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Seismic Rehabilitation of Infilled Reinforced Concrete Moment Frames Using Rocking Wall Systems

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Abstract

This study investigates the seismic rehabilitation of existing reinforced concrete (RC) moment frames with masonry infill walls using a rocking wall system. A 5-story RC building originally designed according to older Iranian seismic codes (Standard 2800, 3rd edition) was selected as a case study. The structure was analyzed in two configurations: 1) original frame with infill walls (without retrofit), and 2) frame retrofitted with a post-tensioned rocking wall system. Nonlinear static pushover analyses were performed using SAP2000, with verification in OpenSees. Results show that the rocking wall system significantly improves seismic performance. Roof displacement decreased by approximately 66% (from 10.8 cm to 3.6 cm), inter-story drift ratios reduced by 65–78% to within allowable limits (≤0.0055), and plastic hinge formation was controlled within acceptable levels (IO and LS). The rocking wall effectively dissipated seismic energy while protecting primary structural elements. However, residual deformations and construction complexity remain challenges. The rocking wall system is confirmed as an effective rehabilitation technique for infilled RC frames in high-seismic regions.

Keywords: Seismic rehabilitation, Rocking wall, infill wall, RC moment frame, Pushover analysis, SAP2000, OpenSees.

1 | Introduction

During severe earthquakes, the performance and resilience of structures, along with their energy dissipation capacity, are critical.a In recent years, the increasing frequency and magnitude of seismic events have highlighted the urgent need for innovative rehabilitation techniques. One promising approach is the use of rocking wall systems, which allow controlled uplift at the base, concentrating damage in replaceable fuse elements and reducing demands on the primary frame [1–3].

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Fig. 1. Damage to infill walls during the 2017 Kermanshah earthquake.

Masonry infill walls are commonly used in Iranian construction, but their structural effects are often neglected in design. Infill walls can increase stiffness and strength but may also create soft-story mechanisms or short-column failures [4–6]. Modern seismic codes (Iranian Standard 2800, 4th edition) now require consideration of infill effects.

The rocking wall system, first studied by Housner [7], allows a reinforced concrete wall to rock on its foundation during an earthquake. Post-tensioning tendons provide self-centering, while energy-dissipating devices (e.g., mild steel bars or dampers) absorb seismic energy [8], [9]. Wu & Yang [10] showed that infilled rocking wall frames exhibit controlled deformations and reduced structural damage.

This study evaluates the seismic rehabilitation of an existing 5-story infilled RC moment frame using a rocking wall system, comparing performance before and after retrofit through nonlinear static (pushover) analysis.

2 | Methodology

2.1 | Case Study Description

A 5-story residential building located in Rudsar, Gilan Province, Iran, was selected. The original design followed the Iranian Standard 2800 (3th edition) and the National Building Code. An additional story was constructed beyond the original permit, making seismic evaluation essential.

Structural properties:

I. Structural system: Intermediate RC moment frame.

II. Number of stories: 5.

III. Story height: 3.25 m (except ground floor: 2.80 m).

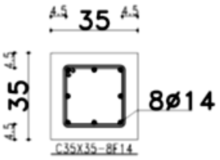
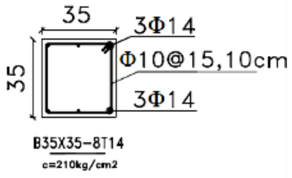
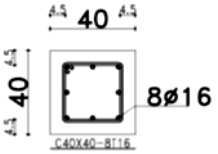
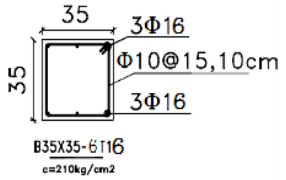
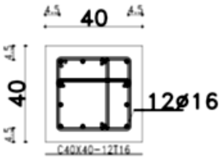
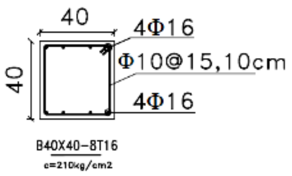
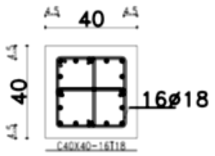
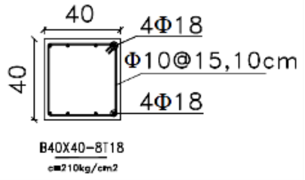
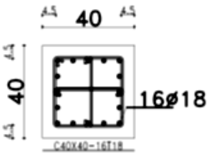
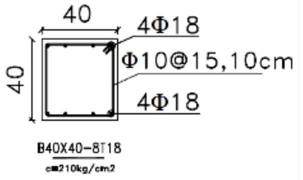
IV. Concrete strength: f'c = 21 MPa.

V. Reinforcement: AIII (fy = 400 MPa) for main bars, AII (fy = 300 MPa) for stirrups.

VI. Soil type: Type IV (very soft soil).

VII. Seismic zone: High-risk (A = 0.30g).

Table 1. Beam and column section properties.

Story	Column Name	Col Sec	Beam Name	Beam Sec
5	C35X35-8T14		B35X35-6T14	
4	C35X35-8T14		B35X35-6T16	
3	C40X40-12T16		B40X40-8T16	
2	C40X40-16T18		B40X40-8T18	
1	C40X40-16T18		B40X40-8T18	

2.2 | Infill Wall Modeling

Infill walls (150 mm thick hollow clay blocks) were modeled using equivalent diagonal strut elements following Iranian Seismic Rehabilitation Code (Publication No. 360). The equivalent strut width (a) was calculated using:

$$a = 0.175 \times (\lambda_1 \times h_{inf})^{\wedge(-0.4)} * r_{inf}, \quad (1)$$

where λ_1 is the relative stiffness parameter, h_inf is the infill height, and r_inf is the diagonal length. Where subscript "inf" denotes the masonry infill wall properties.

Table 2. Calculated diagonal strut widths for each story and span.

NO.	Span	h_{inf} (cm)	Linf (cm)	E_{fe} (kg/cm²)	E_{me} (kg/cm²)	r_{inf} (cm)	t_{inf} (cm)	λ_1	a (cm)
Y-story 5	1-2	290	520	2.10E+06	31550	595.399	15	0.01516	79.9
	2-3	290	605	2.10E+06	31550	670.914	15	0.01484	90.8
Y-story 4	1-2	290	520	2.10E+06	31550	595.399	15	0.01516	79.9
	2-3	290	605	2.10E+06	31550	670.914	15	0.01484	90.8

Table 2. Continued.

NO.	Span	h_{inf}	Linf	E_{fe}	E_{me}	r_{inf}	t_{inf}	λ_1	a
		(cm)	(cm)	(kg/cm²)	(kg/cm²)	(cm)	(cm)		(cm)
Y-story 3	1-2	285	520	2.10E+06	31550	592.98	15	0.0133	83.9
	2-3	285	605	2.10E+06	31550	668.768	15	0.013	95.4
Y-story 2	1-2	285	520	2.10E+06	31550	592.98	15	0.0133	83.9
	2-3	285	605	2.10E+06	31550	668.768	15	0.013	95.4
Y-story 1	1-2	240	520	2.10E+06	31550	572.713	15	0.01353	85.4
	2-3	240	605	2.10E+06	31550	650.865	15	0.01318	98.1

The modulus of elasticity for masonry was taken as E_{me} = 3155 MPa (weak grade with plaster). Strut force capacities (V_{inf}) ranged from 15,246 kg to 20,037 kg depending on story and span.

2.3 | Rocking Wall Modeling

The rocking wall (250 mm thick, 4.0 m long) was added at the building perimeter (Elevations A, D, and 3). The wall was modeled with:

I. Gap elements at the base (Figure 3-39 in thesis) to simulate uplift – these elements resist only compression.

II. Post-tensioned tendons (Grade 270, ASTM A416) with E = 1860 GPa and initial prestress to provide self-centering.

III. Energy dissipation through yielding of mild steel reinforcement at the wall base.

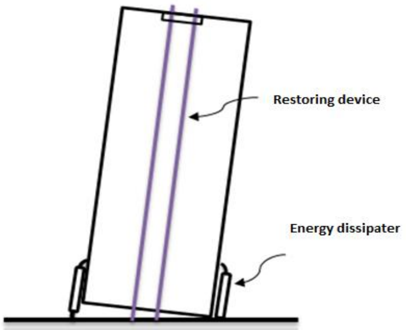
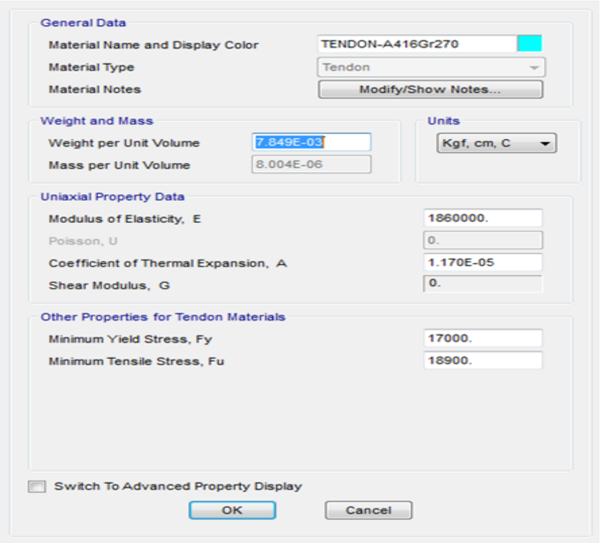


Fig. 2. Schematic of rocking wall system.



Material Name and Display Color: TENDON-A416Gr270
Material Type: Tendon
Weight per Unit Volume: 7.849E-03
Mass per Unit Volume: 8.004E-06
Units: Kgf, cm, C
Modulus of Elasticity, E: 1860000.
Poisson, U: 0.
Coefficient of Thermal Expansion, A: 1.170E-05
Shear Modulus, G: 0.
Minimum Yield Stress, Fy: 17000.
Minimum Tensile Stress, Fu: 18900.
☐ Switch To Advanced Property Display

Fig. 3. 3D model of structure with rocking walls and infill.

2.4 | Nonlinear Static (Pushover) Analysis

Pushover analyses were performed in SAP2000 v.19 according to Publication No. 360. Two load patterns were applied:

I. Modal pattern (proportional to first mode shape).

II. Uniform pattern (constant acceleration).

Target displacements were calculated using the coefficient method (ASCE 41-17):

$$\delta\_t = C_0 \cdot C_1 \cdot C_2 \cdot S\_a \cdot (T\_e^2/(4\pi^2)) \cdot g.$$

For the Life Safety (LS) performance level at Hazard Level 1: $\delta\_target = 7.3$ cm. For Collapse Prevention (CP) at Hazard Level 2: $\delta\_target = 10.95$ cm

Plastic hinges were assigned:

I. Beams: M3 moment hinges (deformation-controlled).

II. Columns: P-M2-M3 interaction hinges (deformation-controlled).

III. Infill struts: axial force hinges (force-controlled).

Verification analyses were conducted in OpenSees using zero-length elements for gap behavior and truss elements for tendons.

3 | Results

3.1 | Original Structure (Without Rocking Wall)

The original infilled frame exhibited unacceptable seismic performance:

I. Drift ratios exceeded the allowable limit (0.0055) by 100–250% across all stories.

II. Maximum roof displacement: 10.8 cm under EX lateral load.

III. Plastic hinges: Many columns exceeded LS and reached CP or near collapse. Several columns showed hinge formation beyond acceptable limits.

IV. Infill walls: All infill panels fractured; equivalent struts reached CP level (complete loss of compressive capacity).

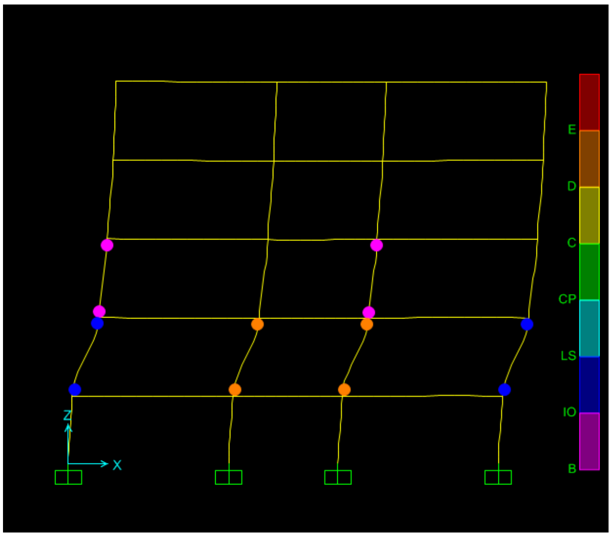


Fig. 4. Plastic hinge formation in original structure (exceeding LS limits)

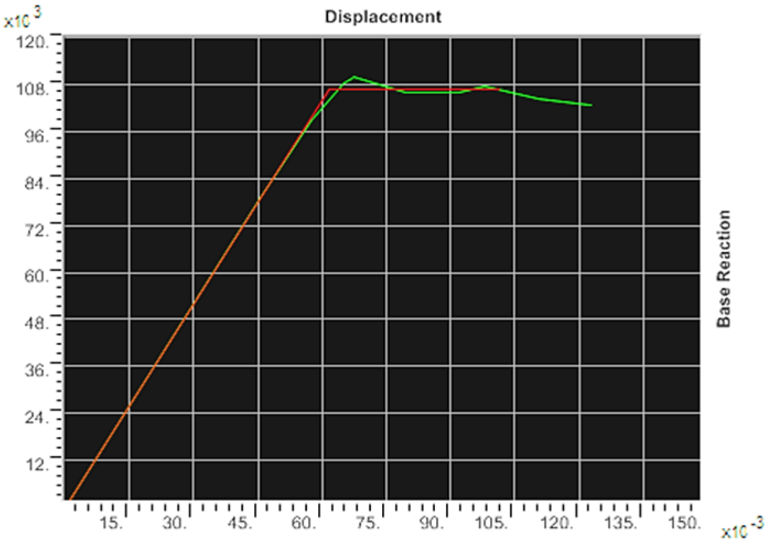


Fig. 5. Pushover curve for original structure (without rocking wall).

3.2 | Retrofitted Structure (With Rocking Wall)

Adding the rocking wall dramatically improved performance:

I. Maximum roof displacement: Reduced to 3.61 cm (66% reduction).

II. Drift ratios: Decreased by 65–78% across all stories; all within the 0.0055 limit.

III. Plastic hinges: Most hinges remained within Immediate Occupancy (IO) or LS. Only infill walls showed collapse, as expected.

IV. Energy dissipation: The rocking wall absorbed significant seismic energy, reducing demands on beams and columns.

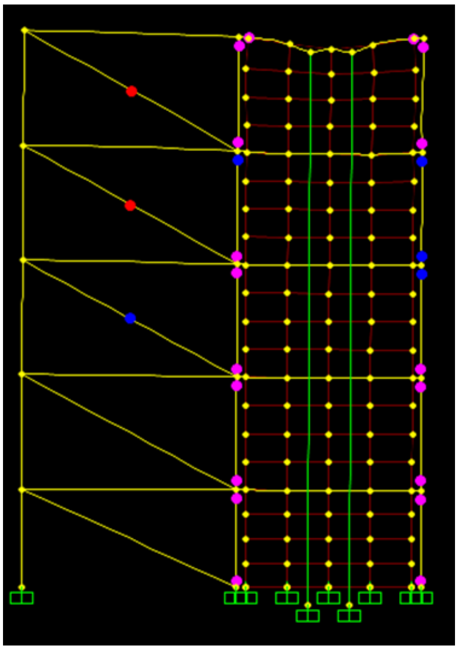


Fig. 6. Plastic hinge formation in retrofitted structure (within IO/LS limits)

3.3 | Comparative Analysis

Table 3. Rocking wall greatly reduces drift (~70%) and improves safety.

Performance Indicator	Without Rocking Wall	With Rocking Wall	Improvement
Max roof displacement (cm)	10.8	3.61	66% ↓
Max inter-story drift ratio	0.011–0.018	0.003–0.005	65–78% ↓
Column hinges	Exceeded LS (near collapse)	Within IO/LS	Acceptable
Beam hinges	Exceeded LS	Within IO/LS	Acceptable
Infill walls	Fractured (CP)	Fractured (CP)	Expected

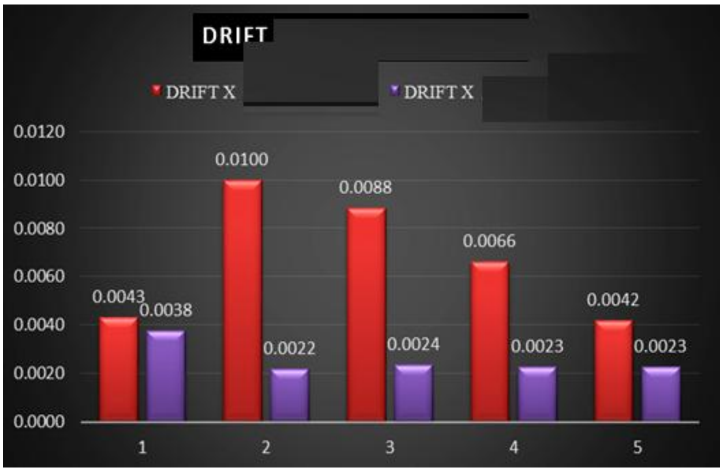
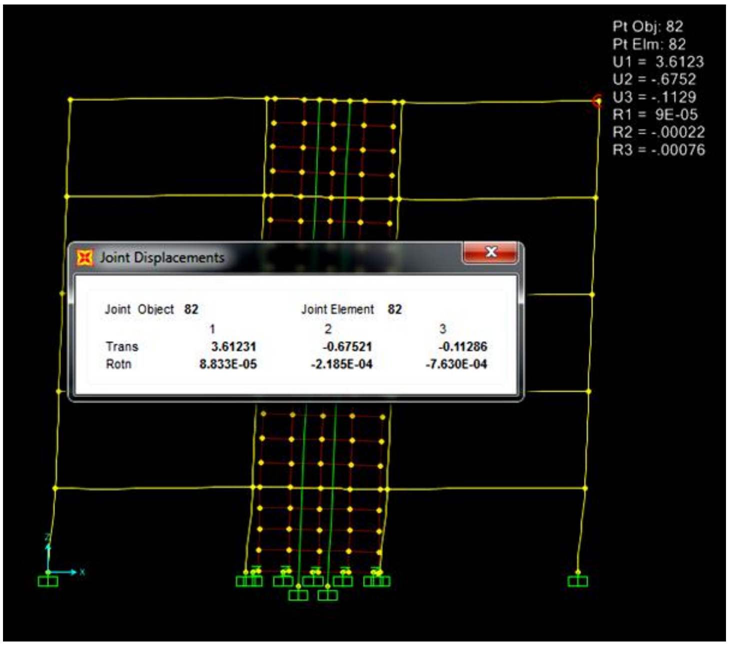


Fig. 7. Comparison of drift profiles.



```
Pt Obj: 82
Pt Elm: 82
U1 =  3.6123
U2 = -.6752
U3 = -.1129
R1 =  9E-05
R2 = -.00022
R3 = -.00076
```

```
Joint  Object   82               Joint Element   82
                  1                    2                    3
Trans          3.61231             -0.67521             -0.11286
Rotn          8.833E-05            -2.185E-04           -7.630E-04
```

Fig. 8. Comparison of roof displacement.

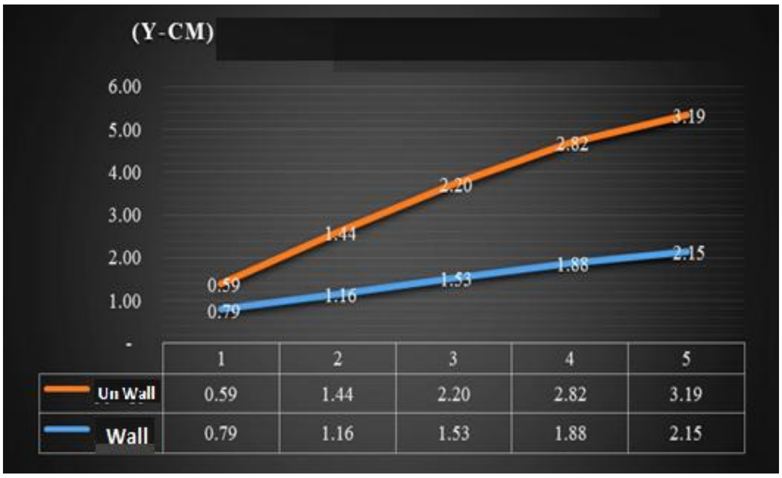
3.4 | OpenSees Verification

OpenSees analyses confirmed SAP2000 results:

I. Base shear demands on the rocking wall reduced by 50–80% compared to a fixed-base wall.

II. Acceleration distribution was more uniform in the retrofitted structure.

III. Residual deformations were present but controlled by post-tensioning.



	1	2	3	4	5
Un Wall	0.59	1.44	2.20	2.82	3.19
Wall	0.79	1.16	1.53	1.88	2.15

Fig. 9. Qualitative comparison of structural element performance.

4 | Discussion

The rocking wall system effectively rehabilitates infilled RC moment frames through several mechanisms:

I. Drift control: By allowing controlled uplift, the rocking wall limits inter-story drift, preventing soft-story mechanisms. The 66% reduction in roof displacement is consistent with findings by Wu & Yang (2017) and Zibaei & Mokari (2014).

II. Energy dissipation: The yielding of mild steel at the wall base (and friction in the gap elements) provides stable hysteresis without significant strength degradation.

III. Protection of primary frame: Plastic hinges were largely confined to the rocking wall and infill panels, protecting beams and columns from severe damage. This aligns with the "damage concentration" concept proposed by Eatherton et al. (2010).

IV. Infill wall interaction: Infill walls contributed initial stiffness but failed at low drift levels. In the retrofitted structure, the rocking wall reduced drift sufficiently to delay infill fracture, though some cracking still occurred.

Limitations:

I. Residual deformations: Despite post-tensioning, some residual drift remained after unloading. Optimizing tendon force could reduce this.

II. Construction complexity: Retrofitting existing foundations with post-tensioning anchorage is challenging and costly.

III. Higher mode effects: Pushover analysis primarily captures first-mode response; dynamic analysis is recommended for validation.

5 | Conclusions

I. The rocking wall system significantly improves seismic performance of infilled RC moment frames. Roof displacement was reduced by 66% and inter-story drifts by 65–78%, bringing them within code limits (≤0.0055).

II. Plastic hinge formation was controlled; most structural elements remained within IO or LS limits after retrofit.

III. Infill walls, though beneficial for initial stiffness, are vulnerable to fracture. The rocking wall reduces drift, mitigating infill damage.

IV. Post-tensioned tendons provide effective self-centering, though some residual deformation remains.

V. The rocking wall is a viable rehabilitation technique for existing infilled RC frames in high-seismic regions, particularly for buildings requiring post-earthquake functionality.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All data generated or analyzed during this study are included in this published article. Additional numerical results, modeling parameters, and finite element analysis outputs are available from the corresponding author upon reasonable request.

Authors' Contributions

R. Roygar: Conceptualization, Methodology, Finite Element Modeling, Data Analysis, Writing–Original Draft Preparation.

R. Madandoust: Supervision, Validation, Interpretation of Results, Writing–Review and Editing, Technical Consultation.

All authors have read and approved the final version of the manuscript.

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Consent for Publication

All authors have reviewed the manuscript and consented to its publication.

Ethics Approval and Consent to Participate

This study did not involve human participants, human data, or animals. Therefore, ethical approval and consent to participate were not required.

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