



Numerical Investigation of Post-Earthquake Fire Resistance of Reinforced Concrete Column

Selamawit Jember Tsegaye, Girmay Mengesha Azanaw*



Abstract: Post-earthquake fire (PEF) is a critical multi-hazard scenario that can cause severe structural degradation and collapse, even in buildings designed for modern seismic and fire codes. This study conducts a comprehensive numerical investigation of a reinforced concrete column's behaviour under seismic lateral loading and post-earthquake fire loading. We developed a validated 3D finite element (FE) model in ANSYS Mechanical to simulate coupled thermal-mechanical behaviour, incorporating nonlinear concrete damage, reinforcement yielding, and heat-dependent material properties. Experimental results reported in the literature were used for validation analyses using FEA tools such as ANSYS, and a comprehensive parametric study was subsequently carried out to examine the influence of axial load ratio (0.1–0.4), concrete cover thickness (25–50 mm), and number of fire-exposed faces (one, three, four) on PEF resistance. Results show that higher axial load ratios significantly reduce ductility and fire resistance, while more fire-exposed surfaces accelerate reinforcement heating and stiffness degradation. Thicker concrete cover improves thermal protection but can reduce lateral resistance by reducing effective depth. Finite element validation results showed good agreement with experimental residual lateral load capacity, with margins of error of 4.7% and 2.2% for lateral load capacity and ductility ratio, respectively. Concrete cover size influenced insulation efficiency and residual strength. Compared with 35, 40, and 50mm concrete cover, a nominal 25mm concrete cover showed a 3.2%, 19.1%, and 59.63% increase in rebar reinforcement temperature. Post-earthquake fire (PEF) peak lateral load capacity and fire resistance also decreased by 8.1% compared with seismic lateral loading alone. The findings highlight critical design-sensitive parameters governing PEF resistance and emphasise the need for integrated multi-hazard design approaches in structural engineering practice.

Keywords: Post-Earthquake Fire; Seismic Lateral Loading; Reinforced Concrete Column; Finite Element Analysis and Thermal-Mechanical Coupling.

Nomenclature:

PEF: Post-Earthquake Fire
FEA: Finite Element Analysis
FEM: Finite Element Method
RC: Reinforced Concrete

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I. INTRODUCTION

A. Background

Post-earthquake fire (PEF) is a serious multi-hazard event that can further compromise the structural integrity of reinforced concrete (RC) buildings and increase the probability of collapse. In particular, previous experiences, such as the 1906 San Francisco earthquake and the 1923 Great Kanto earthquake, indicate that secondary fire can cause damage equivalent to, or greater than, the earthquake itself. However, most international building codes consider seismic and fire hazards separately and still provide limited guidance on what is now a sequential interaction: a building's seismic response followed by fire exposure.

In places like Ethiopia, where experimental testing facilities are limited relative to the size of the test, validated numerical modelling is an important research tool for understanding multi-hazard behaviour. Studies show that seismic cracking affects thermal flow pathways, increases reinforcement heating, and reduces fire resistance. However, uncertainty remains about how key design parameters, including axial load ratio, concrete cover, and fire-exposed surface area, jointly affect the PEF performance of RC columns [9], [10].

This study addresses these gaps by developing and validating a nonlinear FE model that simulates sequential seismic and fire loading on RC columns. The specific objectives are:

- To validate the 3D coupled thermal-mechanical FE model against full-scale experimental results.
- To quantify the influence of axial load ratio, concrete cover thickness, and number of fire-exposed faces on column performance under PEF.
- To compare the residual lateral load capacity and ductility of columns subjected to seismic loading alone versus combined PEF loading.

B. Novelty and Research Gap

Existing studies have focused primarily on either seismic behaviour or fire resistance of RC columns, examined independently. Few investigations have addressed sequential earthquake-fire loading, and those that do often lack fully validated 3D finite element models that capture both pre-fire seismic damage states and subsequent thermal degradation. The gap this FE model fills lies in its ability to:

Integrate cyclic seismic damage with coupled thermo-mechanical degradation within a single validated framework. Quantify how axial load ratio, concrete cover, and fire exposure configuration interact during sequential hazards—an area minimally explored in prior research.



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II. LITERATURE REVIEW

Over the past two decades, research on PEF behaviour has advanced significantly. Experimental investigations show that seismic damage increases thermal penetration into RC members, leading to a faster loss of stiffness and strength than in undamaged sections [1]. Pre-existing lateral deformation significantly reduces fire endurance by causing earlier spalling and exposing the reinforcement to fire [2] [3]. Fire-exposed columns that were previously earthquake-damaged also showed significant losses in ductility and load capacity.

Full-scale fire tests on earthquake-damaged RC frames ([4]; [5]) showed up to a 44% loss in lateral load capacity after fire exposure. Numerical simulation of the PEF behaviour has also increasingly been utilised as an alternative or supplement to experimental work; [6] demonstrated that nonlinear FE models can reasonably estimate the residual strength of RC columns subjected sequentially to EQ–fire loading. However, modelling assumptions vary widely in the literature, and there is little consensus on how sensitive the PEF response is to design parameters such as axial load ratio and cover thickness.

Although notable temperature-dependent constitutive models are established ([7]; [8]), few studies link damage-plasticity models that include both seismic cracking and subsequent thermal degradation in a single framework. This work provides some of that awaited evidence through a fully 3D ANSYS-validated model that considered both thermal and mechanical nonlinearity.

III. MATERIALS AND METHODS

This section presents the mechanical and thermal behaviour and finite element modelling of materials such as concrete and reinforcement [Figure 1]. It also introduces failure criteria and modelling approaches for each material.

A. Overview of Numerical Modelling Approach

We developed a detailed 3D finite element model in ANSYS Mechanical APDL to simulate the behaviour of an RC column under sequential seismic and fire loading. We adopted the geometry, material properties, and loading protocol from the full-scale experimental study of [2] for validation.

B. Geometry and Reinforcement Details

The column is a cantilever specimen with a square cross-section of 300 × 300 mm, height of 1500 mm, and 40 mm concrete cover. We modelled longitudinal steel reinforcement and transverse stirrups discretely using REINF264 elements, with yield strengths of 461 MPa and 472 MPa, respectively. Concrete compressive strength was 36 MPa.

C. Element Types and Material Models

- Concrete:* Modelled using CPT215 elements with a coupled damage-plasticity formulation to capture cracking, crushing, and stiffness degradation.
- Steel Reinforcement:* Modelled using REINF264 truss elements with bilinear isotropic hardening.

- Thermal Analysis:* Conducted using SURF152 surface Elements to apply ISO 834 standard fire exposure.

Assigned temperature-dependent properties for both concrete and steel using Eurocode-based reduction factors.

D. Loading Protocol

The analysis consisted of two sequential stages:

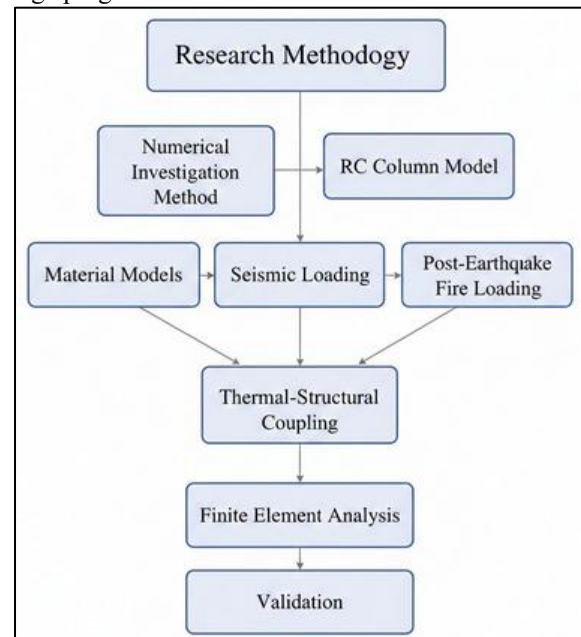
- Seismic Stage:* A constant axial load (axial load ratio $n = 0.2$) was applied, followed by cyclic lateral displacement up to 96 mm.
- Fire Stage:* The damaged column was subjected to ISO 834 fire exposure for 30 minutes. The thermal analysis results were then transferred to a one-way coupled mechanical analysis.

E. Parametric Study

After validation, the model was used to investigate:

- Axial Load Ratios:* 0.1, 0.2, 0.3, and 0.4
- Concrete Cover:* 25, 35, 40, and 50 mm
- Fire-Exposed Faces:* one, three, and four sides

Performance metrics included lateral load capacity, ductility ratio, temperature distribution, and concrete damage progression.



[Fig.1: Flowchart of the Research Methodology]

IV. RESULTS AND DISCUSSION

Based on the comprehensive numerical analysis, the study yielded significant findings on the behaviour of reinforced concrete columns under post-earthquake fire (PEF), which are summarised below.

A. Validation of the Finite Element Model

The Finite Element Model (FEM) accurately replicated experimental results. The predicted lateral load capacity had a marginal error of 4.7%, and the ductility ratio error was only 2.2%. The model also successfully captured the failure mode and concrete damage pattern observed in the physical test, confirming its reliability for subsequent parametric studies.

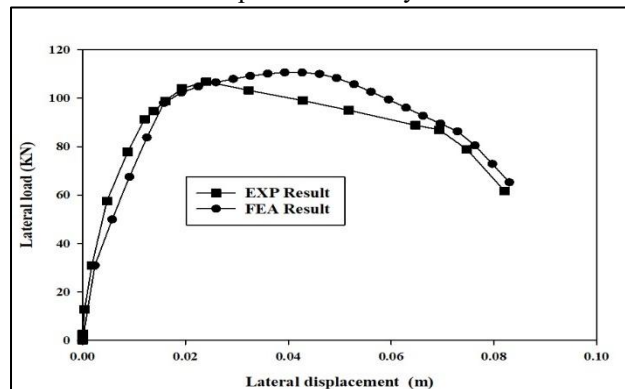




B. Validation Result

The numerical model for an RC column exposed to the PEF condition was validated by comparing the predicted ANSYS load-deflection curve with the measured experimental result. Figure 2 and Table I present this comparison. The APDL verification used a 30min fire duration on four sides with 40mm concrete cover, combined with a 96 mm peak lateral load. From Figure 2 and Table I, the ANSYS lateral load capacity of the column agrees well with the measured experimental results. The ANSYS model accurately captures the trend in the RC column capacity under post-earthquake fire: as temperature increases, material strength and stiffness decrease, and the column expands during initial heating. At ultimate displacement, the concrete and reinforcement lose load-bearing capacity at the failure point; displacement reaches yield at 65 displacements, occurring at the initial crack point on the column. In the present study, the maximum lateral load capacity differs by 4.7% between the experimental and finite element results. We validated the ANSYS analysis against

the reported experimental study. We selected the column specimen's load-displacement response to verify the FE model. This indicates that the ANSYS model accurately predicted the specimen's behaviour, so we can use the RC column under PEF for parametric analysis.



[Fig.2: Comparison of Experimental and Mechanical APDL Load-Deflection Curve on RC Column]

Table I: Comparison of FEA Results with Experimental Results

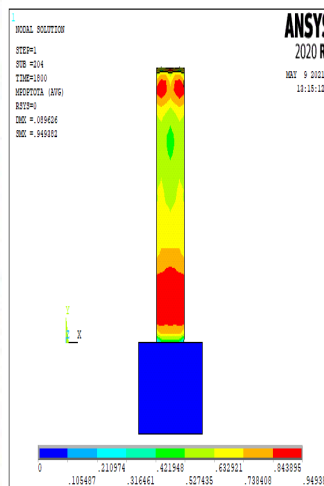
Value	Pmax (kN)	Yield Displacement Δy (mm)	Ultimate Displacement Δu (mm)	Ductility ($\mu = \frac{\Delta u}{\Delta y}$)
Experimental obtained	105.6	14.4	65.7	4.6
Numerical obtained	110.67	15.1	67.2	4.5
Error (% between experiment and numerical)	4.7%	4.9%	2.3%	2.2%

C. Damage Mode of Validation Column

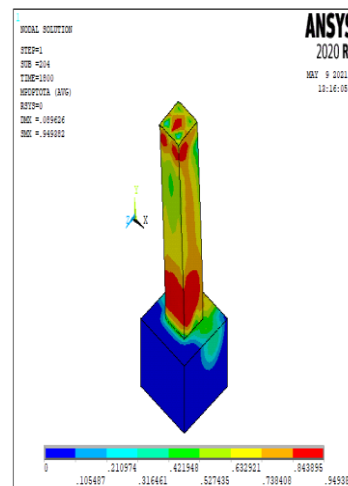
The validation analysis indicated that the RC column failed mainly in flexure, as evidenced by cracking in the tension zone and crushing near the compression face. Spalling of the concrete cover and yielding of the longitudinal reinforcement were concentrated in the plastic hinge regions. These damage patterns closely matched the experimental observations, confirming that pre-existing seismic cracks accelerated heat penetration and material degradation during post-earthquake fire exposure, reducing residual strength and stiffness.



(a) Experimental



(b) FEM Side View



(c) FEM Oblique View

[Fig.3: The RC Column Total Damage of Experimental and FEM (a) Experimental [2] (b) FEM Side View (c) FEM Oblique View]

D. Parametric Study

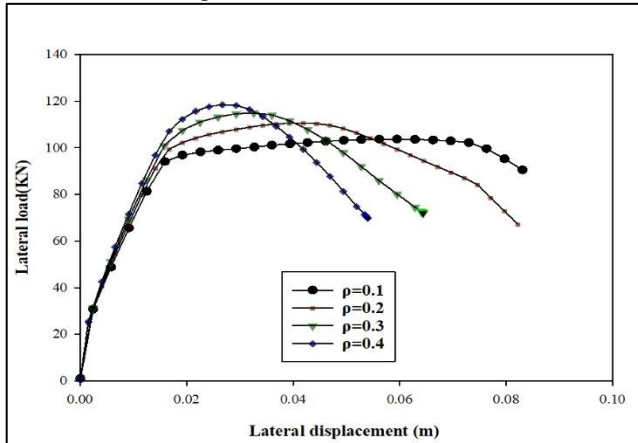
The finite element model was used to study parameters that affect the resistance of an RC column subjected to PEF. The parameters were the axial load ratio, the fire-exposed side, and the column's concrete cover.

i. Effect of Axial Load Ratio

We examined the influence of axial load ratio on deformation and PEF resistance in RC columns at axial load ratios of 0.1, 0.2, 0.3, and 0.4, as defined in

equation 4-1. The test results indicated that increasing the axial load ratio reduced both ductility and residual strength. Correspondingly, the column with ($n=0.1$) has the highest ductility ratio of 4.54, while at ($n=0.4$), ductility drops to 1.9, showing the transition from tension-controlled to compression-controlled failure. Higher axial loads caused more severe concrete crushing and earlier stiffness degradation, reducing fire resistance. Thus, high axial load ratios significantly reduce the deformation capacity and PEF resistance of RC columns because combined thermal and mechanical effects accelerate material deterioration.

$$\rho = \frac{P_{applied}}{P_{design}} \quad \text{Eq.4-1}$$

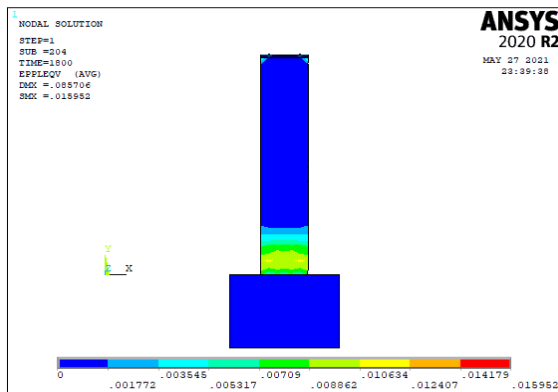


[Fig.4: Effects of Axial Load Ratio vs. Displacement]

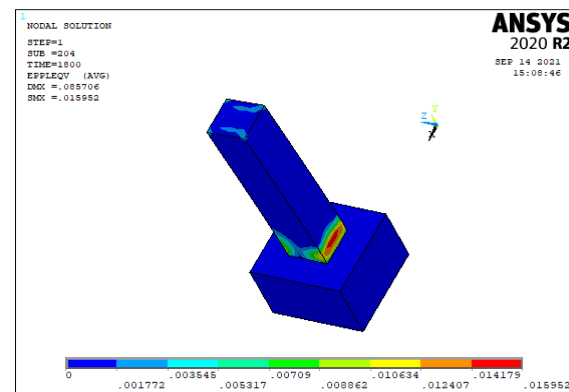
Table II: Ductility Factor of Axial Load Ratio

Axial Load Ratio	$\Delta y(\text{mm})$	$\Delta u(\text{mm})$	$\mu = \frac{\Delta u}{\Delta y}$	Percentage difference (%)
0.1	14.98	68	4.54	+3.1
0.2(reference)	15.1	67.2	4.4	100
0.3	17.2	38	2.21	-66.3
0.4	18	34	1.9	-79.36

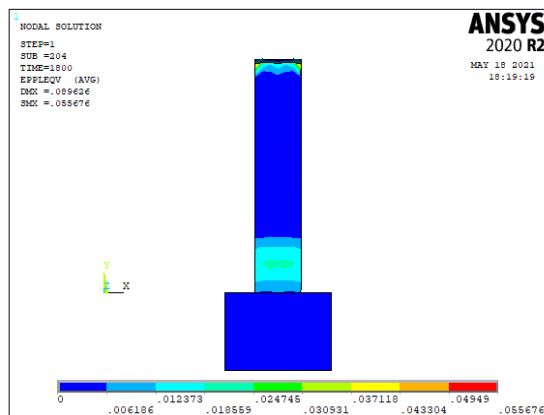
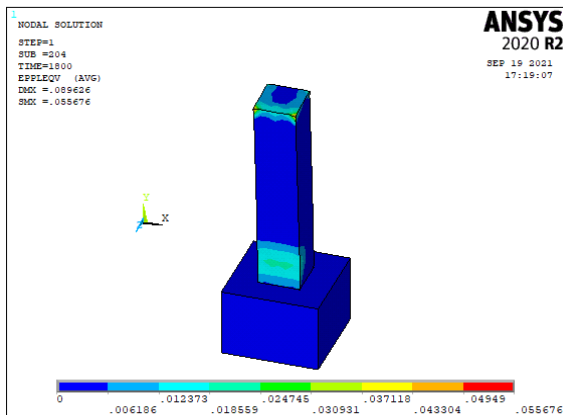
Figure 5 shows the concrete damage of RC columns at failure for different axial load ratios. The equivalent plastic strain for axial load ratios of 0.1 and 0.2 has few 'red' zones, reflecting the minimal amount of concrete damage at failure. A minor crack appears at all axial load ratios from 0.1 to 0.4; as the axial load ratio increases, tension and compression damage increase.

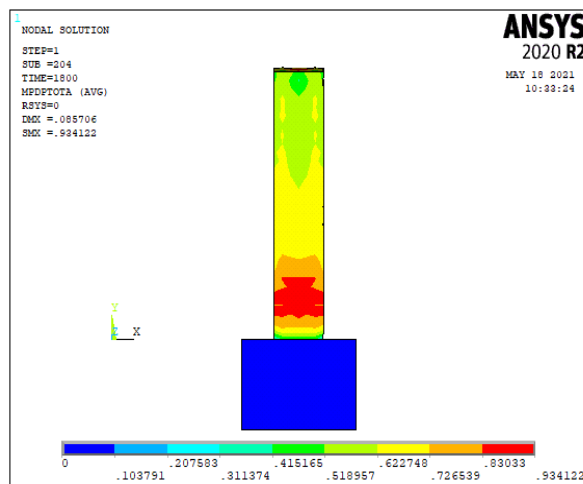


(a) Equivalent Plastic Strain for Axial Load 0.1

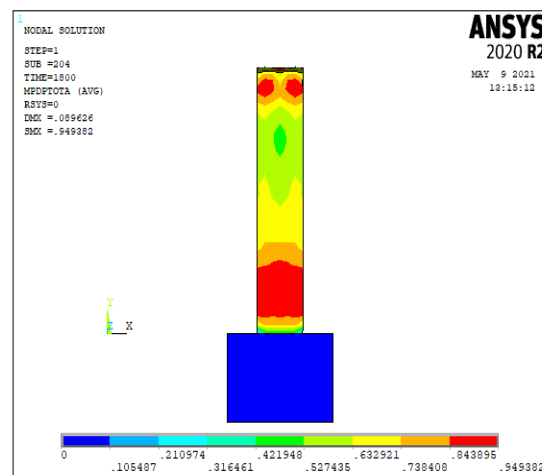


(b) Equivalent Plastic Strain for Axial Load 0.2

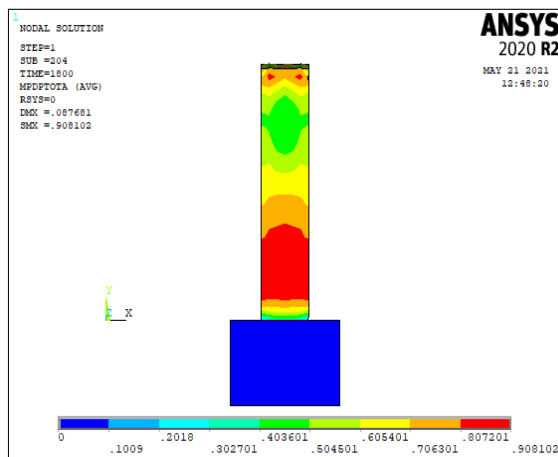




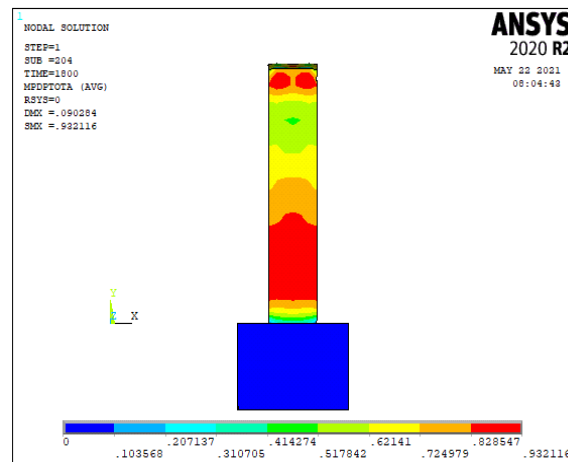
(c) Axial load ratio=0.1



(d) Axial load ratio=0.2



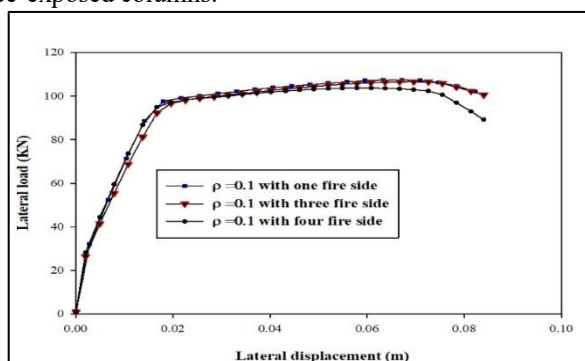
(e) Axial load ratio=0.3



(f) Axial load ratio=0.4

[Fig.5: Strain Damage and Total Damage of Concrete for Different Axial Load Ratio]

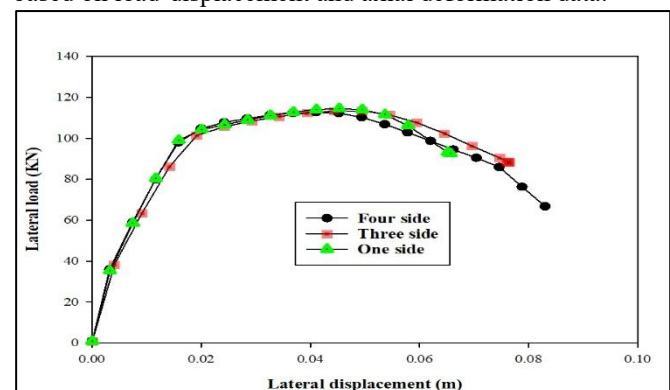
The test results for the RC column under PEF and axial compression showed that the initial crack occurred at 95.4 kN, the peak load was 107.5 kN, and failure occurred at 102 kN for one-face fire exposure at an axial load ratio of 0.1. In addition, three-face exposure reached a peak load of 106.7 kN and failed at 93.6 kN, and four-face exposure failed at 93.6 kN after a peak load of 103 kN. More fire-exposed faces had little effect on the reduction in lateral load capacity, but they significantly influenced the temperature distribution and stiffness of the columns. Columns exposed on more sides showed higher reinforcement temperatures, greater stiffness degradation, and lower ductility than single-face-exposed columns.



[Fig.6: Lateral Load vs. Lateral Displacement of 0.1 Axial Load Ratio with Different Fire Faces]

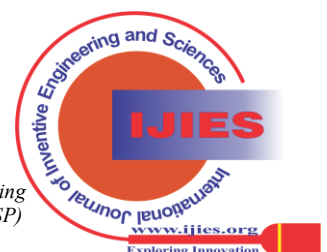
E. Effect of Fire-Exposed Side

This paper investigates how different fire-exposed sides affect the PEF performance of RC columns. We analysed columns with one-, three-, and four-sided fire exposure based on load-displacement and axial deformation data.



[Fig.7: Lateral Load vs. Lateral Displacement Graph for Columns with Different Fire-Exposed Sides]

Accordingly, the one-side fire-exposed column achieved the highest load capacity (114.524 kN) with a ductility ratio of 5.1, outperforming the three- and four-side exposures by 1.5% and 0.832%, respectively. This fire exposure reduced axial deformation by more than

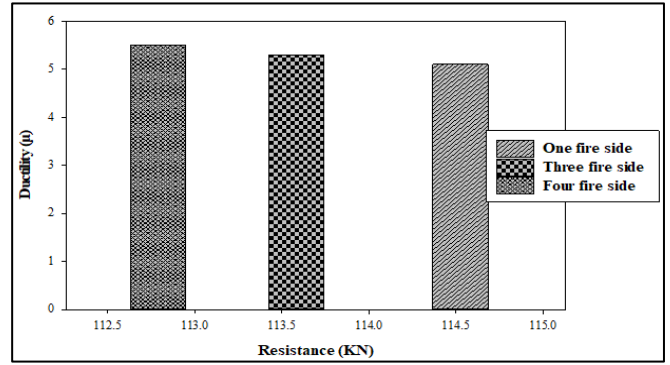


50% compared with multi-side fire exposures. Although the exposure sides did not affect lateral load capacity, the temperature distribution around the column changed, affecting the column's residual strength and stiffness after PEF. [Figure 7](#) presents the load-displacement results, and [Table III](#) summarises the corresponding ductility ratios for each exposure condition.

Table III: Ductility Ratio of Fire-Exposed Side

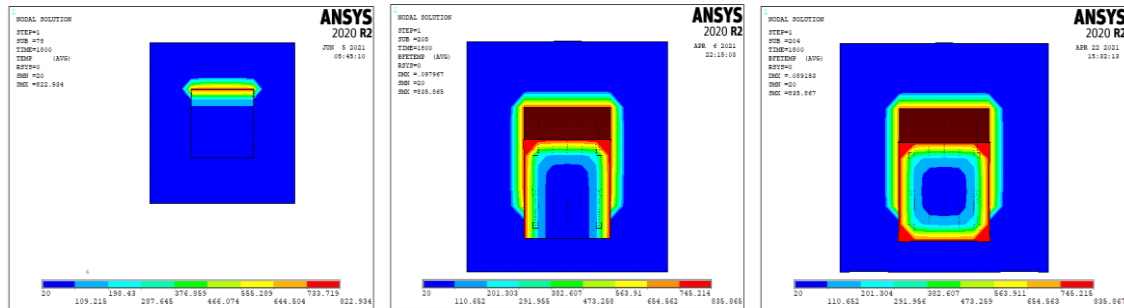
Fire Side	Resistance (Pmax KN)	Δy (mm)	Δu (mm)	$\mu = \frac{\Delta u}{\Delta y}$
One side (reference)	114.525	12.9	65.7	5.1
Three side	113.58	14.2	74.2	5.3
Four side	112.79	12.9	70.8	5.5

[Figure 8](#) shows that the one-side fire-exposed column had 51.5% and 57% less residual axial deformation than the three- and four-side exposures, respectively. This indicates that fewer fire-exposed sides improve axial stability and reduce long-term deformation after cooling.



[Fig.8: Chart for Residual Resistance of RC Column for Different Fire Side]

[Figure 9](#) shows that the maximum body temperature for four-side fire exposure is 8.8% and 44% higher than for three-side and one-side exposures, respectively.



a. One-Face Fire Exposure

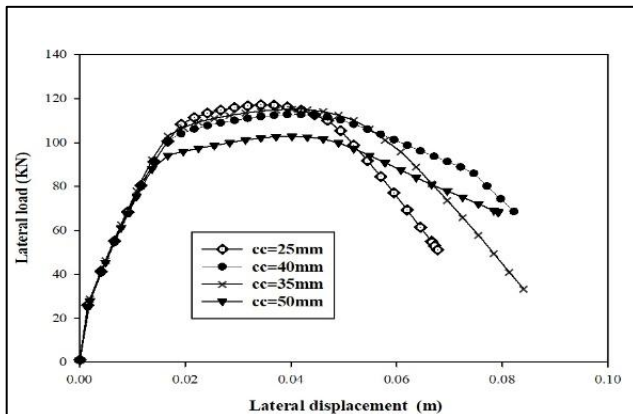
b. Three-Face Fire Exposure

c. Four-Face Fire Exposure

[Fig.9: Temperature Distribution for Top View: (a) One-Face Fire Exposure, (b) Three-Face Fire Exposure, and (c) Four-Face Fire Exposure]

F. Effect of Concrete Cover

The study examined how concrete cover thickness affects the performance of RC columns under post-earthquake fire conditions. Covers measured 25 mm, 35 mm, 40 mm, and 50 mm for a 300×300 mm section. According to [Figure 10](#), thinner concrete covers (25mm and 35mm) failed earlier due to higher heat conduction. The 40mm concrete cover then improved thermal protection. At the same time, the 50mm cover slightly reduced residual lateral load-carrying capacity because increased cover thickness reduced the effective depth and, thus, the column's lateral resistance. [Table IV](#) presents the resistance of different concrete cover thicknesses.



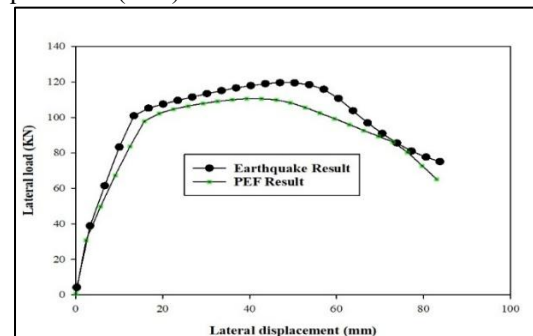
[Fig.10: Effect of Concrete Cover on Post-Earthquake Fire Evaluation on RC Column]

Table IV: Ductility Ratio of Concrete Cover

Concrete Cover	Δy	Δu	$\mu = \frac{\Delta u}{\Delta y}$	Percentage Difference (%)
25	20	54	2.7	-47.9
35	18	62.4	3.5	-22.8
40 (reference)	15.1	65.2	4.4	100
50	14.3	65.4	4.6	+4.44

G. Results of the PEF and EQ

[Figure 11](#) presents the lateral load-displacement behaviour of the RC column subjected to earthquake (EQ) and post-earthquake fire (PEF).

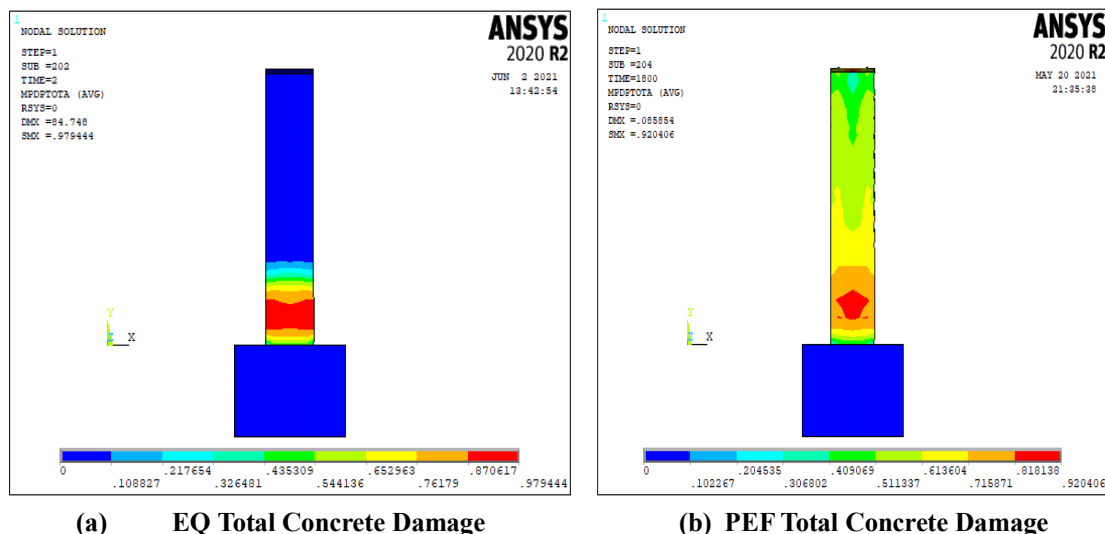


[Fig.11: Comparison of Earthquake and Post-Earthquake Fire]



The EQ-subjected column developed greater capacity, with a maximum lateral load of 119.711 kN at 48.24mm displacement; yield and ultimate displacements of 12.96mm and 67.98mm; and a ductility ratio of 5.24, compared to 4.4 under PEF. Overall, the EQ state increased the column's performance under PEF conditions compared to earthquake (EQ) loading alone—lateral load capacity increased by

8.11% relative to the PEF scenario, indicating better strength and ductility performance. After an earthquake, reinforced concrete structures can sustain various types of damage. This section compares how such damage affects RC columns under post-earthquake fire. [Figure 12](#) compares total concrete damage under the EQ and PEF scenarios.



[Fig.12: Comparison of EQ and PEF for 0.1 Axial Load Ratio Concrete Damage]

V. CONCLUSIONS

This study numerically investigated the response of RC columns subjected to post-earthquake fire using a validated 3D coupled thermal-mechanical finite element model in ANSYS. Key findings include:

- Model accuracy validated with less than 4.7% error.
- Axial load ratio strongly influences ductility and residual load capacity.
- Concrete cover plays a dual structural-thermal role.
- Fire exposure surfaces drastically affect reinforcement temperature.
- PEF reduces lateral load capacity by approximately 8.1%.

Among these parameters, the axial load ratio, concrete cover thickness, and fire-exposed sides most strongly affect PEF performance in RC columns. Their appropriate combination improves post-earthquake fire resistance, and the validated FE model in this study reliably analyses these combined effects on RC columns.

VI. LIMITATIONS AND FUTURE WORK

A. Limitation

This research contributes valuable knowledge about the post-earthquake behaviour of RC columns in fire, but several limitations remain. The numerical model used one-way thermal-mechanical coupling, which cannot account for changes in heat transfer or fire exposure resulting from deformation; we did not directly model bond-slip and degradation at the steel-concrete interface, but these mechanisms could become important after cyclic damage and heating. The analysis used the ISO 834 fire curve, which represents a standardised post-earthquake fire environment rather than a realistic one. The study examined only a single column geometry and detailing arrangement, limiting the

ability to generalise the findings. The concrete constitutive model also does not account for explosive spalling, which may enhance the rate of thermal penetration in real fires. The researchers also used a simplified seismic loading protocol, and they did not account for some mesh-sensitivity effects.

B. Future Work

In future work, we recommend two-way coupling, as interaction between the thermal and mechanical responses is essential for proper modelling. Adding bond-slip models or cohesive interface elements can capture hinge rotation and residual deformation more accurately. It would also be beneficial to study natural and travelling fire scenarios, as these would help us understand post-earthquake fire variability across different buildings. The methodology can also be extended to other column sizes, rebar layouts, and materials (i.e., high-strength concrete and fibre-reinforced systems). Modelling spalling and conducting mesh sensitivity evaluations can also improve prediction quality. Analysing beam-column joints or entire frames at the system level can also improve understanding of the systems' global behaviour. Probabilistic methods, along with experimental or hybrid validation, can provide a more nuanced understanding; even at reduced scale, testing should improve confidence in any numerical methods employed.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- Conflicts of Interest/Competing Interests:** Based on my understanding, this article



has no conflicts of interest.

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- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The data and materials in this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is attributed to the authors. The authors are Selamawit Jember Tsegaye and Girmay Mengesha Azanaw. The authors read and approved the final manuscript.

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