STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 3, 2026
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Review JoPC

Recent Progress in Near-Surface Mounted Fiber-Reinforced Polymer Strengthening Systems: Composite Materials, Adhesive Technologies, and Interfacial Bonding

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Abstract

Fiber-reinforced polymer (FRP) composites have emerged as one of the most promising classes of advanced engineering materials for structural strengthening and rehabilitation owing to their high specific strength, excellent corrosion resistance, fatigue durability, and design flexibility. Among various strengthening approaches, near-surface mounted (NSM) systems have gained significant attention because they provide enhanced bond performance, improved protection against environmental exposure, and superior utilization of FRP reinforcement compared with conventional externally bonded techniques. The effectiveness of NSM systems is strongly governed by the interaction between FRP composite reinforcements, polymer-based adhesive materials, and the surrounding concrete substrate. This review presents a comprehensive assessment of recent advances in FRP composite materials, polymer adhesive technologies, and interfacial bonding mechanisms employed in NSM strengthening systems. Particular attention is devoted to the material characteristics of carbon, glass, basalt, and aramid fiber-reinforced polymer composites, including their manufacturing processes, polymer matrix systems, microstructural features, and mechanical performance. Furthermore, recent developments in epoxy-based, cementitious-polymer hybrid, and nano-modified adhesive systems are critically examined with respect to bond formation, stress transfer efficiency, and durability enhancement. The influence of environmental exposure, moisture ingress, thermal aging, freeze–thaw cycles, and chemical degradation on the long-term performance of composite–adhesive–concrete interfaces is also discussed. In addition, emerging research trends involving sustainable composite materials, bio-based polymers, recycled fibers, smart sensing technologies, and artificial intelligence-assisted predictive modeling are reviewed. Existing knowledge gaps related to durability assessment, interfacial characterization, standardization of testing methodologies, and large-scale implementation are identified. The review highlights future opportunities for developing next-generation NSM composite systems with improved sustainability, durability, and structural reliability. The findings provide valuable insights for researchers, material scientists, and practicing engineers involved in the development and application of advanced polymer composite strengthening technologies.

Keywords: Fiber-reinforced polymer composites; Polymer adhesives; Near-surface mounted systems; Composite–concrete interface; durability; nanomodified adhesives

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Received Date: July 01, 2026
Accepted Date: July 13, 2026
Published Date: July 17, 2026

Citation: R. Chitra, M. Ruban, Zealakshmi D., P. Vasanthi, B. Vijaya. Recent Progress in Near-Surface Mounted Fiber-Reinforced Polymer Strengthening Systems: Composite Materials, Adhesive Technologies, and Interfacial Bonding. Journal of Polymer & Composites. 2026; 14(Special Issue 3): S1145–S1153p.

INTRODUCTION

Fiber-reinforced polymer (FRP) composites have become increasingly important in modern engineering applications due to their unique combination of high mechanical performance, lightweight characteristics, corrosion resistance, and excellent durability. These materials consist of high-strength reinforcing fibers embedded within a polymer matrix, resulting in multifunctional composites capable of meeting demanding structural and environmental requirements. Owing to these advantages, FRP composites have found widespread applications in aerospace, automotive, marine, energy, and civil infrastructure sectors.

The rehabilitation and strengthening of aging infrastructure systems represent one of the major challenges facing the construction industry worldwide. Numerous reinforced concrete structures have experienced performance deterioration due to corrosion, fatigue loading, environmental degradation, design deficiencies, accidental damage, and increased service demands. Traditional strengthening techniques such as steel plate bonding, concrete jacketing, and section enlargement often introduce additional dead loads, construction difficulties, and long-term durability concerns. Consequently, advanced composite-based strengthening technologies have emerged as attractive alternatives for extending structural service life [1].

Among the available composite strengthening approaches, near-surface mounted (NSM) systems have attracted considerable attention over the past two decades. In NSM technology, FRP bars, rods, strips, or laminates are installed within grooves cut into the concrete cover and bonded using polymer-based adhesives. This configuration offers several advantages, including enhanced bond performance, improved protection from environmental exposure, reduced vulnerability to premature debonding, and more efficient utilization of the tensile capacity of FRP reinforcements. These characteristics have contributed to the increasing adoption of NSM systems for flexural, shear, axial, and seismic strengthening applications.

The performance of NSM strengthening systems depends not only on the mechanical properties of FRP reinforcements but also on the characteristics of the polymer matrix, manufacturing processes, adhesive materials, and interfacial bonding mechanisms. Recent developments in composite engineering have led to significant advances in fiber architecture, polymer matrix formulations, nano-enhanced composites, and sustainable reinforcement materials. Similarly, progress in adhesive technology has resulted in the development of high-performance epoxy systems, polymer-modified cementitious adhesives, and nanomaterial-enhanced bonding agents capable of improving stress transfer efficiency and durability.

Despite extensive research efforts, several challenges remain unresolved. Long-term durability under aggressive environmental conditions, moisture-induced degradation, thermal aging, fire resistance, interfacial damage evolution, and the absence of standardized durability assessment procedures continue to limit broader implementation. Furthermore, growing interest in sustainable engineering solutions has stimulated research into bio-based polymers, recycled fibers, environmentally friendly adhesive systems, and intelligent monitoring technologies [2].

Although several review articles have examined structural aspects of NSM strengthening systems, relatively limited attention has been devoted to the underlying polymer and composite science governing system performance. In particular, comprehensive discussions integrating FRP material development, polymer matrix systems, adhesive technologies, microstructural characterization, durability mechanisms, and emerging smart technologies remain scarce in the literature.

Therefore, the objective of this review is to provide a comprehensive evaluation of recent advances in FRP composite materials, polymer adhesive technologies, and interfacial bonding mechanisms used in NSM strengthening systems. The review focuses on material engineering aspects, manufacturing technologies, composite microstructures, durability performance, and future developments aimed at improving the efficiency and sustainability of next-generation NSM composite systems.

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

LITERATURE REVIEW

Research on fiber-reinforced polymer (FRP) composites for structural strengthening has expanded significantly due to the superior mechanical performance, corrosion resistance, and lightweight characteristics of these materials. Early studies primarily focused on the use of carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) systems to improve the strength and serviceability of reinforced concrete structures. The results demonstrated substantial enhancements in load-carrying capacity, stiffness, and durability.

With the development of near-surface mounted (NSM) strengthening technology, research attention shifted toward understanding the interaction between FRP reinforcements, polymer adhesives, and concrete substrates. Several studies have highlighted the importance of adhesive properties, interfacial bonding mechanisms, and stress transfer behavior in determining the overall efficiency of NSM systems. Recent investigations have also explored alternative reinforcement materials such as basalt fiber-reinforced polymer (BFRP) and aramid fiber-reinforced polymer (AFRP), as well as hybrid composite systems designed to improve durability and sustainability [3].

Advances in polymer science have further contributed to the development of high-performance adhesive systems, including nano-modified and polymer-enhanced formulations capable of improving bond strength and resistance to environmental degradation. At the same time, increasing attention has been directed toward the long-term durability of FRP composites under moisture exposure, thermal aging, chemical attack, and cyclic loading conditions.

More recently, research trends have focused on sustainable composite materials, recycled fibers, bio-based polymers, smart sensing technologies, and data-driven predictive models. Despite these developments, challenges related to durability assessment, interfacial characterization, and standardized design methodologies remain unresolved. Therefore, a comprehensive review integrating recent advances in FRP composite materials, adhesive technologies, bonding mechanisms, and durability performance is essential for guiding future developments in NSM strengthening systems [4].

FUNDAMENTALS OF NEAR-SURFACE MOUNTED FRP COMPOSITE SYSTEMS

Near-surface mounted (NSM) fiber-reinforced polymer (FRP) systems have emerged as an effective strengthening technique for rehabilitating and upgrading concrete structures. In this method, FRP reinforcements are embedded into grooves cut within the concrete cover and bonded using polymer-based adhesives. Compared with externally bonded reinforcement techniques, NSM systems provide improved bond performance, greater protection against environmental exposure, and more efficient utilization of FRP materials. The overall performance of the system depends on the interaction between FRP composites, adhesive materials, and the concrete substrate [5].

Evolution of NSM Strengthening Technology

Traditional strengthening techniques such as steel plate bonding and concrete jacketing often increase structural weight and are susceptible to corrosion-related problems. The introduction of FRP composites provided a lightweight and durable alternative for structural rehabilitation. While externally bonded FRP systems gained widespread acceptance, limitations related to premature debonding encouraged the development of NSM technology. Continuous advances in composite materials and adhesive systems have contributed to the increasing adoption of NSM strengthening methods [6].

Components of NSM-FRP Systems

An NSM-FRP system consists of three primary components: FRP reinforcement, polymer adhesive, and concrete substrate. The FRP reinforcement serves as the main load-carrying element and is commonly manufactured using carbon, glass, basalt, or aramid fibers. The adhesive ensures effective stress transfer between the reinforcement and the surrounding concrete, while the concrete substrate provides anchorage and confinement. The combined behavior of these components governs the strength and durability of the strengthening system. Figure 1 presents the principal components of an NSM-FRP system. Efficient load transfer between these components is essential for achieving enhanced structural performance and long-term durability.

Installation Procedure of NSM-FRP Systems

The installation process begins with cutting grooves into the concrete cover. The grooves are then cleaned and partially filled with adhesive before placing the FRP reinforcement. Additional adhesive is applied to ensure complete encapsulation of the reinforcement. After curing, the strengthened member becomes capable of transferring loads effectively through the composite system. Proper installation is critical for achieving reliable bond performance [7].

Advantages and Limitations of NSM-FRP Systems

NSM-FRP systems offer several advantages, including high strengthening efficiency, corrosion resistance, improved bond behavior, and protection against environmental damage. In addition, the lightweight nature of FRP composites minimizes additional dead load on existing structures. However, the performance of NSM systems depends on installation quality, adhesive durability, and environmental conditions. Long-term durability assessment and standardized design procedures remain important areas for future research. As illustrated in Figure 2, NSM-FRP systems provide significant structural and durability benefits; however, challenges associated with adhesive performance and long-term durability continue to motivate further research and material development.

FRP COMPOSITE MATERIALS USED IN NSM APPLICATIONS

Fiber-reinforced polymer (FRP) composites are widely used in near-surface mounted (NSM) strengthening systems because of their high strength-to-weight ratio, corrosion resistance, and durability. These materials consist of reinforcing fibers embedded within a polymer matrix, which together provide efficient load transfer and long-term structural performance [8]. The most commonly used FRP materials in NSM applications are carbon, glass, basalt, and aramid fiber composites.

Carbon Fiber-Reinforced Polymer (CFRP)

CFRP is the most widely used FRP material in NSM strengthening due to its high tensile strength, stiffness, and durability. It provides excellent fatigue and corrosion resistance, making it suitable for long-term structural applications. However, its relatively high cost remains a major limitation.

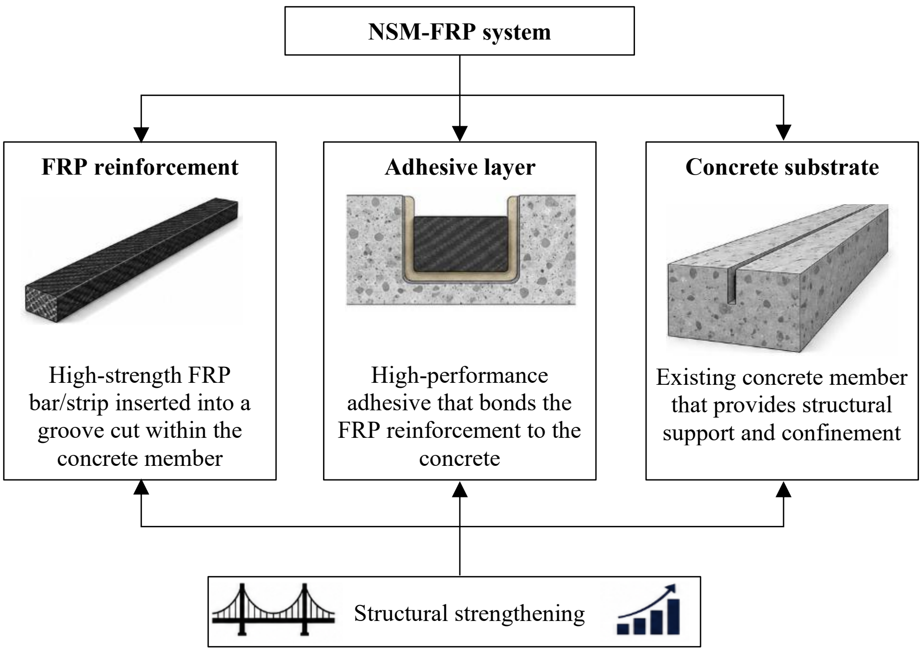

Figure 1. Components of an NSM-FRP strengthening system.

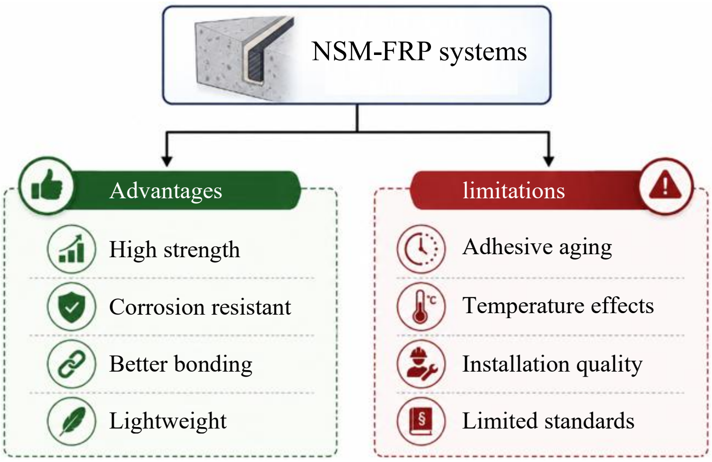

Figure 2. Advantages and limitations of NSM-FRP systems.

Table 1. Comparison of FRP composite materials used in NSM applications.

FRP type	Main advantages	Main limitations
CFRP	High strength, stiffness, and durability	High cost
GFRP	Economical and corrosion resistant	Lower stiffness
BFRP	Sustainable and thermally stable	Limited long-term data
AFRP	High toughness and impact resistance	Moisture sensitivity

Glass Fiber-Reinforced Polymer (GFRP)

GFRP offers a cost-effective alternative to CFRP. It provides good tensile strength, corrosion resistance, and lightweight characteristics. Although its stiffness is lower than that of CFRP, GFRP is widely adopted in rehabilitation projects where economic considerations are important.

Basalt Fiber-Reinforced Polymer (BFRP)

BFRP composites are produced from natural basalt fibers and have attracted attention because of their sustainability and chemical resistance. They exhibit good mechanical performance and thermal stability while offering an environmentally friendly alternative to conventional FRP materials. However, long-term performance data remain limited.

Aramid Fiber-Reinforced Polymer (AFRP)

AFRP composites are known for their high toughness, impact resistance, and fatigue durability. These properties make them suitable for structures subjected to dynamic or seismic loading. Nevertheless, AFRP materials may be sensitive to moisture and ultraviolet exposure under certain environmental conditions [9].

Comparative Assessment of FRP Materials

The choice of FRP material depends on structural requirements, environmental exposure, and economic considerations. CFRP provides the highest strengthening efficiency, GFRP offers economic advantages, BFRP contributes sustainability benefits, and AFRP provides superior impact resistance. Recent studies have also explored hybrid FRP systems that combine the advantages of different fiber types. Table 1 summarizes the key advantages and limitations of commonly used FRP composites in NSM strengthening systems. The selection of a suitable FRP material should consider mechanical performance, durability requirements, environmental conditions, and cost-effectiveness.

POLYMER ADHESIVES AND COMPOSITE–CONCRETE BONDING MECHANISMS

The performance of near-surface mounted (NSM) FRP systems largely depends on the quality of the bond formed between the FRP reinforcement and the concrete substrate. Polymer adhesives play a critical role in transferring stresses, improving load-carrying capacity, and ensuring long-term durability. The effectiveness of the strengthening system is influenced by adhesive properties, bonding mechanisms, and environmental conditions [10].

Epoxy-Based Adhesives

Epoxy adhesives are the most widely used bonding materials in NSM-FRP systems because of their high bond strength, excellent adhesion, and durability. They provide effective stress transfer between FRP reinforcements and concrete substrates while exhibiting low shrinkage and good chemical resistance. However, their performance may decrease at elevated temperatures.

Cementitious and Hybrid Adhesives

Cementitious adhesives have gained attention due to their compatibility with concrete and improved fire resistance. However, they generally possess lower bond strength than epoxy systems. To overcome this limitation, hybrid adhesives combining cementitious materials with polymer additives have been developed, offering improved toughness, crack resistance, and durability.

Factors Influencing Bond Performance

Bond performance is affected by several factors, including adhesive properties, concrete strength, FRP surface characteristics, groove dimensions, and environmental exposure. Temperature fluctuations, moisture ingress, and chemical attack can significantly influence interfacial behavior and long-term durability. Proper material selection and installation are therefore essential for achieving reliable bond performance.

Composite–Concrete Bonding Mechanisms

Load transfer in NSM systems occurs through a combination of chemical adhesion, mechanical interlocking, and frictional resistance. Chemical adhesion develops at the interface between the adhesive and adjacent materials, while mechanical interlocking results from the penetration of adhesive into surface irregularities. These mechanisms collectively ensure efficient stress transfer between FRP reinforcement and concrete.

Bond–Slip Behaviour and Failure Mechanisms

Bond–slip behavior describes the relative displacement between FRP reinforcement and the surrounding concrete during loading [11]. It provides important information regarding interfacial stiffness and load transfer efficiency. Common failure modes include adhesive failure, concrete cover separation, FRP debonding, and cohesive failure within the adhesive layer. Understanding these mechanisms is essential for improving the reliability and durability of NSM-FRP systems. Table 2 summarizes the main characteristics of adhesive systems used in NSM-FRP applications. Epoxy adhesives remain the most common choice, while hybrid and nano-modified systems are emerging as promising alternatives for improving bond durability and long-term performance.

DURABILITY AND LONG-TERM PERFORMANCE OF NSM-FRP COMPOSITE SYSTEMS

The long-term effectiveness of NSM-FRP systems depends on the durability of FRP composites, polymer adhesives, and the composite–concrete interface under various environmental conditions. Exposure to moisture, temperature fluctuations, ultraviolet radiation, chemical attack, and sustained loading can influence material properties and bond performance over time. Therefore, durability assessment is essential for ensuring the reliability and service life of NSM strengthening systems.

Table 2. Comparison of adhesive systems used in NSM-FRP strengthening.

Adhesive Type	Advantages	Limitations
Epoxy Adhesive	High bond strength, excellent adhesion	Sensitive to high temperatures
Cementitious Adhesive	Fire resistance, concrete compatibility	Lower bond strength
Hybrid Adhesive	Improved toughness and durability	More complex formulation
Nano-Modified Adhesive	Enhanced bond performance and crack resistance	Limited field applications

Table 3. Factors affecting durability of NSM-FRP systems.

Durability factor	Potential effect	Mitigation strategy
Moisture Exposure	Matrix degradation and bond reduction	Protective coatings and improved adhesives
Elevated Temperature	Reduced adhesive performance	Thermally stable polymer systems
Chemical Exposure	Interfacial deterioration	Chemical-resistant matrices
Fatigue Loading	Bond degradation and cracking	Improved adhesive toughness
UV Radiation	Surface aging of polymers	UV-resistant coatings

Moisture and Environmental Effects

Moisture ingress is one of the primary factors affecting the durability of FRP composites and adhesive layers. Water absorption may lead to matrix degradation, reduced interfacial bonding, and deterioration of mechanical properties. Environmental exposure can further accelerate aging processes, particularly in aggressive conditions [12].

Thermal and Fire Performance

Temperature variations can significantly influence the behavior of polymer matrices and adhesives. Elevated temperatures may reduce adhesive stiffness and bond strength, while prolonged thermal exposure can accelerate material degradation. Consequently, thermal stability remains an important consideration in the design of NSM-FRP systems.

Chemical and Corrosion Resistance

FRP composites exhibit excellent resistance to corrosion compared with conventional steel reinforcement. However, exposure to alkaline, acidic, or saline environments may affect the polymer matrix and adhesive interface. Understanding chemical degradation mechanisms is important for improving long-term durability in harsh service conditions.

Fatigue and Long-Term Loading Behaviour

Repeated loading and sustained service loads can gradually affect the composite–adhesive–concrete interface. Fatigue-induced damage may reduce bond efficiency and promote crack development within the adhesive layer. Therefore, long-term performance evaluation is necessary for predicting service life and structural reliability.

Strategies for Durability Enhancement

Recent studies have focused on improving durability through advanced polymer matrices, nano-modified adhesives, hybrid composite systems, and protective coatings. These approaches aim to enhance resistance to environmental degradation while maintaining efficient load transfer and long-term bond performance. Table 3 summarizes the major factors influencing the durability of NSM-FRP systems and commonly adopted mitigation strategies. Improving durability remains a key research direction for the development of reliable and sustainable composite strengthening technologies [13].

RESEARCH GAPS AND FUTURE PERSPECTIVES

Despite significant advances in NSM-FRP composite systems, several challenges remain that limit their widespread implementation. Current research has primarily focused on mechanical performance, while comparatively less attention has been devoted to long-term durability, interfacial degradation mechanisms, and the behavior of polymer adhesives under aggressive environmental conditions. Furthermore, the development of sustainable FRP composites, bio-based polymer matrices, and recycled reinforcement materials is still in its early stages. Standardized testing procedures and durability assessment methods are also lacking, making it difficult to compare results across different studies [14]. Future research should focus on nano-modified adhesives, environmentally friendly composite materials, advanced interfacial characterization techniques, and data-driven predictive models for service-life assessment.

Table 4. Research gaps and future directions in NSM-FRP composite systems.

Research area	Current limitation	Future direction
FRP Composites	Limited studies on sustainable and recyclable composites	Development of eco-friendly and recycled FRP systems
Polymer Matrices	Insufficient understanding of long-term aging behavior	Advanced durable and bio-based polymer matrices
Adhesive Technology	Durability concerns under harsh environments	Nano-modified and hybrid adhesive systems
Composite–Concrete Interface	Limited knowledge of interfacial degradation mechanisms	Multi-scale bond characterization and modeling
Durability Assessment	Lack of standardized durability evaluation methods	Unified testing protocols and service-life prediction models
Smart Composite Systems	Limited integration of monitoring technologies	Sensor-enabled and self-monitoring composite systems

In addition, the integration of smart sensing technologies and artificial intelligence-based monitoring systems offers promising opportunities for enhancing the reliability, durability, and sustainability of next-generation NSM-FRP strengthening systems. Table 4 summarizes the major research gaps identified in current NSM-FRP studies and highlights potential future research directions. Particular attention should be directed toward sustainable composite materials, advanced adhesive systems, interfacial durability, and smart composite technologies to improve the long-term performance and reliability of NSM strengthening systems [15].

CONCLUSIONS

Near-surface mounted (NSM) fiber-reinforced polymer (FRP) systems have emerged as an effective composite-based strengthening technology owing to their excellent bonding performance, durability, and efficient utilization of advanced composite materials. The integration of high-performance FRP reinforcements with polymer-based adhesives enables reliable stress transfer and improved protection against environmental exposure, making NSM systems attractive for long-term rehabilitation applications.

This review examined the fundamental aspects of NSM-FRP systems with particular emphasis on FRP composite materials, polymer adhesives, bonding mechanisms, and durability performance. Carbon, glass, basalt, and aramid fiber composites each offer distinct advantages in terms of mechanical properties, durability, sustainability, and cost-effectiveness. Among these materials, CFRP remains the most widely adopted reinforcement due to its superior strength and stiffness, whereas BFRP and hybrid composite systems are gaining increasing attention because of their sustainability potential.

The review also highlighted the critical role of polymer adhesives in governing composite–concrete interaction and long-term bond performance. Recent developments in hybrid and nano-modified adhesive systems have demonstrated significant potential for improving bond strength, crack resistance, and environmental durability. Furthermore, the long-term performance of NSM-FRP systems is strongly influenced by moisture exposure, thermal effects, chemical attack, and fatigue loading, emphasizing the importance of durability-oriented material design.

Although substantial progress has been achieved, several challenges remain regarding durability assessment, interfacial degradation mechanisms, sustainable material development, and standardized testing methodologies. Future research should focus on eco-friendly FRP composites, bio-based polymer matrices, advanced adhesive technologies, multi-scale interfacial characterization, and smart monitoring systems. Continued advancements in these areas are expected to support the development of next-generation NSM-FRP composite systems with enhanced durability, sustainability, and long-term performance.

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