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Review Research Paper

Improving Reinforced Concrete Frames against Lateral Forces and Differential Settlement – A Literature Review

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ABSTRACT

Unexpected differential settling from soil disturbance caused by uncontrolled urbanization in major cities causes cracks and may damage adjacent structures. Thus, basement reinforced concrete frames must be designed to withstand differential settlement. Using appropriate methods, Reinforced Concrete (RC) frames can be improved. This study explores how differential settling, and lateral forces crack reinforced concrete frames. The study reviews previous studies on strengthening strategies, including complete or partial infill of reinforced concrete frames with reinforced concrete or masonry, steel bracing systems, and FRP sheets to restore strength post-cracking.

Introduction

Cracked Reinforced Concrete (RC) frames are common in buildings due to overloading, degradation, and foundation settlement. Towers and structures are prone to accumulated damage and structural collapse due to these fractures. Cracked reinforced concrete frames are made worse by differential settling, which occurs when soil differences, dewatering, adjacent excavation, and fines washing cause uneven settlement. Experimental building rehabilitation approaches using infill materials such masonry, concrete, steel, and Fiber-Reinforced Polymer (FRP) strengthening are examined. This work could extend the lifespan of crumbling buildings, improve their resilience, and make our built environment safer and more sustainable. The report also covers key structural strengthening areas. It investigates employing concrete and masonry infill to repair cracked RC frames. Cracks and differential settling can be reduced by using filler materials. The research also examines how holes or gaps in filler materials affect structural performance. The study examines the efficacy of steel bracing techniques and the use of Fiber Reinforced Polymer (FRP) materials, namely Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP), in reinforcing cracked infilled reinforced concrete (RC) frames. This project will compare and evaluate various approaches to provide engineers and building stakeholders with structural restoration best practices.

1.1 Objectives of the research

The primary aims of this research are:

The study first aims to identify the primary causes of concrete cracking, focusing on the effects of vertical loading from differential settlement and horizontal forces from seismic or wind pressures on RC frames, requiring extensive testing of various strengthening methods. It then rigorously compares structural strengthening options, such as partial and full infill with concrete and masonry, including apertures in the infill materials. The next step explores concentric and eccentric steel bracing systems and their optimal use. Finally, advanced materials like glass and carbon fiber-reinforced polymers (FRP) are

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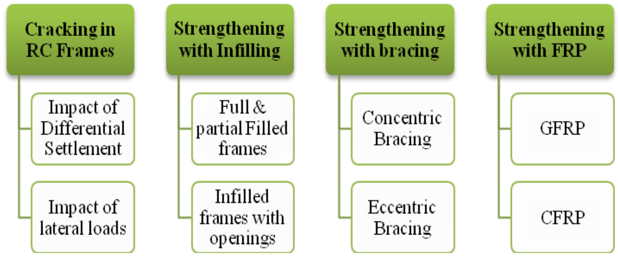
examined for repairing and reinforcing damaged RC frames. These include testing load-carrying capacity, deformation characteristics, energy dissipation, and structural resilience under various loading situations. The research aims to provide engineering practitioners with evidence-based insights to choose the best strengthening strategy for specific structural conditions and loading orientations, improving structural engineering practices and reinforced concrete structure safety and durability in challenging real-world scenarios.



Cracking in Reinforced Concrete Structures

Differential Settlement's Effects

Broken Reinforced Concrete (RC) frames are a recurring structural engineering problem, therefore understanding their characteristics and effects is vital. The literature review must clarify that RC frames with reinforced concrete columns and beams are common structural systems in infrastructure and constructions. RC frame cracking can be caused by excessive loads, harsh weather, ageing materials, and foundation issues. These fractures frequently start as microscopic surface cracks but can develop into structural components, threatening the framework's integrity and load capacity. Fractures reveal structural vulnerabilities. Figure 1 indicates that they must be properly inspected and restored to ensure the affected structures' long-term safety and performance.

(a)Wall and façade failure (b) wall and window failure (c) building failure (Song, 2010)

Fig 01. Differential Settlement's Impacts

Research on differential settling on infilled reinforced concrete (RC) frames has shown how these structures perform under diverse load circumstances. Structures' live loads and gravitational forces affect differential settling, an essential structural analysis component. The structural response of reinforced concrete (RC) frames subjected to differential settlement is largely dictated by fractures and infill materials like masonry, concrete, or FRP, according to the literature. Research has examined how vertical stresses affect these structures using numerical calculations and experimental testing.

In their 2010 study, Negulescu C. et al. employed differential settlement analytical fragility curves to study structural behavior and parameter effects. A one-bay, one-story RC frame was examined. The inclinations were 45°–105°, 105°–135°, and 0°–45°. First class 0-45 damage evaluation is unaffected by the vertical component because foundation horizontal movement affects frame structural behavior. Vertical displacements in the second class (45°–105°) damage structures, with frames most stressed at 90°. Enforced displacements matter at the final class right column bottom (105°–135°).[1]

Son M. et al. (2011) compared excavation-settled earth to shallow foundations. Brick-bearing, open-frame, and brick-infilled frames were evaluated. Simulations used two soils for four stories. Research shows that brick buildings transmit fractures more than frame constructions with brick infill. In elastic or somewhat cracked circumstances, brick-bearing or brick-infilled frames are stiffer than open frames. In elastic state, brick-bearing buildings were stiffer than open-frame structures, but substantial cracking distorted them. These results advise considering structural stiffness and strength when analyzing building reaction.[2]

Dynamic stresses and differential soil settling effect porta-frames. A finite element model was used to examine the portal frame's structural behavior with a 10 mm continuous differential settlement by Lahri A. et al. (2015). The number of floors, bays, moment of inertia, column height, beam length, and others were examined. Increasing beam and column lengths and

heights reduces frame forces by decreasing inertia. Two-bay frames and lower levels are most influenced by differential settling. Member forces strengthen with constant differential settling.[3]
Sayin B. et al. (2016) evaluated how foundation excavation damaged two adjacent buildings in limited urban areas. The study stresses the importance of detailed inspections and preventative steps to prevent structural damage. Unregulated deep excavation produces soil displacement, water drainage, and reduced pore water pressure, causing ground subsidence. The study reveals how excavation-related phenomena like fractures and structural damage in nearby structures emphasize the necessity for rigors inspections and preventative actions, emphasizing the need of accountability and proactivity in this sector.[2][4]

El Naggar A. et al. (2023) used 2D frame finite element analysis to study settlement in RC-framed structures of varying heights and spans. The research examined ductility, plastic hinge development, and settlement damage transfer. For spans of 3 m, proposed tolerances are dangerous, whereas settlements surpass the yielding limit at 4.85 m. The restrictions are more cautious at 50% below the yield level for 7.28 m and 9 m spans. The study recommends studying geometric parameters, material qualities, and reinforcing details to improve settlement prediction.[5].

The researchers examined three settlement scenarios edge, center-intermediate, and intermediate columnsin RC buildings to assess how seismic protections reduce settlement-related damage. They found that structures designed for higher seismic hazard zones are more resistant to foundation settling compared to those in lower seismicity areas. The study highlights the impact of seismic design provisions on load redistribution, stiffness, and damage in RC structures experiencing differential settlement, providing valuable insights into their effectiveness across different seismic zones.[6].

Tests were replicated in a scaled pointed barrel vault, a late-medieval Scottish construction, under non-uniform differential settling. Crack patterns, deformation profiles, and experimental results match the numerical model. Further studies of prospective settlement patterns demonstrate the need of understanding complex failure causes and ongoing deformation processes in ancient barrel vaults. D'Altri et al. 2019 [7] Emphasize the need for minimum intervention to protect architectural heritage and the significance of thorough structural investigation in developing successful strengthening techniques for old masonry vaults.

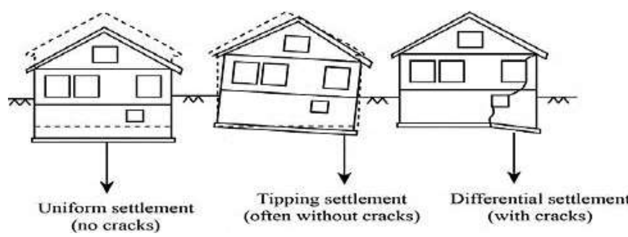


Fig 0- Types of Differential Settlement
The literature has focused on horizontal loading in Reinforced Concrete (RC) frames. This research investigates how RC frameworks respond to lateral stresses including wind and seismic activity. Structural engineers worry about horizontal loads because it may induce deformation, instability, and failure. The investigations provide light on cracking, infill materials, and strengthening methods and emphasize the need of measuring RC frame structural performance under horizontal loads.[8].

After a real-world earthquake, Mostafaei H. et al. (2004) built a 3-D finite element model of reinforced concrete frames with and without infill. The researchers used a unique way to reproduce frame behavior in the finite element model. The researchers found that naked frames in their model had severe nonlinear deformation, whereas infilled frames showed linear behavior and incurred little damage. Their results matched what transpired in the building following the earthquake.[9]

Two-thirds scaled-down three-story space frames with one bay, with and without infill brick masonry, were seismically tested in 2006. Masonry infill affected seismic performance with three times the initial stiffness and 2.75 times baser shear with the same earthquake motion as the bare frame. Retrofitting increased the infilled frame's natural frequency by 120%, whereas the bare frame's frequency was returned to 75%. Retrofitting enhanced strength and stiffness and reduced drift by 25% for the infilled frame and 65% for the bare frame. The researchers found that adding a reinforced concrete jacket to ageing RC frames improves earthquake resistance.[10].

Santhi H. et al. (2006) evaluated 1:3 scale reinforced concrete frame models with and without brick masonry infill on shaking tables. Retrofitting increases fundamental frequency by 20% and infill reduces it by 30%, according to stiffness, shear force, inter-story drift, and dynamic properties. The infilled frame's higher damping ratios indicate better first-mode energy dissipation before and after retrofitting. After retrofitting, the infilled frame's lateral stiffness was three to four times the bare frame's. The allowed inter-story drift is below the infilled frame. Retrofitting doubles seismic performance by reducing strength requirement, which infill greatly increases.[11].

Tasnimi A. et al. (2011) tested filled steel frames with and without apertures under lateral stress. Frames having gaps in the infill walls failed diagonally like solid infill frames. The opening aspect ratio did not alter stiffness decrease, which mirrored elastic behavior. The same cumulative energy was dissipated by frames with openings regardless of aspect ratio.[12].

Wang C. (2017) evaluated four masonry-filled RC frames, one steel frame, and five scaled specimens for strength and out-of-plane behavior. The study examined various gaps at the frame-beam or column interfaces, different infill openings, and pre-existing in-plane damage. It found that the infill-top beam gap is more detrimental than the infill-column gap, and out-of-plane strength declines linearly with in-plane damage. Door openings reduce strength more than window apertures. The mathematical strength estimates for RC and steel frames did not align, highlighting the need for better analytical models to predict masonry infill strength under varying conditions.[13].

Altin et al. (2017) studied lateral loads on non ductile RC frames with infill walls under reversed cyclic loading, using six scaled, two-story specimens. The research addressed damage to column longitudinal reinforcement at lap splices, which was resolved by adding new columns beside the infill walls, welding the lap splices, and incorporating continuous reinforcements at the infill boundaries. These modifications improved lateral strength, stiffness, energy dissipation, and prevented column splice failure. Welding lap splices with external confinement was most effective for seismic performance. Analytical studies confirmed the findings, reinforcing the use of infill walls in non ductile RC frames for better seismic resilience.[14]

Noh M. et al. (2017) modified the traditional material model to better represent concrete and masonry in estimating the lateral load response of infilled RC frames. Their improved model accurately simulated the pinching and hysteretic behavior observed in tested infill RC frames. By refining the standard material models, they aimed to more precisely generate the backbone curve for seismic events. This enhanced model provides a more reliable representation of the lateral load response in infill RC frames, improving predictions during seismic events.[15].

Adnan S. et al. (2022) examined masonry-infilled reinforced concrete frames' lateral load response. Experimental specimens indicated that the border RC frame and infill walls exchange axial stresses. The specimens' details showed that the failure mechanism changed from flexure failure of the bare frame to combined failure of the RC frame and infill as gradual crack propagation in masonry between the major shear cracks in the RC columns at loaded corners corresponding to wall-frame interface sliding in figure 3[16].

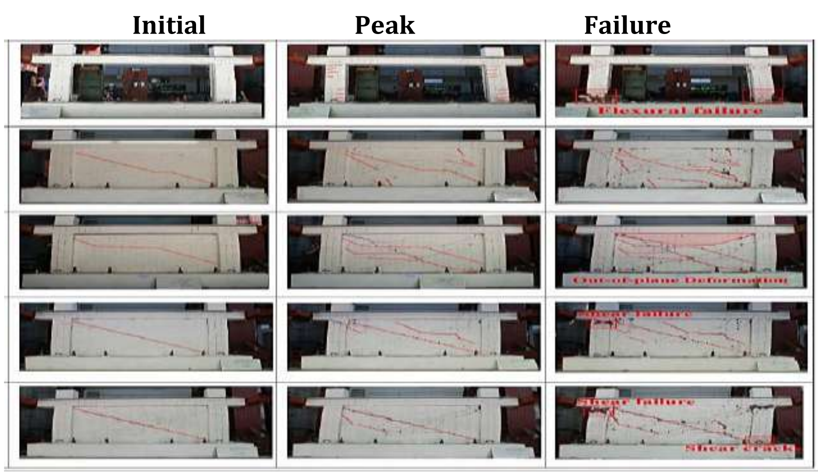


Fig 03. Cracking propagation during lateral loading of fully infilled RC frames (Adnan S. et al.,2022)[16]

This research highlights the impact of cracking on the load-bearing capacity and stiffness of RC frames under horizontal loading. Cracks create weak points that lead to deformation. Infill materials like concrete or masonry can mitigate these effects by increasing support and resistance to lateral forces. Additionally, advanced strengthening methods, such as using Fiber-Reinforced Polymers (FRP) like GFRP and CFRP, significantly enhance the lateral stiffness, flexibility, and energy dissipation of RC frames. These findings help engineers improve structural safety, resilience, and longevity in construction and retrofitting projects.

Enhancing with Infilling

Infill materials play a vital role in structural engineering by strengthening and renovating buildings, particularly when RC frames are damaged. They fill gaps, restore connections between structural elements, and enhance load-bearing capacity. Options like concrete, masonry, and composites offer different benefits and technical properties. Infill materials are crucial in extending the lifespan of existing structures and ensuring they can withstand static and dynamic loads, as well as environmental stresses.

Full and Partial Infilled Frames

Infill materials have become essential tools for engineers and architects seeking cost-effective and eco-friendly solutions for rehabilitating and strengthening existing structures. Rather than opting for costly demolition and rebuilding, infill materials offer a sustainable alternative, reducing financial burdens and environmental impacts. This approach supports the industry's focus on resource efficiency. Additionally, their versatility allows infill materials to address various structural issues, such as reinforcing masonry walls and repairing cracks in RC frames.[17]The growing significance of infill materials in the construction industry is due to their performance and versatility. Engineers are constantly seeking innovative and effective methods to enhance infrastructure safety, resilience, and durability, making these materials increasingly vital in modern construction.

The literature provides a comprehensive review of studies exploring the application of concrete and masonry infill materials in reinforced concrete (RC) frames subjected to differential settlement.[18]. These studies consistently demonstrate the effectiveness of infill materials, like concrete and masonry, in addressing structural issues such as cracking and settlement. Concrete is valued for its high compressive strength, durability, and compatibility with RC structures, often used to restore continuity and improve load distribution in cracked frames. The research highlights concrete's ability to enhance load-carrying capacity under both vertical and horizontal loads. Similarly, masonry infill materials, such as bricks and blocks, significantly improve stiffness and shear resistance, contributing to better overall structural performance.

The literature study highlights the efficacy of partial infill, citing its capacity to provide financial benefits and minimize material use. Engineers may more effectively use their resources by concentrating on strengthening certain portions of a building.[19]For example, partial infill may be done deliberately to address specific regions of localized cracking or inadequacies in RC frames, leaving other sections unaffected and adding extra support just where needed. This strategy is consistent with the building sector's sustainability and resource efficiency values. On the other hand, total infill is preferred when the whole structure has to be strengthened uniformly, especially when there has been significant damage and when there is a requirement for overall increases in stiffness, resistance to deformation, and load-carrying capacity. Both approaches are essential to engineering practice because they are flexible in handling various structural conditions. They are appreciated for their contributions to the construction sector, where economic rehabilitation and resource efficiency are highly valued goals.[20] Figure 4 demonstrates both full and partial infill masonry instances.

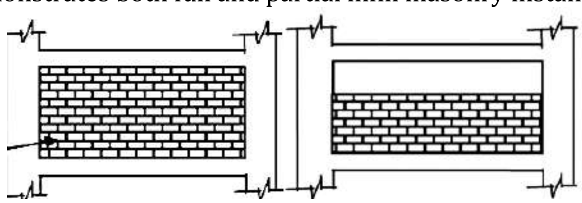


Fig 4 Partially and filled frames

This paper presents a seismic retrofit technique for nonductile RC frames with unreinforced masonry infills using engineered cementitious composites (ECC). Four specimens (UW, EW-25, EWBD-40, EWUD-40) were tested. ECC retrofitting improved strength, stiffness, and ductility, with the best results seen in specimens reinforced with shear dowels. EWBD-40 showed a 61% increase in stiffness and 87% in strength, while EWUD-40 maintained ductility, with 58% strength and 34% stiffness improvements. The study highlights ECC's effectiveness in enhancing lateral stability, recommending further investigation into different setups and failure mechanisms.[21]

Murty C. et al. (2000) investigated the seismic behavior of RC frames with masonry infills, including stiffness, strength, flexibility, and energy dissipation. Infills' lateral stiffness and strength, particularly reinforced ones, are increased. The thickness of reinforced mortar may decrease strength and stiffness. Reinforcement after breaking helps prevent out-of-plane collapse. When intricately designed, brick infills enhance the seismic performance of multistory structures in developing nations. However, short-column and soft-story effects should be considered in robust seismic design.[22].

Al-Chaar G. et al. (2002) investigated the behavior of RC frames with masonry infill in high seismic zones, noting that these structures were conservatively designed without considering lateral loads. Tests on five half-scale, single-story models revealed that infilled frames exhibited higher ultimate, residual, and initial stiffness compared to bare frames, while maintaining flexibility. The study highlighted the importance of nonuniform shear stress in multi-bay structures, with the number of bays influencing shear stress distribution, failure modes, and capacity. Shear strength, compressive strength, and infill geometry were identified as key factors determining failure processes.[23]

Anil O. et al. (2007) focus on tests investigating the behavior of cast-in-place reinforced concrete infills in ductile reinforced concrete (RC) frames under cyclic lateral pressure, particularly those having window or door apertures. Nine one-bay, one-story test specimens with various infill wall aspect ratios and locations were conducted. as shown. Figure 5. The findings indicated that the ultimate strength and initial stiffness of partly infilled RC frames were 3.73 to 7.37 times greater than those of bare frames. The strongest infills were those attached to columns and beams. The research demonstrated how infills, as wing walls strengthen, impact story drift ratio and energy dissipation by infill aspect ratio.[24].

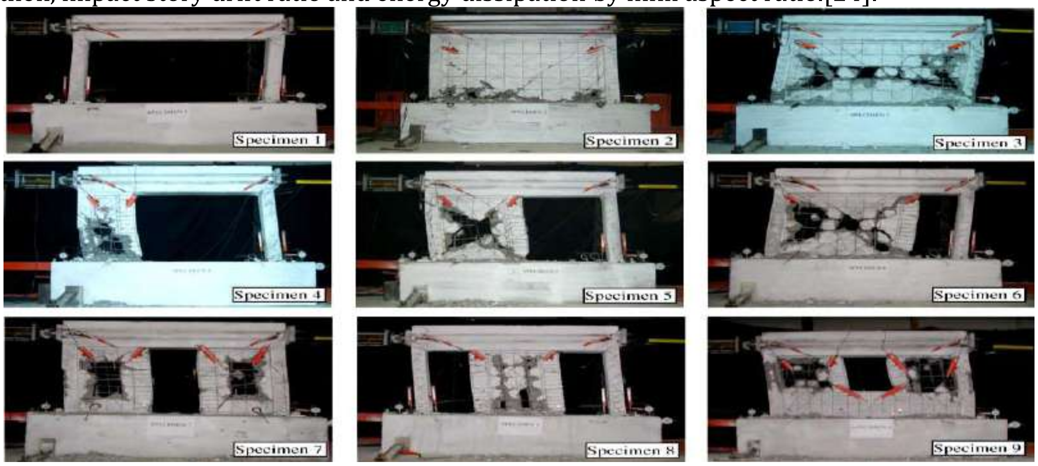


Fig 5*.* Reaction of whole or partial RC frames to lateral loads at failure (Anil O. et al.,2007) [24]

Sattat S. et al. (2010) tested bare, partly, and fully masonry-infilled RC frames for seismic performance. The study showed that infilled frames had higher initial stiffness, strength, and energy dissipation despite brittle failure modes. Dynamic analysis revealed minimal earthquake-induced collapse in both fully infilled and bare frames, with a collapse capacity variance of 1.3 to 2.5. Ongoing research is focused on wall modeling sensitivity and column shear failure. Future studies will explore different masonry materials, stronger walls, and infill apertures. The research offers insights into reducing seismic risk in RC frames with masonry infills[25].

Zovkic J. et al. (2013) studied the impact of various masonry infills on RC frames under lateral stress using 10 scaled frames with hollow clay bricks of different strengths. The composite "framed wall" structures demonstrated higher initial strength, damping, and stiffness compared to bare frames. Masonry infills bridged the load capacity gap up to 0.75% drift and improved resistance up to around 1% drift, despite significant damage at 0.75% drift. The study suggests that masonry infill code requirements should be updated to improve structural performance and minimize damage by reducing allowable drift levels.[26].

Porto F. et al. (2015) reinforced RC frames with weak clay brick infill walls using bidirectional composite meshes, improved textile-reinforced mortar (TRM), and lime-based plaster. The use of better plasters and reinforcing mesh significantly improved the in-plane behavior and post-peak stability of the frames, providing valuable insights for seismic retrofitting of older reinforced concrete buildings. [27]

Akin A. et al. (2016) explored using precast concrete panels to strengthen brick infill walls in RC frames with poor earthquake resistance. Six 1/2 scale, two-story prototypes were tested, replicating common building flaws. The precast panel reinforcement significantly improved energy dissipation, initial stiffness, and resistance to lateral loads. While the reference specimen's columns and beam connections suffered severe damage, the reinforced walls sustained much less damage. This strengthening technique offers an effective way to enhance earthquake resilience without evacuating occupants from adjacent buildings.[28]

Baran M. et al. (2016) studied the impact of seismic loads on RC frames with hollow brick infills and developed an affordable method to reinforce them. Testing six 1/3 scale, two-story RC frames, they found that using high-strength precast concrete (PC) panels in frames with continuous column bars increased stiffness and lateral load capacity by 2.51 to 2.55 times. However, 90% of these frames lost lateral strength due to insufficient column bar lap splice lengths. The PC panels also reduced shear deformations, enhancing seismic performance. This technique presents a cost-effective and occupant-friendly option for seismic retrofitting.[29]

The study of seismic behavior in open, infilled, and bare RC frame buildings under lateral pressure leads to key conclusions. First, infill walls should be included in seismic analysis using the equivalent diagonal strut method for accuracy. Second, infilled first-story frames are preferred in seismic zones as they reduce story drift and structural failure. Third, infill walls strengthen and stiffen structures. Finally, neglecting base shear in bare frame analysis increases the risk of collapse during earthquakes, highlighting the importance of including infill walls in earthquake-resistant design.[30].

Li S. et al. (2016) conducted a quasi-static test on a scaled RC frame with full-height infill walls to assess progressive collapse. Compared to a bare frame, the infilled frame's collapse resistance increased by 37%, and initial stiffness by 42%, though beam ductility decreased. At peak resistance, major cracks in the infill walls and minimal vertical displacement of the removed column were observed. The collapse occurred in two stages, influenced by shear strength, compressive arch and strut actions, beam bending, and catenary action. The equivalent compressive strut model effectively represented the failure process in the seismic analysis.[31].

Baghi H. et al. (2018) studied the effects of masonry infill walls on full-scale RC frames subjected to column failure through experiments and computer analysis. The study found that the quality of mortar determines masonry shear strength, and conventional infill walls are key to resisting progressive collapse by enhancing structural integrity, stiffness, load capacity, and energy absorption. Numerical models showed that frame reinforcement details significantly impact performance, with longitudinal beam reinforcement increasing load capacity. Artificial vision monitoring highlighted the dynamic interaction between RC frames and infill walls, underscoring their importance for structural robustness.[32].

Baran M. et al. (2021) examined seismic strengthening methods for non-ductile RC frames under seismic stresses. Five approaches were used to assess two-story, one-third-scale RC frames reinforced with hollow brick infill: RC infill walls, precast RC plates, steel fiber reinforced mortar, and plain mortar. These methods increased frame stiffness 186%–486% and strength 57%–189%. Simple steel fiber reinforced mortar and precast RC plates were affordable and occupant friendly. These strategies may avoid collapse in low-strength RC structures by increasing lateral strength and stiffness, according to the numerical analysis. Cost, convenience of use, and concrete compressive strength were all considered.[34]

Partial or full infill relies on project needs and a structural evaluation. In the building sector, educated infill strategy selections demonstrate technological versatility. These selections enable sustained and cost-effective RC structure strengthening, meeting industry objectives of structural lifetime and resilience. The literature study helps experts optimize strengthening methods and effectively fix RC frame structural defects.

Frames with openings and fillings

The literature highlights the significant impact of openings or gaps in infill materials on the structural performance of RC frames. These voids, whether from architectural design or utility penetrations, can complicate load distribution and cause stress concentrations. Engineering studies indicate that such openings may lead to localized stress concentrations around the gaps, affecting the overall structural behavior and response, as seen in Figure 6. This emphasizes the importance of considering openings in infill materials during structural assessments to ensure optimal performance.[20], [35]

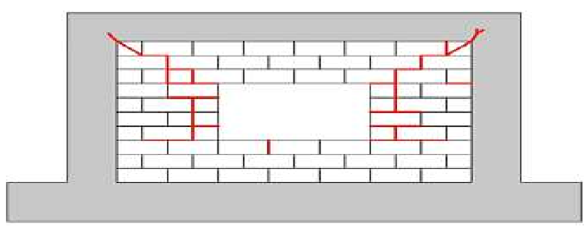


Fig 06. Effects of infill voids.

In the building industry, understanding how gaps or openings in infill materials affect structures is crucial for safety and durability. The literature emphasizes careful design and adding reinforcement around openings to mitigate their effects, especially in historical buildings. This knowledge helps engineers make informed decisions, improving the accuracy and adaptability of strengthening techniques while ensuring long-term structural integrity.[36]

The study featured bare RC frames and fully infilled walls with and without openings. Infill walls, particularly those with eccentric apertures, suffered severe damage at 1.25–2.50% story drift ratios, although their behavior remained unaltered. Deboned infill walls may collapse owing to inertia, altering in-plane behavior. The research demonstrated stability up to 9% story drifts, with opening-containing walls damaged more. Eurocode 8 allowed 2.5% drift, which was safe. The research emphasizes the necessity to understand infill behavior under in- and out-of-plane pressures to avoid seismic wall-frame separation.[37].

Ten infilled and one naked steel frame specimens were tested for concrete masonry infill behavior under in-plane lateral stresses. Frame stiffness, aspect ratio, grouting extent, and infill apertures were important. Solid infills failed mostly owing to corner crushing and diagonal cracking around apertures. Grouting increased rigidity and load while apertures decreased them. Central axis column orientation enhanced ultimate load and stiffness, whereas minor axis orientation improved ductility. Conservatively, the CSA S304 design underestimated strength by 2.3 times and stiffness by 2.7 times.[38]

Masonry infill panels affect the strength and stiffness of RC frames, and modeling openings in these panels is challenging. A reduction factor (λ) is used to simulate openings in infill walls. The study shows that openings reduce the vibration period and increase inter-story drifts, especially in bare frames under cyclic loading. The reduction factor is effective for modeling infill frames with openings.[39].

Mondal G. et al. (2008) calculated initial stiffness for RC frames with central window apertures using a diagonal strut width reduction factor. Testing seven frames with varied opening widths using SAP 2000 and experimental data. The research advises designers on whether to consider or disregard apertures' lateral stiffness effects. The reduction factor may be affected by stiffeners, lintel bands, and opening location in future studies.[40].

Okail H. et al. numerically analyzed and tested restricted brick walls under lateral stresses in 2014. Six full-scale walls with varied brick kinds, reinforcing ratios, and solid or perforated walls were examined. Experimental results demonstrated brick wall diagonal strut failure followed by confining element shear failure. The research indicated that stronger bricks, confinement, and smaller holes increased flexibility and lateral load capability. The findings show that restricting characteristics and brick strength affect restricted masonry wall performance.[41].

Cetisli F. et al. (2015) investigated the effects of apertures in infill materials using analytical, numerical (FEA), and experimental methods. Their research revealed that apertures, whether for utilities or design, can create stress concentration points and alter load distribution. The size, shape, and placement of apertures influence deformation patterns and stress distribution in RC frames. Additionally, the presence of apertures can lead to localized reductions in stiffness and load-carrying capacity. [42]Consequently, the reviewed research highlights the need to give openings significant thought and design reinforcing measures to minimize any possible negative impacts on the structural integrity of RC frames.

Steel Bracing for Strengthening

Steel bracing is a well-established technique in structural engineering used to strengthen RC frames, especially in cases of differential settling. It involves adding steel braces or trusses to provide lateral stability and better resistance to deformation and dynamic stresses, without significantly increasing building weight. Steel bracing helps transfer loads, reduce sway, and improve overall structural performance. This method is particularly effective for retrofitting older buildings to meet modern safety standards by enhancing resistance to lateral forces like wind or seismic loads. Steel bracings are an affordable retrofitting solution that accommodates openings. They come in two types: eccentric bracing, which offers flexibility, and concentric bracing, which provides greater strength and stiffness., as shown in Figure 4-1.

Fig 7. Steel bracing types include (a) eccentric bracings, (b) concentric bracings

Concentric Steel Bracing

Concentric bracing is utilized in vertically aligned frame spans where steel parts connect at the same beam positions, frequently midspan. This approach maximizes lateral stiffness with little energy loss, lowering lateral drift and column shear and bending moments. Research reveals that bracing angles and locations affect concentric braced frames (CBF) efficacy. However, eccentrically braced frames are often utilized to strengthen RC constructions. Various types of concentric bracing systems are illustrated in Figure 8, such as:

X-Bracing: Efficient, "X"-shaped braces, often used for aesthetics but can limit space.
V-Bracing: "V"-shaped braces offer stability with more openness.
Chevron Bracing or inverted V-bracing: Inverted "V," combining X and V benefits stability and design flexibility.
K-Bracing: "K"-shaped braces provide strong stability while allowing larger open areas.

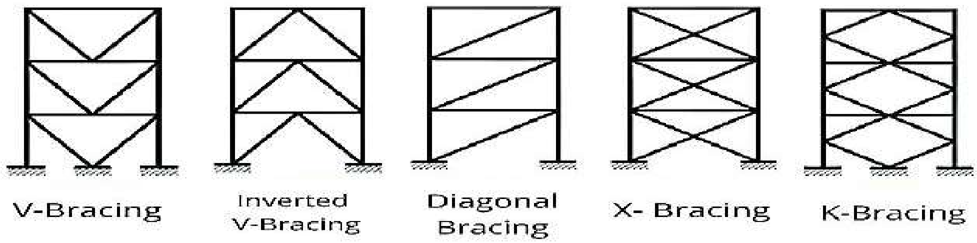


Fig 08. Concentric steel bracing types

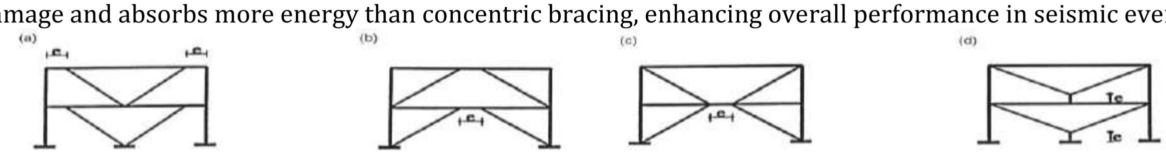
Massumi A. et al. (2013) experimentally tested two scaled concrete frame specimens, one unbraced and the other with cross-bracings. Results showed that bracing improved system stiffness, strength, and energy absorption. The ultimate strength increased by 18.34% due to positive frame-bracing interaction, significantly enhancing stiffness and energy dissipation. The study highlights the importance of connection details in the bracing system and recommends steel bracing with proper connections to improve earthquake performance in RC frames.[45]

Qian K. et al. (2019) tested five one-quarter-scale specimens, one bare frame and four braced frames under pushdown loads. Steel bracing significantly improved early rigidity and peak load capacity. However, brace buckling and failure limited performance. Braced frames showed a 24% to 44% higher yield load, 36% to 157% greater initial stiffness, and 41% to 129% higher peak load capacity compared to the bare frame. The study concludes that steel bracing enhances the stiffness and load resistance of RC frames, particularly against progressive collapse.[46].

Kafi M. et al. (2020) evaluated six reinforcement techniques for RC frames, finding that steel divergent bracing with a link beam outperformed concrete X-bracing. This system reduced base shear by 20% and steel usage by 10% to 30%. In 20-story buildings, the stress ratio dropped to 35%. Taller structures improved the steel-braced design, showing 25% more base shear, 50% better ductility, double the behavior coefficient, and 60% higher elastic stiffness compared to shorter buildings.[47]

Eccentric Steel Bracing types

Eccentric steel bracing offers excellent seismic performance by increasing energy dissipation, making it ideal for high seismic zones. However, it reduces lateral rigidity due to concentrated lateral loads at bracing-beam intersections. Despite this, it delays damage and absorbs more energy than concentric bracing, enhancing overall performance in seismic events.[48]



(a) V-bracing, (b) K-bracing, (c) X-bracing, and (d) Y-bracing

Fig 9. Various kinds of steel frames with eccentric bracing (Ghobarah A. et al. (2001)

Buckling-restrained braced frames (BRBF) are favored for their strong and flexible response to seismic activity, as they prevent brace buckling and control deformations, ensuring structural integrity during earthquakes. The choice of bracing system depends on the specific project needs, seismic risks, and structural conditions, as highlighted in the literature.[49]

Ghobarah A. et al. (2001) studied eccentric steel bracing for repairing non-ductile low-rise RC frames under varying seismic loads. They found eccentric bracing caused less damage and deformation than concentric bracing. The design of RC frames with eccentric bracing requires careful attention to factors like the angle of steel members, connection details, and the arrangement of bracing along the building height.[50].

Strengthening with Fiber Reinforcement Polymer (FRP)

Carbon fiber-reinforced polymer (CFRP) and glass fiber-reinforced polymer (GFRP) have been the subject of a sizable body of study in the literature. Figure 5-1GFRP and CFRP composites, known for their tensile strength, corrosion resistance, and lightweight nature, are effective solutions for strengthening RC frames against differential settling. Research consistently shows their ability to improve structural performance in such conditions, making them ideal for structural rehabilitation.[51]

Fig 10. (GFRP) and also (CFRP)

FRP materials like CFRP and GFRP are studied for concrete repair due to their high strength-to-weight ratios and tensile properties, with CFRP being superior. Research includes their epoxy matrices and mechanical properties, such as tensile and flexural strengths.Figure 5-2CFRP's tensile strength and lightweight properties make it ideal for seismic retrofitting, increasing load capacity, and expanding structural spans. GFRP, while cheaper, is especially useful in corrosive environments. Research shows that flexural strengthening with FRP can enhance load-bearing capacity by 40%. The analysis highlights FRP's potential to transform modern construction, particularly in restoring sustainable infrastructure.[52]

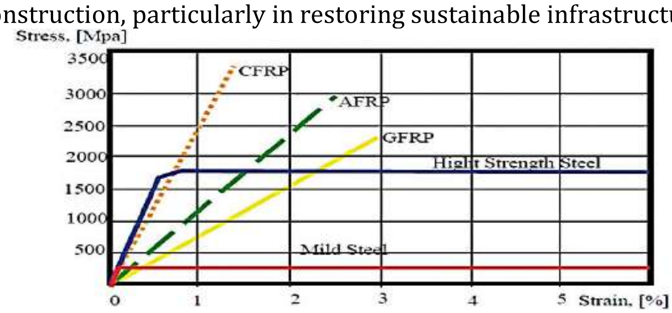


Fig 11 Stress-Strain Curves of some FRP composites {adapted from ref [53]}

Using Glass Fiber Reinforced Polymers for Strengthening (GFRP)

Since sample size and shape affect GFRP pole elastic and rigidity moduli (E&G), the project will develop exact measuring methods instead of using factory data. Critical slenderness ratio (L/r) defines a 10% shear deformation contribution and an E&G testing upper limit.[54].

GFRP and CFRP reinforcement, either externally bonded or near-surface mounted (NSM), improves RC frame tensile strength, shear resistance, and flexibility, according to research. NSM embeds bars in grooves, whereas externally bonded reinforcement employs sheets or strips. Multiple studies show that GFRP and CFRP increase load capacity and fracture resistance in differential settling structures. Their lightweight design makes them perfect for structural repair and retrofitting, solving difficult RC frame challenges.[55], [56].

Awad Y. et al. (2023) study focuses on determining the most effective method of controlling lateral deflection and reinforcing GFRP poles using internal steel bracing bars. Flexural stiffness was enhanced by 44%, 66%, and 38% using various strengthening techniques, with the external steel angle approach being the most successful. [57].

This analysis highlights the benefits of Fiber Reinforced Polymer (FRP) poles, such as their high strength-to-weight ratio, durability, and lightweight nature, making them increasingly popular in the utility industry. It also reviews testing, modeling, and production techniques, showing FRP's adaptability to various applications. Engineers can optimize FRP products by selecting appropriate fibers, matrix materials, and design features.[58]

Strengthening Using Carbon Fiber Reinforced Polymers(CFRP)

Altin S. et al. (2007) examined CFRP strip width on 10 scaled RC frame specimens under cyclic lateral stress. The frames had 6.4-fold greater beginning stiffness and 1.54 to 2.61 times more ultimate lateral strength than unmodified frames. However, large tale drift ratios decreased these improvements, emphasizing the necessity for anchoring and rigidity repairs. The research reveals that CFRP strips may reinforce masonry-filled RC frames, but design issues remain. [59]

Hudson J. et al. (2017) examined how FRP strengthened Gothic barrel vaults and addressed differential settling. FRP-reinforced vaults (BV2) withstood 162 mm of settlement with less cracking and higher stiffness than unreinforced vaults (BV1). FRP has been shown to strengthen and safeguard antique masonry buildings like Gothic vaults against differential settling.[60]

Erdem et al. (2006) investigated two strengthening techniques on scaled Turkish building frames. One utilized CFRP hollow clay pieces with RC infill. Strength, stiffness, and narrative drifts were measured under cyclic stress. Both methods boost stiffness and lateral strength by 500%. While CFRP strip strengthening does not need evacuation, column bar slips restrict throughput. If anchor dowels are correctly installed, RC infills and CFRP strips improve brickwork without reinforcing frame components.[18].

Garcia R. et al. (2010) examined how CFRP composites improve poorly specified RC frame seismic resistance. CFRP fortification decreased global damage during earthquake excitations by 65% in two-story RC shake table testing. This was due to improved beam-column joints. The research shows how CFRP greatly decreases seismic damage, improving structural safety and resilience.[61]

Sebastian W. et al. (2016) examined near-surface mounted CFRP and under-reinforced tension steel RC frames. The CFRP frame held 37% greater weight but broke abruptly at midspan due to fragile FRP bar separation in the peak moment zone, demonstrating performance disparities. At larger loads, the control frame dispersed moments to avoid breaking. The CFRP frame's brittle failure behavior before yielding needs more study.[62].

Conclusion

The investigations show that RC frames exposed to vertical and horizontal loads are vulnerable to cracking, differential settlement, and lateral stresses. Strengthening techniques like concrete and masonry infill, steel bracing, and FRP systems offer tailored benefits depending on specific structural needs.

Infill Materials: Improve stiffness, load-bearing capacity, and reduce cracks, especially during differential settlement.

Steel Bracing: Concentric bracing enhances lateral stiffness and stability, while eccentric bracing is ideal for high-seismic areas, boosting energy dissipation.

FRP (GFRP/CFRP): Lightweight and strong, these polymers increase structural robustness and prevent further cracking under dynamic loads.

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