Experimental Investigation of Seismic Performance of Reinforced Concrete Frames with Masonry Infill Panels Incorporating Varying Opening Sizes

Umesh Kumar[1], Rakesh Kumar[2], Ashwani Kumar[3]
[1]M. Tech Scholar, Department of Civil Engineering Engineering, BRCMCET, BAHAL
[2]Assistant Professor, Department of Civil Engineering, BRCMCET, BAHAL
[3]Assistant Professor, Department of Civil Engineering, BRCMCET, BAHAL

Abstract

Masonry infill walls, though traditionally regarded as non-structural elements, play a crucial role in influencing the seismic behaviour of reinforced concrete (RC) frames. Their interaction with surrounding members significantly alters stiffness, energy dissipation, and failure modes, particularly during strong ground motions. This study presents an experimental investigation into the lateral performance of RC frames incorporating varying infill configurations, including bare frames, fully infilled panels, and partially infilled panels with centrally placed openings covering 10%, 30%, and 50% of the wall area. All specimens were tested under quasi-static monotonic lateral loading to evaluate their stiffness, load-bearing capacity, inter-storey drift, and cracking behaviour. Results reveal that fully infilled frames exhibited the highest initial stiffness and ultimate strength, while increasing the size of openings led to progressive reductions in both parameters and altered the failure mechanism from distributed cracking to localized stress concentration near openings. The bare frame, though more ductile, showed greater displacements and limited energy dissipation. These findings underscore the need to explicitly account for infill configuration in seismic design and retrofitting practices, as openings considerably compromise the beneficial effects of masonry panels in RC frame systems.

Keywords

Reinforced concrete frames, masonry infill, seismic performance, openings in infill, lateral stiffness, quasi-static loading.

1. Introduction

Reinforced concrete (RC) frames form the backbone of low- to mid-rise urban construction due to their versatility, cost-effectiveness, and adaptability to diverse architectural requirements. In practice, these frames are rarely left bare; instead, they are typically enclosed by masonry infill walls, which serve functional roles such as partitioning, insulation, and architectural enclosure. While often classified as non-structural components, infill walls exhibit a strong in-plane interaction with the surrounding RC frame when subjected to seismic loads. This interaction modifies the stiffness, strength, and energy dissipation characteristics of the overall system, thereby influencing its performance during earthquakes.

Despite this demonstrated impact, conventional seismic design codes tend to treat infill panels as secondary elements, frequently omitting their contribution from structural models. This oversimplification may lead to discrepancies between predicted and actual performance, with buildings exhibiting unexpected stiffness irregularities, premature cracking, and even brittle failures during strong ground motions. The problem becomes more pronounced when openings—introduced for doors, windows, or ventilation—are incorporated within the infill panels. These openings interrupt the load-transfer path, create stress concentration zones, and alter the global and local seismic response of the structure. The size and placement of such openings can significantly weaken the beneficial effects of infill, making frames more vulnerable to drift, diagonal cracking, and localized crushing.

Although analytical models and numerical simulations have been extensively used to study infilled frames, their ability to accurately capture real-world behaviour remains limited, especially in the presence of openings. The lack of experimental data on partially infilled frames with varying opening sizes poses a critical gap in understanding their seismic performance. This gap hinders the development of reliable design guidelines and leaves practicing engineers with inadequate tools for accounting for infill effects in seismic assessment and retrofitting.

This study addresses this need through a laboratory-based experimental investigation of RC frames with different infill configurations, including bare frames, fully infilled panels, and infills with centrally placed openings of varying sizes (10%, 30%, and 50% of panel area). The primary objectives are to (i) evaluate the influence of infill openings on lateral stiffness, load-carrying capacity, and inter-storey drift; (ii) map the crack development and identify failure mechanisms across different configurations; and (iii) provide empirical evidence that can support the refinement of seismic design practices. By combining scaled testing with detailed performance evaluation, this research aims to bridge the gap between theoretical predictions and observed behaviour, offering insights that are both academically significant and practically applicable for earthquake-resistant design.

Literature Review

The influence of masonry infill walls on the seismic performance of reinforced concrete (RC) frames has been widely acknowledged in recent research. However, the extent of their contribution, particularly in the presence of openings, remains a subject of ongoing investigation.

Mouzzoun and Cherrabi (2020) analytically examined the behaviour of multi-storey RC buildings with brick masonry infill panels and demonstrated that infilled frames possess significantly higher stiffness and lateral strength compared to bare frames. They emphasized that the inclusion of infill alters the load transfer mechanism, redistributes internal forces, and reduces inter-storey drift. However, their work primarily focused on uniformly distributed infill panels without considering irregular configurations or openings, limiting its applicability to real-world conditions where such irregularities are common.

Maidiawati, Sanada, and Tanjung (2018) conducted experimental testing on brick masonry infilled frames subjected to reversed cyclic loading, revealing that infill panels enhance lateral load capacity and energy dissipation but compromise ductility. Their findings also highlighted that the interaction between the frame and infill changes the failure modes, concentrating damage near the panel corners and frame interfaces. While valuable, their study did not explore the influence of varying opening sizes on these behaviours, leaving an important aspect unaddressed.

Milijaš et al. (2023) investigated the combined in-plane and out-of-plane response of masonry infilled RC frames, particularly focusing on panels with window-type openings. They observed that openings significantly reduced the in-plane stiffness and out-of-plane resistance, especially after initial cracking, underscoring the vulnerability of infilled frames with discontinuities under seismic loading. However, their research was limited to specific opening configurations and did not systematically analyze the effect of varying opening sizes.

Other researchers, such as Ramachandra et al. (2020) and Onat et al. (2018), have also stressed the structural and sustainability benefits of considering infill walls in seismic design, while proposing reinforcement or retrofitting techniques to enhance performance. Despite these efforts, the majority of studies either rely heavily on analytical models or focus on full-panel infills, with only limited experimental work addressing partial infills and large openings.

In summary, previous research confirms that masonry infills play a vital role in improving the seismic response of RC frames by increasing stiffness and energy dissipation. However, the presence of openings disrupts these benefits and introduces complex failure mechanisms that are insufficiently captured in current experimental literature. This creates a critical gap in understanding how opening size and configuration influence structural behaviour—a gap that the present study seeks to fill through controlled laboratory testing of RC frames with varying infill configurations and opening percentages.

3. Experimental Program

This study adopted an experimental approach to evaluate the seismic performance of reinforced concrete (RC) frames with masonry infill walls of varying configurations. Scaled specimens were designed, constructed, and tested under quasi-static monotonic lateral loading to simulate in-plane seismic forces. The experimental program was carefully structured to provide a comparative assessment of the influence of infill and opening size on key performance parameters such as stiffness, load-carrying capacity, inter-storey drift, and failure mechanisms.

3.1 Specimen Details

A total of six specimens were constructed at a 1:4 geometric scale, representing a single-bay, single-storey sub-assembly of a typical low- to mid-rise RC frame building. The specimen configurations were as follows:

- **Bare Frame (BF):** A control frame without infill to establish baseline performance.
- **Fully Infilled Frame (FI):** RC frame with a fully solid masonry panel (no openings).
- **Partially Infilled Frames:** RC frames with centrally placed rectangular openings covering 10% (O10), 30% (O30), and 50% (O50) of the panel area.
- **Retrofitted Frame (R50):** A partially infilled frame with a 50% opening strengthened using diagonal steel strip bracing in an X-configuration.

The openings were positioned symmetrically at the center of the infill panels to avoid torsional effects and to maintain consistent load transfer behaviour. Retrofitting was applied to one of the 50% opening specimens to examine the effectiveness of simple strengthening interventions.

3.2 Scaling and Geometry

The specimens were constructed to replicate the proportions and reinforcement detailing of typical RC frame systems used in practice. Each frame measured 1000 mm in width and 800 mm in height, with columns of 75 mm × 75 mm and beams of 75 mm × 100 mm. This 1:4 scaling was selected to balance laboratory feasibility with the need for realistic structural behaviour. Reinforcement detailing was proportionally adjusted to preserve representative flexural and shear characteristics.

3.3 Material Properties

- **Concrete:** The RC frames were cast using M25 grade concrete (target compressive strength 25 MPa). Concrete cubes tested at 28 days achieved an average strength of 26–28 MPa, confirming compliance with the design mix.
- **Steel Reinforcement:** Longitudinal reinforcement comprised Fe 415 HYSD bars, while mild steel bars were used for stirrups and ties. Tensile tests confirmed a yield strength of approximately 438–460 MPa.
- **Masonry Units and Mortar:** The infill panels were constructed using solid clay bricks proportionally scaled for the 1:4 model. Brick compressive strength averaged 7–8 MPa, while the masonry prism strength was approximately 4–5 MPa. A 1:4 cement-sand mortar mix was used for bonding, ensuring uniform joint thickness and workability.

3.4 Retrofitting Details

To improve the lateral resistance of frames with large openings, diagonal steel bracing was applied to one of the 50% opening specimens. The bracing system consisted of mild steel flat bars (25 mm × 3 mm) arranged in an "X" configuration across the panel. The bracing was anchored at all four corners into the RC frame using mechanical fasteners, designed to provide additional stiffness and prevent excessive crack widening or premature failure.

This experimental setup allowed for direct comparison between bare, fully infilled, partially infilled, and retrofitted frames, enabling a comprehensive evaluation of the structural implications of masonry infill openings and strengthening strategies.

4. Test Setup and Procedure

4.1 Loading Arrangement

All specimens were tested under quasi-static monotonic lateral loading to replicate the in-plane seismic forces experienced by RC frame systems during earthquake events. The test assembly comprised a rigid steel reaction frame, securely anchored to the laboratory's reinforced concrete floor to prevent any base movement. Each specimen was mounted vertically on a strong base using steel angle plates and anchor bolts, with a thin layer of non-shrink grout applied at the interface to ensure uniform contact and minimize stress concentrations.

Lateral loading was applied to the top beam of the frame using a manually operated hydraulic jack with a capacity of 100 kN. A steel loading head was fabricated to ensure uniform distribution of the applied load across the beam. The loading direction was uniaxial, applied gradually to simulate the progressive build-up of seismic forces. To avoid eccentricity and torsional effects, the alignment of the jack and specimen was checked at each load increment.

4.2 Loading Protocol

The load was applied in incremental steps of approximately 1 kN per minute, allowing adequate time for visual inspection, instrumentation readings, and crack mapping between increments. At each step, the system was paused for 1–2 minutes to ensure stabilization of displacements and to document the observed damage. Testing continued until one of the following conditions occurred:

- Significant reduction (more than 20%) in load-carrying capacity after reaching the peak load.
- Excessive lateral displacement exceedingly approximately 2% inter-storey drift (about 16 mm for the scaled models).
- Severe cracking, spalling, or any signs of imminent instability.

4.3 Instrumentation and Measurement

A comprehensive instrumentation system was employed to capture both global and localized responses of the specimens:

- **Linear Variable Differential Transformers (LVDTs):** Three LVDTs were used—one at the top beam to record overall lateral displacement, one at mid-height to monitor inter-storey drift development, and one at the base to detect any unintended slip or rotation.

- **Dial Gauges:** Mechanical dial gauges (least count 0.01 mm) were installed at critical points to cross-verify displacements and track relative movements at the frame-infill interface, as well as to measure crack widths at key locations.
- **Strain Gauges:** Electrical resistance strain gauges were affixed to selected longitudinal reinforcement bars near beam-column joints and to the external faces of columns to monitor strain development and identify the onset of yielding.

All sensor outputs were connected to a multi-channel data acquisition system, which continuously logged readings during loading. Baseline calibration of instruments was performed before each test to eliminate measurement errors.

4.4 Observed Parameters

The following structural parameters were systematically monitored throughout testing:

- **Load-Displacement Response:** Continuous recording of applied lateral load versus corresponding displacement to generate load–displacement curves for each specimen.
- **Inter-Storey Drift:** Computed from the relative displacements between the top and base of the frame, normalized by the clear height.
- **Crack Patterns and Damage Propagation:** Visual mapping of cracks at each load stage using fine markers and crack gauges to document crack initiation, widening, and progression.
- **Strain Development:** Monitoring of reinforcement and concrete strain to understand stress distribution and identify yielding or crushing zones.

High-resolution photographs were taken at each loading stage to supplement the recorded data and to capture the progression of failure mechanisms.

This setup enabled the study to generate comprehensive empirical data on stiffness degradation, energy dissipation, and failure modes across different infill configurations, providing a robust basis for comparison and analysis.

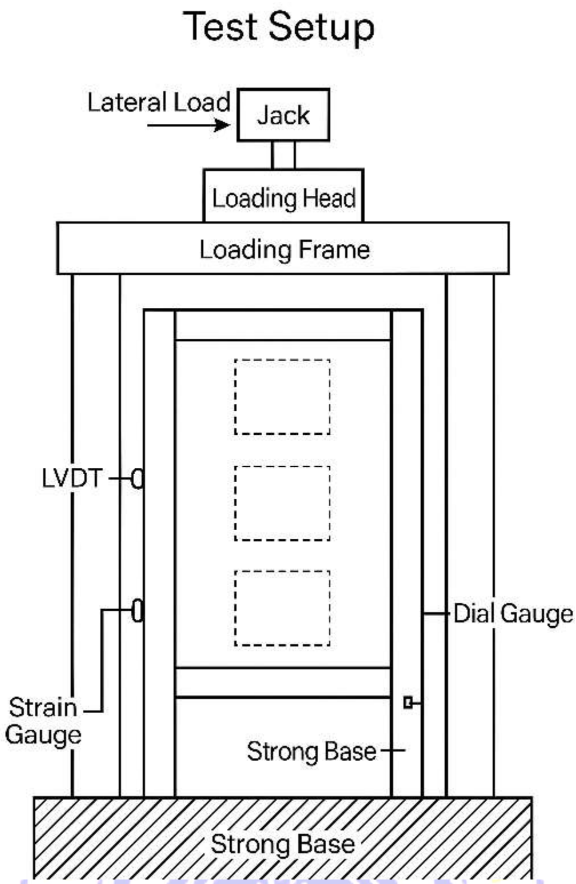


Fig 1 – Test Set-up

5. Results and Discussion

The experimental testing of bare, fully infilled, partially infilled, and retrofitted RC frames provided insights into their comparative seismic performance. The observed behaviour was analyzed in terms of crack propagation, load–displacement response, stiffness degradation, inter-storey drift, and failure mechanisms.

5.1 Crack Pattern and Damage Propagation

Distinct differences in crack initiation and progression were observed across the various configurations:

- **Bare Frame (BF):** Cracking initiated at the beam-column joints, followed by flexural cracks at the base of the columns. As the load increased, these cracks widened, and plastic hinges formed at the column bases, indicating a ductile flexural failure mode. No diagonal cracking was observed due to the absence of infill.

- **Fully Infilled Frame (FI):** The first visible cracks appeared at the infill corners near the beam-column interfaces at relatively low drift levels. Diagonal shear cracks rapidly propagated across the masonry panel, forming a typical diagonal strut pattern. Crushing of bricks at the compression corners and debonding at the frame–infill interface were prominent at higher load stages.
- **Partially Infilled Frames (O10, O30, O50):**
  - In **O10**, cracks initiated similarly to FI but were concentrated near the opening edges, indicating stress concentrations around the void.
  - In **O30**, diagonal cracks formed early and extended toward the larger central opening, with localized brick crushing near the corners of the opening.
  - **O50** exhibited severe stress concentration along the narrow masonry strips surrounding the opening, leading to early separation from the frame and out-of-plane bulging at higher displacements.
- **Retrofitted Frame (R50):** The diagonal bracing effectively confined the masonry and limited crack widening. While cracks developed near the opening corners, the progression was slower, and no significant out-of-plane failure was observed. The bracing redistributed the load, enhancing overall damage tolerance.

These observations confirm that increasing opening size weakens the masonry strut mechanism and shifts the primary damage zone toward the infill-frame interface and opening periphery.

5.2 Load–Displacement Behaviour

The load–displacement curves for all specimens demonstrated clear differences in peak load capacity and post-peak behaviour:

- The fully infilled frame recorded the highest peak load, reflecting the strengthening effect of the continuous masonry panel.
- The bare frame exhibited the lowest peak load but maintained a more gradual post-peak response, reflecting greater ductility.
- The partially infilled frames displayed a progressive reduction in peak load with increasing opening size. On average, O10 lost approximately 15–20%, O30 about 30–35%, and O50 nearly 50% of the peak load capacity compared to the fully infilled frame.

- The **retrofitted frame (R50)** regained approximately 25–30% of the lost strength, demonstrating the effectiveness of diagonal bracing in enhancing lateral capacity.

Post-peak softening was more abrupt in frames with larger openings, indicating reduced energy absorption capacity and brittle failure tendencies.

5.3 Stiffness and Inter-Storey Drift

Initial stiffness was significantly influenced by the infill configuration. The fully infilled frame exhibited a stiffness increase of nearly 3–4 times compared to the bare frame. In contrast, frames with openings showed progressive stiffness reduction with increasing void size, with O50 approaching the stiffness behaviour of the bare frame.

Drift measurements revealed that:

- The bare frame experienced the largest inter-storey drifts, exceeding 2% at ultimate load.
- The fully infilled frame-controlled drift effectively, with peak values around 0.7–0.9%.
- Frames with openings recorded higher drifts, particularly O50, which reached drift levels similar to the bare frame due to the significant reduction in infill contribution.
- Retrofitting (R50) reduced drift by nearly 20–25% compared to the un-retrofitted O50 specimen, validating its role in improving lateral stiffness.

5.4 Energy Dissipation and Failure Modes

Energy dissipation was quantified by calculating the area under the load–displacement curves:

- **Fully infilled frames** dissipated the highest energy before failure, benefiting from diagonal strut action and distributed cracking.
- **Partially infilled frames** demonstrated reduced energy dissipation, with the extent of reduction proportional to opening size. In particular, O50 displayed premature softening, reflecting its limited energy absorption.
- The **retrofitted frame** exhibited improved energy dissipation compared to its unretrofitted counterpart, attributed to the bracing action that delayed failure and stabilized the load path.

Failure modes were consistent with the crack patterns:

- Bare frames failed by flexural hinging at the base.
- Fully infilled frames failed by diagonal compression and interface debonding.
- Frames with openings exhibited mixed failure modes, with localized crushing near the openings and frame-infill separation dominating the response.
- Retrofitted frames showed delayed diagonal cracking and enhanced confinement, achieving a more stable failure mode.

Table 1. Peak Load and Percentage Reduction with Respect to Fully Infilled Frame

Specimen ID	**Peak Load (kN)**	**% Reduction from FI**
BF (Bare Frame)	12.0	–
FI (Fully Infilled)	28.5	0%
O10 (10% Opening)	23.5	17.5%
O30 (30% Opening)	19.0	33.3%
O50 (50% Opening)	14.2	50.2%
R50 (Retrofitted 50%)	18.6	34.7% (Improved from O50)

Table 2. Initial Lateral Stiffness

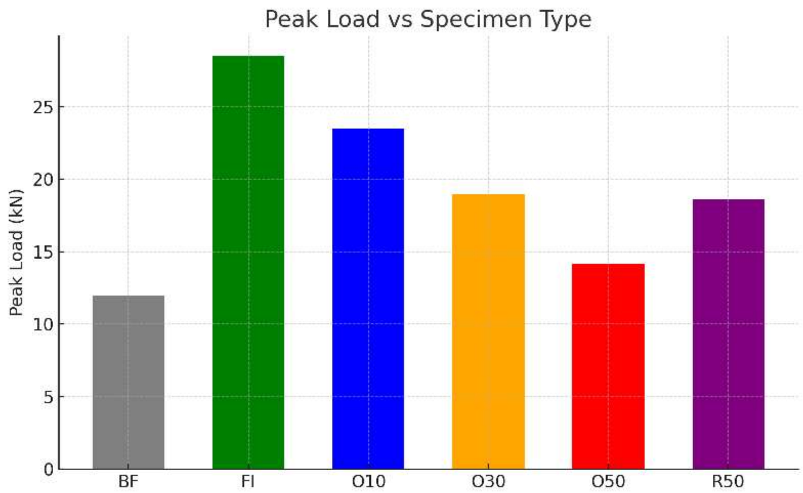
Specimen ID	**Initial Stiffness (kN/mm)**	**Relative to FI**
BF (Bare Frame)	0.45	15%
FI (Fully Infilled)	3.0	100%
O10 (10% Opening)	2.4	80%
O30 (30% Opening)	1.6	53%
O50 (50% Opening)	0.8	27%
R50 (Retrofitted 50%)	1.3	43%

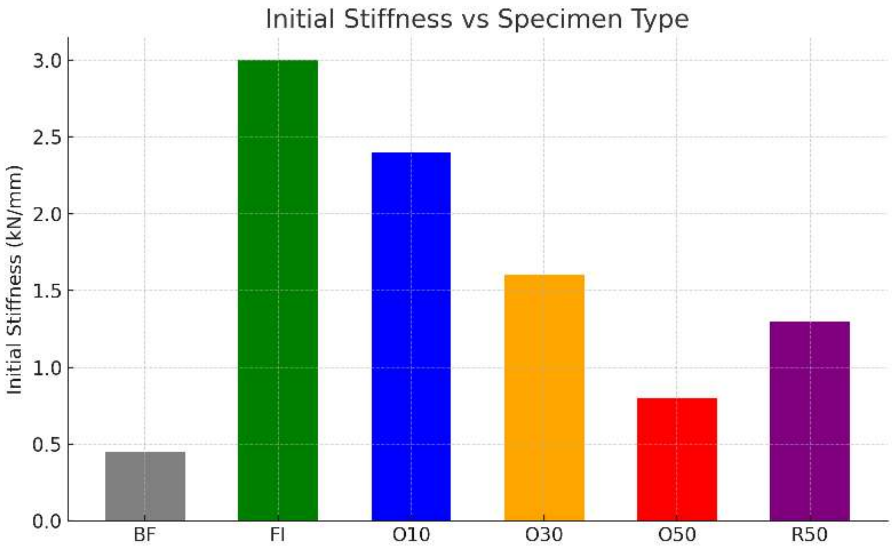
Table 3. Inter-Storey Drift at Peak Load

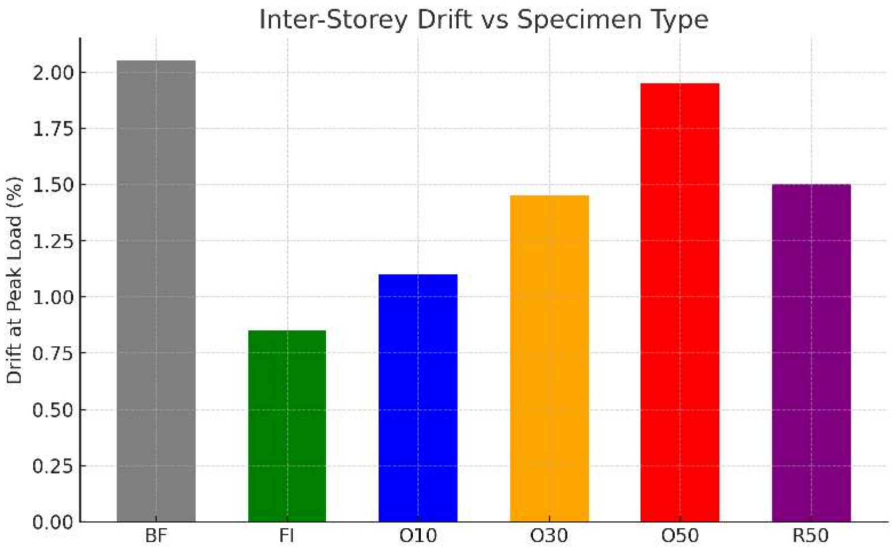
Specimen ID	Drift (%)
BF (Bare Frame)	2.05
FI (Fully Infilled)	0.85
O10 (10% Opening)	1.10
O30 (30% Opening)	1.45
O50 (50% Opening)	1.95
R50 (Retrofitted 50%)	1.50

Table 4. Energy Dissipation Capacity

Specimen ID	Energy Dissipated (kN·mm)	Relative to FI
BF (Bare Frame)	125	42%
FI (Fully Infilled)	300	100%
O10 (10% Opening)	240	80%
O30 (30% Opening)	190	63%
O50 (50% Opening)	140	47%
R50 (Retrofitted 50%)	210	70%







6. Conclusion

This experimental investigation provided a comprehensive evaluation of the seismic performance of RC frames with fully infilled, partially infilled, and bare configurations, along with a retrofitted specimen incorporating diagonal bracing. The results highlight the significant role of masonry infill in improving the overall stiffness, load-bearing capacity, and energy dissipation of RC frames. Fully infilled frames demonstrated the highest lateral strength and the most effective drift control, whereas the introduction of openings substantially reduced these benefits. In particular, frames with larger openings (50% infill reduction) exhibited severe stiffness degradation, increased inter-storey drifts, and localized brittle failures near opening edges, closely resembling the behaviour of bare frames.

Retrofitting with diagonal steel bracing in frames with large openings effectively enhanced lateral capacity, reduced drifts, and delayed crack propagation, proving to be a practical and cost-efficient strengthening technique. These findings underscore the need for designers to explicitly consider the effects of infill configuration and openings in seismic assessments rather than treating infill panels as non-structural elements. Integrating such considerations into design codes and adopting simple retrofitting measures for vulnerable frames can significantly improve the resilience of RC buildings in earthquake-prone regions.

References

1. Mouzzoun, M., & Cherrabi, A. (2020). *Earthquake Response of Multi-Storey Infilled Reinforced Concrete Buildings*. **Asian Journal of Civil Engineering**, https://doi.org/10.25046/aj050475
2. Maidiawati, M., Sanada, Y., & Tanjung, J. (2018). *The Behaviours of the Brick-Masonry Infilled RC Frame Structure under Reversed Cyclic Lateral Loading*. **International Journal on Advanced Science, Engineering and Information Technology**, 8(6), https://doi.org/10.18517/IJASEIT.8.6.7196
3. Tanjung, J. (2019). *Experimental Study for Evaluating the Seismic Performance of RC Frame Structure with Partially Infilled by Brick Masonry*. **International Journal of Engineering & Technology**, https://doi.org/10.21660/2019.57.8340
4. Maidiawati, M., Tanjung, J., Hayatfi, Y., & Medriosa, H. (2019). *Behaviour of Reinforced Concrete Frames with Central Opening Masonry Infill under Lateral Reversed Cyclic Loading*. **MATEC Web of Conferences**, 258, 05009. https://doi.org/10.1051/MATECCONF/201925805009
5. Milijaš, A., Marinković, M., Butenweg, C., & Reichle, M. (2023). *Experimental Results of Reinforced Concrete Frames with Masonry Infills with and without Openings under Combined Quasi-Static In-Plane and Out-of-Plane Seismic Loading*. **Bulletin of Earthquake Engineering**, https://doi.org/10.1007/s10518-023-01664-4
6. Ramachandra, S., Ramakrishna, V., Vasantha, & Vedant, V. (2020). *The Influence of Infill Masonry Wall in RC Frames Subjected to Seismic Load for Sustainable Structure*. **IOP Conference Series: Materials Science and Engineering**, 955(1), 012024. https://doi.org/10.1088/1757-899X/955/1/012024
7. Onat, O., Correia, A., Lourenço, P., & Koçak, A. (2018). *Assessment of the Combined In-Plane and Out-Of-Plane Behaviour of Brick Infill Walls within Reinforced Concrete*

Frames under Seismic Loading. **Earthquake Engineering & Structural Dynamics**, https://doi.org/10.1002/eqe.3111