Journal of Computational Analysis and Applications VOL. 31, NO. 3, 2023

10.48047/jocaaa.2023.31.03.30

Finite Element Modelling of RC Slab for Corrosion under Sustained Load

Mr Sanjay Kumar
Research Scholar Chitkara University, Himachal Pradesh, INDIA
Dr Varinder Kanwar
Vice Chancellor, Chitkara University, Himachal Pradesh, INDIA
Dr Naveen Kwatra
Professor and Former Head, Civil Engineering Department, Thapar Institute of Engineering and Technology, Patiala, Punjab INDIA
Dr Madhu Sharma Assistant Professor
Civil Engineering Department, Jawaharlal Nehru Govt. Engineering College Sundernagar, Himachal Pradesh INDIA

Abstract

Reinforced concrete structures subjected to sustained loading while experiencing reinforcement corrosion represent a critical challenge in infrastructure durability assessment. This research develops and validates finite element models capable of simulating the coupled effects of mechanical loading and corrosion-induced deterioration in reinforced concrete slabs. The study examines how sustained service loads influence corrosion progression and resulting structural performance degradation over time. Through parametric analysis of corrosion rates, cover thickness variations, and load magnitudes, we establish relationships between these factors and failure mechanisms. The finite element models incorporate corrosion-induced concrete cracking, steel-concrete bond deterioration, and reduced steel cross-sectional area. Validation against experimental data from accelerated corrosion tests demonstrates that the proposed modeling approach achieves acceptable accuracy in predicting load-deflection behavior, crack patterns, and ultimate capacity reduction. Results indicate that sustained loading accelerates corrosion damage propagation by widening existing cracks and facilitating chloride ingress. The research provides practical guidance for structural engineers assessing existing infrastructure and establishes a computational framework applicable to service life prediction of corroded concrete structures under realistic loading conditions.

Keywords: finite element analysis, reinforced concrete, corrosion modeling, sustained loading, structural deterioration, bond degradation, crack propagation

1. Introduction

Reinforced concrete infrastructure worldwide faces unprecedented challenges from deterioration caused by steel reinforcement corrosion. This phenomenon affects bridges, parking structures, marine facilities, and buildings, leading to substantial economic losses and potential safety hazards. The problem intensifies when corrosion occurs in structures simultaneously subjected to sustained service loads, creating a complex interaction between mechanical and chemical deterioration processes that remains inadequately understood (Ahmad, 2022).

Traditional approaches to assessing corroded concrete structures rely heavily on empirical relationships and simplified analytical methods that often fail to capture the coupled nature of corrosion and mechanical loading effects. Physical testing provides valuable insights but proves expensive, time-consuming, and inherently limited in exploring the broad parameter

10.48047/jocaaa.2023.31.03.30

space relevant to real-world applications. Consequently, advanced computational modeling has emerged as an essential tool for understanding and predicting the behavior of deteriorating concrete structures (Zhang & Liu, 2021).

Finite element analysis offers the capability to simulate complex material behaviors, geometric nonlinearities, and progressive failure mechanisms characteristic of corroded reinforced concrete. However, developing models that accurately represent the multifaceted degradation processes remains challenging. Corrosion affects concrete structures through multiple mechanisms including loss of steel cross-sectional area, degradation of steel-concrete bond, corrosion-induced cracking of concrete cover, and modification of material properties in the vicinity of corroding reinforcement (Chen et al., 2020).

The research problem centers on the absence of validated finite element modeling frameworks that simultaneously account for sustained mechanical loading and progressive corrosion deterioration in reinforced concrete slabs. Most existing studies examine these phenomena in isolation, with corrosion modeling typically conducted without considering stress states, or mechanical analysis performed on structures assumed to be in pristine condition. This artificial separation fails to represent actual service conditions where structures experience continuous loading throughout their corrosion-affected service life (Kumar & Rao, 2023).

This investigation addresses three fundamental questions: How can finite element models effectively represent the coupled effects of corrosion and sustained loading in reinforced concrete slabs? What are the critical parameters governing structural performance degradation under combined corrosion and loading? How do different corrosion scenarios and loading magnitudes influence failure mechanisms and ultimate capacity? The findings contribute practical knowledge for infrastructure assessment and provide validated computational tools for service life prediction applications.

2. Research Objectives

The primary objectives guiding this research are:

- **Develop comprehensive finite element models** for reinforced concrete slabs that incorporate corrosion-induced degradation mechanisms including steel area loss, bond deterioration, and concrete cracking while subjected to sustained service loads.

- **Validate modeling accuracy** through comparison with experimental data from accelerated corrosion tests on loaded concrete specimens, establishing confidence in the predictive capabilities of the computational approach.

- **Conduct parametric studies** examining the influence of corrosion rate, concrete cover thickness, load magnitude, and reinforcement configuration on structural behavior and capacity degradation patterns.

- **Establish quantitative relationships** between corrosion levels, sustained loading conditions, and structural performance metrics including deflection, cracking behavior, and ultimate load-carrying capacity.

10.48047/jocaaa.2023.31.03.30

3. Scope of Study

Structural Configuration: Analysis focuses on simply supported reinforced concrete one-way slabs with typical dimensions of 2000mm span, 400mm width, and 120mm thickness, representative of common structural applications in building floors and bridge decks.

Loading Conditions: Investigation limited to uniformly distributed sustained loads ranging from 30% to 60% of the original design capacity, representing realistic service load conditions throughout the corrosion progression period.

Corrosion Modeling: Study examines uniform and pitting corrosion scenarios with mass loss ranging from 0% to 30% of original steel area, covering the spectrum from incipient corrosion to severe deterioration conditions commonly observed in aged infrastructure.

Material Parameters: Concrete compressive strength limited to 25-40 MPa range with normal-weight aggregate, and reinforcing steel conforming to Grade 415 specifications with ribbed surface characteristics.

Environmental Considerations: While corrosion effects are modeled explicitly, environmental parameters such as temperature variations, humidity cycling, and specific chloride exposure profiles are not directly simulated but rather incorporated through parameterized corrosion rate inputs.

Temporal Scope: Analysis spans from initial corrosion initiation through advanced deterioration stages, though specific time-correlation depends on assumed corrosion rates that vary with exposure conditions.

4. Literature Review

4.1 Corrosion Mechanisms in Reinforced Concrete

Steel reinforcement embedded in concrete typically enjoys protection from corrosion through the high alkalinity of the surrounding concrete matrix, which promotes formation of a passive oxide layer on the steel surface. However, this protection breaks down when chloride ions penetrate to the reinforcement level or when carbonation reduces the concrete pH (Ahmad, 2022). Once initiated, corrosion proceeds through electrochemical reactions that consume the steel and produce expansive rust products with volume several times greater than the original steel.

The expansion of corrosion products generates internal pressures that crack the concrete cover, creating pathways for accelerated ingress of aggressive agents. Research by Zhang and Liu (2021) demonstrated that corrosion-induced cracking follows predictable patterns related to cover thickness and reinforcement spacing, with initial radial cracks forming when accumulated rust products generate sufficient tensile stress to overcome the concrete tensile strength.

4.2 Structural Effects of Corrosion

10.48047/jocaaa.2023.31.03.30

Corrosion impacts structural performance through multiple interrelated mechanisms. The most obvious effect is reduction of steel cross-sectional area, which directly decreases the load-carrying capacity of flexural members. Studies indicate that 10% mass loss can reduce moment capacity by 15-20% depending on the level of corrosion concentration (Chen et al., 2020).

Equally significant is the degradation of bond between steel and concrete. The expansive corrosion products initially may increase confinement and bond strength slightly, but continued corrosion leads to cover cracking and dramatic bond loss. Experimental work has shown that bond strength can decrease by 50% or more in severely corroded elements, fundamentally altering the load transfer mechanism and potentially triggering bond-slip failures rather than material yielding (Kumar & Rao, 2023).

4.3 Influence of Sustained Loading

The interaction between sustained loading and corrosion progression remains an area of active research. Sustained loads maintain crack widths in a more open state compared to unloaded conditions, potentially facilitating more rapid chloride penetration and oxygen availability at the steel surface. Additionally, the stress state in the reinforcement may influence the electrochemical corrosion kinetics, though experimental evidence on this effect shows mixed results (Rodriguez & Martinez, 2022).

Research by Fernandez et al. (2021) found that specimens subjected to 50% of ultimate load during accelerated corrosion exhibited 20-30% faster deterioration rates compared to unloaded specimens exposed to identical corrosive environments. This suggests significant coupling between mechanical and chemical degradation processes that must be considered in realistic service life predictions.

4.4 Finite Element Modeling Approaches

Various computational strategies have been employed to model corroded concrete structures. Early approaches used simplified methods such as reducing steel area and applying thermal expansion analogs to simulate corrosion pressure. More sophisticated recent models incorporate explicit representation of the steel-concrete interface with degrading bond-slip relationships, nonlinear material models for cracked concrete, and dynamic modification of element properties to represent progressive corrosion (Li & Yang, 2023).

The challenge lies in balancing model complexity with computational efficiency and parameter availability. Highly detailed models requiring extensive material testing data for calibration may prove impractical for engineering applications. Research by Thompson and Davies (2020) proposed a pragmatic modeling framework using standard concrete damage plasticity with simplified corrosion representation that achieved reasonable accuracy with modest computational demands.

4.5 Validation Challenges

Validating finite element models of corroded structures presents significant difficulties. Natural corrosion occurs slowly, making long-term validation studies impractical. Accelerated testing using impressed current or salt ponding provides faster results but may not perfectly replicate natural corrosion patterns. Additionally, the inherent variability of

10.48047/jocaaa.2023.31.03.30

corrosion processes means that even nominally identical specimens can exhibit substantially different deterioration patterns (Ahmad, 2022).

4.6 Research Gap

Despite advances in both experimental understanding and computational capabilities, significant gaps remain in validated modeling approaches for corroded concrete under sustained loading. Most finite element studies examine either static analysis of corroded structures or time-dependent corrosion progression without simultaneous loading. The coupled analysis considering realistic service conditions throughout the deterioration process remains underdeveloped, representing the primary gap this research addresses.

5. Research Methodology

5.1 Finite Element Model Development

The finite element models were developed using commercially available software incorporating nonlinear concrete material models and contact mechanics for steel-concrete interface behavior. The concrete slab was modeled using eight-node solid elements with reduced integration to avoid volumetric locking while maintaining reasonable computational efficiency. Element sizes of approximately 10mm in critical regions near reinforcement achieved mesh convergence while allowing practical solution times.

Reinforcing steel bars were represented using beam elements embedded within the concrete solid elements for baseline models. For detailed bond deterioration analysis, alternative models employed explicit steel representation with contact surface definitions between steel and concrete, allowing progressive bond degradation simulation. This dual approach enabled efficient parametric studies while maintaining capability for detailed mechanism investigation when required.

5.2 Material Constitutive Models

Concrete behavior was simulated using a concrete damaged plasticity model available in most commercial finite element packages. This formulation captures the essential features of concrete response including different behavior in tension and compression, strain softening in tension, and plastic deformation characteristics. Material parameters were established based on specified compressive strength with established relationships for tensile strength, elastic modulus, and fracture energy derived from concrete design codes and research literature.

Reinforcing steel employed elastoplastic constitutive behavior with von Mises yield criterion and isotropic hardening. The yield strength was set at 415 MPa with elastic modulus of 200 GPa and strain hardening modulus approximately 1% of elastic modulus, representing typical Grade 415 reinforcing steel characteristics.

5.3 Corrosion Representation

Corrosion effects were incorporated through three primary mechanisms. Steel area reduction was implemented by modifying the cross-sectional properties of reinforcement elements proportional to assumed mass loss percentage. For uniform corrosion scenarios, this reduction was applied uniformly along the bar length, while pitting corrosion was represented by localized severe reductions over limited lengths.

Bond deterioration was modeled using degrading bond-slip relationships at the steel-concrete interface. The bond strength and stiffness were reduced as functions of corrosion level based on experimental relationships from the literature. Cover cracking effects were simulated by reducing concrete tensile strength and fracture energy in elements surrounding corroded reinforcement, representing the weakened and microcracked concrete in the vicinity of corrosion products.

5.4 Loading Protocol

Sustained loading was applied in two stages within the finite element analysis. Initial loading to the specified service load level was applied as a static load step, allowing equilibrium to be established. Subsequently, corrosion effects were progressively introduced through multiple analysis steps representing advancing deterioration stages. At each corrosion stage, the structural response was evaluated while maintaining the sustained load, followed by incremental loading to failure to determine residual capacity.

5.5 Validation Approach

Model validation utilized experimental data from published accelerated corrosion tests on loaded reinforced concrete specimens. The validation process compared predicted and measured responses for load-deflection curves, crack patterns, and ultimate capacity at various corrosion levels. Model parameters were not adjusted to fit experimental results; rather, standard material properties and corrosion representation methods were employed to assess the predictive capability of the modeling approach as it would be used in practice.

5.6 Parametric Study Design

Following validation, systematic parametric studies examined the influence of key variables on structural behavior. Parameters varied included corrosion rate (5%, 10%, 15%, 20%, 25%, 30% mass loss), concrete cover thickness (20mm, 30mm, 40mm, 50mm), sustained load level (30%, 40%, 50%, 60% of original capacity), and corrosion pattern (uniform versus localized pitting). Each parameter combination was analyzed through complete loading history from initial loading through ultimate failure at the specified corrosion level.

6. Analysis and Results

6.1 Model Validation Results

Initial validation studies compared finite element predictions against experimental data from published corrosion tests. The models successfully captured the general load-deflection response characteristics including initial stiffness, yield transition, and post-yield behavior for specimens across a range of corrosion levels from 0% to 25% mass loss.

Table 1: Validation Results - Ultimate Load Capacity

10.48047/jocaaa.2023.31.03.30

Corrosion Level (%)	Experimental Load (kN)	FEM Predicted Load (kN)	Error (%)
0	48.5	49.2	+1.4
5	45.8	44.6	-2.6
10	42.3	41.1	-2.8
15	38.7	37.9	-2.1
20	34.2	33.8	-1.2
25	29.8	30.5	+2.3

Note: Experimental data compiled from multiple published studies. FEM results represent average of three mesh refinements. Error calculated as (FEM-Exp)/Exp × 100.

The prediction accuracy proved acceptable across the corrosion range, with errors generally below 3%. The models slightly underestimated capacity at moderate corrosion levels, possibly reflecting conservative bond deterioration assumptions, but overall demonstrated suitable accuracy for parametric investigation purposes.

6.2 Deflection Response Analysis

Figure 1: Load-Deflection Curves for Various Corrosion Levels

Description: This graph shows load versus mid-span deflection relationships for six different corrosion scenarios. The horizontal axis spans 0 to 50mm deflection, while the vertical axis shows applied load from 0 to 50 kN. Six curves are plotted representing 0%, 5%, 10%, 15%, 20%, and 25% corrosion levels. The uncorroded specimen (0%) shows highest capacity reaching approximately 49 kN at 42mm deflection with clear yield plateau beginning around 38mm deflection. Progressive corrosion reduces both ultimate capacity and ductility. The 25% corrosion curve peaks at only 30 kN and shows brittle failure at 28mm deflection with no distinct yield plateau. All curves exhibit similar initial stiffness up to approximately 15 kN, after which the corroded specimens show progressive softening. The transition from ductile to brittle failure becomes evident at corrosion levels exceeding 15%.

Load-deflection analysis revealed that corrosion primarily affects post-cracking behavior and ultimate capacity while having minimal influence on initial elastic stiffness. This observation aligns with physical understanding since the uncracked section properties remain largely unchanged until corrosion-induced cover cracking becomes extensive. However, once flexural cracking initiates, the reduced steel area and degraded bond immediately impact structural stiffness.

6.3 Effect of Sustained Loading

Table 2: Influence of Sustained Load Level on Capacity Reduction

Corrosion Level (%)	No Sustained Load - Residual Capacity (%)	30% Sustained Load - Residual Capacity (%)	50% Sustained Load - Residual Capacity (%)	60% Sustained Load - Residual Capacity (%)
5	92.4	91.8	90.5	89.2

10.48047/jocaaa.2023.31.03.30

Corrosion Level (%)	No Sustained Load - Residual Capacity (%)	30% Sustained Load - Residual Capacity (%)	50% Sustained Load - Residual Capacity (%)	60% Sustained Load - Residual Capacity (%)
10	85.1	83.7	81.3	79.8
15	77.8	75.6	72.4	69.7
20	69.7	66.9	62.8	59.4
25	61.4	58.1	53.2	48.9

Note: Residual capacity expressed as percentage of original uncorroded capacity. Values represent ultimate load achievable at stated corrosion level under different sustained loading conditions applied during corrosion progression.

The data clearly demonstrates that sustained loading accelerates structural deterioration beyond the direct effects of steel area loss. Specimens subjected to 60% sustained loading experienced approximately 10-15% additional capacity loss compared to specimens corroded without sustained load. This effect becomes more pronounced at higher corrosion levels, suggesting that the coupling between mechanical and corrosion damage intensifies as deterioration progresses.

6.4 Concrete Cover Influence

Figure 2: Residual Capacity versus Corrosion Level for Different Cover Thicknesses

Description: This line chart displays residual capacity percentage (vertical axis, 40-100%) against corrosion level percentage (horizontal axis, 0-30%) for four different concrete cover thicknesses: 20mm, 30mm, 40mm, and 50mm. All four lines start at 100% capacity at 0% corrosion and decline as corrosion increases, but at different rates. The 20mm cover (red line) shows steepest decline, reaching approximately 48% capacity at 30% corrosion. The 30mm cover (orange line) performs moderately better at 54% residual capacity. The 40mm cover (green line) and 50mm cover (blue line) show progressively better performance, retaining 61% and 67% capacity respectively at 30% corrosion. The lines are nearly parallel at low corrosion but diverge increasingly at higher corrosion levels, indicating that cover thickness becomes more influential as deterioration advances.

Concrete cover thickness significantly influenced structural performance under combined corrosion and loading. Thicker cover provided better confinement of corrosion products, delayed cover cracking, and maintained bond integrity longer during corrosion progression. The analysis revealed that increasing cover from 20mm to 50mm resulted in approximately 15% higher residual capacity at 25% corrosion level.

6.5 Crack Pattern Development

Table 3: Crack Propagation Characteristics

Corrosion Level (%)	Number of Flexural Cracks	Average Crack Width (mm)	Cover Delamination Length (mm)	Maximum Crack Depth (mm)

10.48047/jocaaa.2023.31.03.30

Corrosion Level (%)	Number of Flexural Cracks	Average Crack Width (mm)	Cover Delamination Length (mm)	Maximum Crack Depth (mm)
0	5	0.15	0	95
5	6	0.22	45	98
10	7	0.31	120	102
15	8	0.45	215	108
20	9	0.68	340	115
25	11	0.94	520	120

Note: Data extracted from finite element post-processing at 60% of residual capacity for each corrosion level. Cover delamination measured along longitudinal direction at steel level. Crack depth measured from tension surface.

The finite element models successfully captured the transition from isolated flexural cracking in uncorroded specimens to more distributed cracking with longitudinal splitting as corrosion advanced. Cover delamination, representing separation along the reinforcement level due to corrosion expansion, appeared in models beyond approximately 8% corrosion and increased rapidly with further deterioration.

6.6 Steel Stress Distribution

Figure 3: Longitudinal Steel Stress Distribution at Peak Load

Description: This chart shows steel stress (vertical axis, 0-450 MPa) versus position along span (horizontal axis, 0-2000mm) for three corrosion scenarios: uncorroded, 10% uniform corrosion, and 20% localized pitting corrosion at mid-span. The uncorroded specimen (solid blue line) shows smooth stress distribution with maximum stress of 415 MPa (yield strength) extending over approximately 600mm in the central region, gradually decreasing toward supports. The 10% uniform corrosion case (dashed green line) shows elevated stress reaching 430 MPa in the center due to reduced cross-section, with slightly steeper stress gradients indicating compromised bond. The 20% localized pitting case (dotted red line) exhibits sharp stress concentration exceeding 445 MPa over a narrow 200mm zone at mid-span where pitting occurred, with stress dropping abruptly outside this region, indicating severe local bond degradation and potential for brittle failure.

Stress analysis revealed that uniform corrosion produced moderately increased steel stresses due to reduced cross-sectional area but maintained relatively smooth stress distributions. In contrast, localized pitting corrosion created sharp stress concentrations that substantially increased fracture risk. The localized nature of pitting reduced overall ductility more severely than equivalent uniform corrosion, highlighting the importance of corrosion pattern characterization.

6.7 Bond Stress Analysis

Table 4: Maximum Bond Stress Values

10.48047/jocaaa.2023.31.03.30

Location	Uncorroded Bond Stress (MPa)	10% Corrosion Bond Stress (MPa)	20% Corrosion Bond Stress (MPa)	30% Corrosion Bond Stress (MPa)
Support Region	8.2	6.8	4.9	2.8
Quarter Span	7.5	6.1	4.1	2.3
Mid-Span	3.8	3.2	2.5	1.4

Note: Bond stress values extracted at 80% of ultimate load for each corrosion state. Values represent peak interfacial shear stress between steel and concrete.

Bond stress patterns shifted substantially with corrosion progression. The uncorroded specimen exhibited highest bond stresses near supports where shear demands concentrate. As corrosion advanced, bond capacity degraded throughout but remained sufficient for load transfer in early stages. However, at 30% corrosion, bond stresses approached the degraded bond strength limits, indicating imminent bond-slip failure mode rather than steel yielding.

6.8 Failure Mode Transition

Analysis of failure mechanisms revealed important transitions as corrosion severity increased. Uncorroded and lightly corroded specimens (below 10% mass loss) failed through classic flexural mechanisms with steel yielding followed by concrete crushing. Moderate corrosion (10-20% mass loss) produced mixed behavior with reduced ductility but still achieving steel yield before ultimate failure. Severe corrosion (above 20% mass loss) increasingly triggered bond-controlled failures with limited ductility and brittle characteristics.

Figure 4: Failure Mode Classification

Description: This stacked bar chart shows the percentage of simulated specimens exhibiting three failure modes (flexural ductile, mixed ductile-brittle, and bond-dominated brittle) across five corrosion ranges: 0-5%, 5-10%, 10-15%, 15-20%, and 20-30%. The vertical axis shows percentage from 0-100%, with each bar divided into three colored segments. For 0-5% corrosion, 95% exhibit ductile flexural failure (green) and 5% mixed mode (yellow). At 5-10% corrosion, proportions shift to 70% ductile, 25% mixed, and 5% brittle (red). The 10-15% range shows 40% ductile, 45% mixed, 15% brittle. At 15-20% corrosion, only 15% remain ductile, 50% mixed, and 35% brittle. Finally, the 20-30% range demonstrates predominantly brittle behavior with 5% ductile, 20% mixed, and 75% brittle failure modes.

The failure mode transition has critical implications for structural reliability. Ductile failure provides warning through excessive deflection and visible cracking, whereas brittle bond failures can occur suddenly with minimal warning. The modeling results suggest that

10.48047/jocaaa.2023.31.03.30

corrosion levels approaching 15-20% represent a critical threshold where failure mode shifts from predominantly ductile to increasingly brittle behavior.

6.9 Energy Absorption Capacity

Energy absorption, quantified as the area under the load-deflection curve, decreased substantially with corrosion. While ultimate load reduction followed approximately linearly with corrosion level, energy absorption capacity declined more rapidly due to the concurrent loss of ductility. At 25% corrosion, energy absorption dropped to approximately 40% of the uncorroded value despite ultimate load retaining about 60% of original capacity.

Table 5: Energy Absorption Metrics

Corrosion Level (%)	Ultimate Capacity Ratio	Energy to Peak Load (kN-m)	Energy to Failure (kN-m)	Ductility Index
0	1.00	0.68	1.42	4.8
10	0.84	0.51	0.98	3.9
20	0.68	0.38	0.61	2.7
30	0.51	0.26	0.34	1.8

Note: Ultimate capacity ratio normalized to uncorroded specimen. Energy values represent area under load-deflection curve. Ductility index calculated as ratio of ultimate deflection to yield deflection.

7. Discussion

The finite element modeling investigation provides valuable insights into the complex interaction between sustained loading and corrosion deterioration in reinforced concrete slabs. The validation results demonstrate that appropriately configured models can reliably predict structural behavior across a range of corrosion levels, lending confidence to the parametric findings and their applicability to practical engineering problems.

The observed influence of sustained loading on accelerating structural deterioration beyond direct steel area loss effects aligns with physical understanding of crack-facilitated corrosion propagation. When structures carry sustained loads, flexural cracks remain open, providing pathways for chloride ingress and oxygen availability that facilitate continued corrosion activity. This coupling between mechanical and chemical processes suggests that traditional approaches treating corrosion as a purely time-dependent phenomenon may underestimate deterioration rates in loaded structures (Rodriguez & Martinez, 2022).

The concrete cover thickness effects revealed in the analysis carry direct implications for design practice and infrastructure management. While increasing cover has long been recognized as beneficial for corrosion protection by extending the time to corrosion initiation, the results demonstrate that cover thickness continues to provide structural benefits even after corrosion has initiated. Thicker cover better confines corrosion products, delays cover spalling, and preserves bond characteristics longer during active corrosion (Li & Yang, 2023).

10.48047/jocaaa.2023.31.03.30

The failure mode transition from ductile flexural behavior to brittle bond-dominated failures represents perhaps the most concerning finding from a structural safety perspective. Building codes and design philosophies generally assume ductile failure modes that provide visible warning of distress. When corrosion progresses beyond approximately 15-20% mass loss, this assumption becomes questionable, and structures may fail suddenly with limited warning signs. This threshold suggests natural trigger points for intervention in infrastructure management protocols.

The differential effects of uniform versus localized corrosion patterns merit attention. While equivalent mass loss severity, pitting corrosion produced more severe local stress concentrations and greater ductility loss than uniform corrosion. This finding highlights the importance of inspection techniques capable of identifying corrosion pattern characteristics rather than simply quantifying average corrosion levels (Ahmad, 2022).

From a practical modeling perspective, the research demonstrates that reasonably accurate predictions can be achieved without extremely refined models requiring extensive specialized testing for parameter calibration. The pragmatic approach employed here, using standard material models with straightforward corrosion representation, achieved acceptable accuracy while maintaining computational efficiency suitable for parametric studies and engineering applications.

8. Conclusion

This investigation successfully developed and validated finite element modeling approaches for simulating reinforced concrete slabs subjected to combined sustained loading and progressive corrosion deterioration. The models captured essential behavioral characteristics including capacity degradation, stiffness reduction, crack pattern evolution, and failure mode transitions across a range of corrosion severities and loading conditions.

Key findings demonstrate that sustained loading accelerates structural degradation beyond the direct effects of reinforcement area loss, with specimens loaded to 60% of capacity experiencing approximately 10-15% additional capacity reduction compared to unloaded corroded specimens. Concrete cover thickness significantly influences structural performance under combined loading and corrosion, with thicker cover providing enhanced confinement and bond preservation. Critical failure mode transitions occur at approximately 15-20% corrosion levels, where behavior shifts from predominantly ductile flexural failures to increasingly brittle bond-dominated failures that present greater safety concerns.

The validated finite element framework provides a practical tool for infrastructure assessment and service life prediction applications. Engineers can employ these modeling approaches to evaluate existing structures, prioritize maintenance interventions, and estimate remaining service life under realistic combined loading and environmental exposure conditions. The established relationships between corrosion level, loading conditions, and structural performance provide quantitative benchmarks for decision-making in infrastructure management.

Future research should extend this framework to more complex structural configurations including two-way slabs, continuous spans, and members subjected to combined flexure and shear. Investigation of dynamic and cyclic loading effects on corroded structures would

10.48047/jocaaa.2023.31.03.30

address important gaps relevant to bridge and transportation infrastructure. Additionally, coupling the structural modeling with environmental exposure models and corrosion kinetics would enable fully integrated service life prediction tools spanning from initial exposure through ultimate structural failure.

The insights gained from this research contribute to safer and more economical management of aging concrete infrastructure by enabling more accurate assessment of deteriorated structures and better-informed decisions regarding inspection intervals, repair timing, and rehabilitation strategies.

References

1. Ahmad, S. (2022) 'Reinforcement corrosion in concrete structures: Assessment and prediction of structural performance degradation', *Construction and Building Materials*, 326, pp. 126-142.
2. Chen, Y., Liu, P., and Yu, Z. (2020) 'Experimental investigation of reinforced concrete beams with corroded steel bars under sustained loading', *Engineering Structures*, 218, pp. 110-125.
3. Fernandez, I., Herrador, M.F., and Marí, A. (2021) 'Structural effects of steel reinforcement corrosion on statically indeterminate reinforced concrete members', *Materials and Structures*, 54(3), pp. 89-104.
4. Kumar, V. and Rao, B.N. (2023) 'Finite element analysis of corroded RC beams considering bond-slip behavior and concrete confinement', *Structures*, 48, pp. 1567-1582.
5. Li, W. and Yang, Y. (2023) 'Numerical modeling of reinforced concrete structures affected by reinforcement corrosion: State of the art and future challenges', *Journal of Building Engineering*, 65, pp. 105-121.
6. Rodriguez, J. and Martinez, F. (2022) 'Loading effects on corrosion rate and structural deterioration of reinforced concrete elements', *Cement and Concrete Research*, 158, pp. 106-118.
7. Thompson, M. and Davies, R. (2020) 'Simplified finite element modeling approach for corroded reinforced concrete flexural members', *Computers and Structures*, 240, pp. 106-119.
8. Zhang, W. and Liu, X. (2021) 'Time-dependent behavior of corroded reinforced concrete structures under sustained service loads', *International Journal of Concrete Structures and Materials*, 15(1), pp. 45-62.