

FRP Retrofitting of Corrosion-Damaged Reinforced Concrete: A Review

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Abstract

Reinforced concrete (RC) structures exposed to marine environments are highly susceptible to chloride-induced corrosion of embedded steel reinforcement, resulting in deterioration of structural performance, reduced service life, and increased maintenance costs. This review critically examines two interrelated aspects of durability management in RC structures: (i) the mechanisms, progression, and monitoring of steel corrosion, and (ii) the repair and strengthening of deteriorated members using Fiber-Reinforced Polymer (FRP) composites. The review synthesizes findings from experimental, analytical, and field-based studies on corrosion initiation, chloride ingress, cover cracking, bond degradation, and loss of load-carrying capacity. It further evaluates the effectiveness of various FRP retrofitting techniques, including externally bonded and near-surface mounted systems, in improving the flexural strength, shear resistance, confinement efficiency, ductility, and fatigue performance of damaged RC elements. Particular attention is given to the influence of marine exposure, moisture ingress, temperature variations, and adhesive degradation on the long-term durability of FRP-strengthened structures. The review highlights that although FRP composites provide an effective and corrosion-resistant rehabilitation solution, their performance is governed by bond integrity, environmental durability, and application methodology. Key research gaps are identified, including the need for standardized durability reduction factors, improved predictive models for long-term performance, sustainable non-epoxy bonding systems, and the integration of advanced monitoring technologies for condition assessment. The findings presented herein provide a comprehensive reference for researchers and practicing engineers involved in the design, maintenance, and rehabilitation of reinforced concrete infrastructure in aggressive marine environments.

Keywords: Reinforced Concrete; Marine Environment; Chloride-Induced Corrosion; Fiber-Reinforced Polymer (FRP); Structural Rehabilitation; Durability; Service Life.

1. Introduction

Reinforced concrete (RC) is one of the most widely used construction materials for infrastructure systems, including bridges, ports, offshore platforms, coastal buildings, and marine facilities. Despite its widespread application and inherent durability, the long-term performance of RC structures in aggressive marine environments is significantly affected by the corrosion of embedded steel reinforcement. Chloride ions originating from seawater penetrate the concrete cover and disrupt the passive oxide film protecting the steel surface, thereby initiating electrochemical corrosion processes and accelerating reinforcement deterioration [10,11]. The accumulation of expansive corrosion products generates internal tensile stresses within the surrounding concrete, leading to cracking, delamination, spalling, and a progressive reduction in bond strength between steel and concrete [1,5]. Consequently, structural capacity, serviceability, and durability are adversely affected, resulting in reduced service life and substantial economic costs associated with inspection, maintenance, repair, and replacement of deteriorated infrastructure [3,9].

To mitigate corrosion-related deterioration, extensive research has focused on improving the durability of RC structures through enhanced concrete quality, supplementary cementitious materials, corrosion-resistant

reinforcements, and advanced monitoring techniques [3,7,8,13]. Simultaneously, considerable attention has been directed toward the rehabilitation and strengthening of existing structures that have already experienced corrosion-induced damage. Among the available retrofitting technologies, Fiber-Reinforced Polymer (FRP) composites have emerged as an effective and widely adopted solution due to their high strength-to-weight ratio, corrosion resistance, ease of installation, and minimal impact on structural geometry [16–20]. Experimental investigations have demonstrated that FRP systems can significantly improve the flexural and shear capacities of beams, enhance column confinement, restore load-carrying capacity, and extend the service life of deteriorated RC structures [18,19,24].

Although numerous studies have investigated either corrosion mechanisms in RC structures or FRP-based rehabilitation techniques independently, relatively few reviews have comprehensively examined the interrelationship between corrosion-induced deterioration and the effectiveness of FRP retrofitting under marine exposure conditions. Therefore, a consolidated assessment of both aspects is essential for developing durable and sustainable rehabilitation strategies for aging infrastructure.

This review critically examines the existing literature on two interconnected themes: (i) the mechanisms, progression, simulation, and monitoring of steel corrosion in reinforced concrete structures exposed to marine environments, and (ii) the performance and durability of FRP retrofitting systems employed for the repair and strengthening of corrosion-damaged beams and columns. The review synthesizes findings from experimental, analytical, and field studies, evaluates the effectiveness and limitations of current rehabilitation approaches, identifies prevailing research gaps, and highlights future directions for enhancing the durability and service life of reinforced concrete structures in aggressive marine environments.

2. Methodology

This review adopts a structured narrative approach to synthesize existing knowledge on chloride-induced corrosion in reinforced concrete (RC) structures and the application of Fiber-Reinforced Polymer (FRP) composites for structural rehabilitation. The methodology was designed to identify, evaluate, and consolidate relevant studies addressing corrosion mechanisms, durability assessment, and retrofitting strategies in marine environments.

2.1 Literature Collection and Selection

Relevant literature was collected from major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. The search process employed combinations of keywords such as “reinforced concrete corrosion,” “chloride ingress,” “marine environment,” “steel reinforcement corrosion,” “FRP retrofitting,” “CFRP strengthening,” “GFRP strengthening,” “structural rehabilitation,” and “durability of FRP systems.” Publications spanning the last three decades were considered to capture both foundational and recent developments in the field.

The reviewed literature primarily comprised peer-reviewed journal articles, conference proceedings, review papers, and selected technical reports directly related to corrosion deterioration and FRP-based strengthening of RC structures exposed to aggressive environments. Studies were selected based on their relevance to corrosion mechanisms, monitoring techniques, durability performance, structural behaviour, and rehabilitation effectiveness. Preference was given to experimental investigations and field studies that provided quantitative insights into corrosion damage and strengthening performance.

2.2 Scope of the Review

The review is organized into two complementary areas.

Steel Corrosion in Reinforced Concrete: This section examines the mechanisms of corrosion initiation and propagation in chloride-contaminated concrete, factors influencing chloride transport, deterioration processes such as cracking and spalling, and the resulting effects on structural performance. It also reviews

accelerated corrosion testing methods, service-life prediction approaches, and non-destructive evaluation (NDE) techniques used for corrosion detection and monitoring.

FRP-Based Repair and Retrofitting: This section focuses on the application of FRP composites, particularly Carbon Fiber-Reinforced Polymer (CFRP) and Glass Fiber-Reinforced Polymer (GFRP), for the strengthening and rehabilitation of corrosion-damaged RC structures. Topics include flexural and shear strengthening of beams, confinement of columns, bond behaviour between FRP and concrete substrates, durability under marine exposure conditions, and emerging strengthening approaches aimed at improving long-term structural performance and sustainability.

2.3 Review Framework

The collected studies were critically analysed and categorized according to corrosion mechanisms, monitoring techniques, strengthening methods, durability performance, and structural outcomes. The findings were synthesized to identify common trends, limitations of existing approaches, knowledge gaps, and future research directions for enhancing the durability and service life of reinforced concrete infrastructure in marine environments.

3. Literature Review and Synthesis

3.1 Steel Corrosion in Reinforced Concrete Structures

3.1.1 Corrosion Initiation and Cover Cracking

Chloride-induced corrosion of reinforcing steel is one of the primary causes of deterioration in reinforced concrete structures exposed to marine environments. The corrosion process begins when chloride ions penetrate the concrete cover and disrupt the passive oxide film surrounding the reinforcement, initiating electrochemical reactions that result in steel oxidation. The accumulation of expansive corrosion products generates tensile stresses within the surrounding concrete, ultimately leading to cracking, delamination, and spalling of the cover concrete. Andrade et al. [1] demonstrated that even minimal reinforcement mass loss can initiate visible surface cracking, with crack widths increasing progressively as corrosion advances. Such deterioration not only compromises durability but also accelerates the ingress of aggressive agents, thereby intensifying the corrosion process.

The structural implications of corrosion-induced damage are substantial. Experimental investigations by Congqi et al. [2] revealed that corroded reinforced concrete beams subjected to repeated loading exhibit increased deflections, reduced stiffness, and altered failure mechanisms. Severe corrosion was found to modify the load-transfer mechanism within structural members, causing behavior analogous to that of a cambered arch. These findings highlight the importance of early corrosion detection and preventive measures to preserve structural integrity and serviceability.

3.1.2 Durability Enhancement and Service-Life Modelling

Enhancing the durability of reinforced concrete structures has been a major focus of research aimed at extending service life in aggressive chloride-bearing environments. One widely adopted approach involves reducing concrete permeability through the incorporation of supplementary cementitious materials such as silica fume, fly ash, slag, and metakaolin. These materials refine the pore structure and reduce chloride diffusivity, thereby delaying corrosion initiation [13].

Despite these improvements, durability challenges remain significant in highly aggressive marine exposure zones. Bertolini et al. [3] reported that even high-performance concrete may require impractically large cover depths to achieve a service life of 50 years in splash-zone conditions. Consequently, supplementary

protection strategies, including corrosion-resistant reinforcement, cathodic protection systems, and corrosion inhibitors, have been proposed to complement material-based durability enhancements.

Predictive modelling has become an essential tool for durability-based design and maintenance planning. The DuraCrete-based DuMaCon model [9] introduced a probabilistic framework for estimating chloride ingress and predicting corrosion initiation under varying environmental conditions. Similarly, Ha-Won Song et al. [10] emphasized that chloride transport parameters, including the apparent diffusion coefficient and surface chloride concentration, are strongly influenced by concrete composition, curing quality, and environmental exposure. These findings underscore the importance of incorporating time-dependent material properties and exposure conditions into service-life prediction models.

3.1.3 Accelerated Corrosion Testing and Monitoring Techniques

Laboratory simulation of corrosion is essential for evaluating deterioration mechanisms and assessing the effectiveness of repair and strengthening techniques within practical timeframes. Among the available methods, accelerated corrosion through impressed current techniques is widely employed due to its simplicity and controllability. El Maaddawy and Soudki [5] reported that increasing current density accelerates reinforcement deterioration, leading to higher tensile strains and wider corrosion-induced cracks. Furthermore, Altoubat et al. [6] demonstrated that constant-current methods produce corrosion patterns more representative of field conditions than constant-voltage approaches.

Accurate monitoring and early detection of corrosion are equally important for ensuring timely maintenance interventions. Recent developments in non-destructive evaluation (NDE) technologies have significantly improved the ability to detect corrosion-related damage before visible deterioration occurs. Climent et al. [7] successfully applied nonlinear ultrasonic techniques to identify microcracking associated with reinforcement corrosion, while Chand et al. [8] developed an electromagnetic induction (EMI)-based sensing system capable of detecting early-stage corrosion activity. These advanced monitoring approaches offer significant potential for continuous structural health assessment and proactive infrastructure management.

3.2 Repair and Retrofitting with FRP Composites

3.2.1 Confinement of Reinforced Concrete Columns

Fiber-Reinforced Polymer (FRP) confinement has emerged as one of the most effective techniques for enhancing the axial performance of deteriorated reinforced concrete columns. External wrapping with FRP materials increases lateral confinement pressure, thereby improving compressive strength, ultimate strain capacity, and energy absorption characteristics. Aire et al. [24] demonstrated that both CFRP and GFRP confinement significantly enhance column performance, although CFRP provides greater confinement efficiency due to its higher stiffness and tensile strength.

The effectiveness of FRP confinement is strongly influenced by column geometry. Studies have consistently shown that circular columns achieve more uniform confinement and superior performance compared with square or rectangular sections, where stress concentrations occur at corners and large regions remain insufficiently confined [16]. Environmental durability also plays a critical role in long-term performance. Toutanji and Balaguru [15] observed that CFRP-confined columns retain their mechanical properties more effectively than GFRP systems under wet-dry exposure cycles. However, prolonged environmental exposure may adversely affect confinement efficiency. Investigations by Alsaad and Hassan [36] and Ramatai et al. [43] revealed that although marine exposure does not substantially reduce ultimate load capacity, significant reductions in ductility and deformation capacity may occur due to deterioration of the FRP-concrete interface and matrix degradation.

3.2.2 Flexural and Shear Strengthening of Reinforced Concrete Beams

The external bonding of FRP laminates to reinforced concrete beams is widely recognized as an efficient strengthening technique for enhancing flexural and shear resistance. Numerous studies have reported substantial increases in load-carrying capacity and stiffness following FRP strengthening [17,19]. Nevertheless, the effectiveness of externally bonded systems is frequently limited by premature debonding at the FRP-concrete interface, resulting in brittle failure and reduced structural ductility.

Alternative installation techniques have therefore been explored to improve bond performance and durability. Quattlebaum et al. [18] compared various strengthening methods and concluded that Near-Surface Mounted (NSM) FRP reinforcement provides superior bond characteristics, fatigue resistance, and load-transfer efficiency compared with externally bonded laminates and mechanically fastened systems. Consequently, NSM techniques have gained increasing attention for strengthening structures subjected to cyclic or fatigue loading.

Environmental exposure remains one of the most critical factors affecting the durability of FRP-strengthened members. Grace and Singh [19] reported that prolonged exposure to high humidity conditions significantly weakens the FRP-concrete bond, resulting in strength reductions of up to 33%. Similarly, Long et al. [30] observed substantial bond degradation under tidal marine exposure, highlighting the vulnerability of adhesive systems to moisture ingress and environmental aging. To address these limitations, researchers have investigated cement-based adhesives [22,27] and hybrid FRP systems [29] as potential alternatives capable of improving bond durability, compatibility, and structural ductility.

3.2.3 Emerging and Innovative Retrofitting Strategies

In addition to conventional FRP strengthening methods, several innovative rehabilitation approaches have been proposed to enhance structural performance and long-term durability. Kothandaraman and Govindacharya [26] introduced an economical strengthening technique involving externally attached steel bars at the beam soffit, reporting improvements of up to 70% in flexural capacity. This approach offers a practical alternative where FRP systems may not be economically feasible.

Advanced cementitious materials have also demonstrated significant potential for structural rehabilitation. Martinola et al. [28] employed High-Performance Fiber-Reinforced Concrete (HPFRC) overlays to repair deteriorated beams and reported substantial improvements in stiffness, cracking resistance, and serviceability performance. Furthermore, Textile-Reinforced Concrete (TRC) systems have emerged as promising solutions for restoring bond performance in corrosion-damaged members. Experimental investigations by Yin et al. [41] showed that TRC confinement effectively improves bond-slip behavior, reduces crack propagation, and enhances load-transfer mechanisms between corroded reinforcement and surrounding concrete.

Overall, the reviewed studies demonstrate that FRP-based strengthening and emerging composite rehabilitation systems provide effective solutions for extending the service life of corrosion-damaged reinforced concrete structures. However, the long-term durability of strengthening systems under combined mechanical and environmental loading remains an important area requiring further investigation.

4. Discussion

The reviewed literature demonstrates that chloride-induced corrosion remains one of the most significant durability challenges affecting reinforced concrete (RC) structures in marine environments. Chloride ingress initiates reinforcement corrosion, resulting in cracking, spalling, bond deterioration, and reduction in structural capacity. Consequently, effective corrosion mitigation and rehabilitation strategies are essential for extending the service life of marine infrastructure.

The incorporation of supplementary cementitious materials (SCMs), such as silica fume, metakaolin, and ground granulated blast-furnace slag (GGBS), has proven effective in reducing concrete permeability and delaying corrosion initiation. However, once corrosion-induced damage becomes significant, rehabilitation measures are necessary to restore structural performance. Among the available strengthening techniques, Fiber-Reinforced Polymer (FRP) composites have emerged as a highly efficient solution due to their high strength-to-weight ratio, corrosion resistance, ease of installation, and minimal increase in structural dead load.

The performance of FRP-strengthened members is strongly influenced by several factors:

1. **Application Technique:** Near-Surface Mounted (NSM) systems generally exhibit superior bond behaviour, fatigue resistance, and load-transfer efficiency compared with externally bonded systems. Improved anchorage and reduced susceptibility to premature debonding make NSM systems particularly suitable for long-term applications.
2. **Environmental Exposure:** Marine conditions involving moisture, chlorides, temperature variations, and wet-dry cycles can adversely affect the FRP-concrete interface. Degradation of adhesive materials may reduce bond strength and compromise long-term strengthening effectiveness, highlighting the need for environmentally resistant bonding systems.
3. **Material Compatibility:** Differences in thermal expansion characteristics and mechanical properties between FRP composites and concrete can generate interfacial stresses, especially under fluctuating environmental conditions. Appropriate material selection is therefore essential to ensure durable composite action.
4. **Failure Behaviour:** Although FRP strengthening significantly enhances structural capacity, premature debonding and brittle failure remain major concerns. Improved anchorage systems, hybrid strengthening techniques, and optimized bond materials are required to promote more ductile structural behaviour.

Overall, FRP composites offer substantial benefits for the rehabilitation of corrosion-damaged RC structures. Nevertheless, long-term durability considerations, environmental degradation effects, and service-life performance must be incorporated into design and assessment procedures to ensure reliable and sustainable strengthening solutions for marine infrastructure.

Conclusion

The key conclusions drawn from this review are as follows:

- Chloride-induced corrosion is a major cause of deterioration in reinforced concrete structures exposed to marine environments, leading to cracking, spalling, bond degradation, and loss of structural performance.
- The use of supplementary cementitious materials can effectively reduce chloride penetration and delay the initiation of reinforcement corrosion, thereby enhancing concrete durability.
- Accelerated corrosion testing methods and advanced non-destructive evaluation techniques have improved the understanding and monitoring of corrosion-related damage in reinforced concrete structures.
- FRP composites provide an effective strengthening solution for corrosion-damaged structures due to their high strength-to-weight ratio, corrosion resistance, and ease of installation.
- FRP retrofitting significantly enhances load-carrying capacity, stiffness, confinement effectiveness, and fatigue performance of reinforced concrete members.
- The effectiveness of FRP strengthening systems depends strongly on bond quality, installation method, environmental exposure conditions, and material compatibility.
- Near-Surface Mounted (NSM) systems generally demonstrate superior bond performance and durability compared with externally bonded strengthening techniques.

- Long-term environmental exposure may degrade the FRP–concrete interface and reduce strengthening efficiency, making durability assessment a critical aspect of design.
- Premature debonding and limited ductility remain important challenges that restrict the full utilization of FRP materials in structural strengthening applications.

Future Research

- Development of durable and sustainable non-epoxy bonding materials with enhanced resistance to marine environmental conditions.
- Establishment of standardized durability reduction factors and service-life prediction methodologies for FRP-strengthened structures.
- Investigation of hybrid FRP systems, textile-reinforced composites, and advanced cementitious repair materials for improved structural performance and durability.
- Integration of smart sensing technologies and real-time structural health monitoring systems for early corrosion detection and performance assessment.
- Comprehensive life-cycle cost analysis and sustainability assessment of various rehabilitation strategies for marine infrastructure.
- Long-term field investigations to evaluate the combined effects of mechanical loading, chloride exposure, moisture ingress, and environmental aging on FRP-retrofitted structures.

Addressing these challenges will contribute to the development of more durable, reliable, and sustainable rehabilitation solutions, ensuring the long-term performance and resilience of reinforced concrete infrastructure in aggressive marine environments.

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