

The Behavior of Corroded Reinforced Concrete Beams under External Loads: A Literature Review

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ABSTRACT

The phenomenon of Reinforced Concrete (RC) corrosion refers to the deterioration of metal and specifically steel, due to the chemical, electrochemical, and electrolytic processes occurring within the concrete surface. This type of corrosion leads to major weaknesses. Initially, early bar failure induces a decrease in the reinforcement's ductility and cross-sectional area. Secondly, the expansion of the corrosion products reduces the total load-bearing capacity of the RC beams by generating concrete cracking, degradation of the steel-concrete connection, and an impact on the bending stiffness of the RC members. This study aims to review and analyze the effects of corrosion on the structural behavior of over forty corroded RC beams under external loads. It aims to identify the main factors of corrosion, evaluate prevention techniques, and provide alternatives to enhance the durability and performance of corroded RC structures.

Keywords-shear strength; corroded RC beams; corrosion period; causes of corrosion; corrosion evaluation; structural behavior; failure modes; corrosion prevention; durability; rehabilitation techniques; bond strength; flexural capacity; service life

I. INTRODUCTION

Concrete is a durable material used to embed steel due to its ability to protect the latter, and allows it to function effectively as reinforcement. When chloride ions from seawater or de-icing salts penetrate the concrete through pores and cracks and reach the surface of the steel bars, corrosion occurs [1]. The presence of carbon dioxide and chloride ions into the concrete structures and the steel surfaces within them, along with air, is considered the primary cause of corrosion in reinforced steel [2].

Chloride intrusion occurs when its ions from internal and external sources, typically found in cement, aggregates, water, or admixtures, seep into the mortar or concrete. Severe degradation occurs if the chloride concentration rises over a specific threshold. When the steel corrodes, oxides or rust are created and occupy greater volume compared to uncorroded steel. This volume expansion, caused by the subsequent

ettringite and gypsum development, speeds up the degradation process by creating internal stress leading to concrete fractures and spall. Subsequently, sulfate ions alone degrade concrete. However, the simultaneous presence of sulfate and chloride ions reduces the expansive properties associated with the formation of secondary ettringite and gypsum. This reduction can be attributed to either a smaller concentration of C_3A and Ca^{+2} , which readily react with the chloride ions to yield soluble calcium chloride and chloroaluminate complexes, or an increase in the solubility of gypsum and ettringite due to the decreased pH induced by the Cl^- ions [3, 4]. The degree of corrosion is one of the primary factors used to forecast the service life of corroding RC buildings. The quantity of steel dissolving and generating oxides can be measured, with varying degrees of accuracy. Equations (1) and (2) are utilized to measure the electric current produced by the anodic reaction [5].



And consumed by cathodic reaction:



II. THE OCCURRENCE OF CORROSION

Various inorganic and organic acids, such as sulfuric, nitric, hydrochloric, phosphoric, acetic, and lactic, can damage concrete [6]. The corrosion begins when these elements enter the concrete and encounter the steel reinforcement. The anodic dissolution of iron and often the cathodic reduction of oxygen are two electrochemical processes that contribute to the steel corrosion in concrete. In addition, a decrease of protons is observed according to the pH and oxygen availability on the steel surface. The electrons must be transferred by an electrical connection between the anode and the cathode. Finally, the ions in the solution must be transferred via an electrolytic environment [7]. Ferrous ions are produced at the anode and hydroxide ions at the cathode as a result of electrons travelling from the anodic to the cathodic zone. This eventually may result in a distinction between the reinforcement's anodic and cathodic regions near the surface, producing rust as a byproduct [8]. On the other hand, the expansion of rust around the steel creates internal pressure, cracking the concrete around it. When additional pressure is applied, these cracks move closer to the concrete's surface, allowing more CO₂ and chloride to enter, and thus accelerating the corrosion process. Corrosion is responsible for about 90% of the damage to RC structures [8, 9].

While numerous studies have explored the behavior of corroded RC beams under external loads, certain critical aspects remain underexplored. First, the relationship between the degree of corrosion and the transition of the failure modes from flexural to shear have not been analyzed across different corrosion levels. Additionally, there is limited attention to high-strength concrete beams. Furthermore, prior studies have measured the load and deflection responses, without providing detailed insights into the stress and strain distributions within the corroded beams. The effects of the sulfate attack, either independently or in combination with the chloride attack, also warrant further investigation. By synthesizing and critically analyzing the findings from 43 specimens reported across nine key studies, this review aims to highlight these gaps and offer new perspectives and directions for future research.

III. CAUSES OF CORROSION IN RC STRUCTURES

The most common causes of corrosion of concrete buildings are salt corrosion, (sulfate and sea water), acid corrosion (including carbonation, alkali-silica reaction, efflorescence), and frost damage. In industrial environments there are a few other reasons that complement the corrosion process. These include corrosion by certain chemical or biological agents, abrasion (cavitation and erosion), and high temperature corrosion [10]. Groundwater may damage the concrete constructions. Sulfuric acid in groundwater can occur naturally or as a result of the chemical waste from industrial operations, which is released into the ground. Only sulfuric acid is likely to be present in natural groundwater due to the oxidation of sulfide minerals, like marcasite and pyrites [11]. Moreover, in

manufacturing environments, higher amounts of sulfuric acid can damage concrete through leaks and unpredictable spills that range from a continuous, long-term drip to an abrupt, brief dousing [12].

IV. FACTORS INFLUENCING THE CORROSION OF THE RC STRUCTURES

The development of corrosion in RC structures is significantly influenced by:

- The quality of concrete: The rate of corrosion in concrete increases with its porosity. Therefore, dense concrete, or high strength concrete, is largely immune to and typically resists the corrosion of the embedded steel [8].
- The cover thickness of concrete reinforcement: The degree of protection against different climatic and other environmental variables increases with the cover thickness [8].
- The condition of reinforcement: After the concrete placement, the corrosive action on the reinforcement is accelerated if salt is present or if corrosion is already present. The pace at which the steel reinforcement corrodes is influenced by its surface state when concrete is placed [8].
- The effect of high thermal stress: Cracks may form in concrete due to high thermal stress. Corrosion begins when environmental chemicals eventually harm concrete buildings that have cracks in them [8].
- The freezing and thawing conditions: In cold climates, the moisture in concrete's pores freezes. The ice development leads to volumetric expansion, raising the internal pressure of the surrounding concrete mass. The result is the formation of concrete cracks causing reinforcement corrosion [8].
- The chloride corrosion: Corrosion initiated by chloride depends on the kind of aggregate or water used in the original concrete composition. Additionally, there is a considerable quantity of chloride in admixtures that can be used in the mixing of concrete [13].
- The moisture and oxygen availability at the rebar level [13].
- The carbonation and entry of acidic gaseous pollutants to rebar level [13].

V. EFFECTS OF CORROSION IN RC STRUCTURES

The properties of RC structures are impacted by the reinforcement corrosion. The results of corrosion on the RC structures are [14-18]:

- The reduction in the structural element section thickness.
- Deterioration of the water bodies' metal surfaces.
- Metal surfaces decay, reduced area of tensile bars, and crack visibility.
- Reduced bond strength between the bars and concrete, especially after the formation of longitudinal cracks along

the bars, which affects the strength and durability of the structures.

VI. METHODS OF CORROSION PREVENTION

The methods utilized to prevent corrosion are [12]:

- Corrosion inhibitors: Chemical compounds that are added to concrete or applied externally to reduce or delay the corrosion of embedded steel reinforcement.
- Steel coatings: Protective layers, such as epoxy or galvanization, applied to the steel surfaces to act as a physical barrier against moisture or chlorides.
- Cement coating: Application of cement-based materials on the concrete surfaces to improve impermeability and provide ingress protection from harmful substances.
- Fiber Reinforced Polymer (FRP) materials: Replacing or supplementing traditional steel reinforcement with corrosion-resistant FRP materials.
- Metallic connections to wrap grout: To improve the flexural strength of the concrete beams and provide added protection against corrosion.
- Carbon FRP (CFRP) sheets on damaged members: Externally bonding CFRP sheets to restore or enhance the load-bearing capacity of corroded or damaged concrete elements.
- Sacrificial cathodic protective layer: Applying a layer or installing sacrificial anodes that corrode preferentially, thereby protecting the primary steel reinforcement from corrosion.

VII. CORROSION TYPES

Corrosion may occur in different configurations [6].

- Uniform corrosion: Defined as an even attack on a material's surface affecting most of its surface. It occurs primarily due to uniform exposure to a corrosive environment, such as moisture, oxygen, and chlorides, resulting in a consistent electrochemical reaction over the surface.
- Pitting corrosion: Holes gradually develop on the metal surface caused by the breakdown of protective passive films due to the presence of aggressive anions.
- Galvanic corrosion: This occurs when two dissimilar metals are electrically connected in the presence of an electrolyte. The difference in the electrode potential causes the more anodic metal to corrode preferentially. For example, using steel screws to fasten copper plates leads to galvanic corrosion because of their different electrochemical potential.
- Crevice corrosion: Localized corrosion that occurs in crevices where the access to oxygen is restricted, such as at joints, gaskets, or under deposits. The lack of oxygen leads to differential aeration, resulting in an anodic reaction inside the crevice, while the exterior remains cathodic, driving corrosion.

- Selective dissolution: Occurs when one component of an alloy is preferentially leached out due to chemical instability in the corrosive environment. This can result in the presence of aggressive ions or environmental conditions that selectively attack certain phases.

VIII. CORROSION EVALUATION

The corrosion levels of reinforcements were assessed through the mass loss of reinforcements and cross-section area loss techniques [10]. The cross-sectional area loss of reinforcements is determined by:

$$\text{Section area loss} = \frac{F - F_{min}}{F} \times 100 \quad (3)$$

where F and F_{min} are the cross-section areas of reinforcements before and after the corrosion, respectively.

The inhibitor's efficiency based on the weight loss, or a decrease in corrosion can be calculated by:

$$\text{Weight loss (\%)} = \frac{W_1 - W_2}{W_1} \times 100 \quad (4)$$

where W_1 is the initial weight of the rebar and W_2 is the weight rebar after the removal of the corrosion products.

IX. CONCLUSIONS

The experimental results of the max load and the deflection of the reference and corroded Reinforced Concrete (RC) beams are summarized in Table I. Table I displays the beam size (width \times effective depth \times length), the concrete compressive strength (F_{cu}), the ultimate failure load (P_u), and the deflection at ultimate failure load (Δ_u). Based on the reviewed literature, the following conclusions are drawn:

- To delay the corrosion initiation, the use of high-strength dense concrete with an adequate cover thickness must be prioritized.
- The implementation of routine inspection and monitoring for corrosion indicators in existing structures, particularly in marine environments or where de-icing salts are used.
- In new construction or during retrofitting, corrosion-resistant reinforcement, such as epoxy-coated rebars or stainless steel, or protective techniques (Fiber Reinforced Polymer (FRP) wrapping, sacrificial anodes) must be adopted.
- To prolong the service life of aging RC beams, corrosion inhibitors must be applied judiciously in maintenance strategies.
- In design calculations and safety evaluations, flexural and shear capacity models should be adjusted to account for the observed reduction in the load-carrying capacity and ductility due to corrosion.

The following research topics should be addressed in future studies.

- Conduction of systematic investigations into the bond performance between the corroded reinforcement and concrete.

- Exploration of the combined effects of chloride and sulfate attack, as this interaction is under-researched.
- Investigation of the behavior of corroded beams made with high-strength or fiber-RCs to expand the current knowledge beyond normal-strength concrete.
- Assessment of continuous beams under corrosion conditions, as most current studies focus on simply supported beams.
- Performance of advanced stress-strain analysis of corroded beams under external loads, not only load-deflection measurements.
- Investigation of the effects of higher chloride concentrations (>5%) to understand extreme exposure scenarios.
- Development and validation of practical guidelines and predictive models that engineers can use for assessing the residual capacity of the corroded beams in the field.

TABLE I. EXPERIMENTAL RESULTS OF MAX LOAD AND DEFLECTION OF REFERENCE CORRODED RC BEAMS

Reference	Beam ID	Beam size (mm)	F_{cu} (MPa)	Mass loss (%)	Chloride content (%)	Duration (days) ^a	P_u (kN) ^d	Δ_u (mm) ^e	Failure mode
[1]	N-0	100×150×1200	35	-	-	-	52	4.2	Shear
	N-10	100×150×1200	35	10.00	2	100	46	5.3	Spalling of concrete
	N-15	100×150×1200	35	15.00	2	150	42	5.6	Spalling of concrete
[7]	Beam-2	100×150×1800	60	-	-	-	64	3.8	Shear
	Beam-1	100×150×1800	60	5.00	Corroded Steel	-	31	6.1	Brittle shear
[9]	BL 0-0	120×200×1700	30	-	-	-	52	5.3	Shear
	BL 0-1	120×200×1700	30	1.98	5	5	49	5.5	Longitudinal cracks
	BL 0-2	120×200×1700	30	4.62	5	10	45	6.0	Concrete crushing
	BL 0-3	120×200×1700	30	8.78	5	20	42	7.0	Fracture of tensile reinforcements
[10]	B-0	150×200×2300	25	-	0	-	28	5.0	Shear
	B-20	150×200×2300	25	-	20	-	20	6.5	Shear
	B-40	150×200×2300	25	-	40	-	19	7.0	Shear
[11]	Ref. 1	150×200×1200	41	-	-	-	82	37.0	Flexural
	C 5	150×200×1200	41	2.5	5	5	80	33.6	Flexural
	C 10	150×200×1200	41	3.0	5	10	73	27.9	Flexural
	C 20	150×200×1200	41	8.5	5	20	69	23.4	Flexural
[12]	Regular	150×250×2000	42	-	-	-	92.0	9.46	Flexural
	Corroded	150×250×2000	42	-	-	-	76.5	5.88	Flexural
[8]	B0	120×200×1500	30	-	-	-	104.0	4.0	Flexural
	B1	120×200×1500	30	2	5	1	97.1	4.2	Flexural
	B2	120×200×1500	30	4	5	3	94.1	4.2	Flexural
	B3	120×200×1500	30	6	5	4	96.0	4.3	Flexural
	B4	120×200×1500	30	8	5	5	95.7	4.4	Flexural
	B5	120×200×1500	30	10	5	6	89.2	4.4	Flexural
	B6	120×200×1500	30	12	5	7	88.7	4.5	Flexural
	B7	120×200×1500	30	14	5	8	83.3	4.5	Flexural
	B8	120×200×1500	30	16	5	9	80.6	4.5	Flexural
	B9	120×200×1500	30	18	5	10	76.27	5.0	Flexural
B10	120×200×1500	30	20	5	11	54.6	5.0	Flexural	
[13]	C0	100×150×1000	39	-	-	-	22.8	3.4	Flexural
	C1	100×150×1000	39	-	3.5	1	22.7	4.5	Flexural
	C2	100×150×1000	39	-	3.5	2	21.0	3.4	Flexural
	C3	100×150×1000	39	-	3.5	3	23.6	4.7	Flexural
	C4	100×150×1000	39	-	3.5	5	23.1	4.5	Flexural
	C5	100×150×1000	39	-	3.5	7	22.4	5.3	Flexural
	C6	100×150×1000	39	-	3.5	14	21.3	4.0	Shear
	C7	100×150×1000	39	-	3.5	21	19.6	4.5	Shear
	C8	100×150×1000	39	-	3.5	28	20.8	5.1	Shear
C9	100×150×1000	39	-	3.5	35	17.4	4.6	Shear	
[14]	B1	200×300×3000	28	-	-	-	187.5	23.12	Strand slip
	B2	200×300×3000	28	7.0	3	2	183.3	26.55	Concrete crushing
	B3	200×300×3000	28	7.5	3	3	182.9	22.87	Strand broken
	B4	200×300×3000	28	9.0	3	7	181.1	23.69	Strand broken

a. Duration of samples' exposure to NaCl solution

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