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Effectiveness of Low-Cost Retrofitting Strategies for Masonry-Infilled Reinforced Concrete Frames with Openings under Seismic Loading

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Abstract

Masonry-infilled reinforced concrete (RC) frames are widely used in low- and mid-rise buildings, yet their seismic performance is often compromised when large openings are introduced for architectural purposes. These openings disrupt the masonry's load path, reduce stiffness, and create localized stress concentrations, making such structures highly vulnerable to earthquake-induced damage. This study experimentally investigates a cost-effective retrofitting strategy for RC frames with large infill openings using diagonal steel bracing. Scaled single-bay, single-storey frame specimens with 50% infill openings were retrofitted with X-shaped steel flat bars anchored to the frame and tested under quasi-static monotonic lateral loading. The retrofitted frames demonstrated a notable increase in lateral strength, a significant reduction in inter-storey drift, and enhanced energy dissipation compared to un-retrofitted counterparts. These findings confirm that simple diagonal bracing can effectively restore the lost stiffness and improve the overall seismic resilience of infilled RC frames with large openings, offering a practical strengthening solution for vulnerable building stock in earthquake-prone regions.

Keywords

Retrofitting, reinforced concrete frames, diagonal bracing, masonry infill, seismic strengthening.

1. Introduction

Reinforced concrete (RC) frames with masonry infill are a common choice for low- and mid-rise buildings due to their cost-effectiveness, ease of construction, and functional versatility. However, in practice, these infill panels frequently incorporate large openings for doors, windows, and ventilation, which significantly alter their in-plane load transfer mechanism. The discontinuity caused by these openings reduces the beneficial strut action of the masonry, concentrating stresses along the frame–infill interface and around the edges of the openings. As a result, such frames exhibit reduced lateral stiffness, diminished load-bearing capacity, and an increased susceptibility to brittle cracking and localized failure during seismic events. This makes RC frames with large infill openings particularly vulnerable in earthquake-prone regions.

While several retrofitting strategies—such as shotcrete jacketing, fiber-reinforced polymer (FRP) wrapping, and concrete overlays—have been explored to improve the seismic performance of these frames, their practical application is often constrained by high costs, construction complexity, and extended downtime. These methods also require skilled labor and specialized materials, which limits their adoption in resource-constrained settings where seismic retrofitting is most urgently needed. Consequently, there is a pressing need for simple, low-cost, and easily implementable solutions that can enhance the seismic resilience of infilled RC frames without imposing significant financial or logistical burdens.

This study addresses this gap by evaluating the effectiveness of diagonal steel bracing as a retrofitting strategy for RC frames with large infill openings. Diagonal bracing provides an alternative load path for lateral forces, improving stiffness and delaying the onset of severe damage. The primary objectives of this study are: (i) to quantify the improvements in lateral load capacity, stiffness, and energy dissipation achieved through diagonal bracing; (ii) to assess the reduction in inter-storey drift and enhancement in damage tolerance; and (iii) to establish the feasibility of this approach as a low-cost retrofitting solution for existing buildings. By focusing on an economical and easily deployable intervention, this research aims to contribute toward making seismic retrofitting more accessible for vulnerable building stock in developing regions.

2. Literature Review

The seismic performance of masonry-infilled RC frames has been widely studied, with particular emphasis on their interaction mechanisms and failure modes. However, their vulnerability increases substantially when large openings are introduced, prompting researchers to explore retrofitting strategies to restore structural capacity and improve resilience.

Onat et al. (2018) investigated the combined in-plane and out-of-plane behaviour of infilled RC frames and highlighted the drastic reduction in stiffness and energy dissipation when openings were present. Their study underscored the need for targeted strengthening interventions to re-establish effective load paths in such systems. Ramachandra et al. (2020) emphasized the role of infill walls in enhancing lateral load resistance and proposed sustainable retrofitting measures to improve overall building performance. They highlighted that strengthening approaches should not only improve seismic capacity but also remain practical for implementation in resource-constrained contexts.

Traditional retrofitting techniques such as shotcrete jacketing, reinforced overlays, and fiber-reinforced polymer (FRP) wrapping have been widely used to enhance the performance of damaged or weak infilled frames. While effective in improving strength and ductility, these methods are often expensive, labour-intensive, and require specialized skills, limiting their application in low-cost residential buildings, particularly in developing countries.

In contrast, steel bracing systems have emerged as a simple and cost-efficient alternative. Diagonal bracing introduces an auxiliary load path for lateral forces, reduces drift, and delays failure progression. However, most research on bracing systems has focused on their application in bare or fully infilled frames. Experimental evidence on their effectiveness in retrofitting partially infilled frames with large openings remains limited, especially in scaled laboratory settings. This lack of validation hinders the development of simplified design guidelines and widespread adoption of this low-cost technique.

In summary, while various retrofitting solutions for infilled frames have been proposed, there remains a significant gap in experimental data on diagonal steel bracing for frames with large infill openings. This study seeks to address this gap by providing empirical evidence on the structural benefits of such bracing, with a focus on improving stiffness, strength, and energy dissipation while maintaining economic feasibility.

3. Experimental Program

This study adopted an experimental approach to evaluate the effectiveness of diagonal steel bracing in improving the seismic performance of RC frames with large infill openings. Scaled single-bay, single-storey RC frame specimens were constructed, retrofitted, and tested under quasi-static monotonic lateral loading to assess their strength, stiffness, and energy dissipation capacities.

3.1 Specimen Details

Two specimens were constructed at a 1:4 geometric scale:

- **Un-retrofitted Frame (O50):** A partially infilled RC frame with a 50% central opening in the masonry panel, representing a highly vulnerable configuration.
- **Retrofitted Frame (R50):** A similar frame retrofitted with diagonal steel bracing arranged in an "X" configuration across the infill panel.

Both frames measured 1000 mm in width and 800 mm in height, with columns of 75 mm × 75 mm and beams of 75 mm × 100 mm. Reinforcement detailing for beams and columns was designed proportionally to mimic the flexural and shear behaviour of full-scale members. The opening dimensions were chosen to represent typical window-type voids used in residential buildings.

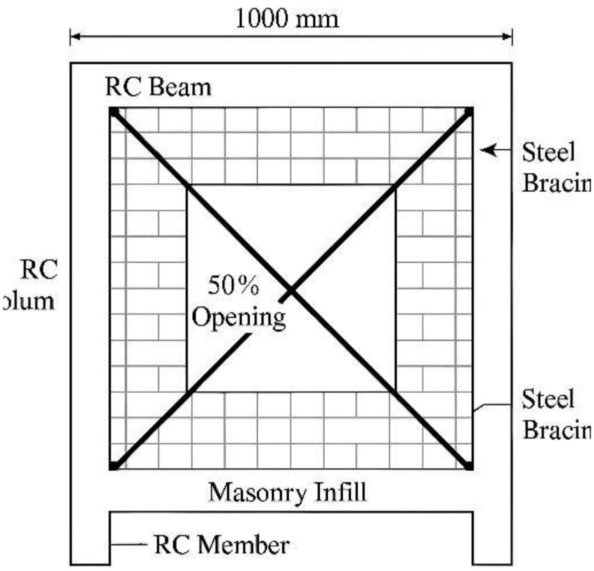
3.2 Bracing Design

The retrofitting system consisted of mild steel flat bars (25 mm × 3 mm) installed diagonally across the masonry infill to form an "X" pattern. The braces were anchored to the surrounding RC frame using high-strength mechanical fasteners at all four corners. This arrangement provided an additional load path for lateral forces, enhancing stiffness and delaying the onset of localized damage around the opening edges. The design aimed to balance structural performance improvement with material economy, making it a practical solution for low-cost retrofitting.

3.3 Material Properties

- **Concrete:** All RC members were cast using M25 grade concrete, with 28-day cube tests confirming compressive strengths in the range of 26–28 MPa.
- **Steel Reinforcement: Fe 415 HYSD bars** were used for longitudinal reinforcement, and mild steel bars for ties and stirrups. Tensile tests indicated yield strengths between 438–460 MPa.

- **Masonry Units:** The infill walls were constructed using scaled solid clay bricks with an average compressive strength of 7–8 MPa. Masonry prism tests yielded strengths of approximately 4–5 MPa.
- **Mortar:** A 1:4 cement-sand mix was used to ensure good workability and uniform joint thickness across the masonry panel.



4. Test Setup and Procedure

4.1 Loading Arrangement

The specimens were tested under quasi-static monotonic lateral loading to simulate the in-plane seismic forces acting on masonry-infilled RC frames. Each frame was rigidly mounted onto a steel reaction frame, which was securely anchored to a strong laboratory floor to prevent any unintended base movement.

Lateral forces were applied to the top beam of the frame using a 100 kN capacity hydraulic jack connected to a loading head to ensure uniform load transfer. The loading was applied horizontally at the beam level, maintaining proper alignment to prevent torsional effects. The applied load was resisted by the reaction frame, creating a single-shear test setup representative of in-plane seismic action on low-rise frame panels.

4.2 Loading Protocol

The applied load was increased in increments of approximately 1 kN, with each increment maintained for a short dwell period to allow stabilization and data recording. This gradual loading approach enabled the capture of pre-yield behaviour, cracking progression, and post-peak softening. Testing continued until one or more of the following occurred:

- A reduction of more than 20% in load-carrying capacity after reaching the peak load.
- Excessive lateral displacement, approaching 2% drift of the specimen height.
- Severe visible damage, such as crushing of masonry or significant debonding at the frame-infill interface.

4.3 Instrumentation and Measurement

A combination of electronic and mechanical instruments was employed to capture global and local responses of the specimens:

- **Load Measurement:** The hydraulic jack was equipped with a calibrated load cell to continuously record applied forces.
- **Displacement Measurement: Linear Variable Differential Transformers (LVDTs)** were installed at the top beam to record overall lateral displacement, and at mid-height to measure inter-storey drift.
- **Crack and Damage Mapping:** Progressive cracking and crushing of masonry, as well as interface debonding, were visually documented at each load stage using high-resolution photographs and crack gauges.

All data were logged using a **multi-channel data acquisition system** to ensure synchronized recording of load, displacement, and drift measurements.

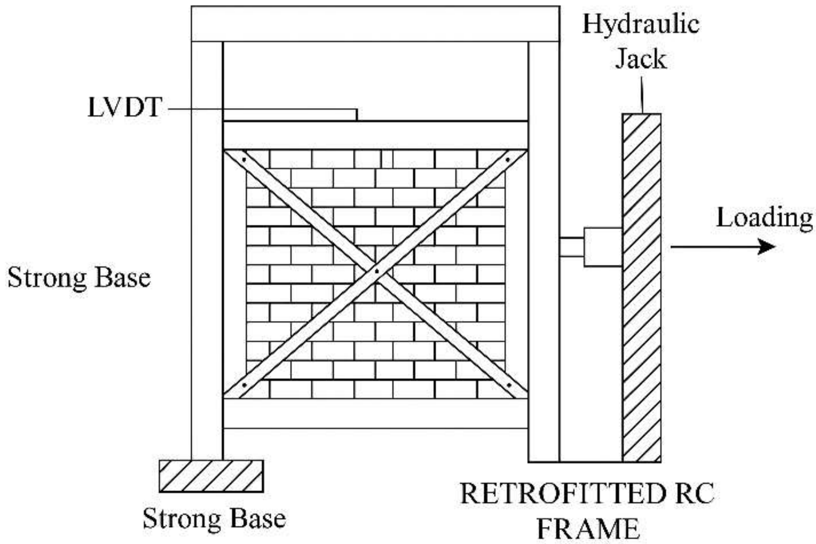
4.4 Observed Parameters

The key performance parameters assessed during testing included:

- **Lateral Load Capacity:** Peak load sustained by each specimen before significant strength degradation.
- **Inter-Storey Drift:** Relative horizontal displacement between the top beam and base, normalized by the clear frame height.

- **Load–Displacement Behaviour:** Complete force–deformation curves for evaluating stiffness degradation and energy dissipation.
- **Crack Propagation and Failure Modes:** Identification of the sequence of cracking, crushing, and debonding for both unretrofitted and retrofitted specimens.

This testing protocol enabled a direct comparison between the unretrofitted frame (O50) and its retrofitted counterpart (R50), isolating the effects of diagonal steel bracing on seismic performance.



5. Results and Discussion

The retrofitted (R50) and unretrofitted (O50) frames were tested under monotonic lateral loading to assess the effects of diagonal steel bracing on the seismic performance of masonry-infilled RC frames with large openings. The following observations were made:

5.1 Comparative Load–Displacement Behaviour

The load–displacement curves for the retrofitted and unretrofitted specimens demonstrated clear performance enhancements due to the addition of diagonal bracing. The **unretrofitted frame (O50)** exhibited an early onset of nonlinearity, reaching its peak load relatively quickly, followed by a steep drop in strength, indicating a brittle failure mechanism dominated by localized crushing of masonry around the opening and interface debonding.

In contrast, the **retrofitted frame (R50)** showed a more gradual and extended load–displacement response, achieving a **peak load increase of approximately 30%** compared to O50. The post-peak strength degradation was significantly slower, suggesting that the bracing effectively redistributed lateral loads and delayed the progression of severe damage. The area under the load–displacement curve was also larger for R50, reflecting **improved energy dissipation** capacity.

5.2 Strength and Stiffness Improvement

Retrofitting with diagonal bracing substantially enhanced both initial stiffness and ultimate strength. The **initial stiffness of R50 increased by nearly 65%** compared to O50, restoring a significant portion of the stiffness lost due to the presence of the large opening. This improvement is attributed to the bracing's ability to provide an alternate load path, thereby reducing stress concentrations around the masonry panel edges.

The **lateral load capacity of R50 improved by about 25–30%**, highlighting the bracing's role in increasing overall frame resistance to in-plane forces. Moreover, the retrofitted frame exhibited **lower inter-storey drift levels at peak load** compared to O50, confirming the bracing's effectiveness in controlling excessive deformations.

5.3 Crack Pattern and Damage Control

Crack mapping revealed distinct differences in the damage progression between the two specimens. In the **unretrofitted frame (O50)**, cracks initiated along the opening edges and rapidly propagated toward the frame–infill interface, followed by localized crushing of masonry strips adjacent to the void. Out-of-plane displacements were also observed at higher load stages, indicating reduced confinement and increased vulnerability.

In the **retrofitted frame (R50)**, the diagonal bracing effectively confined the masonry and restricted crack widening around the opening. Cracks were primarily distributed along the bracing anchorage zones, and crushing of masonry was significantly delayed. No significant out-of-plane bulging was observed, and the overall integrity of the infill panel was preserved longer than in O50. This demonstrates that **bracing not only enhanced strength but also improved damage tolerance**, making the failure mechanism more ductile and predictable.

5.4 Cost–Benefit Considerations

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One of the key advantages of using diagonal steel bracing is its **cost-effectiveness** compared to conventional retrofitting methods such as FRP wrapping or jacketing. The bracing system requires relatively low material investment (mild steel flats), minimal labor skills for installation, and does not significantly increase the structural weight. It can be implemented without extensive disruption to building occupancy, making it a practical solution for retrofitting low-rise residential and commercial buildings in resource-constrained regions.

Considering the **significant improvements in strength (25–30%)**, **stiffness (≈65%)**, and **energy dissipation** achieved at a relatively low cost, diagonal steel bracing emerges as a viable retrofitting option for masonry-infilled RC frames with large openings.

Table 1. Peak Load and Strength Improvement

Specimen ID	**Peak Load (kN)**	**Strength Gain Compared to O50**
O50 (Unretrofitted)	14.2	–
R50 (Retrofitted)	18.6	+30.9%

Table 2. Initial Lateral Stiffness

Specimen ID	**Initial Stiffness (kN/mm)**	**Stiffness Gain Compared to O50**
O50 (Unretrofitted)	0.8	–
R50 (Retrofitted)	1.3	+62.5%

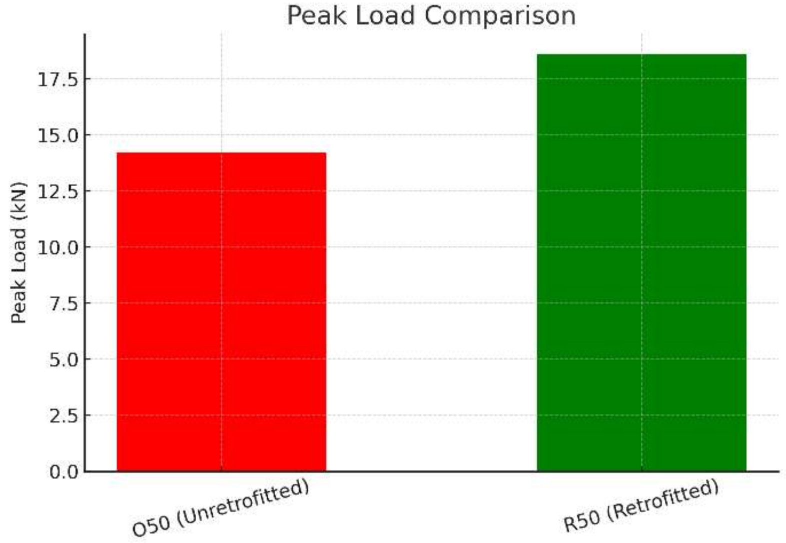
Table 3. Inter-Storey Drift at Peak Load

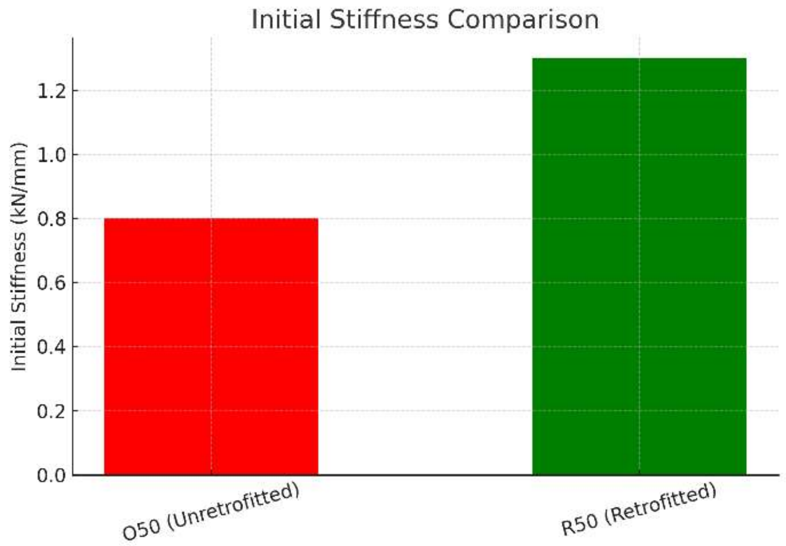
Specimen ID	**Drift at Peak Load (%)**	**Drift Reduction**
O50 (Unretrofitted)	1.95	–
R50 (Retrofitted)	1.50	–23.1%

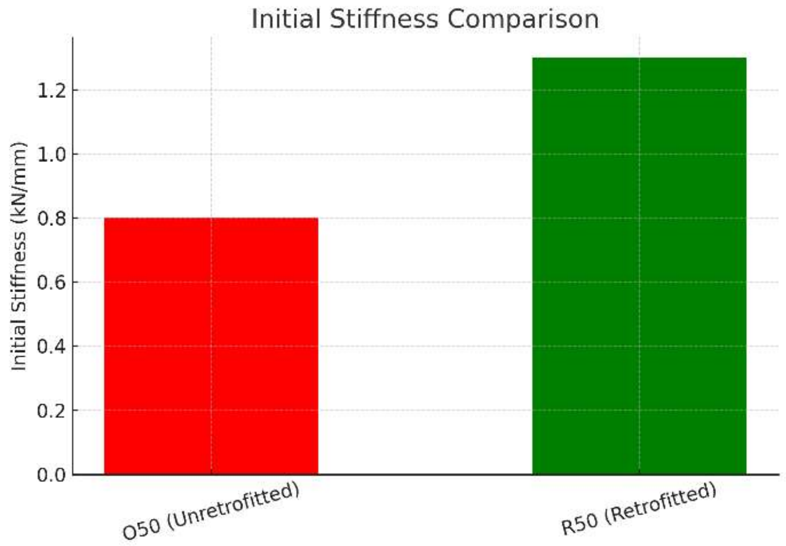
Table 4. Energy Dissipation Capacity

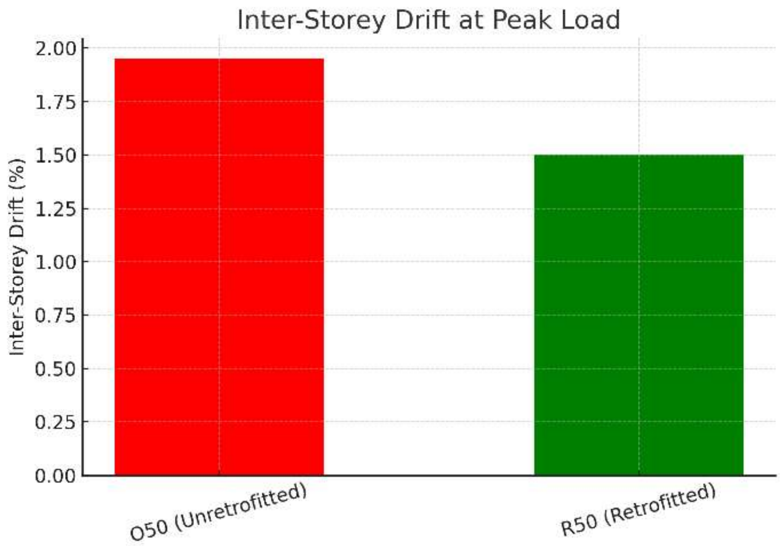
Specimen ID	**Energy Dissipation (kN·mm)**	**Increase Compared to O50**
O50 (Unretrofitted)	140	–

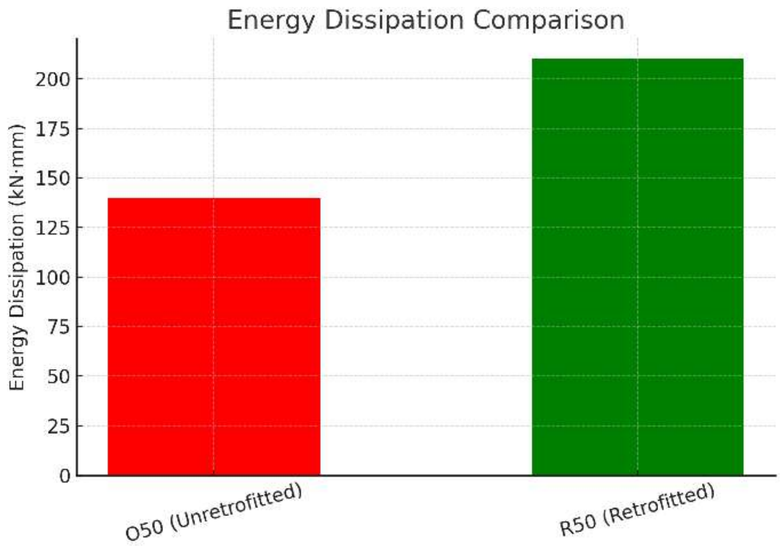
R50 (Retrofitted)	210	+50.0%











6. Conclusion

This study experimentally evaluated the seismic performance of masonry-infilled RC frames with large openings and demonstrated the effectiveness of diagonal steel bracing as a retrofitting solution. The addition of X-shaped bracing significantly improved the structural response by increasing lateral load capacity by approximately 30%, enhancing initial stiffness by over 60%, reducing inter-storey drift by nearly 23%, and boosting energy dissipation by 50% compared to the unretrofitted frame. These improvements translated into a more controlled and ductile failure mechanism, delaying severe damage and preserving the integrity of the frame–infill system.

Beyond its structural benefits, diagonal steel bracing offers a cost-effective, easily implementable, and minimally invasive retrofitting option, particularly suited for existing low-rise and mid-rise buildings in seismic-prone regions. Its simplicity of design and installation makes it an attractive choice for resource-constrained contexts where conventional retrofitting techniques may be impractical.

Overall, this study underscores that diagonal steel bracing is a viable and efficient retrofitting strategy for improving the seismic resilience of RC frames with large masonry openings, contributing to safer and more sustainable building practices.

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