications.

Processing and Application Techniques in Externally Applied CFRP Systems

Processing techniques markedly influence the quality and mechanical behavior of polymer matrix CFRP (carbon fiber reinforced polymer) composites, especially in external type application where the processing, i.e., lay-up and curing, is performed on site. The processing parameters and environment control the resin flow and wetting, cure kinetics and residual stress formation and interfacial morphology. Application procedures usually consist of surface conditioning, adhesive application, laminate lay-up and curing, all of them affecting the evolution of the interface and the performance of the composite as a whole.

Control of the thickness and uniformity of adhesive layers is important, since a thick layer may lead to the formation of stress concentrations, while an insufficient amount of adhesive may result in incomplete wetting of the adhesive and weak bonding. As a result, application techniques including roll-impregnation, vacuum-assisted processes have been elaborated to allow the uniform distribution of the adhesive, to minimize voids formation and to improve interfacial quality [7]. The influence of different processing methods on bond quality, defect sensitivity, and field applicability is compared in Table 6.

Table 5. Interfacial failure modes and polymer-related causes in CFRP composite systems.

Failure Mode	Polymer-Related Cause	Influencing Factors	Mitigation Strategy
Adhesive failure	Poor chemical compatibility	Inadequate surface preparation, moisture	Surface treatment, coupling agents
Cohesive failure	Low adhesive toughness	Brittle polymer network	Polymer toughening modifications
Interlaminar failure	Weak fiber–matrix bonding	Poor fiber sizing, curing defects	Fiber surface treatment, optimized curing

Table 6. Performance envelope table.

Processing method	Bond quality	Defect sensitivity	Field applicability
Wet lay-up	Medium	High	High
Prepreg	High	Low	Low
Vacuum-assisted	High	Medium	Medium

Table 7. Processing methods for polymer-based CFRP laminates in externally applied configurations.

Processing Method	Polymer State During Application	Key Advantages	Processing Limitations
Wet lay-up	Low-viscosity liquid resin	Simple application, good surface wetting	Sensitive to environment, resin variability
Pre-impregnated (prepreg)	Partially cured polymer	Uniform resin distribution, controlled fiber volume	Requires temperature control
Vacuum-assisted application	Liquid resin under vacuum	Reduced void content, improved consolidation	Equipment complexity
Roller-assisted impregnation	Liquid resin	Improved resin penetration	Operator-dependent quality

Comparative investigations show that both the vacuum assisted and the prepreg technique more or less consistently result in lower void content and more uniform adhesive layers than the wet lay-up technique with associated improvements in bond strength of the order of 15–30%. Nevertheless, these sophisticated techniques have to be more tightly controlled in terms of equipment and skilled workers, for this reason their application in field strengthening is quite limited. A classification of processing methods used for polymer-based CFRP laminates in externally applied configurations is provided in Table 7.

Quality Control and Defect Formation

Quality control in externally bonded CFRP systems is the control of defects like voids, resin rich areas and interfacial fractures. In addition, uneven resin distribution and inadequate curing can cause localized weak points which start failure under service environment. Among the inspection techniques, the visual inspection, ultrasonic testing and thermal analysis to check the curing degree are the most employed ones. From the polymer processing perspective, defect prevention and mitigation strategies are the development of resin system, the application methods, and the cure schedules so as to provide uniform material properties through the composite system [8]. Nevertheless, the lack of standardized inspection criteria complicates direct comparison of defect tolerance across studies [9].

Influence of Processing on Long-Term Performance

Processing-related parameters have a pronounced influence on the long-term performance of externally bonded CFRP systems, often resulting in measurable reductions in bond capacity and stiffness. Studies commonly report decreases in interfacial strength and fracture resistance in the range of approximately 20–40% when inadequate surface preparation, non-uniform adhesive thickness, incomplete curing, or void formation is present. These processing-induced defects promote stress concentrations and accelerate moisture diffusion, thermal fatigue, and chemical degradation at the adhesive–substrate interface. In externally applied systems, where curing and application occur under variable field conditions, such effects become more pronounced compared to factory-manufactured bulk composites. Consequently, processing quality and curing control are critical determinants of durability and service life and must be treated as primary performance variables rather than secondary construction-related factors. The effects of key processing parameters on polymer behavior, interfacial characteristics, and overall performance are summarized in Table 8.

Mechanical and Functional Performance of Polymer-Based CFRP Composite Systems

The mechanical performance of polymer-based CFRP composite systems is governed by the combined response of fibers, polymer matrices, adhesives, and interfacial bonding mechanisms. In externally bonded CFRP applications, load transfer from the strengthened member to the composite occurs primarily through the adhesive layer and the adhesive–substrate interface, rather than through the laminate itself. As a result, system-level performance is often controlled by interfacial properties such as bond strength, fracture toughness, and stress redistribution capability. Experimental studies consistently show that externally bonded CFRP systems fail predominantly through interfacial

debonding, cohesive adhesive failure, or substrate-related failure, while fiber rupture is comparatively rare. This behavior contrasts with bulk CFRP composites, where fiber-dominated failure governs ultimate strength.

Functional performance under service conditions is strongly influenced by polymer viscoelasticity, environmental exposure, and processing quality. Temperature, moisture, and sustained loading affect polymer stiffness, creep behavior, and interfacial durability, leading to progressive reductions in effective stiffness and load-carrying capacity over time. Reported studies indicate that environmental exposure and processing-induced defects can reduce interfacial strength and fracture resistance by approximately 20–40%, significantly affecting long-term performance. Furthermore, polymer-controlled functional properties such as damping, crack-bridging capability, and stress relaxation play a critical role in mitigating stress concentrations and delaying debonding. The combined influence of polymer chemistry, interfacial properties, and environmental exposure on system-level behavior is represented through a performance envelope, as shown in Figure 2.

Influence of Polymer Modification on Performance

Polymer modification methods including rubber toughening, thermoplastic blending and addition of nano-fillers have been broadly investigated to improve the mechanical and functional properties of CFRP composites. Comparative studies report that rubber and thermoplastic toughening strategies improve fracture toughness by approximately 30–70%, while nano-filler incorporation enhances interfacial strength by 20–45%. However, these improvements are often accompanied by reductions in stiffness or processing challenges such as increased viscosity and filler agglomeration. These competing effects highlight the need for optimization-based polymer modification rather than single-property enhancement. Polymer modification strategies modify molecular-scale architecture, which directly alters interphase compliance, crack-bridging capacity, and damage tolerance under mechanical and environmental loading. The dominant failure mechanisms in polymer-based CFRP composites and their polymer-level origins are outlined in Table 9.

Table 8. Influence of Processing Parameters on Polymer and Interfacial Characteristics.

Processing Parameter	Polymer-Level Effect	Influence on Interface	Performance Implication
Resin viscosity	Controls flow and wetting	Affects interfacial contact	Poor wetting → weak adhesion
Processing temperature	Alters curing kinetics	Influences bond development	Incomplete curing reduces durability
Curing duration	Determines crosslink density	Stabilizes interface	Insufficient curing weakens bonding
Environmental humidity	Moisture absorption	Disrupts adhesion	Long-term degradation

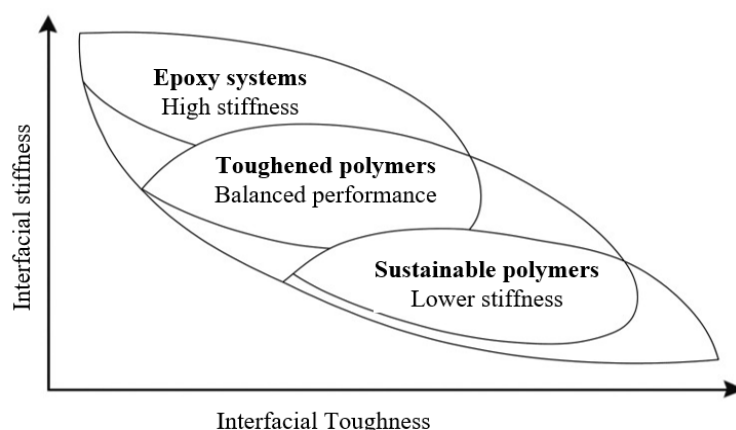


Figure 2. Performance Envelope of Polymer-Based CFRP System.

Table 9. Dominant Failure Mechanisms in Polymer-Based CFRP Composites.

Failure Mechanism	Polymer-Level Cause	Interfacial Role	Performance Impact
Matrix cracking	Brittle polymer network	Stress concentration	Reduced stiffness
Interfacial debonding	Poor adhesion	Load transfer loss	Premature failure
Delamination	Weak interlaminar bonding	Crack propagation	Reduced durability
Fiber breakage	Stress localization	Interface constraint	Sudden failure

Data-Driven Prediction of Mechanical Performance

Several recent studies have demonstrated the application of machine learning models for predicting the mechanical performance of polymer-based CFRP systems. Neural networks and ensemble learning methods have been trained using datasets comprising polymer chemistry, adhesive thickness, curing temperature, and interfacial roughness to predict tensile strength, flexural capacity, and fracture toughness. Reported prediction errors typically range between 5–15% for well-curated laboratory datasets. However, model transferability to field-applied CFRP systems remains limited due to variations in workmanship and environmental conditions, underscoring the need for hybrid physics-informed ML frameworks.

Durability and Environmental Effects on Polymer-Based CFRP Composites

Durability is a critical consideration for polymer-based CFRP composites, particularly in externally applied configurations, as environmental exposure can significantly influence long-term performance. Physical and chemical interactions at the polymer matrix and adhesive–substrate interface, driven by factors such as moisture, temperature fluctuations, UV radiation, and chemical agents, induce both physical and chemical aging. Reported studies indicate that moisture-induced degradation can reduce bond strength by 10–35%, hygrothermal conditioning can lead to up to 40% loss in interfacial performance, UV exposure primarily affects surface adhesion with reductions generally below 25%, and combined thermal and cyclic loading may result in fatigue life decreases exceeding 40%, underscoring the sensitivity of polymer-based CFRP systems to service conditions. Accelerated aging tests reveal strength retention typically ranging from 60% to 85%, with degradation rates highly dependent on polymer chemistry, adhesive formulation, and processing quality, while epoxy-based systems often retain short-term performance better than toughened or modified polymers, which exhibit slower but more uncertain long-term stiffness retention. Durability strategies including polymer modification to reduce moisture uptake, protective coatings, surface functionalization, and optimized curing enhance interfacial stability, although each approach carries trade-offs such as increased cost, processing complexity, or time requirements. Overall, environmental effects predominantly manifest at the adhesive–substrate interface, where moisture ingress, thermal cycling, and chemical interactions accelerate bond deterioration, highlighting the need for durability-oriented polymer design, predictive modeling, and careful processing to ensure long-term performance of externally bonded CFRP composites.

Accelerated Aging and Performance Assessment

The durability of a polymer-based CFRP composite is usually assessed by accelerated aging tests. Performance evaluation after aging, gives valuable information on degradation mechanisms and residual mechanical properties.

Prediction of the relationship between accelerated aging results and actual performance has become a subject of study, and advancements in testing methodologies and predictive modeling are needed.

While accelerated aging tests provide valuable insight into degradation mechanisms, their correlation with real service-life performance remains uncertain. Reported strength retention after accelerated exposure ranges from 60% to 85%, depending on test protocols. The lack of standardized aging procedures complicates direct comparison across studies and limits predictive reliability. Beyond

accelerated aging experiments, service-life prediction models increasingly integrate time–temperature superposition, moisture diffusion kinetics, and damage accumulation frameworks to estimate long-term CFRP performance. In contrast, toughened and modified polymer systems demonstrate slower degradation rates but with increased uncertainty in long-term stiffness retention, highlighting the need for unified durability modeling approaches.

Although data-driven modeling and machine learning techniques have shown growing potential in polymer-based CFRP research, their application remains constrained by several critical limitations. Most existing datasets are small, study-specific, and lack standardized descriptors for polymer chemistry, interfacial morphology, and processing conditions. Model validation is often limited to internal cross-validation, with few studies demonstrating predictive capability across independent experimental campaigns or field-applied systems.

Furthermore, the black-box nature of many ML models complicates physical interpretability, limiting their adoption for design-critical applications. Future progress requires the development of shared, curated datasets, physics-informed ML frameworks, and benchmark validation protocols that explicitly link polymer molecular architecture to interfacial performance and durability. Common polymer-based strategies for enhancing durability and interfacial stability of CFRP systems are summarized in Table 10.

Sustainability and Future Polymer Systems

The focus on sustainability has increasingly become a dominant theme in polymer and composites science and engineering in recent years due to both environmental and governmental policy/legislative influences. Although sustainable polymer systems offer clear environmental benefits, their adoption in externally bonded CFRP applications remains constrained by performance and durability limitations. Comparative studies indicate that bio-based and recyclable polymers generally exhibit 10–30% lower mechanical performance than conventional epoxy systems, highlighting the ongoing trade-off between sustainability and structural reliability.

Unlike existing sustainability-focused reviews, this section evaluates emerging polymer systems specifically in terms of their interfacial performance and durability limitations in externally bonded CFRP applications.

Future sustainable polymer systems must therefore be designed at the molecular level to achieve interphase architectures that simultaneously satisfy mechanical performance, durability, and environmental compatibility requirements. A failure map linking environmental conditions to dominant degradation mechanisms and failure modes is presented in Table 11.

Table 10. Strategies for Enhancing Durability of Polymer-Based CFRP Systems.

Durability Strategy	Polymer-Based Approach	Interfacial Benefit	Limitation
Polymer modification	Reduced moisture uptake	Improved stability	Cost increase
Protective coatings	Barrier formation	Reduced environmental ingress	Additional processing
Surface functionalization	Enhanced chemical bonding	Stronger interfaces	Processing complexity
Optimized curing	Increased crosslink density	Residual stress reduction	Time requirements

Table 11. Failure map table for Environmental conditions.

Environment	Dominant degradation	Failure mode
Moisture	Plasticization	Interfacial
UV	Chain scission	Adhesive
Thermal cycling	Residual stress	Cohesive

Bio-Based and Biodegradable Polymer Matrices

Renewable resource derived bio-based polymers are considered to be the effective solution to sustainable CFRP composites.

Polymers, like bio-based epoxies, polyesters, or polyamides, are becoming more and more investigated as matrix alternatives to petroleum-based ones.

Although biodegradable polymers have environmental benefits, it is still a challenge to obtain the mechanical properties and durability for high performance CFRP applications.

Experimental studies demonstrate that bio-based epoxies can achieve mechanical properties approaching those of petroleum-based systems; however, increased moisture sensitivity and reduced glass transition temperatures remain critical challenges. Reported reductions in bond strength of up to 25% under humid conditions indicate the need for further material optimization.

Recyclable and Reprocessable Polymer Systems

Recyclability is a great hindrance to traditional thermoset based CFRP systems. Recently, research efforts have been devoted to the development of recyclable thermosets and thermoplastic matrices that make it possible to recover materials.

Recyclable thermoset and thermoplastic systems show promising recoverability but often require elevated processing temperatures or specialized curing conditions. Studies report interfacial strength reductions of 15–35% compared to conventional epoxies, underscoring the need to balance recyclability with structural performance.

A comparative ranking of polymer systems based on sustainability, performance retention, and overall suitability is provided in Table 12.

Future Polymer Architectures for CFRP Systems

Polymer-based CFRP composites will find their future in tailor-made polymer architectures. With an appropriate balance of polymer system performance and inherent sustainability, the sophisticated polymer systems can potentially enhance interfacial durability, damage tolerance, and environmental resistance (service) related performance requirements while meeting with the sustainability of goals. Future polymer architectures aim to integrate adaptive bonding, self-healing, and reprocessability while maintaining high interfacial integrity.

However, scalability, cost, and long-term durability remain unresolved challenges, limiting near-term field implementation. The relationships between polymer architecture, interphase characteristics, and performance outcomes are summarized in Table 13.

Table 12. Ranking table for various polymer types.

Polymer type	Sustainability	Performance retention	Overall suitability
Epoxy	Low	High	High
Bio-epoxy	Medium	Medium	Medium
Recyclable	High	Low–Medium	Medium

Table 13. Structure–Interphase–Performance Mapping in Polymer-Based CFRP System.

Polymer Architecture	Interphase Characteristic	Performance Outcome
High crosslink density	Thin, stiff interphase	High strength, low durability
Toughened networks	Energy-dissipating interphase	Improved fracture resistance
Nano-modified polymers	Reinforced interphase	Enhanced load transfer
Sustainable polymers	Chemically weaker interphase	Reduced durability

Challenges, Research Gaps, and Future Directions

While there have been a number of developments in polymer CFRP composite systems, challenges and unknowns still exist. Polymer–fiber interfacial interactions are difficult to interrogate as a result of the constraints imposed by the existing experimental methodologies, and the bonding processes and long-term performance are uncertain.

In addition, the reliability and durability of the structure are still affected by environmental induced degradation, bake-induced residual stresses, and inadequate process control. The recent literature suggest that data-driven modeling and machine learning techniques are becoming very powerful tools, the utility are constrained by the absence of established datasets and validation approaches.

For future research, at the molecular level the design of polymer matrices and interfaces at elevated temperature for the balancing of mechanical performance versus sustainability to affect enhanced durability and environmental stability is anticipated. Furthermore, the development of sustainable and recyclable polymer systems and the availability of opportunities through advanced interfacial engineering will be significantly important in the next generation of high performance and green CFRP composites [10].

Despite growing research activity, inconsistencies in experimental methodologies and reporting metrics continue to hinder cross-study synthesis. Establishing standardized testing frameworks and shared databases will be essential to advance predictive modeling and data-driven design. A key research need is the establishment of quantitative structure–interphase–property relationships that directly link polymer molecular design to long-term performance of externally applied CFRP systems.

A key research gap in externally bonded CFRP systems lies in the limited availability of substrate-specific bond models and long-term interfacial durability data, which restricts reliable design and life-cycle prediction. Key research gaps, current limitations, and future focus areas in polymer-based CFRP systems are identified in Table 14.

Summary

In this review, the polymer-based CFRP composite systems have been presented and questioned to detail, focusing on interfacial bonding, adhesive polymer systems, processing schemes, mechanical and functional performances, durability, modeling approaches and sustainability issues. Taking advantage of developments in polymer chemistry, polymer physics, materials engineering, and data science methodologies, the article underlines the importance of polymer matrices and interfaces in determining the performance and long term reliability of CFRP composites.

Among other effects, the implications of polymer molecular architecture, crosslink density, viscoelasticity and interfacial chemistry upon load transfer, fracture behavior and environmental stability are investigated. This review demonstrates the importance of processing-induced interfacial formation and its impact on the performance of the composite. Advances in multiscale modeling and machine learning have been recognized as potential tools for the prediction of polymer–property relations and the acceleration of polymer composite design.

Table 14. Identified Research Gaps and Future Focus Areas.

Research Gap	Current Limitation	Future Direction
Interface modeling	Oversimplified assumptions	Multiscale coupling
Sustainable polymers	Reduced mechanical properties	Molecular-level design
Data availability	Fragmented datasets	Standardized databases
Long-term durability	Limited predictive models	Accelerated aging correlation

In addition, the present review covers new trends for sustainable polymer systems, i.e., biobased matrices, recyclable thermosets, reprocessable polymer networks, pointing out the challenges to be met and opportunities ahead. The article thus assembles experimental studies, theoretical models and sustainability-based technology advancements in such a way that it serves as a guideline to the state-of-the-art research in polymer based CFRP composites. Data-driven modeling and machine learning are identified as emerging tools capable of accelerating polymer and interface design, provided that standardized datasets and validation strategies are established.

CONCLUSIONS

Based on the above concise review, the following results can be concluded:

1. Contribution to the Mechanical Performance of CFRP Composite Systems The polymer matrix and the adhesive systems have a significant effect on the mechanical properties and the interfacial stability of the CFRP combined systems or they can be even more influential than that of the fibres in externally bonded systems.
2. Interfacial adhesion, which is a function of the polymer chemistry, surface energetics and processing, is essential to achieve good load transfer and damage tolerance.
3. Mechanical and functional properties of polymer based CFRPs are highly affected by polymer modification techniques such as toughening, blending and nano-scale reinforcement, all of which enhance fracture resistance and fatigue behaviour.
4. Environmental durability is still a major open issue as moisture, temperature cycling, UV radiation, and chemical media can attack polymer matrices and interfaces and cause property degradation and performance loss in the long term.
5. Modeling, simulation, and data science approaches offer a great potential for predicting composite behavior as well as providing material design guidance.
6. Polymer systems oriented towards sustainability, for example, bio based and recyclable matrices, are an important direction for the future, however matching conventional systems on the mechanical and durability fronts is still an active line of research.
7. Future progress in polymer based CFRP composites is expected to be centered around integrated approaches at the molecular level design of polymers with advanced characterization, multiscale modeling, and development of sustainable materials.

To conclude, the present review reveals that high potential strength and wear resistance of CFRP composites in polymer science and interfacial engineering. Continued cooperation and work in these areas will be essential in bringing to fruition the next generation of polymer based composite systems with enhanced capabilities, life and environmental acceptability. The synthesis presented in this review emphasizes the critical role of polymer chemistry, interfacial engineering, and processing optimization in advancing durable and sustainable CFRP composite systems. The novelty of this review lies in its integrated treatment of polymer chemistry, interfacial mechanisms, processing, durability, and sustainability for externally applied CFRP systems. By synthesizing cross-disciplinary findings and identifying contradictions and performance trade-offs, the manuscript provides actionable insights that extend beyond descriptive summaries offered by previous CFRP interface reviews. This review provides a polymer-centric, application-driven synthesis of externally bonded CFRP systems that complements and extends existing CFRP interface literature. Overall, externally bonded CFRP systems represent an interface-dominated class of composites in which polymer behavior, adhesive performance, and substrate characteristics must be jointly considered, rather than extrapolated from bulk CFRP composite behavior.

REFERENCES

1. Joo JH, Kim SH, Yim YJ, Bae JS, Seo MK. Interfacial interlocking of carbon fiber-reinforced polymer composites: A short review. *Polymers*. 2025;17:267. doi:10.3390/polym17030267.
2. Xue L, Wang M, Zhang Y. Characterization of interfacial properties between fibre and polymer matrix in composite materials – A critical review. *J Mater Res Technol*. 2021;13:1441–1484. doi:10.1016/j.jmrt.2021.05.030.
3. Zhang Q, Li J, Chen R. Recent advances of interphases in carbon fiber-reinforced polymer composites: A review. *Compos Part B Eng*. 2022;233:109639. doi:10.1016/j.compositesb.2022.109639.
4. Markouti P, Tzouma E, Paipetis AS, Barkoula NM. Conventional thermoset composites and their sustainable alternatives with vitrimer matrix—Waste management/recycling options with focus on carbon fiber reinforced epoxy resin composites. *Materials*. 2025;18:351. doi:10.3390/ma18020351.
5. Castro-Dominguez B, Gröls JR, Alkandari S, et al. Biopolymers and biocomposites: A comprehensive review of feedstocks, functionalities, and advanced manufacturing techniques for sustainable applications. *Biotechnol Sustain Mater*. 2025;2:25. doi:10.1186/s44316-025-00029-y.
6. Liu YY, Liu GL, Li YD. Biobased high-performance epoxy vitrimer with UV shielding for recyclable carbon fiber reinforced composites. *ACS Sustain Chem Eng*. 2021;9:4638–4647. doi:10.1021/acssuschemeng.3c03248.
7. Polanco J, Torres F. The sustainability spectrum of carbon fibre: Balancing high performance CFRP composites with environmental responsibility. *Adv Compos Hybrid Mater*. 2025;8:1143–1159. doi:10.1007/s42114-025-01497-6.
8. Smith T, Johnson K. Bio-based and biodegradable polymers for composites: Sustainability, challenges, and future perspectives. *Sci Adv Mater*. 2025;20:450–472. doi:10.1016/j.sam.2025.04.002.
9. Wu H, Zhang Y, Li Q. Durability of externally bonded fiber-reinforced polymer composites in concrete polymers: A critical review. *Polymers*. 2021;13:765. doi:10.3390/polym13050765.
10. Joseph H, Giboz J, Li Z. Multiscale modelling and simulation approaches for polymer composites. *Compos Sci Technol*. 2022;221:109301. doi:10.1016/j.compscitech.2022.109301.