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Pushover Analysis of Corroded RC Buildings by User-Defined Plastic Hinge Properties

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Abstract:
It is well known that a significant portion of architectural heritage worldwide comprises reinforced concrete residential buildings constructed before the 1980s. These structures were often built without adherence to specific seismic design standards and, in many cases, now exhibit poor structural conditions. A major contributing factor to the degradation of these buildings is corrosion, which adversely affects the mechanical properties of the steel reinforcement and consequently reduces the structural capacity of the buildings. This study aims to evaluate the impact of corrosion-induced damage on the seismic performance of existing reinforced concrete structures. To achieve this, a nonlinear analysis was conducted on a representative RC residential building. The effects of corrosion, including strength degradation and reduction in rebar cross-section were incorporated into the numerical modeling. The study explores how varying levels and scenarios of corrosion influence the pushover response of structures. Static pushover analyses were performed using SAP2000 software under multiple corrosion scenarios. Load-displacement curves obtained from these scenarios were compared with those of an uncorroded reference model. The results indicate that corrosion significantly compromises the building's lateral load-bearing capacity. Furthermore, the location and extent of corrosion were found to alter the structural collapse mechanisms.
Key Word: *Corrosion, RC building; Plastic hinge; Nonlinear analysis; Pushover analysis.*

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I. Introduction

Corrosion is a primary factor contributing to the degradation and damage of reinforced concrete (RC) infrastructure. The formation of rust and other corrosion products leads to the expansion of steel reinforcement. This expansion generates internal tensile stresses and microcracking within the surrounding concrete. Such effects result in various forms of structural damage, including spalling of the concrete cover, a decrease in the compressive strength of the concrete, diminished confinement effectiveness provided by transverse reinforcement, and potential failure of the longitudinal steel bars [1]-[3]. Despite numerous updates to standards and technical codes over the years, the use of low-strength concrete and insufficient concrete cover thickness remains prevalent [4]. As a result, many reinforced concrete (RC) structures, such as bridges and buildings, are in poor condition due to aging, even in areas not prone to seismic activity [1],[5]. Furthermore, inspection and maintenance processes used to assess the serviceability of these structures are frequently insufficient or missed. Studies suggest that over 10% of RC bridges in the United States are structurally deficient and functionally obsolete, demanding a $2.5 trillion investment to restore them to acceptable conditions. Additionally, a survey estimates that the direct cost related to corrosion prevention and repair for RC structures in the U.S. amounts to $25 billion [6]-[9].

Several experimental studies have been undertaken on the seismic and non-seismic performance of structural components exposed to corrosion, including beams [10]-[17], columns [18]-[19], and steel reinforcements. Research on the performance of entirely corroded RC structures has also been conducted. Khan et al. [11] studied the behavior of 26-year-old RC beams subjected to natural corrosion and discovered significant losses in load-bearing capacity, stiffness, and deflection. Coronelli and Gambarova [20] conducted numerical analysis to predict the performance of corroded RC beams, noting stiffness degradation, strength loss in bending and shear, and bond failure. Rodriguez et al. [21] found that corrosion negatively impacts RC columns, reducing their load-bearing capacity and causing premature failure of rebars due to damaged concrete covers. Xia et al. [12] performed experimental work on RC columns under eccentric loading and different corrosion levels, discovering that corrosion causes large cracks, reducing compressive strength. Vu and Li's

[22] studies highlighted a significant decrease in shear strength and deformation capacity of RC columns in corrosive environments, with increased corrosion leading to weaker structural responses. Meda et al. [23] reported a 30% decrease in base shear and a 50% reduction in drift capacity for corroded RC columns subjected to seismic loading. Yalciner et al. [5] analyzed a 50-year-old school building, using non-linear static and dynamic analyses to assess the impact of corrosion over time. Their findings showed decreased bond strength with increasing corrosion. Studies by Zhang et al. [24] found a significant decrease in seismic performance and increase in inter-story drift ratios due to corrosion. These investigations highlight the critical role of corrosion on the load-bearing capacity, shear strength, and ductility of RC structures, which is particularly troublesome in seismic areas with insufficient lateral confinement. However, despite these findings and more, research on the seismic performance of corroded RC structures remains vital and renovated, and further studies are necessary to understand the three-dimensional behavior of these structures. While 2D studies offer valuable insights, they fail to account for frame interactions and redistribution actions.

This paper presents a novel approach to evaluate the ultimate capacity of corroded RC components. The study uses a finite element method with force-based elements to simulate the performance of corroded RC structures under various corrosion levels, evaluating ductility, shear strength, and inter-story displacements. The findings show a considerable loss in both ductility and base shear, as well as a shift in the failure mode when the structure is exposed to different corrosion scenarios and high corrosion levels. This research on full-scale corroded RC structures provides valuable insights into the seismic vulnerability of RC buildings in corrosive environments, offering a better understanding of their behavior and helping to improve seismic assessment and retrofitting strategies.

Research Significance and Scope

This study aims to evaluate the impact of corrosion on reinforced concrete (RC) structures through static pushover analysis. Initially, experimental data from existing literature are reviewed to establish simplified empirical relationships that capture the degrading effects of corrosion on the mechanical properties of steel reinforcement. These relationships are then applied to assess how corrosion alters the curvature–moment behavior of RC cross-sections and affects the overall pushover response of a typical RC residential building.

II. Description of the Structure

A Six-story RC building was considered as a testbed for this study. Three typical columns with cross-sections of 350 × 350, 400 × 400, and 500 × 500 mm^2 were used for C1 (corner column), C2 (edge column), and C3 (interior column), respectively, for all types of floors. Longitudinal reinforcement bars for columns are 4T16mm, 8T16, and 8T18 for C1, C2, and C3, respectively, and transverse T8 mm stirrups with 150 mm spacing for all column types. Two typical beams (B1 and B2) with cross-sections 250 × 500, and longitudinal reinforcements of 4T12 mm and 3T16 mm are considered, as listed in Table 1. Rigid diaphragms were implemented for slabs to ensure in-plane stiffness properties. Fully supported rigid connections were applied to all the joints connected to the ground. The model of the RC structure is given in Fig. 1. Two scenarios involving corrosion were tested for four different corrosion ratios (0%, 10%, 20%, and 30%). In the first scenario, the corrosion ratio was applied to all floors of the building, while in the second scenario, the corrosion was applied to only one side of the building. This procedure allowed for an evaluation of the corrosion impact on the testbed building by considering various configurations.

Table 1: Summary of the geometric dimensions and other features of the building.

Description	Information
Number of floors	6 (Basement + 5 normal floors)
Plan dimensions	16m*16m
Floor thickness	12cm
Beams size	B1and B2: 25cm * 50cm
Columns size	C1: 35cm * 35cm, C2: 40cm *40cm, C3: 50cm * 50cm
Floor loads	Dead load 0,15t/m^2, Live load 0,2 t/m^2
Wall load	0,15 t/m^2
Beams Reinforcement	B1: 4T12, B2: 3T16
Columns Reinforcement	C1: 4T16, C2: 8T16, C3: 10T18
Floor Height	3.00 m

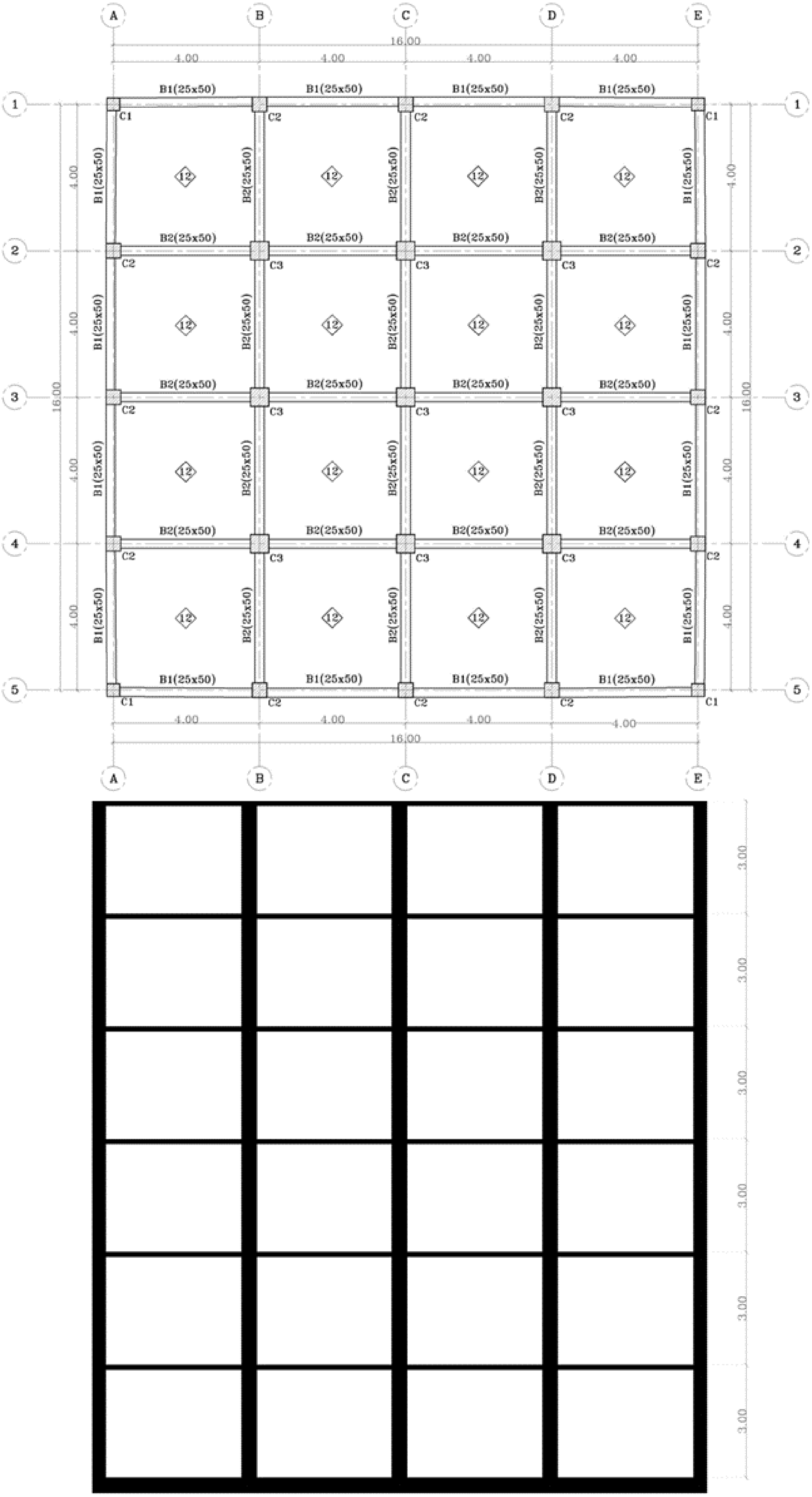


Fig. 1: Plan and elevation of the building.

III. Methodology

Mechanical Properties of Concrete and Steel Exposed to Corrosion.

The study considers the effects of reinforcement corrosion, taking into account the reduction in the properties of both steel and concrete. Equations (1) to (3), sourced from Kai Qian [25] and Ahmed [26], are used to estimate the reduction in mechanical properties of the corroded joints.

$$f_{cu,c} = (1 + K\frac{\varepsilon_t}{\varepsilon_0})^{-1} \times f_{cu} \quad \text{Eq.1}$$

$$f_{yc} = (1 - \alpha 1(CR/100) \times f_y \quad \text{Eq.2}$$

$$E_{sc} = (1 - \alpha_2(CR/100) \times E_S \quad \text{Eq.3}$$

In the equation provided, f_{cu} represents the concrete compressive strength, K represents a coefficient that bases on the roughness and the diameter of the rebar (K is assigned a value of 0.1 for ribbed bars of moderate diameter [27]), and ε_0 represents the strain value at the ultimate f_{cu}, ε_t is the average tensile strain in the cracked concrete normal to the direction of the applied compression [28]. Furthermore, α1 and α2 refer to empirical factors with values of 1.24 and 0.75, respectively, in the case of uniform corrosion of rebars, and CR stands for the corrosion ratio, while E_s and f_y refer to the elastic modulus and yield strength of uncorroded rebars, respectively. Experimentally measured mechanical properties of the materials used are extracted from [26] and summarized in Table 2.

Table 2: Mechanical properties of materials without and with corrosion.

Corrosion degree	Average yield strength (MPa)	Average ultimate strength (MPa)	Average elongation (%)	Elastic modulus (MPa)	Concrete Compressive strength (MPa)
0	484	624	15	200	30
10	421.00	542.00	12.10	184	24
20	350	457	10	170	18
30	309	407	7.2	155	12

Moment-Curvature Behavior of RC Sections

Moment–curvature relationships were developed to define user-defined plastic hinge properties over time. For columns, these relationships were derived from the computed section properties and the applied constant axial loads, while axial forces in beams were considered negligible. Corrosion-induced reductions in the strength and ductility of steel reinforcement contribute to decreased deformation capacity in both beams and columns, particularly under horizontal loading, where critical sections near joints experience significant forces. To perform a nonlinear analysis of the RC building, the plastic behavior was assumed to be concentrated at specific cross-sections of beams and columns, represented by plastic hinges. These hinges are characterized by moment–curvature (M–∅) relationships and, in the case of columns, by normal force–moment (N–M) interaction diagrams. Estimating the mechanical properties is essential for determining the moment–curvature behavior of each cross-section. The plastic hinge properties for beams and columns were defined by using the RC-ABC software [28], which is based on a sectional fiber model [29]. The (M–∅) relationships for beams are shown in Figs. 2 to 5. The corrosion degree influences both the maximum bending moment and curvature; these values are decreased, and so is the ductility. In Figs. 6 to 9, the N-M interaction domain of columns is plotted.

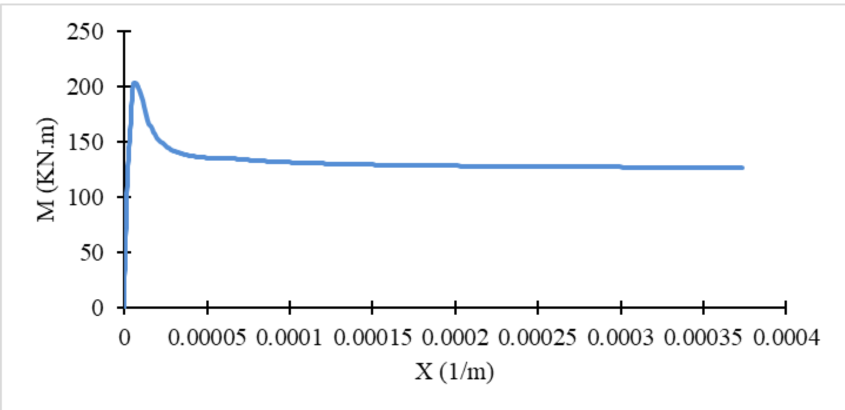


Fig. 2: Curvature-Bending Moment relationships for RC beam - 0% corrosion.

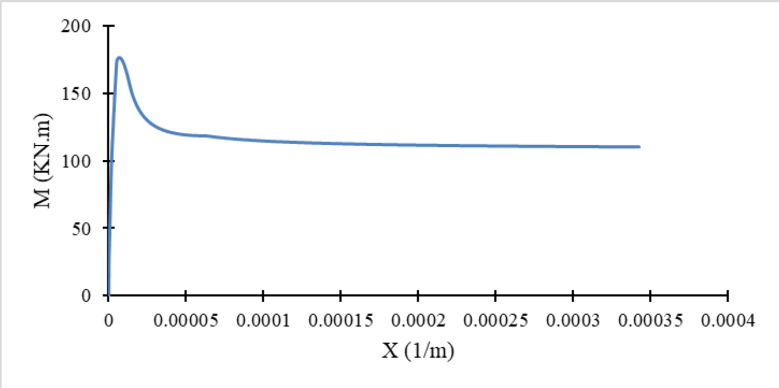


Fig. 3: Curvature-Bending Moment relationships for RC beam - 10% corrosion**.**

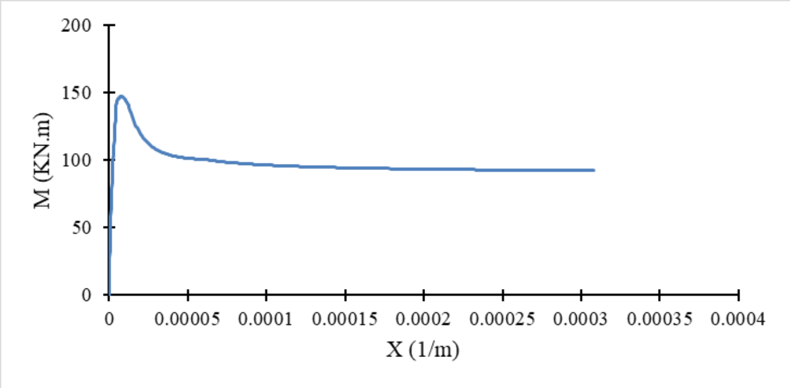


Fig. 4: Curvature-Bending Moment relationships for RC beam - 20% corrosion**.**

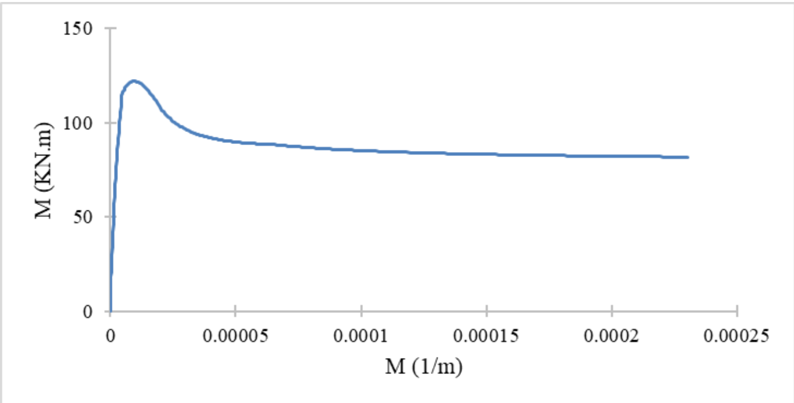


Fig. 5: Curvature-Bending Moment relationships for RC beam - 30% corrosion**.**

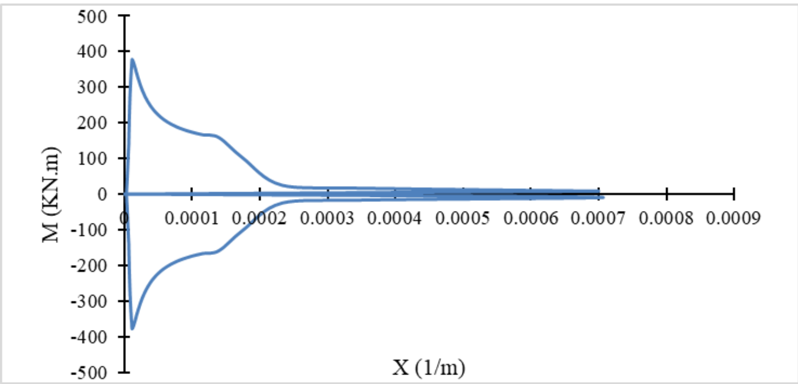


Fig. 6: Curvature-Bending Moment relationships for RC column - 0% corrosion**.**

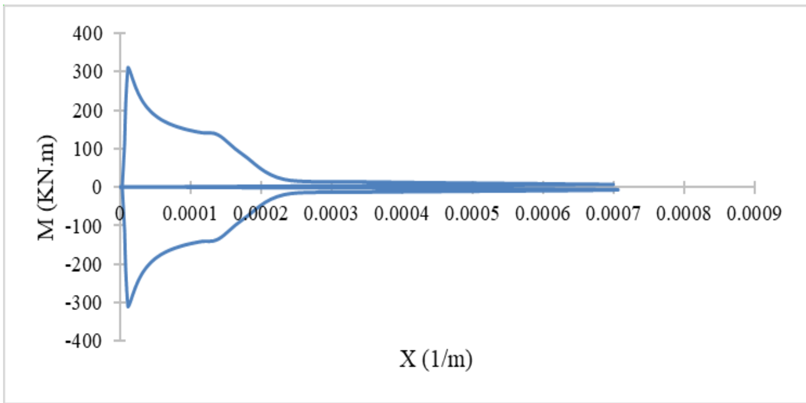


Fig. 7: Curvature-Bending Moment relationships for RC column -10% corrosion**.**

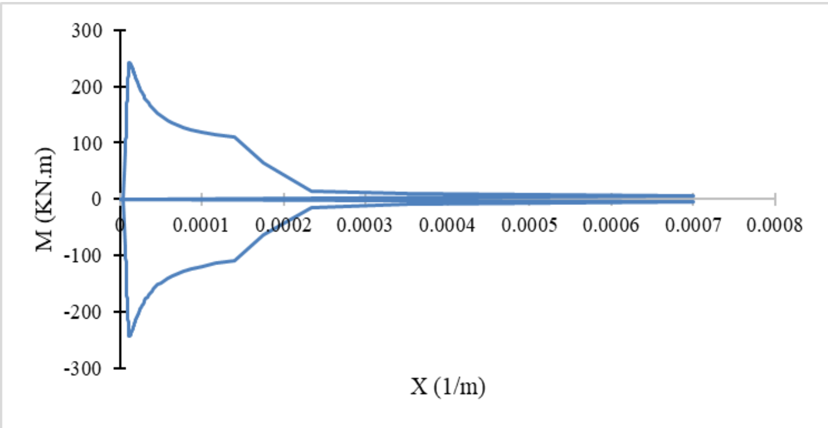


Fig. 8: Curvature-Bending Moment relationships for RC column -20% corrosion.

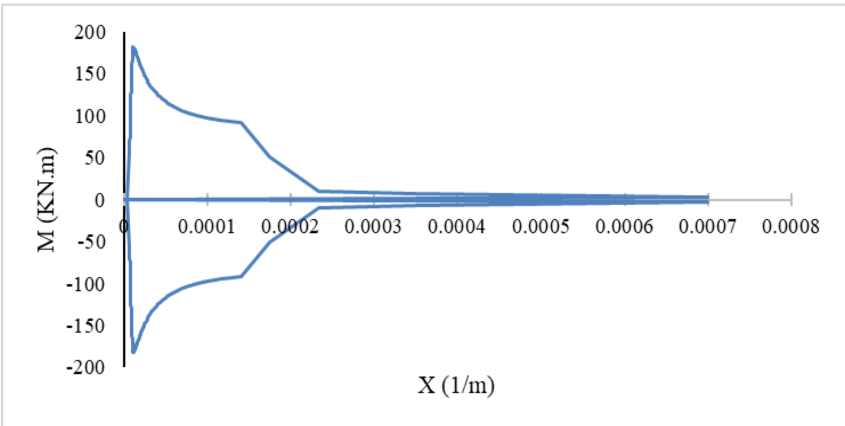


Fig. 9: Curvature-Bending Moment relationships for RC column-30% corrosion.

IV. Static Pushover Analysis

SAP2000 computer program was used to analyze the RC building models. To determine the behavior of plastic hinges based on user-defined characteristics, the force-deformation behavior must be plotted. Fig. 10 shows a typical force-deformation relationship that defines the behavior of the plastic hinge by FEMA-356 [30], and the required acceptance criteria of immediate occupancy (IO), life safety (LS), collapse prevention (CP), and collapse (C).

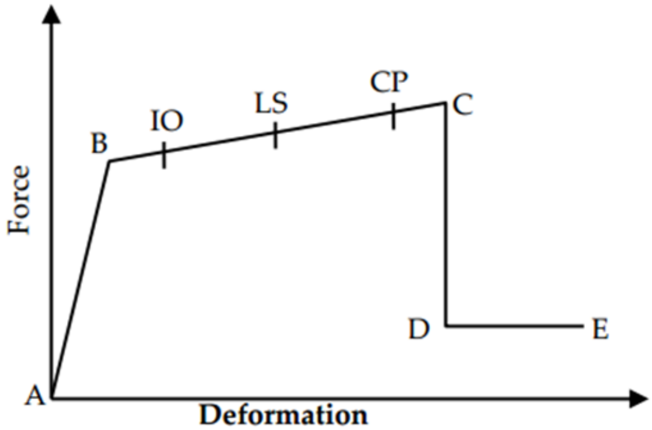


Fig. 10. Force-deformation relationship of a plastic hinge

V. Results

Force-Displacement Curves

Static pushover analysis is performed under different corrosion scenarios in the X direction of the building; the total base shear force-displacement curves are presented in Figs. 11 to 13. The results show that increasing the corrosion ratio leads to a decrease in the top displacement, indicating that higher corrosion levels result in less structural deformation. However, this trend is not consistent for the ultimate total base shear. While there is a general decrease as the corrosion ratio increases, the decrease is not linear. For the scenario where corrosion is applied to only one side of the building, the top displacement remains relatively stable across different corrosion ratios, suggesting that corrosion on one side does not significantly impact the overall deformation of the building. The ultimate total base shear also shows a decreasing trend as the corrosion ratio increases, but again, the decrease is not linear. When the load-displacement curves were analyzed, the reference scenario yielded the highest base shear force of 3294 t. The smallest base shear force measured from 30% corrosion in all building damaged scenarios was 2148t, representing a 34.7% drop. When displacements were compared, the maximum peak displacement was 50 cm in the reference building, while the minimum displacement was 41.28 cm in the corrosion-damaged scenario in beams, representing a 17.44% drop. Overall, these results suggest that the impact of corrosion on structural performance varies depending on the location and extent of corrosion. Corrosion of the whole floor seems to have a more pronounced effect on the structural response compared to corrosion on only one side. Table 3 summarizes the maximum load and displacement values for the scenarios.

Table 3: Static pushover results for different scenarios.

Case Study	Top Displacement (cm)	Ultimate Total Base Shear (ton)
0% (control)	50.00	3294.00
10%-All	49.98	2713.00
20%-All	44.69	2407.00
30%-All	41.28	2148.00
10%-One Side	49.99	3170.00
20%-One Side	49.99	3165.00
30%-One Side	48.13	3018.00

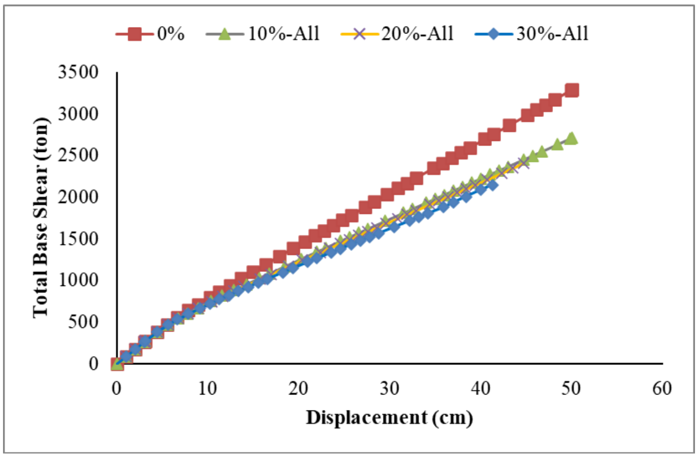


Fig. 11. Load-displacement curves of "All corrosion" scenario.

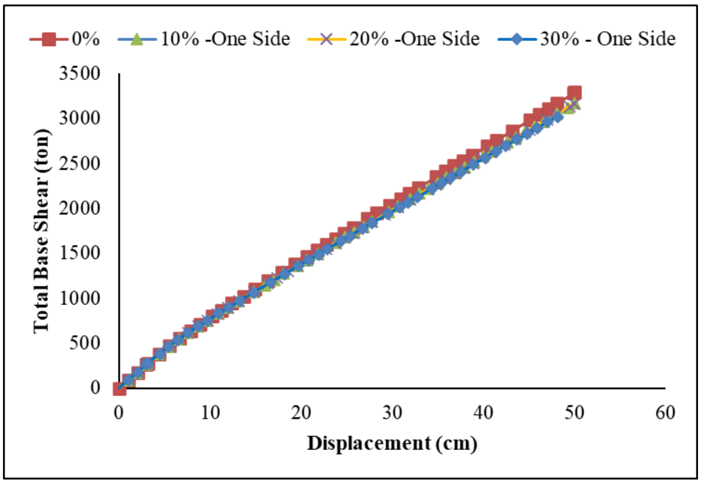


Fig. 12. Load-displacement curves of "One side corrosion" scenario.

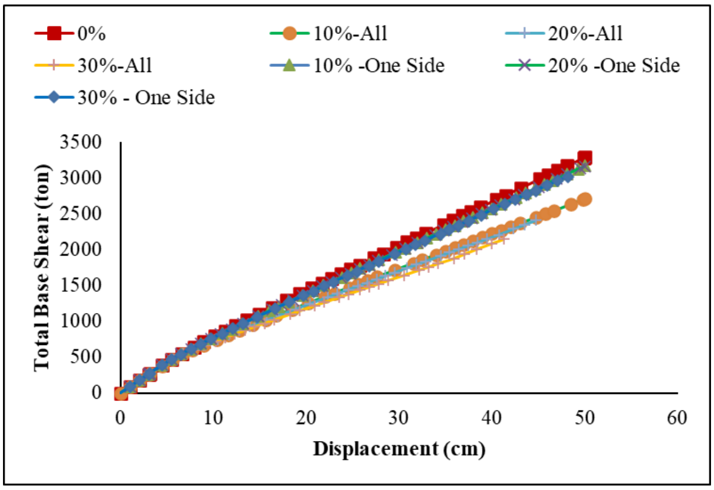


Fig. 13. Load-displacement curves of all scenarios**.**

Mode of Failure

The analysis results revealed that in the case where corrosion of the whole floor occurs, the damage levels throughout the building increased by plastic hinges formation in the beams at full capacity, followed by the damage levels of the plastic hinges in the columns, and the building collapsed as shown in Figs. 14 and 15. On the other hand, for the scenario where corrosion is applied to only one side of the building, rather than the progression of the damage level of the hinges in the beams, the hinge formation jumped to the columns, and thus, the upper floor beams remained in the elastic region and the structure collapsed as shown in Figs. 14 and

15. Plastic hinges were formed on the lower floors of the reference building, whereas the columns and beams on the upper floors exhibited elastic behavior, as illustrated in Figs. 14 and 15

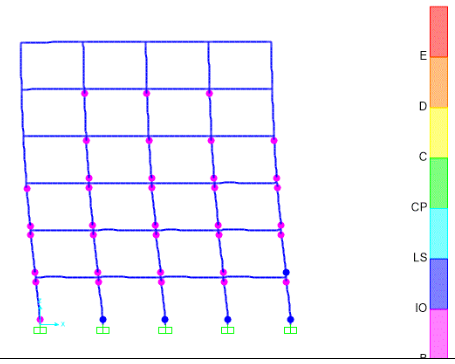
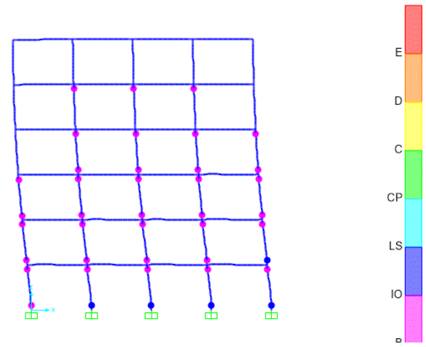
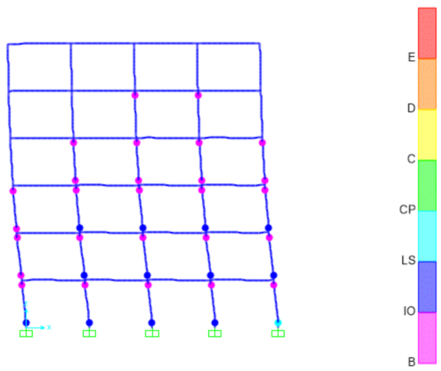
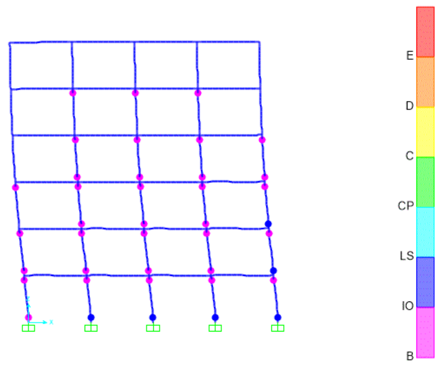
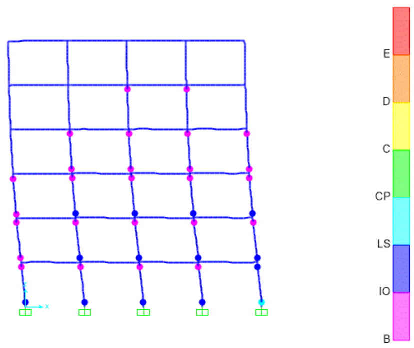
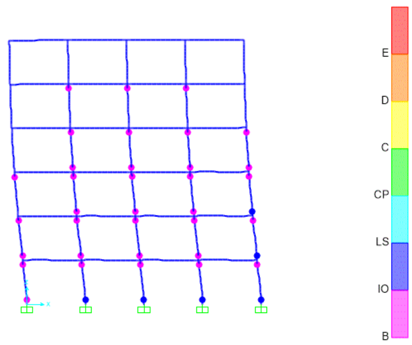
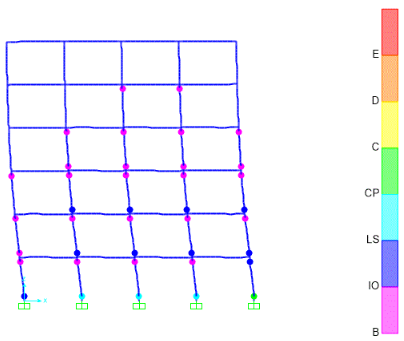
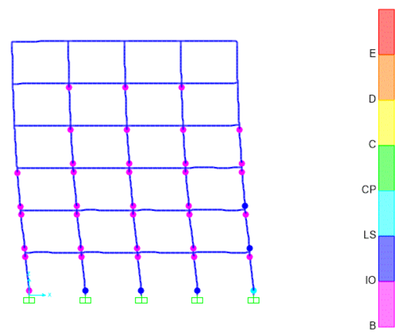
Case	"All corrosion" scenario	"One Side corrosion" scenario
0%		
10%		
20%		
30%		

Fig. 14. Distribution of plastic hinges.

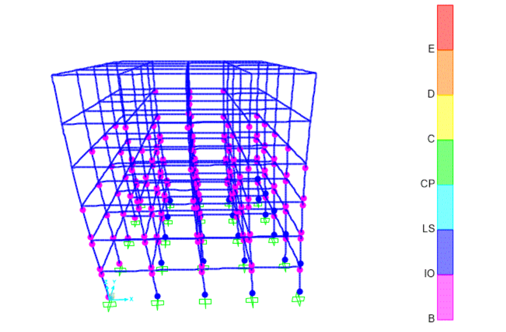
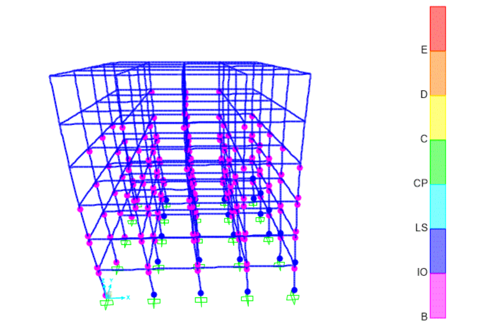
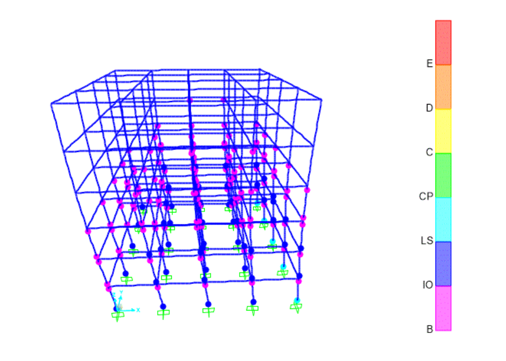
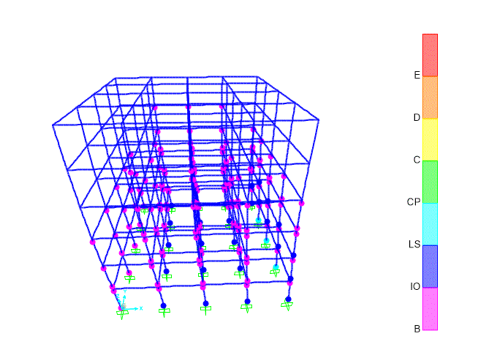
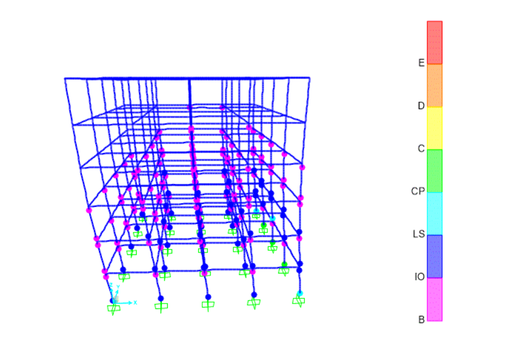
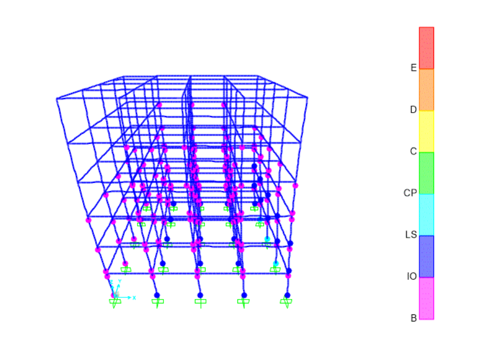
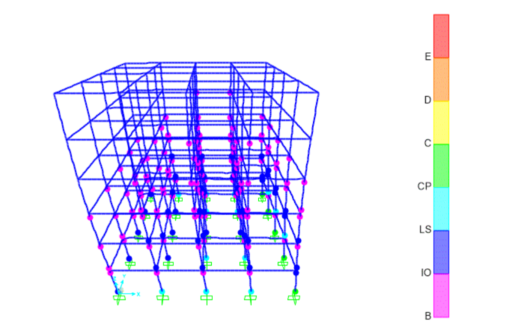
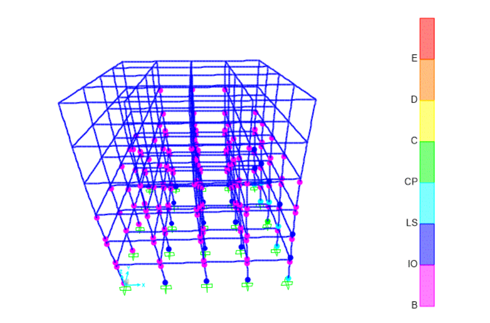
Case	"All corrosion" scenario	"One Side corrosion" scenario
0%		
10%		
20%		
30%		

Fig. 15. Distribution of plastic hinges**.**

VI. Discussion

Force–Displacement Behavior

The force–displacement curves derived from the static pushover analyses (Figs. 11 to 13) offer significant insights into the impact of corrosion on the seismic performance of RC buildings. The curves reflect a clear trend: increasing the corrosion level leads to reductions in both the ultimate base shear capacity and top displacement of the structure. However, this trend is non-linear, especially with regard to base shear capacity.

In the reference scenario (0% corrosion), the building exhibits the highest structural performance, with an ultimate base shear of 3294 t and a peak top displacement of 50 cm. These values represent the benchmark for comparing degraded states.

For corrosion applied throughout the entire structure, the reduction in performance becomes increasingly evident. At 30% corrosion, the base shear drops to 2148 t, indicating a 34.7% reduction compared to the reference case. This loss in capacity is accompanied by a noticeable decrease in top displacement to 41.28 cm, a 17.44% decrease, suggesting a marked deterioration in the building's ductility and energy dissipation capacity. These reductions highlight the substantial weakening of both the strength and deformation capacity due to the corrosion-induced degradation of reinforcement steel and concrete confinement.

Interestingly, the scenarios involving corrosion only on one side of the building display a different behavioral pattern. The top displacement remains almost unchanged across 10% and 20% corrosion levels (≈ 49.99 cm), with a slight drop to 48.13 cm at 30%. This implies that localized corrosion, while still degrading structural strength, does not significantly impair global deformation capacity at moderate levels. However, the base shear values do decline progressively—from 3170 t at 10% to 3018 t at 30% corrosion—suggesting that even asymmetrical damage can weaken the structural resistance to lateral forces.

The non-linear degradation trend for both global stiffness and strength can be attributed to the complex interaction between material degradation and force redistribution within the structural system. In some scenarios, even with high corrosion ratios, the structural system adjusts by redistributing forces to less damaged members, momentarily maintaining deformation capacity before rapid strength deterioration occurs. This also indicates that damage localization and redistribution mechanisms play critical roles in seismic performance under corrosion scenarios.

Mode of Failure and Plastic Hinge Distribution

The distribution and progression of plastic hinges (Figs. 14 and 15) provide further insight into the failure mechanisms under various corrosion conditions. In the reference model, the expected formation of plastic hinges primarily occurred in beams and columns at lower stories, while upper-story members remained in the elastic range. This is consistent with classical pushover behavior in regular RC buildings where plasticity initiates at the base.

In contrast, the "All corrosion" scenarios exhibit a different pattern. Due to the compromised material strength across the entire structure, plastic hinges formed more rapidly and extensively in both beams and columns, particularly in lower stories. As the corrosion ratio increases, the sequence of hinge development becomes more critical: initial beam hinge formation is quickly followed by hinge formation in columns, which accelerates the progression toward global collapse. This indicates a shift in the collapse mechanism driven by reduced confinement and cross-sectional area of corroded reinforcement.

On the other hand, in the "One Side corrosion" scenarios, the plastic hinge development is less uniform and tends to localize on the damaged side. In these cases, an asymmetric structural response is observed. Interestingly, due to less extensive damage in the beams, the structure attempts to redistribute the loads, causing hinges to form earlier in the columns on the damaged side. As a result, upper floor beams remain mostly elastic, and collapse is initiated through a more brittle mechanism, with a sudden failure in the columns, potentially due to unbalanced force paths.

This asymmetric hinge formation highlights the vulnerability of irregular corrosion patterns, as they can shift the failure mode from ductile (beam-dominated) to more brittle (column-dominated), reducing the warning signs before collapse and complicating retrofitting strategies.

VII. Summary and Conclusions

This study investigates the impact of corrosion on the structural performance of reinforced concrete (RC) buildings employing static pushover analysis. The primary focus is on how varying levels and locations of corrosion affect the force-displacement behavior, failure modes, and plastic hinge development of the building. The analysis was performed using different corrosion scenarios, including uniform corrosion across the entire structure and localized corrosion on one side. Key findings include:

- As corrosion levels increase, there is a decrease in both base shear capacity and top displacement. Specifically, the base shear decreased by 34.7% when corrosion was applied to the entire building, while the top displacement reduced by 17.44% under 30% corrosion.
- In the case of full building corrosion, plastic hinges first formed in beams and then progressed to columns, leading to a progressive failure pattern. In contrast, localized corrosion caused early hinge formation in columns, bypassing beam failure and leading to more rapid collapse.
- Localized corrosion (applied to one side of the building) had a less significant effect on displacement but still led to a decrease in base shear. This suggests that while corrosion on one side may not drastically affect deformation, it can compromise the structure's strength and load-carrying capacity.
- Full building corrosion led to a progressive failure starting from the beams and moving to the columns, while localized corrosion shifted the damage from beams to columns earlier. The reference building, with no corrosion, exhibited typical ductile behavior, where hinges formed in expected locations without compromising overall performance.

- The reference building, with no corrosion, demonstrated the expected ductile behavior, where plastic hinges formed at the base while the upper floors remained elastic, providing a safe response under seismic loading.
- Load redistribution occurred as corrosion-damaged structural elements, causing a shift in the location and nature of plastic hinge formation. This altered the expected seismic response of the building, potentially leading to unexpected collapse modes.
- The use of user-defined plastic hinge properties and nonlinear analysis proved crucial in accurately predicting the behavior of corroded buildings. These methods allowed for a more realistic simulation of damage progression and structural response under seismic conditions.

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