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Review on the Effects of Corrosion on Reinforced Concrete Beams: Structural Performance, Durability, and Failure Mechanisms

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Abstract

Reinforcement corrosion in reinforced concrete (RC) beams is of significant concern with regard to structural performance, durability, and failure modes. In this review, the impact of corrosion on RC beams is investigated, with focus on pitting corrosion as the most harmful type because of its localized character that causes extensive cross-sectional loss and bond degradation. Corrosion-driven degradation diminishes flexural and shear strength, changes failure mechanisms from ductile to brittle, and promotes concrete cracking and spalling. Environmental conditions, especially chloride exposure in marine and industrial environments, significantly enhance corrosion rates, causing early structural failures. The research also investigates the impact of durability-enhancing techniques like corrosion-resistant reinforcement, protective coatings, supplementary cementitious materials, and electrochemical monitoring systems. In spite of the progress in corrosion mitigation, more research is required to create better predictive models and sustainable protection strategies. This review emphasizes the importance of proactive corrosion management to prolong the service life and structural integrity of RC beams in aggressive environments.

Keywords: Reinforced Concrete, Corrosion Mechanism, Pitting Corrosion, Durability, Corrosion mitigation

1. Introduction

Reinforced concrete (RC) beams are commonly used in building construction because of their durability and strength. Corrosion of embedded steel reinforcement, though, is a major risk to their long-term performance (Gong et al., 2022; Roshan & Ghalehnovi, 2023; Sahebi & Dehestani, 2023; Stella et al., 2024). Corrosion reduces the load-bearing capacity, deteriorates the bond between concrete and steel, and causes cracking, spalling, and structural failure (Udhaya Kumar & Vinod Kumar, 2023; D. Wang & Zhong, 2022; S. Yang et al., 2025; Q. Zhang et al., 2025). Among different types of corrosion, chloride corrosion, carbonation corrosion, pitting, and uniform corrosion are the most prevalent in RC structures, especially in aggressive environments like marine and industrial areas.

Corrosion damage intensity varies with parameters such as exposure to the environment, concrete type, and protection of reinforcement. Pitting corrosion produces localized imperfections, increasing structural degradation, whereas uniform corrosion progressively decreases the cross-section of reinforcement. Furthermore, synergistic effects like freeze-thaw attack and cyclic loading further enhance corrosion damage. More recent developments in high-performance concrete, corrosion inhibitors, and protective coatings seek to counteract these effects, thereby increasing structural longevity.

Many Researchers have tried to study the corrosion process, which includes the uniform and pitting forms as well as crevice and stress corrosion cracking (SCC) (Gao et al., 2022; Han et al., 2023; Khorasani et al., 2024; W. wen Li et al., 2024; T. Zhang, Cui, et al., 2023). Several non-destructive methods have been developed to evaluate the corrosion, including Electrochemical Impedance Spectroscopy (EIS) and Wire Beam Electrode (WBE) methods (Ahmed et al., 2024; Guo, Wang, et al., 2024; H. Liu et al., 2023). In addition, predictive numerical modeling has been done to estimate the corrosion’s effect on the structural performance, such as cracks and magnitudes of load that the structure can support (Bohane et al., 2024; El-Khoriby et al., 2023; Vu et al., 2024; J. Wu, Zhang, et al., 2023).

Corrosion effects are best dealt with through the use of alternative materials and reinforcement techniques. Recycled tire steel fibers (RTSF), and hybrid steel-FRP composite bars (SFCB), have all been successful in corroded or degraded beams under varying stress conditions. These alternative approaches have proven to improve mechanical performance while also increasing the structure's ability to withstand corrosion. Coral aggregate concrete (CAC), ultra-high performance concrete (UHPC), and geopolymer aggregate concrete (GPAC) are also suitable replacements for the typical concrete, as they have showcased better performance through intense durability challenges. Lastly, zirconium alloys, titanium alloys, high-entropy alloys, and electron beam-fabricated nickel-aluminum bronzes (NAB) have all shown promise when it comes to advanced metallic materials, particularly towards withstanding harsh environments like nuclear reactors and marine constructions (Campione & Zizzo, 2022; L. Chen et al., 2024; Dasar et al., 2022; Z. Xu et al., 2024; S. Yang et al., 2025; K. Zheng et al., 2024).

Several researchers have tried testing the relationship between corrosion and mechanical performance under the conditions of seismic loading and fatigue. Under tenderized conditions, fatigue life significantly decreases and the likelihood of failing increases with achieving improved performance through the use of fiber-reinforced polymer (FRP) bars and prestressed concrete (PC) beams (W. wen Li et al., 2024; Y. Li et al., 2023; Zhai et al., 2023; T. Zhang, Cui, et al., 2023).

In this Review Reinforced Concrete (RC) is used to denote structures with traditionally reinforced bars, whereas Prestressed Concrete (PC) is used to denote systems with pre-tensioned or post-tensioned tendons. The mechanisms of corrosion and the responses of the structure are quite different for the two, especially regarding crack initiation and progression to failure.

The resistance of corroded reinforced concrete (RC) structures to progressive collapse has been examined through finite element modeling, which underscores the critical roles of tensile catenary and compressive arch actions in maintaining structural stability(Bansal et al., 2024b; Q.

Q. Yu et al., 2022; W. Zhang et al., 2024). To evaluate corrosion damage in real-time, various structural health monitoring (SHM) techniques have been suggested. These include embedded piezoelectric sensors, self-magnetic flux leakage (SMFL) technology, and distributed optical fiber sensing, all of which help in detecting changes in stiffness, the evolution of corrosion phases, and the formation of cracks(Su et al., 2022; B. Zhang et al., 2024; A. Zheng et al., 2022). Furthermore, advancements in self-healing concrete technologies that utilize hydroxyapatite and ultra-high-toughness cementitious composites (UHTCC) have been investigated for their potential in crack mitigation and enhancing durability (C. Wang et al., 2024; K. Zheng et al., 2024). Corrosion in large-scale infrastructure such as bridges, marine platforms, and prestressed concrete (PC) structures raises significant economic and environmental issues. Research has highlighted the necessity for design solutions that prioritize sustainability, optimize costs and CO_2 footprints, and employ probabilistic modeling to enhance long-term durability while reducing repair expenses (Z. Chen et al., 2025; Khorasani et al., 2024; Sahebi & Dehestani, 2023; J. Wu, Yang, et al., 2023; K. Xu et al., 2023).

The development of advanced coatings, including electron beam (EB)-cured nanocomposite coatings and SiO_2-GO/HEP composite coatings, presents promising solutions for improving corrosion resistance in both marine and industrial settings.(Van Nguyen et al., 2022; Xiao et al., 2023; Y. Zheng et al., 2022) However, despite notable advancements, there are still challenges in accurately predicting and addressing corrosion-related deterioration in reinforced concrete (RC) and prestressed concrete (PC) structures. Additional research is essential to enhance numerical models, create better corrosion-resistant materials, and formulate effective rehabilitation strategies to prolong service life(Bansal et al., 2024a; D. Feng et al., 2025; Qin et al., 2024; T. Wu et al., 2024; J. Yang et al., 2023). In PC beams, pitting corrosion of tendons may result in sudden loss of prestress and brittle failure, while in RC beams, corrosion will result in gradual deterioration of strength through uniform or non-uniform loss of rebar. Chloride ingress is particularly important in PC beams, where prestressing steel is more prone to local corrosion, which can be undetected until collapse(Ahmed et al., 2024; Y. Li et al., 2023; Qian, Li, Fu, Zhang, Wang, Jin, et al., 2023).

This review offers a thorough analysis of corrosion mechanisms, assessment techniques, mitigation strategies, and the degradation of structural performance due to corrosion. By integrating recent experimental results and modeling methods, this paper seeks to aid in the development of sustainable and long-lasting reinforced concrete infrastructure.

To better understand the application of corrosion control methods, a clear distinction between preventive and repair strategies needs to be made. Preventive measures seek to slow down or suppress the onset of corrosion and consist of corrosion-resistant reinforcements (e.g., stainless steel, FRP, SFCB), protective coatings (e.g., SiO_2-GO/HEP), corrosion inhibitors (e.g., migrating inhibitors), and high-strength concretes such as UHPC, CAC, and GPAC. By contrast, repair measures are utilized after corrosion damage and aim at restoring functionality, typically through the utilization of fiber-reinforced polymer (FRP) blankets, self-healing concretes, or electrochemical techniques like cathodic protection and re-alkalization treatments.

2. Durability of RC Beams Under Corrosion Effects

Corrosion has a significant impact on the durability of reinforced concrete (RC) beams, accelerating the degradation of the structure and its service life. Deterioration due to corrosion is mostly caused by oxidation of the steel reinforcement embedded within it, which causes expansion, cracking of concrete, loss of bond strength, and failure. Research shows that even minor corrosion levels (5-10%) may lead to as much as a 55% loss of flexural strength and considerable shear capacity loss(W. wen Li et al., 2024; Udhaya Kumar & Vinod Kumar, 2023). Non-uniform corrosion changes bond stress-slip behaviour, promoting increased slippage and decreased load transfer efficiency between concrete and steel(J. Wu, Zhang, et al., 2023). Studies emphasize that corrosion-fatigue interaction reduces fatigue life drastically in cyclically loaded structures, especially in marine and industrial environments(T. Zhang, Cui, et al., 2023). In addition, chloride exposure, carbonation, and freeze-thaw cycles are accelerative environmental factors enhancing corrosion rates, thus weakening structural durability(Kim et al., 2024; Qian, Li, Fu, Zhang, Wang, Jin, et al., 2023). Although novel materials like ultra-high-performance concrete (UHPC), fibre-reinforced polymers (FRP), and self-healing concrete have shown great promise in corrosion mitigation, their long-term performance and engineering applications on a large scale are still warranted(El-Khoriby et al., 2023; C. Zhang et al., 2022; W. Zhang et al., 2024). Future research should emphasize the creation of better corrosion-resistant materials, more advanced numerical modelling methods, and real-time monitoring systems to improve the longevity and sustainability of RC beams in aggressive environments.

The following table indicates different types of corrosion in RC structures, associated damage, and severity, together with reference studies. Major Corrosion types, namely chloride induced, pitting, uniform, and carbonation-induced corrosion, seriously affect structural durability.

Table 1: Corrosion Types, Associated damage and severity in RC structures

Corrosion Type	Type of Damage	Description	Severity Level	Reference
Chloride-Induced Corrosion	Load-bearing loss, extensive cracking	Chloride ingress leads to severe cracking, steel oxidation, and premature failure.	**Severe** (>25% mass loss)	(Bansal et al., 2024b; Dasar et al., 2022; Han et al., 2023; Qian, Li, Fu, Zhang, Wang, Jin, et al., 2023; Udhaya Kumar & Vinod Kumar, 2023)
Pitting (Localized) Corrosion	Fatigue cracks, cross-section loss	Deep localized pits create stress concentrations and abrupt failure under cyclic loading.	**Severe** (Localized >30% loss)	(Ahmed et al., 2024; Guo, Wang, et al., 2024; Stella et al., 2024; Q. Zhang et al., 2025)
Uniform / General Corrosion	Cross-section loss, shear reduction	Even material loss across reinforcement surface, reducing capacity progressively.	**Moderate to Severe** (10–30% loss)	(Fu et al., 2023; Guo, Wang, et al., 2024; Y. Li et al., 2023; Sahebi & Dehestani, 2023; Y. Zhang et al., 2024;

				Zhong et al., 2023)
Carbonation-Induced Corrosion	Bond loss, rebar oxidation	CO_2 penetration lowers pH, allowing steel to corrode and reducing bond strength.	**Moderate** (10–20% loss)	(Alexander et al., 2025; Hussein et al., 2023; Qian, Li, Fu, Zhang, Wang, Jin, et al., 2023; Y. Zheng et al., 2022)
Non-Uniform Corrosion	Localized cracks, high stress zones	Uneven steel loss causing localized failure and crack propagation.	**Severe**	(Fu et al., 2023; Sahebi & Dehestani, 2023; J. Wu, Zhang, et al., 2023; W. Zhang et al., 2024)
Stress Corrosion Cracking (SCC)	Crack growth, premature fracture	Accelerated by tensile stress; critical in alloys under stress.	**Severe**	(Gao et al., 2022; W. wen Li et al., 2024; C. Wang et al., 2024; T. Zhang, Cui, et al., 2023)
Crevice Corrosion	Extreme localized damage	Oxygen depletion in crevices causes acidification and high-rate steel loss.	**Severe (localized)**	(H. Liu et al., 2023)
Macro-Cell Corrosion / Flow-Accelerated	Early-stage material loss, turbulence zone corrosion	Electrochemical potential differences cause localized corrosion.	**Moderate**	(Q. Zhang et al., 2025)
Acid Rain Corrosion	Mechanical property degradation	Sulphuric/nitric acid in rainwater causes surface and bond degradation in PC beams.	**Moderate**	(K. Xu et al., 2023)
Oxygen Absorption Corrosion	Surface cracking in marine zones	Caused by oxygen-rich environments and chloride accumulation in tidal zones.	**Mild to Moderate**	(Gómez et al., 2024; Gong et al., 2022; W. wen Li et al., 2024; Z. Xu et al., 2024)
Redox Corrosion	Micro cracking, porosity increase	Caused by metal-water reactions; e.g., in Zr alloys forming oxide layers.	**Mild**	(S. Yang et al., 2025)
Electrochemical Corrosion	Rust formation, bond loss	Corrosion initiated by electrochemical reactions in embedded steel.	**Moderate**	(Ferenc et al., 2024)

Freeze-Thaw & Corrosion	Rapid deterioration, cracking	Coupled damage mechanism accelerating degradation under repeated cycles.	**Severe (synergistic)**	(Khorasani et al., 2024; Kim et al., 2024)
Bending Failure + Corrosion	Early flexural cracks	Corrosion reduces flexural strength, promoting brittle bending failure.	**Severe**	(Z. Chen et al., 2025)
Localized Corrosion (Marine)	Premature failure, severe cracking	Confined to marine splash and tidal zones, causes early collapse.	**Severe (localized)**	(L. Chen et al., 2024; Gao et al., 2022; H. Liu et al., 2023; D. Wang & Zhong, 2022; B. Zhang et al., 2024)
Selective Phase Corrosion	Preferential microstructure damage	In alloys like NAB; certain phases corrode faster, weakening the structure.	**Moderate**	(J. Yang et al., 2023; Zhai et al., 2023)
Galvanic Corrosion	Accelerated attack on anodic regions	Different metals/alloys in contact lead to preferential corrosion.	**Moderate to Severe**	(T. Wu et al., 2024)
Intergranular Corrosion	Loss of ductility in alloys	Happens at grain boundaries after improper heat treatment in titanium.	**Moderate**	(Hou et al., 2024)
Atmospheric Corrosion	Surface degradation in humid air	Formation of surface products like hydroxides and carbonates in exposed metals.	**Mild**	(Kovivchak et al., 2024)
Extreme Corrosion & Load Loss	Up to 80% strength loss at 30% mass loss	Very high material loss leads to collapse; often simulated/extreme cases.	**Severe (critical threshold)**	(Campione & Zizzo, 2022)
Induced Corrosion (Lab Simulated)	Controlled cross-section loss	Artificially introduced using current in NaCl solution to simulate field corrosion.	**Variable (based on test)**	(Roshan & Ghalehnovi, 2023)

3. Analysis of Corrosion Effects on Reinforced Concrete Structures

Corrosion in reinforced concrete (RC) structures is a major issue with negative effects on mechanical performance, service life, and structural reliability. This part examines different topics related to corrosion, such as its assessment procedures, mechanical implications, numerical simulations, and preventive measures, through recent research output.

3.1 Corrosion Assessment and Monitoring Techniques

The research applied electrochemical measurement methods to determine corrosion in reinforcement cages of concrete beams in tidal conditions, suggesting an equivalent quantization approach to quantify corrosion damage. The connection between linear polarization resistance and electrochemical impedance spectroscopy (EIS) was made, yielding a consistent method for corrosion examination(Gong et al., 2022). In the same line, thermogravimetric analysis (TGA) has been employed in comparing theoretical vs. actual corrosion rates in reinforced concrete

(FRC) beams to show how recycled steel fiber reinforcement (RTSF) enhances corrosion resistance(Roshan & Ghalehnovi, 2023). Application of finite element modeling (FEM) and machine learning has enhanced corrosion monitoring. A neural network was made using results from FEM. This model predicts how much corroded RC beams will bend. It also looks at costs and CO2 emissions to help with eco-friendly designs(Sahebi & Dehestani, 2023). Also, researchers are looking into using piezoelectric sensors with electro-mechanical impedance (EMI) methods. These tools help monitor corrosion in prestressed concrete structures in real-time. They can successfully spot stiffness loss caused by corrosion(Bansal et al., 2024b).

Table 2: Comparative Assessment of Corrosion Monitoring techniques

Method	**Advantages**	**Limitations**	**Field Applicability**	**Reference**
Electrochemical Methods (e.g., LPR, EIS, Half-cell, OCP, WBE, Potentiodynamic Polarization, Electrochemical Noise, Electrical Resistivity)	-Real-time. -In-situ corrosion rate measurement. -Quantitative assessment. -Applicable to embedded steel reinforcement. -Effective for understanding corrosion kinetics and protective layers. -Widely validated and cost-effective for long-term monitoring.	-Data interpretation is complex (e.g., EIS) -Accuracy affected by rust layers and concrete resistivity -May not capture localized corrosion -Can be subjective and time-consuming	Widely used in RC structures and prestressed concrete, especially in marine and chloride environments	(Alexander et al., 2025; Bansal et al., 2024b; Y. Chen et al., 2023; Fan et al., 2021; G. Feng et al., 2022; Gong et al., 2022; Nasser et al., 2022; D. Wang & Zhong, 2022; Zhai et al., 2023; Q. Zhang et al., 2025; T. Zhang, Zhang, et al., 2023; Zhong et al., 2023; Zhu et al., 2025)
Optical Methods (e.g., Digital Imaging, X-ray Radiography, DIC, SEM, XRD, TEM, DOFS, FT-IR, Raman, 3D Optical Scanning)	-Non-destructive imaging -High-resolution data on surface and internal morphology. -Effective in visualizing corrosion-induced cracks, steel loss, and chloride penetration. -Suitable for post-corrosion characterization and failure analysis	-Limited depth penetration -Expensive equipment -Requires expert handling, sample prep, and controlled conditions -Often post-processing based and lab-dependent	Suitable for post-analysis and research validation; increasingly used in laboratory and controlled field studies	(Cavallini et al., 2024; Dackman et al., 2024; D. Feng et al., 2025; Guo, Ma, et al., 2024; Guo, Wang, et al., 2024; Khorasani et al., 2024; Kovivchak et al., 2024; Y. Li et al., 2023; Qian, Li, Fu, Zhang, Wang, & Jin, 2023; Tang et al., 2024; Z. Xu et al., 2024; S. Yang et al., 2025; X. R. Yu

				et al., 2024)
Piezoelectric Methods (e.g., Electro-Mechanical Impedance (EMI), PZT Sensors)	-Real-time monitoring without structural intrusion. -High sensitivity to incipient damage -Dual use as sensor and actuator -Fast response -Potential for embedding during casting	-Influenced by environmental variables. -Requires dense sensor network for large structures. -Limited commercial adoption. -Needs calibration and robust signal interpretation.	Ideal for health monitoring of PC and RC structures; gaining traction in bridges and prestressed systems	(Ai et al., 2022; Bansal et al., 2024b, 2024a)

3.2 Corrosion-Induced Structural Degradation: The study shows that corrosion really affects how well RC beams hold up under different conditions. When it comes to FRC beams that lack web reinforcement, more corrosion means less shear strength. Instead of failing from bending, they start to fail from shear-compression (Roshan & Ghalehnovi, 2023). Pitting corrosion has also been found to promote fatigue crack initiation, enhancing the likelihood of brittle failure in corroded beams (Guo, Wang, et al., 2024). In prestressed concrete beams, corrosion causes severe reduction in mechanical properties. Experimental evidence of pitting depth and weight loss in PC beams demonstrates that chloride ingress reduces tendon strength and enhances failure tendencies (Ahmed et al., 2024; Grandić et al., 2024). Although RC beams show progressive reduction of flexural strength, PC beams can experience sudden loss of strength due to corrosion-induced rupture of prestressing strands, which are single critical elements (Y. Li et al., 2023; Zhai et al., 2023). Lack of initial visible cracks in PC beams can postpone detection of corrosion, making sudden collapse more likely. Finite element simulation shows that stimulated corrosion leads to concrete breaking down even after the steel has yielded. This changes how failures happen and greatly reduces the flexibility of the concrete (Hussein et al., 2023).

Although new materials such as UHPC, FRP, and self-healing concretes have been shown to provide substantial corrosion resistance improvements, their extensive adoption is presently restricted because of high material and installation prices, elaborate production procedures, and the lack of sufficient field experiences under different environmental conditions. For example, UHPC demands specialized curing and costs more to produce compared to regular concrete, although it can lower lifecycle costs. Likewise, FRP bars are not standardized yet in international codes, and their bond behavior under extreme corrosion are investigated. Self-healing concretes, particularly those incorporating superabsorbent polymers (SAPs), have demonstrated encouraging laboratory-scale performance; however, their healing effectiveness under cyclic repeated cracking and exposure is still a source of concern. Applications are mostly experimental, with the commercial introduction being restricted to pilot projects.

3.3 Innovative Materials and Mitigation Methods for Corrosion

Recent studies show that new materials can really help reduce corrosion. For example, ultra-high-performance concrete (UHPC) and fiber-reinforced polymer (FRP) sheets are getting a lot of attention. UHPC is tough and lasts longer, even in harsh conditions. It also has a stronger bond with steel. On the other hand, beams reinforced with FRP improve their ability to handle bending. But, if corrosion sets in, it can weaken that bond and lower the effectiveness of the reinforcements. There are also self-healing materials that can fix tiny cracks and slow down the way salt gets into corroded concrete. Experimental investigation of super absorbent polymers and calcium-treated SAP indicates that these materials greatly improve self-healing efficiency and corrosion resistance in marine environments (C. Zhang et al., 2022). Protective coatings like SiO_2-GO/HEP coatings have also shown a 99.995% decrease in corrosion current density, providing an effective method for enhancing structural lifespan (T. Zhang, Zhang, et al., 2023).

Table 3: Comparative quantitative data on post corrosion residual performance

Type of Beam	Residual Flexural Capacity	Fatigue strength impact	Reference
RC Beam	60% reduction in flexural strength	Fatigue life significantly reduced especially with pitting corrosion	(Hussein et al., 2023)
RC beams	15 to 26% reduction in yield load	Reduction in energy dissipation impacts fatigue strength	(Kim et al., 2024)
RC beams	Shift in failure mode from shear to flexure	Fatigue life reduced by 19.6% to 40.4%	(Khorasani et al., 2024)
RC Beams	Reduction in flexural stiffness; ductile to brittle transition	Requires further investigation	(Imperatore et al., 2024)
RC Beams	0.85–1% bending capacity loss per 1% cross-section loss	Under-researched fatigue correlation	(Nasser et al., 2022)
RC Beams	55% reduction in flexural strength	Not specified	(Udhaya Kumar & Vinod Kumar, 2023)
RC Beams with HPS (High performance Steel)	Significant reduction in strength and stiffness	Not addressed	(Xiao et al., 2023)
RC Beams (FRP grid–ECC repaired)	Flexural capacity improved compared to unrepaired specimens	Fatigue life improved; residual deflection reduced	(A. Zheng et al., 2022)
PC Beams	Linear reduction in flexural capacity	Decreased energy dissipation capacity and increased fatigue risk	(K. Xu et al., 2023)

PC Beams	Failure mode shifts from bar to strand fracture	fatigue life decreases exponentially with corrosion	(Su et al., 2022)
PC beams	80% reduction in load carrying capacity	Increased risk of brittle failure	(Campione & Zizzo, 2022)
LWAC (Light weight Aggregate Concrete) beam	Ultimate moment reduced upto 52.32%	Fatigue performance affected by bond degradation	(Y. Liu et al., 2024)
UHPC vs RC	Bond strength loss:1.69% (UHPC) vs 66.24% (RC)	Not addressed	(El-Khoriby et al., 2023)
RC Beams (Steel bars)	Not specified	Fatigue life reduced; multiple fracture locations observed	(Guo, Ma, et al., 2024)

3.4 Limitations and Challenges in Large-Scale Application of Current Corrosion Protection Methods

3.4.1. Chemical Inhibitors and Surface Coatings: Corrosion inhibitors like Darex and water resistance coatings have proved beneficial in improving corrosion resistance of concrete structures. But most research studies neglect important parameters like chloride ion diffusion effects and are confined to certain environmental conditions, such as tidal zones, lowering their general applicability. Surface treatments like high-current pulsed electron beam (HCPEB) alloying are plagued by non-uniform debris distribution and thin remelted layers, which restrict their uniformity and longevity.

3.4.2. Electrochemical Methods: Electrochemical techniques (e.g, LPR, EIS, half-cell potential) are suitable for in-situ corrosion monitoring and yield quantitative information. But these methods are difficult to analyze, highly dependent on variables such as concrete resistivity and rust coatings and tend to not accurately detect localized corrosion. Also, their application at a large scale is time-consuming, labor-intensive, and non-automated, making it difficult for real-time monitoring.

3.4.3. Fiber Reinforcements and Hybrid Systems: Recycled and hybrid steel fibers are used to arrest microcracking and enhance corrosion resistance. However, their effectiveness in highly aggressive environments remains under investigation. Smaller fiber diameters can create localized corrosion points, and theoretical predictions of corrosion rates often diverge from experimental results, raising concerns about long-term reliability

3.4.4. Surface Modification and Metallurgical Techniques: Surface treatments like plasma nitriding, electron beam welding, and alloying techniques enhance corrosion resistance but are plagued with issues such as insufficient uniformity, generation of residual stresses, and microstructural inhomogeneity's. Specialized equipment and technical knowledge are needed for these advanced processes, restricting their use in the field.

3.4.5. Advanced Cementitious Composites and FRP Systems: Ultra-high-performance concrete (UHPC) and fiber-reinforced polymers (FRPs) offer superior corrosion resistance and strength. But excessive cracking under overloads, compromised bond performance, susceptibility to environmental conditions (e.g., UV, heat), and construction complexity tend to severely restrict their protective functions. Premature debonding and wet surface compatibility issues add to their complexities in application.

3.4.6. Cathodic Protection (CP): Although cathodic protection is capable of controlling corrosion, its performance is extremely variable when subjected to alternating current (AC) interference. Its limitations are in terms of irregular deposition of calcareous coating, hydrogen evolution interfering with adhesion, and retrofitting into existing old RC structures, increasing the cost and complexity of application.

3.4.7. Experimental and Modeling Constraints: Several experimental and computational methods bypass corrosion mechanisms by assuming uniform corrosion, while it does not reflect actual conditions where non-uniform corrosion will result in accelerated degradation. The models frequently lack the ability to consider the compounded impacts of corrosion, fatigue, and cracking, thus restricting their predicative potential as well as their application in various environmental conditions.

3.4.8. Sensor Technologies and Self-Healing Systems: Novel sensor-based monitoring methods such as electro-mechanical impedance (EMI) and self-magnetic flux leakage (SMFL) are limited in detecting early-stage or localized corrosion precisely. These systems are usually based on dense networks of sensors, which are hard to install on huge structures. Self-healing cementitious materials also hold promise, but it is hard to achieve uniform healing in large elements and under different widths of cracks and environmental conditions.

3.5 Corrosion Modeling and Service Life Prediction

Numerical simulation has been widely utilized to model damage due to corrosion and estimate corroded structures remaining service life. A number of modeling approaches, such as pit depth prediction, stress-strain analysis, and crack propagation models, have been compared. Studies on fatigue life prediction models for corroded PC beams indicate the significance of spatial pitting corrosion variability, which demonstrates that uniform corrosion assumptions tend to overestimate fatigue life(Guo, Wang, et al., 2024). Moreover, machine learning-based prediction models have also been established to predict corrosion distribution in RC beams by combining finite element analysis (FEA) with Monte Carlo simulations for more precise predictions(Srivaranun et al., 2023). Bayesian models and probability methods have improved how we estimate the chance of corrosion failures. They take into account things like external load, how chloride spreads, and the surrounding environment(T. Wang et al., 2023).

3.6 Environmental and Sustainability Considerations

The effect of environmental conditions on corrosion development has been well investigated. Investigations of chloride attack of 7-year exposure on marine concrete beams showed that chloride content maxima at 3-5 mm depths emphasize the requirement for improved protection in tidal and submerged areas(Qian, Li, Fu, Zhang, Wang, & Jin, 2023). Analogously, corrosion due to carbonation in various cementitious composites has been studied, and it was found that slag concrete shows greater carbonation depths than OPC(Qian, Li, Fu, Zhang, Wang, Jin, et al., 2023).

From a sustainability point of view, beam design optimization for lower environmental footprint has emerged as an increasing area of research. Research on low-carbon geopolymer concrete (GPC) aggregate indicates that GPC has lower corrosion rates and improved chloride attack resistance compared to traditional OPC-based concrete and is a potential substitute for future infrastructure development(Udhaya Kumar & Vinod Kumar, 2023). CO2 footprint analyses also highlight the need for corrosion-resistant materials to reduce long-term repair expenses and minimize environmental footprint(Sahebi & Dehestani, 2023).

4. Critical Analysis of Numerical Modelling Approaches: Role of Probabilistic Models and Artificial Intelligence

Numerical modelling is an integral part of evaluating the structural performance of corrosion-damaged reinforced concrete (RC) members. Although classical deterministic methods have been extensively applied, recent literature describes the shortcomings of these methods and the increasing importance of probabilistic and artificial intelligence (AI)-driven models.

Limitations of Traditional Numerical Models: Standard Finite Element models frequently do not simulate correctly the intricate performance of corroded structural elements because of simplifying assumptions. For example, perfect bond conditions between steel and concrete might result in unrealistic stiffness and strength predictions for corroded members. Additionally, models with average mass loss do not capture the effect of spatial corrosion variability, especially under non-uniform or pitting corrosion cases.

Integration of Probabilistic Modelling: Probabilistic modeling has been found to be an effective means of tackling the immanent uncertainties in corrosion development and material deterioration. By accounting for statistical variability in corrosion rates, reinforcement properties, and crack distribution, such models offer a more rational estimation of structural reliability. For example, Monte Carlo simulations coupled with FE analyses are able to provide probability density functions of flexural capacity, facilitating risk-based decision-making in structural assessment and retrofitting. Yet these methods are computationally expensive and extremely sensitive to the quality of input data, such as corrosion patterns and material properties, which can prove difficult to obtain in field situations.

4.1. Advancements through Artificial Intelligence (AI):

Artificial intelligence, in the form of machine learning (ML) and deep learning techniques, is being widely used to improve modelling accuracy and efficiency. Neural networks have been trained on large FE simulation data sets to model key performance indicators like mid-span deflection. Models have been found to correlate well with numerical results, indicating their promise for predictive modelling. Higher-level architectures such as generative adversarial networks (GANs), in particular pix2pix, have been utilized to approximate spatially correlated corrosion distributions with the aid of random field theory. The models are not only able to mimic real-world corrosion patterns in transverse and longitudinal directions but also enable easy integration with FE models for performance analysis. Yet another novel path involves image-based machine learning, in which crack distribution maps are analyzed to deduce corrosion severity, allowing data-driven, non-destructive evaluation.

4.2. Challenges and Recommendations

- The performance of models is significantly dependent on the quality and availability of training data, which should be indicative of actual corrosion conditions.
- Models developed for RC beams might not be transferable to prestressed concrete (PC) systems directly because of variations in prestressing behavior.
- Neural networks tend to be uninterpretable, which creates a

hurdle for engineering acceptance and regulatory compliance.

To alleviate these issues, future work should be directed towards:

- Hybrid approaches that integrate physics-based and data-driven models.
- Large-scale dataset generation using experiments and simulations.
- Comprehensive validation against field data for enhanced generalizability.

5. Results:

The examination of corrosion impact on reinforced concrete (RC) beams shows that pitting corrosion is the worst form of corrosion, having a serious impact on the structural integrity and durability of RC structures. Unlike uniform corrosion, pitting corrosion causes localized steel reinforcement degradation, resulting in a loss of cross-sectional area and bond strength, which reduces load-carrying capacity. Experiments validate that even small levels of corrosion (5-10% mass loss) are capable of causing significant flexural and shear strength loss, while excessive corrosion (>30% mass loss) leads to brittle fracture and instability of the structure.

The results also identify the development of corrosion damage, where reinforcement expansion causes tensile stresses, resulting in micro-crack initiation, concrete spalling, and bond deterioration. The transition from ductile to brittle failure modes by corrosion-induced embrittlement of steel reinforcement has been reported extensively, which makes structures susceptible to sudden collapse.

With regard to durability, the review of reinforcement corrosion ranks marine and chloride-bearing environments as the most severe conditions for corrosion of the reinforcement. Chloride ingress enhances corrosion rates greatly, shortening service life by over 50% in unprotected structures. The review is also clear that mechanical properties of corroded RC beams decline progressively, with decreased flexural stiffness, increased deflection, and greater susceptibility to fatigue failure.

Experimental results indicate that PC beams undergoing pitting corrosion are more prone to brittle failure than RC beams, as a result of stress concentration effects on tendons and prestress force loss. A number of corrosion mitigation measures have been investigated in the literature, and these include corrosion-resistant reinforcement (e.g., stainless steel, fiber-reinforced polymer bars), protective coatings, and supplementary cementitious materials (SCMs) that have been shown to slow down corrosion rates. Electrochemical protection techniques such as cathodic protection and real-time corrosion monitoring systems have also been shown to slow down corrosion development and prolong service life.

In general, the research confirms that corrosion adversely affects RC beams' performance, durability, and failure mechanisms. Although there are numerous mitigation methods, continuous research is needed to improve predictive modelling, enhance corrosion monitoring methods, and create sustainable materials to extend RC structures' lifespan in harsh environments.

6. Conclusion

Over the last few years, extensive studies have aimed at revealing the effects of different types of corrosion on RC beams. Chloride corrosion, particularly in seawater, causes serious damage by lowering the load-carrying capacity of beams, producing widespread cracking and spalling of concrete. The corrosion process accelerates with chloride ions that penetrate the concrete cover, initiating corrosion in steel reinforcement and leading to localized degradation, which reduces the overall strength of the beam.

Pitting corrosion, which is also one of the most extensively researched corrosion mechanisms, results in localized loss of mass on the surface of the rebar. This localized weakening gives rise to the creation of deep pits, which interfere with the steel-concrete bond and generate areas of weakness in the structure. Crack initiation by pitting corrosion drastically lowers the fatigue life of RC beams, and these become prone to failure under cyclic loading. This corrosion is the riskiest in that it causes an unbalanced reduction of material, which increases the damage at certain points of the beam to the point of early collapse.

Uniform corrosion, while less explored compared to other forms, contributes significantly to the slow deterioration of RC beams as well. The steel reinforcement in this form of corrosion is compromised uniformly, and its cross-sectional area is decreased over time. The structural capability of the beam is slowly degraded by this action. While uniform corrosion's attack might seem to be less invasive compared to pitting, long-term effects may be just as devastating because continuous weakening of steel reinforcement occurs. The resistance of RC beams to these types of corrosion is largely dependent on environmental conditions, the quality of concrete, and the availability of protective systems like coatings or corrosion inhibitors. Studies have established that new materials such as ultra-high-performance concrete (UHPC) can offer improved corrosion resistance, enhancing the durability and lifespan of RC structures.

The review highlights that RC and PC beams are both subjected to corrosion-related degradation, PC beams are particularly susceptible to localized pitting, which may lead to premature failure with little or no warning. This distinction is important in corrosion-resistant system design.

In summary, chloride-induced and pitting corrosion are still the most significant and researched corrosion mechanisms in RC beams. These forms of corrosion cause extensive damage, such as decreased load-carrying capacity, enhanced crack propagation, and eventual collapse. Effective countermeasures, including the application of corrosion-resistant materials and protective coatings, are necessary to extend the service life of RC structures and avoid premature failure through corrosion. Future studies should persist in the development of corrosion-resistant technologies and further clarify the intricate interaction of corrosion processes to ensure the integrity of RC beams in the long term.

7. Future Research Directions:

Future research in corrosion and structural performance should focus on gaining deeper insights into the corrosion of reinforcement cages in concrete beams and understanding the impact of different corrosion levels and distributions on structural responses. Sustainability remains a crucial aspect, necessitating studies on the long-term performance of corroded reinforced concrete (RC) beams under various environmental conditions while considering time-dependent repair and maintenance costs. Additionally, innovative materials and protective measures should be explored, including the effectiveness of corrosion inhibitors such as darex and migrating inhibitors, as well as self-produced protective materials in concrete structures.

Structural modeling and experimental studies should be enhanced by developing advanced modeling approaches to account for corrosion-induced damage in RC structures, with a specific focus on the phase-field method for predicting structural damage. Furthermore, the interplay between corrosion and fatigue loading on reinforced concrete beams should be thoroughly studied, particularly regarding long-term performance under repeated loading cycles. Research should delve into the relationship between bond deterioration, cover cracking, and structural performance, as well as the connection between crack width, corrosion levels, and ultimate load-bearing capacity.

Sustainability and environmental impact studies should concentrate on optimizing concrete mixes with eco-friendly alternatives such as recycled materials while evaluating the effects of corrosion-related damage on the carbon footprint of RC structures. The integration of machine learning and artificial intelligence in corrosion prediction models presents a promising avenue for future research, while embedded sensor technologies should be examined for their effectiveness in real-time corrosion assessment. By addressing these research areas, future studies can contribute to developing more durable and resilient reinforced concrete structures, enhancing both structural performance and sustainability.

Emerging Technologies for Corrosion-Resistant RC Structures

Though there has been notable development in corrosion effects modeling and understanding in RC beams, operationalization of such insights into usable instruments requires more work. Priority should be given to:

- Integrating AI and probabilistic methods with field data to increase robustness.
- Developing structure-specific digital twins for corroded structures.
- Implementing predictive models on BIM platforms for smooth structural health management.
- Standardizing data collection and sharing protocols to enable training of AI and calibration of probabilistic models.
- Examining multi-objective optimization of corrosion mitigation strategies based on cost, performance, and sustainability.

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