Journal of Mines, Metals and Fuels, *73(1): 189-198; 2025. DOI: 10.18311/jmmf/2025/46985*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Corrosion in Steel Structures: A Review

K. C. Manu[1], C. Madhushree[1], M. S. Chandini[1], Nudi Shree[1], Siri Hemanth[1] and T. P. Jeevan[2]*

[1]Department of Civil Engineering, Malnad College of Engineering, Hassan affiliated to Visvesvaraya Technological University, Belagavi - 590018, Karnataka, India

[2]Department of Mechanical Engineering, Malnad College of Engineering, Hassan affiliated to Visvesvaraya Technological University, Belagavi - 590018, Karnataka, India; jeevantpce@gmail.com

Abstract

Corrosion is a critical challenge affecting the longevity and safety of steel structures across various industries, including construction, automotive, and infrastructure. This review highlights the significance of understanding corrosion mechanisms, such as uniform corrosion, localized corrosion, and stress corrosion cracking, which can severely compromise the integrity of steel components. The review discusses various corrosion prevention strategies, including advanced coatings, and protective measures for retrofitting corroded structures. Advancements in numerical and experimental studies have provided valuable insights into assessing and predicting corrosion-related damage, thus facilitating timely maintenance and repair strategies. The review underscores the necessity for a proactive approach to corrosion management, informed by accurate modelling and innovative materials, to ensure the durability and sustainability of steel structures. Corrosion poses a critical challenge to the durability of steel structures, necessitating a deep understanding of mechanisms like uniform and stress corrosion. Advances in modelling, experimental studies, and protective strategies, such as advanced coatings, enable better predicting and preventing corrosion-related damage. Collaborative efforts among researchers and industry stakeholders are essential for developing effective, sustainable solutions.

Major Findings: *The review highlights key corrosion mechanisms, prevention strategies like advanced coatings, and the role of modelling in damage prediction, urging collaborative efforts for sustainable solutions.*

Keywords: *Corrosion, Steel, Structures and Coatings*

1.0 Introduction

Steel is a crucial material in the construction industry, particularly for large-scale and complex structures like skyscrapers, bridges, and industrial buildings. Its high strength-to-weight ratio, versatility, and recyclability make it an irreplaceable component in modern construction. Due to its excellent tensile strength, steel can support substantial loads and resist stresses, making it a prime choice for use in beams, columns, and girders. Recent research indicates that structural steel is favoured for its capacity to carry heavy loads while minimizing deformation, ensuring the safety of high-rise buildings and bridges. Its application in tall structures allows architects to design lighter yet taller buildings that remain stable under dynamic conditions, such as wind and seismic activity[1].

In vehicle manufacturing, steel is indispensable due to its optimal balance of strength, weight, and cost. It plays a key role in improving vehicle safety, reducing emissions, and enhancing performance. In recent times, Advanced High-Strength Steel (AHSS) has become the preferred material for automakers, as it boosts fuel efficiency by reducing vehicle weight without sacrificing safety or

*Author for correspondence

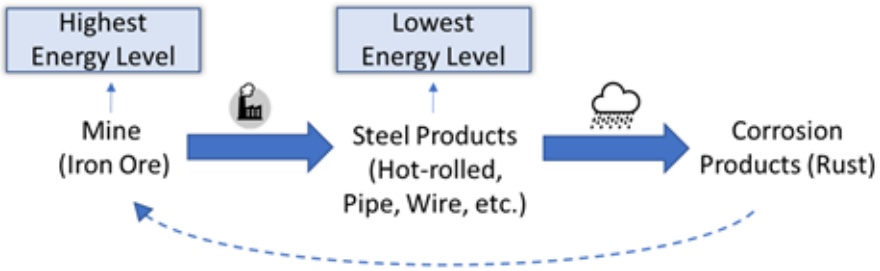


Figure 1. Refining corrosion cycle of steel components[4].

performance. These steels are critical for enhancing a vehicle's ability to withstand crashes[2]. As the automotive industry moves toward Electric Vehicles (EVs), steel remains an important material for constructing lightweight chassis and components to offset the extra weight of batteries. Furthermore, the magnetic properties of steel make it suitable for motor components and battery enclosures. The industry's adoption of recycled steel has also grown, as steel can be recycled without losing its properties, making it vital for a circular economy.

Across the construction, automotive, and infrastructure sectors, steel's versatility, strength, and sustainability are evident. Recent advances, such as AHSS and corrosion-resistant alloys, are broadening steel's applications while simultaneously decreasing its environmental impact. Whether in high-rise buildings, bridges, electric vehicles, or offshore platforms, steel continues to be a critical material for maintaining the integrity and longevity of modern structures[3].

Metals rarely exist in their pure elemental states; instead, they usually create thermodynamically stable ores by combining them with common elements like oxygen. These ores must be refined using energy-intensive procedures because the majority of them are oxides or mineral complexes (Figure 1).

Corrosion of steel is a slow, electrochemical process that occurs due to interactions between the material's surface and environmental elements, leading to changes in surface morphology, material loss, and performance degradation. Atmospheric corrosion is particularly common since roughly 80% of metal components are exposed to atmospheric conditions. Corrosion in steel structures presents significant issues, including material degradation, safety risks, higher maintenance costs, and environmental consequences[5]. These challenges are especially significant in industries heavily reliant on steel, such as construction, infrastructure, transportation, and energy. Uniform corrosion leads to a reduced cross-sectional area in steel components, causing gradual weakening, while localized corrosion (such as pitting) can create stress concentrations that result in sudden failures, particularly in load-bearing structures like bridges[6].

The global cost of corrosion exceeds $2.5 trillion annually, factoring in both direct repair costs and indirect losses, such as operational downtime and decreased productivity due to corrosion-related failures[7]. Although service life prediction models exist, their accuracy is often compromised by the variability in environmental conditions. Historical failures, such as the collapse of the Silver Bridge in 1967 due to a corroded suspension chain, underscore the catastrophic potential of unchecked corrosion. Steel production, responsible for around 7-9 % of global CO_2 emissions, exacerbates the environmental burden when corroded steel needs to be frequently replaced[8]. This review will delve into the latest numerical investigations and modelling approaches, shedding light on their potential to better predict and manage corrosion in steel structures, and ultimately guide future efforts in enhancing the longevity and sustainability of steel-based infrastructure.

2.0 Principles of Corrosion Processes

Corrosion forms are often characterized as dry or wet, with conditions including liquid (aqueous), underground, atmospheric, and high temperature. Electrochemical principles are applied in all circumstances. Corrosion can

take many different forms depending on the environment[9]. Figure 2 shows the proportion of different corrosion forms. Corrosion types and their effects on industry are very different depending on the material used and the surroundings. Due to repeated mechanical pressures in corrosive settings, fatigue corrosion (23.0% of all corrosion) is most common in industries like aerospace, automobile, and heavy machinery. It usually affects parts like airplane wings and car suspensions. In the same way, constant atmospheric contact causes full corrosion (22.0%), which has big effects on the sea, transportation, and infrastructure sectors. It causes buildings like bridges, pipes, and ships to slowly lose material.

In the nuclear, industrial, and aircraft industries, stress corrosion fracture (19.0%) is a big problem because it happens when tension stress meets corrosive agents. This is very important in chemical plants and oil wells. To the other hand, pitting corrosion (11.0%), which is caused by localized breakdown in chloride-rich environments, is a common problem in the chemical processing, desalination, and marine industries. It impacts pipes, heat exchangers, and marine structures.

Abrasion (6.0%) is a type of erosion-corrosion that happens in water treatment, oil and gas, and mining systems. Pipelines and slurry systems wear out materials faster when fluids moving at high speeds hold particles. Intergranular corrosion (8.0% of all corrosion) mostly happens in the food preparation, chemical, and nuclear industries because of bad heat treatment, which causes attack along grain boundaries, especially in acidic environments.

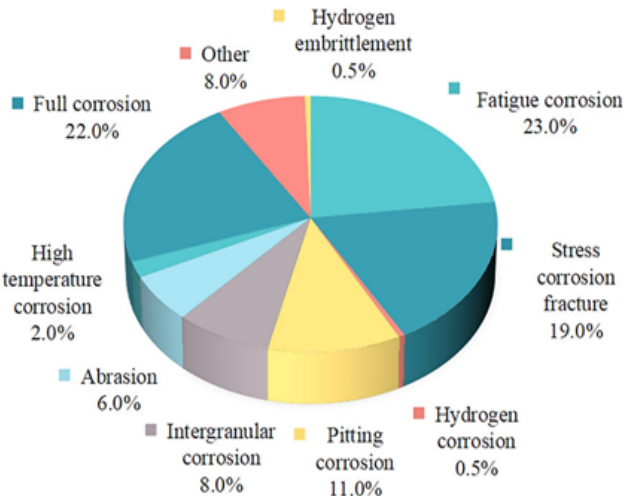


Figure 2. The proportion of different corrosion forms.

2.0% of high-temperature corrosion happens in the aerospace, automobile, and power production industries because of oxidation or sulfidation at very high temperatures. It usually happens in turbines and boilers. Hydrogen embrittlement (0.5%) happens less often, but it is very dangerous in the aircraft, nuclear, and automobile industries because it makes metals weaker in places with a lot of hydrogen, especially in fuel systems. Finally, other types of corrosion (8.0%), like galvanic corrosion and corrosion caused by microbes, affect specific places like electronics and pipes.

Common industrial classifications are as follows[10].

(a) Uniform corrosion.
(b) Galvanic corrosion.
(c) Localized corrosion such as Crevice corrosion, Pitting, Filiform corrosion.
(d) Selective leaching as in alloys such as brass (Dezincification).
(e) Intergranular/Transgranular attack.
(f) Erosion, Impingement and Cavitation corrosion.
(g) Stress cracking and stress corrosion cracking (hydrogen embrittlement, sulfide stress cracking, Liquid metal embrittlement).
(h) Fretting corrosion, Corrosion fatigue.
(i) High temperature oxidation.

Electrochemical and microbiological corrosion reactions involve electrochemical cells (corrosion cells) that contain an anode, a cathode, and an electrolyte, as well as anodic (oxidation) and cathodic (reduction) processes. When the electrodes are coupled, a potential difference is created (Figure 3). Every oxidation event is accompanied by a reduction reaction, and the net reaction indicates the whole electrochemical process[11].

Anode: Electrode where oxidation (corrosion) occurs

$$M = M^{++} + 2e \quad (1)$$

Cathode: Electrode where reduction (deposition) occurs

$$M^{++} + 2e = M \quad (2)$$

The anode and cathode's potential differential (cell EMF) drive the corrosion reaction. A corroding metal contains several anodic and cathodic sites. Because the absolute potential of an individual electrode cannot be measured directly, all potential measurements in

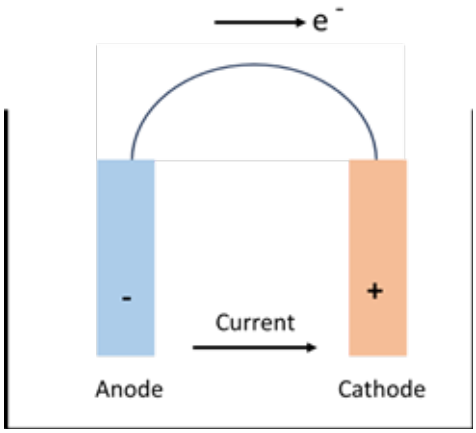


Figure 3. Basic galvanic corrosion cell.

electrochemical corrosion cells are made relative to a reference electrode[12,13].

3.0 Corrosion Protection

Corrosion avoidance usually entails separating a substrate from its surroundings and/or utilizing materials that are more anodic (lower noble) than the protected substrate. A popular example of combining these techniques is putting a zinc-rich primer to a steel base, followed by a polyurethane finish. Because of its highly crosslinked structure, polyurethane functions as an environmental barrier. Normal wear and scrapes, as well as environmental conditions like as heat stress and UV exposure, can deteriorate the topcoat over time, reducing its barrier characteristics. The Strategic Environmental study and Development Program (SERDP) and the Environmental Security and Technology Certification Program (ESTCP) have supported extensive study to better understand the breakdown processes of these topcoats and primers[14,15]. Figure 4 shows different corrosion prevention methods.

3.1 Coatings for Corrosion Prevention

Corrosion-preventive coatings are divided into three types: organic, inorganic, and metallic. Organic coatings, such as paints, powder coatings, stains, varnishes, lacquers, and resins, are the most prevalent type. Pretreatments commonly use inorganic coatings such as anodization, conversion coatings, enamels, and ceramics. Metallic coatings are also commonly used to prevent and control corrosion, with examples including cladding, electroplating, and thermal spraying[17].

3.1.1 Organic Coatings

Paints are among the most widely used methods for preventing corrosion due to their cost-effectiveness and

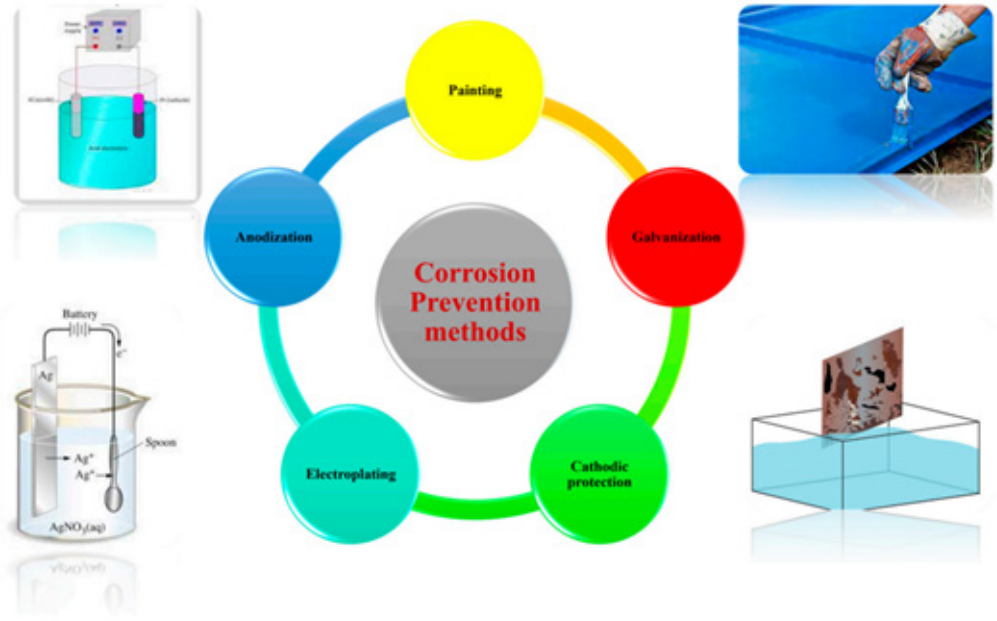


Figure 4. Corrosion prevention methods[16].

effectiveness when matched with the right environmental conditions and asset usage. Major coating manufacturers produce a variety of paint formulations, each with unique properties tailored to different applications. Some formulations, like polyurethanes, are known for their superior environmental protection, making them popular choices as topcoats. Other formulations, such as epoxies, are recognized for their excellent adhesion and are often selected as primers. Common types of coatings include alkyds, epoxies, vinyls, rust converters, polyureas, and polyurethanes.

Despite the diversity in their formulations, most paints share three fundamental components: solvents, binders (or resins), and pigments. Solvents may be either water-based or solvent-based (oil-based). The binder functions as the crosslinking agent that holds the paint together, often comprising materials with isocyanate functional groups. The pigments serve as additives that provide color and enhance properties, including UV resistance and corrosion inhibition, as well as biocides to prevent microbial growth[18].

3.1.2 Inorganic Coatings

Inorganic coatings primarily focus on modifying the surface chemistry of metals rather than functioning solely as protective layers. This modification enhances corrosion resistance and improves adhesion for subsequent coatings. Common types of inorganic coatings include anodization, conversion coatings, and phosphatizing, with anodization and conversion coatings typically used for aluminum and phosphatizing applied to steel.

Anodization is primarily performed on aluminum and its alloys, as it enhances corrosion resistance through intentional surface passivation. The anodization process is electrolytic and involves applying direct current through acidic solutions while immersing the metal. Although the industry standard, MIL-A-8625, has not been updated in over two decades, it outlines the anodization of aluminum alloys using acids like chromic and sulfuric acid. Various factors, such as acid concentration, dwell time, voltage, and temperature, can be adjusted to achieve desired corrosion protection and hardness levels. For thinner metals, chromic or thin-film sulfuric acid is preferred to minimize etching depth, reducing fatigue risk. However, sulfuric acid is often favored due to its cost-effectiveness.

The anodization process generally includes pretreatment, rinsing, etching, anodizing, and sealing. Pretreatment cleans the substrate using a heated alkaline solution, followed by rinsing in deionized water to remove contaminants. The metal is then etched in a sodium hydroxide solution to increase surface area for enhanced passivation during anodization. The anodizing step generates an oxide layer ranging from 2 to 25 μm in thickness. Finally, sealing is performed using boiling water or chemicals like nickel acetate to prevent electrolytic intrusion, thus improving corrosion resistance[19].

3.1.3 Metallic Coatings

Metallic coatings are often integrated into a multilayer protective system to enhance corrosion resistance without relying on organic binders or resins. These coatings leverage galvanic potential differences to safeguard underlying substrates and can be applied using several methods, including electroplating, cladding, thermal spray, and immersion in molten metals.

Electroplating involves immersing a cathodically charged substrate in a solution containing anodically charged metallic particles. This process deposits a noble and abrasion-resistant coating onto the substrate, creating a barrier against environmental factors. Common applications include zinc plating on steel fasteners, which provides moderate protection, and cadmium plating in aerospace applications, known for its effectiveness despite its toxicity. Low hydrogen embrittlement zinc-nickel (LHE Zn-Ni) coatings are being explored as safer alternatives to cadmium. Other methods, such as barrel plating and brush plating, allow for efficient coating application but can present challenges like hydrogen embrittlement, particularly in high-strength steels. Hot-dip galvanizing is a prevalent method of immersing steel in molten zinc, resulting in a thicker coating than electroplating, which offers superior corrosion protection. This cost-effective approach is widely used for protective coatings in various applications.

Cladding involves joining two metals through processes such as rolling, extrusion, or welding to form a protective layer. Examples include coins and aircraft components, where pure aluminum is applied to aluminum alloys to prevent localized corrosion from impurities. Thermal spray metallization provides robust

corrosion protection, particularly in harsh environments. This method involves heating and pneumatically spraying molten metal onto the substrate. The metal wire arc spray technique, where two charged wires create an arc to melt and spray the material, is commonly used. The United States Air Force, for instance, employs a blend of 85% zinc and 15% aluminum wire for steel substrate protection. Proper surface preparation is critical for adhesion, often requiring a specific angular surface profile to ensure effective coating.

3.2 Recent Trends and Innovations in Corrosion Prevention

Recent advancements in corrosion prevention have introduced innovative and sustainable solutions across various industries. Nanotechnology has been instrumental in enhancing coatings by incorporating materials like graphene oxide, Zinc Oxide (ZnO), and Titanium dioxide (TiO_2) to improve barrier properties, adhesion, and corrosion resistance. Self-healing coatings with embedded nanocapsules or microcontainers release inhibitors upon damage, autonomously repairing and prolonging their lifespan. Smart coatings, engineered to respond to environmental changes such as pH or temperature, offer dynamic protection by releasing inhibitors or sensing corrosion onset, while multifunctional coatings combine corrosion resistance with UV or antibacterial properties[20-22].

Bio-inspired strategies, such as superhydrophobic surfaces modelled after the lotus leaf, reduce water interaction and mitigate corrosion risks. Eco-friendly alternatives, including plant-based green inhibitors, are replacing toxic heavy-metal coatings, contributing to environmental sustainability. Advanced surface modification techniques, like laser engineering and plasma treatments, are also gaining prominence for creating durable, corrosion-resistant layers. Hybrid coatings that merge organic and inorganic materials, such as epoxy-silica hybrids, exhibit enhanced toughness and adhesion, making them suitable for harsh environments. Composite materials, including Carbon Fiber-Reinforced Polymers (CFRPs), are being developed to provide both structural strength and corrosion resistance, particularly in aerospace and offshore applications. These innovations collectively reflect a shift toward more durable, efficient, and sustainable corrosion prevention methods, addressing both industrial needs and environmental challenges[23-28].

4.0 Experimental and Numerical Studies on Corrosion of Steel

4.1 Experimental Studies

Ensuring the maintenance and safety of present structures is crucial. Corrosion may result in structural deterioration, resulting in a significant loss of strength. The complexity of corrosion lies in its various forms and unique surface characteristics, making experimental approaches alone insufficient to accurately predict the remaining strength of an existing structure. Therefore, a comprehensive approach combining nonlinear Finite Element Method (FEM) analysis and analytical methods is recommended[29] to reliably assess the residual strength of corroded steel members, providing valuable insights for maintenance and repair strategies.

Assessing the buckling strength of corroded steel structural members is crucial, and this is typically done by determining the minimum thickness ratio. Buckling strength tests were conducted on steel specimens, and the results were used to validate the predictions made using Finite Element Method (FEM)[30-33]. This approach enables the evaluation of residual strength in complex structures, providing valuable insights for maintenance and repair strategies. By combining experimental testing and numerical modelling, engineers can accurately assess the buckling strength of corroded steel members and ensure the safety and integrity of structures.

Corrosion damage significantly impacts the performance of steel structures, making corrosion control crucial for both existing and new structures. This study[34] aimed to prevent corrosion by retrofitting corroded angle sections with CFRP composites and epoxy adhesives. The specimens were corroded using the galvanostatic method and alternate wetting and drying in 3.5% NaCl solution. After retrofitting, the specimens were subjected to compression tests to assess their strength. Numerical validation was performed using ABAQUS software. The results showed a significant 11.8% improvement in strength for retrofitted specimens compared to corroded specimens without retrofitting, demonstrating the

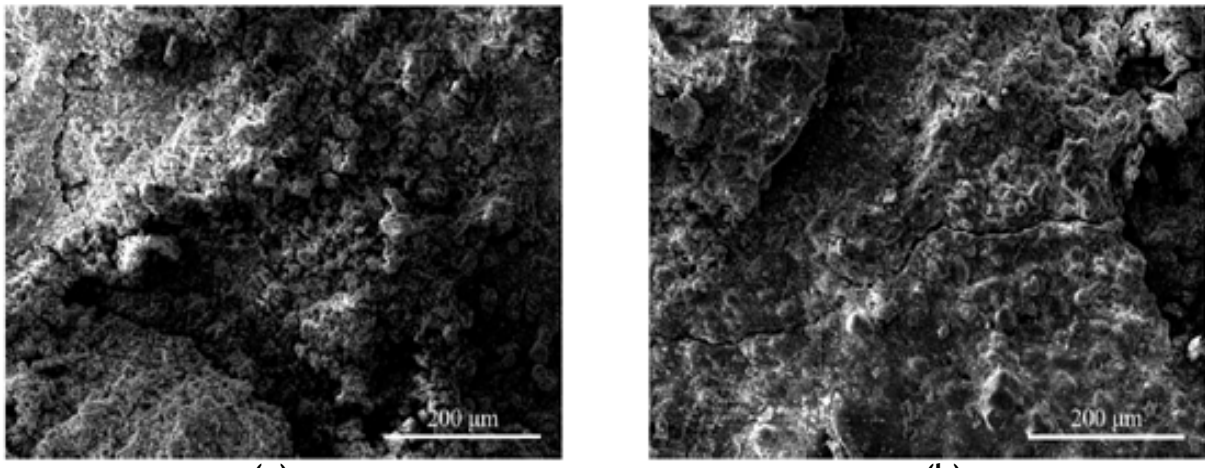


Figure 5. Micromorphology of the rust layer after 84 months of atmospheric exposure[38].

effectiveness of CFRP retrofitting in restoring strength to corroded structures.

As steel is used in aggressive environments, consistent renovation of corroded steel is uneconomical. Loss of strength in a steel section is determined by yield strength. The stress-strain characteristics for both angular and tubular coupons were used for the analyses and verified with the experimental values. Numerical simulation was performed based on the FEM in which corroded coupons from the experiment were extracted and simulated using the discretisation technique. Later compared and validated with experimental results[35].

When designing critical structural systems like ships, offshore platforms, pipelines, and pressure vessels, two key criteria - strength capacity and integrity - must be considered concerning localized corrosion and pitting corrosion. To perform reliability analysis, accurate engineering models are crucial for forecasting corroded material loss and maximum pitting depth. Recently, new probability-based models for both localized and pitting corrosion have been proposed and validated against a comprehensive dataset[36], providing a robust tool for predicting corrosion behaviour and ensuring the safety and reliability of these critical structures

Corrosion of steel reinforcement is recognised as the most important durability issue in reinforced concrete design. Corrosion in reinforcement is due to chloride ingress in concrete or due to the de-passivation of the protective thin oxide film of steel through the action of carbon dioxide from the atmosphere. In the present study[37] mechanical properties and pit depth are evaluated on steel bars embedded in concrete, directly exposed and immersed in a salt spray chamber. A tension test was performed and it was observed that salt spray steel bars produced moderate loss of strength and reduction of ductility. An increase in the loss was observed when steel bars were embedded in concrete and it produced severe pitting corrosion in terms of depth of pitting compared to steel samples directly exposed to the same corrosive medium for the same mass loss.

Wu H. *et al.,*[38], investigated the corrosion behaviour of Q235 steel exposed to an urban industrial atmosphere for seven years, focusing on mass loss for corrosion dynamics analysis. Rust layers were characterized using SEM (Figure 5), EDS, and XRD. The corrosion rate follows a two-stage power function law, indicating short-term results may not fully reflect long-term performance. Rust layers transition from loose and flat to compact, with phases like α-FeOOH, β-FeOOH, Fe_3O_4, and γ-Fe_2O_3. Initially, corrosion products are mainly α-FeOOH, followed by β-FeOOH and Fe_3O_4/γ-Fe_2O_3. Corrosion is driven by SO_2 and Fe_3O_4/γ-Fe_2O_3, shifting from acid cycle reactions in early years to oxygen-absorbing mechanisms after five years.

4.2 Numerical Modeling and Simulation

Shenghui Zeng *et al.,*[39] investigated the simulation of corroded steel surface morphology to improve

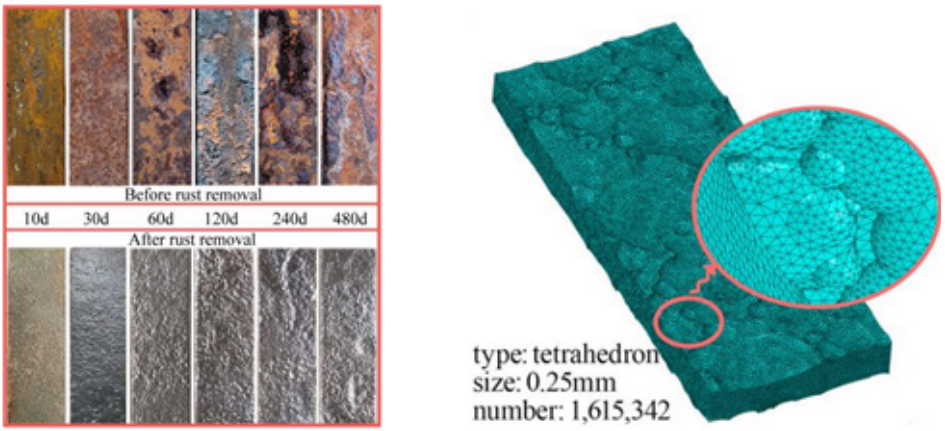


Figure 6. Study of steel corrosion **(a)** Experimental **(b)** Numerical (FEM model).[39]

modelling precision through accelerated corrosion tests. They examined six sets of corroded specimens, analyzing pitting characteristics such as depth, width, and diameter–depth ratio, which exhibited a log-normal distribution. To replicate the corroded surface, they developed a random pitting model using ABAQUS (Figure 6). Additionally, they introduced a Rough Surface Meshing Method (RSMM) to enhance the element quality in the Finite Element Analysis (FEA) model. By employing hexahedron elements, the FEA model accurately predicted the mechanical behaviour of corroded steel beams, closely matching experimental data. This approach provides valuable insights for further research on the mechanical performance of corroded steel structures

5.0 Conclusion

Corrosion represents a significant challenge to the longevity and safety of steel structures across various industries, including construction and automotive sectors. As steel remains a vital material in modern engineering due to its high strength-to-weight ratio, the understanding of corrosion mechanisms becomes increasingly important. Various forms of corrosion, such as uniform corrosion, localized corrosion, and stress corrosion cracking, can severely compromise the integrity of steel components. This necessitates the development of effective corrosion prevention strategies, including advanced coatings and protective measures. Recent advances in numerical and experimental studies have provided valuable insights into the assessment and prediction of corrosion-related damage, facilitating timely maintenance and repair strategies. As the industry continues to evolve, a proactive approach towards corrosion management, informed by accurate modelling and advanced materials, will be essential for ensuring the durability and sustainability of steel structures in a changing environment. Ultimately, ongoing research and collaboration among engineers, materials scientists, and industry stakeholders are crucial for enhancing our understanding of corrosion processes and developing robust solutions to mitigate their impact.

6.0 References

1. Khan K, Chen Z, Liu J, Javed K. State-of-the-art on technological developments and adaptability of prefabricated industrial steel buildings. Appl Sci. 2023; 13(2):685. https://doi.org/10.3390/app13020685
2. Quintana P, Veleva L, Cauich W, Pomes R, Peña JL. Study of the composition and morphology of initial stages of corrosion products formed on Zn plates exposed to the atmosphere of southeast Mexico. Appl Surf Sci. 1996; 99(4):325-34. https://doi.org/10.1016/0169-4332(96)00597-1
3. Di Sarno L, Majidian A, Karagiannakis G. The effect of atmospheric corrosion on steel structures: A state-of-the-art and case-study. Buildings. 2021; 11(12):571. https://doi.org/10.3390/buildings11120571
4. Guo H, Zhou X, Liu Z. Advanced Lightweight Structural Materials for Automobiles: Properties, Manipulation, and Perspective. Sci Adv Mater. 2024; 16(5):563-80. https://doi.org/10.1166/sam.2024.4686

5. Ali M, Ul-Hamid A, Khan T, Bake A, Butt H, Bamidele OE, Saeed A. Corrosion-related failures in heat exchangers. Corros Rev. 2021; 39(6):519-46. https://doi.org/10.1515/corrrev-2020-0073
6. Li CQ, Yang W. Steel corrosion and degradation of its mechanical properties. CRC Press; 2021. https://doi.org/10.1201/9781003119791
7. Dudi L, Krishnan S, Bishnoi S. Numerical modelling for predicting service life of reinforced concrete structures exposed to chloride. J Build Eng. 2023; 79:107867. https://doi.org/10.1016/j.jobe.2023.107867
8. Jones DA. Principles and prevention. Corrosion. 1996; 2:168.
9. Kruger J, Revie RW. Uhlig's Corrosion Handbook. Cost of metallic corrosion, Edited by RW Revie. Ney Jersy: Willey; 2011. p. 15. https://doi.org/10.1002/9780470872864.ch2 PMid:21332911
10. Fontana MG, Greene ND. Corrosion Engineering; 1967.
11. Revie RW. Corrosion and corrosion control: An introduction to corrosion science and engineering. John Wiley & Sons; 2008. https://doi.org/10.1002/9780470277270
12. Zhang XG. Galvanic corrosion. Uhlig's Corrosion Handbook. 2011; 51:123. https://doi.org/10.1002/9780470872864.ch10
13. Jones MC. Corrosion prevention. corrosion processes: sensing, monitoring, data analytics, prevention/protection, diagnosis/prognosis and maintenance strategies; 2020. p. 105-17. https://doi.org/10.1007/978-3-030-32831-3_4
14. Avance V, Clark B, Agnew L, Friedersdorf F. Predictive coating condition model for coating lifetime under environmental stressors. InAMPP CORROSION 2022 Mar 6; 2022. p. D021S008R009.
15. Bijapur K, Molahalli V, Shetty A, Toghan A, De Padova P, Hegde G. Recent trends and progress in corrosion inhibitors and electrochemical evaluation. Appl Sci. 2023; 13(18):10107. https://doi.org/10.3390/app131810107
16. Roberge P. Corrosion engineering: Principles and practice. Hoboken: Wiley; 2008. p. 604–608.
17. Society for Protective Coatings (SSPC). Aerospace engineering coating application training, Unit 6. SSPC; p. 1–3.
18. Roberge P. Handbook of corrosion engineering. 2nd ed. New York: McGraw Hill; 2012. p. 791.
19. Singh R, Gupta T, Sharma S. Graphene-based coatings for corrosion prevention. Journal of Coating Technology and Research. 2023.
20. Zhang S, Li H, Wang Y. Nanostructured materials for corrosion protection: A review. Progress in Organic Coatings. 2022; 167:106867.
21. Smith K, Brown A, Taylor R. Self-healing coatings for anti-corrosion applications. Mater Today. 2021; 24(7):45–52.
22. Wong J, Chan P, Lee M. Multifunctional coatings for industrial applications. Surf Coat Tech. 2022; 426:127805.
23. Li D, Zhou F, Zhang H. Superhydrophobic coatings inspired by nature. Adv Mater Interfaces. 2021; 8(13):2100213.
24. Kumar R, Sharma S, Singh A. Green corrosion inhibitors for sustainable solutions. J Mol Liq. 2022; 350:118569.
25. Chen M, Wu Z, Liang Y. Laser surface modification for corrosion resistance. J Alloys Compd. 2023; 941:168852.
26. Gupta A, Patel V, Mehta S. Hybrid epoxy-silica coatings for marine environments. J Mater Sci. 2022; 57:15327–38.
27. Johnson T, Parker G, White D. Composite materials for corrosion prevention in aerospace. Advanced Engineering Materials. 2023; 25(1):2200834.
28. Appuhamy JMRS, Ohga M, Kaita T, Fujii K, Dissanayake PBR. Development of analytical method for predicting residual mechanical properties of corroded steel plates. Int J Corros. 2011; 2011:385083. https://doi.org/10.1155/2011/385083
29. Sandamali WKN, Wijesena HP, Appuhamy JMRS. Prediction of residual buckling strength in corroded steel bridge members. In: Proceedings of the 6th International Conference on Structural Engineering and Construction Management, Kandy, Sri Lanka; 2015.
30. Appuhamy JMRS, Kaita T, Ohga M, Fujii K. Analytical study on significance of corroded surface measurement on residual strength prediction. Procedia Engineering. 2011; 14:2260–8. https://doi.org/10.1016/j.proeng.2011.07.285
31. Appuhamy JMRS, Kaita T, Ohga M, Fujii K. Prediction of residual strength of corroded tensile steel plates. International Journal of Steel Structures. 2011; 11:65–79. https://doi.org/10.1007/S13296-011-1006-6
32. Appuhamy JMRS, Ohga M, Dissanayake PBR, Wijesundara KK. Development of brisk finite element analytical method of predicting tensile strength reduction due to corrosion. In: SAITAM Research Symposium on Engineering Advancements (SAITAM-RSEA); 2012.
33. Aparna B, Vikraman R, Cinitha A, Umesha PK, Sakaria E. Compressive strength of uniformly corroded steel angle members retrofitted with CFRP. International Journal of

Emerging Technology and Advanced Engineering. 2014; 4(8):2250–2459.
34. John S, BanuPriya C, PreethyDharanya Y, Muthulakshmi M, Suresh R, Kumar MSD, *et al.* Numerical investigation on corroded and uncorroded structural steel coupons. Indian Journal of Science and Technology. 2016; 9(16):0974–6846. https://doi.org/10.17485/ijst/2016/v9i16/92241
35. Melchers RE. The effect of corrosion on the structural reliability of steel offshore structures. Corrosion Science. 2005; 47:2391–410. https://doi.org/10.1016/j.corsci.2005.04.004
36. Apostolopoulos CA, Demis S, Papadakis VG. Chloride-induced corrosion of steel reinforcement: mechanical performance and pit depth analysis. Constr Build Mater. 2013; 38:139–46. https://doi.org/10.1016/j.conbuildmat.2012.07.087
37. Sarveswaran V, Smith JW. Structural assessment of corrosion-damaged steel beams using minimum capacity curves. Struct Eng. 1999; 77(14):17–23.
38. Wu H, Luo Y, Zhou G. The evolution of the corrosion mechanism of structural steel exposed to the urban industrial atmosphere for seven years. Appl Sci. 2023; 13(7):4500. https://doi.org/10.3390/app13074500
39. Zeng S, Gu S, Ren S, Gu Y, Kong C, Yang L. A modeling method for finite element analysis of corroded steel structures with random pitting damage. Buildings. 2022; 12(11):1793. https://doi.org/10.3390/buildings12111793