Strengthening the RC Frames To Resist Lateral Loads and Differential Settlement – Review

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Abstract

Unexpected differential settlement due to the soil disturbance that result from the unplanned urbanization in large cities causes the cracking and may be a severe damage to the adjacent buildings. Thus, the reinforced concrete frames at the basement floors should be designed and constructed to resist the effects of the differential settlement. This goal can be achieved by the strengthening of the Reinforced Concrete (RC) frames by the appropriate techniques. This paper presents the impact of both differential settlement and lateral loads on the cracking of the reinforced concrete frames. Then, the study presents a literature review of the previous efforts to investigate the various strengthening strategies including the complete/partial infill of the RC frames using reinforced concrete or masonry, applying steel bracing systems and the application of Fiber Reinforced Polymer (FRP) sheets to restore the strength of the RC frames after cracking.

Keywords: *RC frames, Lateral loads; Differential settlement; Concrete cracking; Strengthening Techniques; Infill walls; Braced Frames*

1. Introduction

1.1. Overview of the research topic and its significance

Cracked Reinforced Concrete (RC) frames are a widespread problem in the built environment, resulting from various factors such as structural overloading, material deterioration, and foundation settlement. These cracks weaken the structural integrity of buildings and infrastructure, rendering them susceptible to progressive damage and, in extreme cases, structural failure. Differential settlement, a phenomenon where different parts of a structure settle unevenly due to factors like soil variations dewatering, adjacent excavation, fines washing, etc. , exacerbates the challenges posed by cracked RC frames. The research topic is centered on investigating innovative solutions to rehabilitate these structures, focusing on infill materials like masonry, concrete, steel, and Fiber-Reinforced Polymer (FRP) strengthening techniques. The significance of this research lies in its potential to extend the service life of deteriorating structures, enhance their resilience, and contribute to the safety and sustainability of our built environment.

Furthermore, the research delves into several key aspects of structural strengthening. It examines the use of infill materials, such as concrete and masonry, to restore the structural integrity of cracked RC frames partially or completely. The inclusion of infill materials is a promising approach to mitigating the impact of cracks and differential settlement. Additionally, the study explores the effect of openings or voids within infill materials, as these can influence the overall performance of the structure. Furthermore, the research investigates the efficiency of employing steel bracing systems and the application of FRP materials, including Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP), in strengthening cracked-infilled RC frames. By comparing these various techniques and assessing their effectiveness, this research aims to provide valuable insights into best practices for structural rehabilitation, offering guidance to engineers and stakeholders in the construction industry.

1.2. Research objectives

The main objectives of this study are:

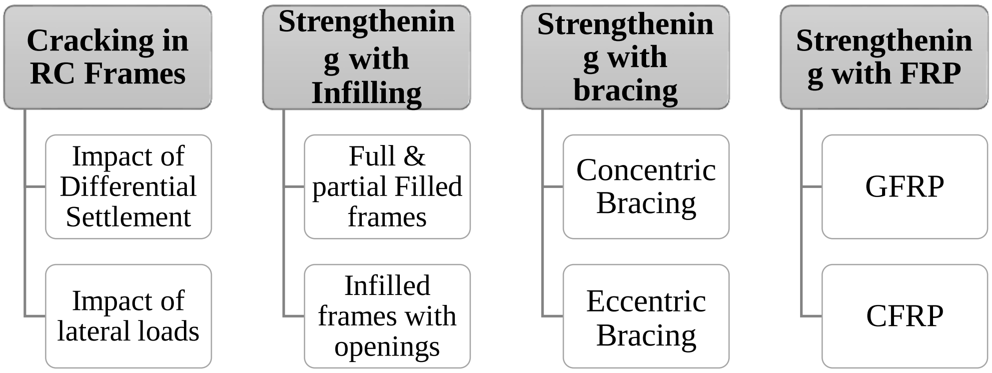
First, the research aims to elucidate the main reasons of concrete cracking including the impact of loading direction, both vertically due differential settlement and horizontally due to seismic or wind loading, in governing the response of these strengthened RC frames. This entails a thorough investigation into how different strengthening techniques perform under different loading conditions.

Then, to systematically assess and compare the effectiveness of different structural strengthening techniques, including partial and complete infill with concrete and masonry, the influence of openings within infill materials.

After that, the utilization of steel bracing systems in the form of concentric and eccentric bracing strategies and the best situations to apply each.

Finally, the application of advanced construction materials including the Fiber-Reinforced Polymer (FRP) materials (specifically, Glass FRP and Carbon FRP) in rehabilitating and reinforcing cracked Reinforced Concrete (RC) frames.

These objectives involve scrutinizing factors such as load-carrying capacity, deformation characteristics, energy dissipation, and structural resilience under varying loading scenarios. And by addressing these objectives, the research aspires to provide engineering practitioners with evidence-based insights to inform the selection of the most suitable strengthening strategy tailored to specific structural conditions and loading orientations, thus contributing to the advancement of structural engineering practices and the enhancement of the safety and longevity of RC structures in the face of challenging real-world scenarios.



2. Cracking in Reinforced Concrete Frames

2.1. Impact of Differential Settlement

Cracked Reinforced Concrete (RC) frames represent a pervasive challenge in the domain of structural engineering, and comprehending their characteristics and the implications of these cracks is essential. In the context of the literature review, it is important to clarify that RC frames are fundamental structural systems commonly employed in buildings and infrastructure, comprising columns and beams constructed using reinforced concrete. Cracking in RC frames typically results from a multitude of factors, including excessive loads, environmental conditions, material aging, and foundation issues. These cracks often initiate as fine surface cracks but can progressively propagate into the structural elements, compromising the integrity and load-carrying capacity of the entire framework. In a structural context, these cracks represent vulnerabilities as shown in figure 2-1 that require careful assessment and rehabilitation to ensure the long-term safety and functionality of the affected structures.

(a) Failure of wall and façade (b) Failure of wall and windows (c) Failure of a building (Song, 2010)

Figure 2-1 Impact of Differential Settlement

The examination of studies involving differential settlement on infilled Reinforced Concrete (RC) frames has yielded valuable engineering insights into the behavior and performance of these structures under different load conditions. differential settlement, often associated with gravitational forces and live loads in buildings, represents a critical aspect of structural analysis. The literature review consistently indicates that when RC frames are subjected to differential settlement, the presence of cracks and the utilization of infill materials, such as concrete or masonry or FRP, play a significant role in influencing the structural response. Studies have used a combination of experimental testing and numerical simulations to evaluate the effects of vertical loading on these structures.

Negulescu C. et al. (2010), studied the influence of factors on structural behavior using analytical fragility curves for differential settlements. Researchers examined a one-bay-one-story (RC) frame. The inclination angles were 0°–45°, 45°–105°, and 105°–135°. In first class 0-45, the foundation's horizontal deformation affects frame structure behavior, so the vertical component can be ignored without affecting damage evaluation. In the second class (45°–105°), vertical displacements damage structures, with frames stressed most at 90°. In the last class (105°–135°), enforced displacements are crucial in the right column bottom.[1]

Son M. et al. (2011), compared shallow foundation structures exposed to excavation-induced settled ground. Brick-bearing, open-frame, and brick-infilled frame constructions were examined. Four stories were modeled with two soils. According to research, brick-bearing buildings propagate cracks farther out, while brick-infilled frame constructions limit crack propagation. A brick-bearing or brick-infilled frame is stiffer than an open-frame structure in elastic or slightly fractured conditions. A brick-bearing structure in elastic condition was stiffer than an open-frame construction, but severe cracking reduced its stiffness and increased distortion. These findings suggest considering structure strength and stiffness when assessing building response.[2]

Dynamic loads and soil properties cause differential settlement, which affects structural behavior of porta, frames. Lahri A. et al. (2015), developed a finite element model to analyze the structural behavior of the portal frame with constant 10 mm differential settlement. The number of stories and bays, beam length, column height, moment of inertia, and others were examined. Increased beam lengths and column heights reduce frame forces, as does reducing beam and column moment of inertia. The lower stories and two-bay frames are more affected by differential settlement. Constant differential settlement increases forces in stiffer members.[3]

Sayin B. et al. (2016), investigated the impact of foundation excavation on nearby structures in constrained urban settings, focusing on damage seen in two specific buildings. It emphasizes the disregard for initial ground conditions by stating that unabated deep excavation causes soil displacement, water drainage, and decreased pore water pressure, which results in ground subsidence. The study emphasizes the importance of thorough assessments and protective measures in preventing structural damage. It also reveals that excavation-induced phenomena such as cracks and structural damage in neighboring buildings highlight the importance of thorough inspections and precautionary measures. [4]

El Naggar A. et al. (2023), investigated the response of RC-framed buildings with varying spans and heights to differential settlement. The non-linear structural behavior is investigated using a 2D frame finite element analysis, which investigates mechanical damage transmission, plastic hinge formation due to induced settlements, and ductility considerations. The results show that the recommended tolerances are dangerous for 3 m spans and exceed yield settlements for 4.85 m spans, but they take a more conservative approach for larger spans (7.28 m and 9 m), with restrictions 50% lower than the yielding limit. Future research should include geometric characteristics, material properties, and reinforcement details for more precise settlement limit predictions, emphasizing the need for improved prediction models in frame structures subjected to differential settlements.[5].

The researchers also studied three different settlement scenarios involving center-intermediate, intermediate, and edge columns in RC structures. This study assesses the effectiveness of seismic provisions in mitigating structural damage caused by settlement. Structures designed for higher seismic hazard areas are more resilient to foundation settlement than those designed for lower seismicity zones. The investigation examines how seismic design provisions influence load redistribution, stiffness, and damage across varying seismic hazard zones in the context of RC structures experiencing differential settlement, providing valuable insights into their effectiveness [6].

Differential settlement, a phenomenon linked to cracked RC frames, introduces a complex layer of challenges. It transpires when various segments or supports of a structure settle unevenly due to disparities in soil conditions, construction practices, or subsurface movements. This differential settlement results in the tilting or distortion of the structure, causing structural elements to experience non-uniform stresses and strains. When combined with existing cracks in RC frames, differential settlement can exacerbate the situation, leading to additional cracking, changes in load distribution, and even structural instability as shown in figure 2-2 consequently, the interaction between cracked RC frames and differential settlement is a multifaceted issue, demanding precise engineering solutions to restore structural integrity and mitigate risks effectively. In reviewing the literature on this topic, a comprehensive understanding of these challenges and potential solutions will be developed to inform future research and practical applications in the field of structural engineering.

Under non-uniform differential settlement, experiments were replicated on a scaled pointed barrel vault typical of late-medieval Scottish architecture. Crack patterns and deformation profiles match experimental results, validating the numerical model. Complex failure modes and the importance of understanding ongoing deformation processes in historic barrel vaults are revealed by further analyses of plausible settlement patterns. D’Altri A. et al. 2019 [7], emphasize the importance of detailed structural analysis in designing effective strengthening strategies for historic masonry vaults and the need for minimal intervention to preserve architectural heritage.

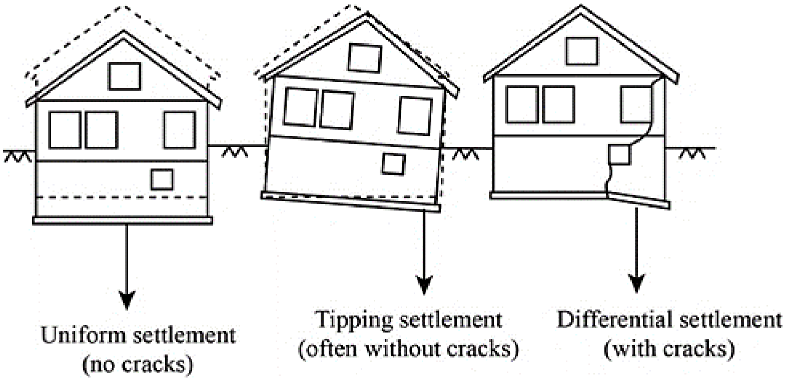


Figure 2-2 Types of Differential Settlement

Research examining horizontal loading scenarios in the context of Reinforced Concrete (RC) frames has been a critical area of investigation in the literature. This body of work encompasses a wide range of studies that aim to understand the structural behavior of RC frames under lateral forces, such as those generated by wind or seismic events. Horizontal loading represents a significant concern for structural engineers, as it can lead to structural deformation, instability, and even failure. The reviewed studies consistently emphasize the importance of evaluating the structural performance of RC frames under horizontal loading conditions and provide valuable insights into the impact of cracking, infill materials, and strengthening techniques[8].

Mostafaei H. et al. (2004), developed 3-D finite element model of reinforced concrete frames with and without infill under the effect of actual previous earthquake. The researchers developed a new approach to simulate the behavior of the frames and applied it in the finite element model. The researchers' model achieved the same results as occurred in the building after the earthquake as the bare frames experienced a large nonlinear deformation while the infilled frames showed linear behavior with no significant damage [9].

Santhi H. et al. (2006), tested under the effect of seismic loading Two one third scaled down one-bay three-story space frames with and without brick masonry infill. Masonry infill significantly impacted seismic performance, with three times the initial stiffness and 2.75 times greater base shear under the same earthquake motion compared to the bare frame. Retrofitting increased the natural frequency of the infilled frame by 120%, while the bare frame regained 75% of its original frequency. Retrofitting showed a significant increase in strength and stiffness, with drift reduced by 65% for the bare frame and 25% for the infilled frame. The researchers found that retrofitting RC frames with a reinforced concrete jacket improves their seismic resistance[10].

Santhi H. et al. (2006), studied the seismic performance of 1:3 scale reinforced concrete frame models with and without brick masonry infill and is tested on shake tables. Analysis of dynamic characteristics, shear force, inter-story drift, and stiffness shows that infill reduces fundamental frequency by 30% and retrofitting increases it by 20%. The infilled frame has a higher damping ratio, indicating more first-mode energy dissipation before and after retrofitting. The infilled frame has three times the lateral stiffness of the bare frame, and over four times after retrofitting. The infilled frame has below allowable inter-story drift. Infill increases strength demand threefold, but retrofitting reduces it to twofold, improving seismic performance[11].

Tasnimi A. et al. (2011), conducted a series of filled steel frames with and without opening s under the effect of lateral loading. The frames with openings in the infill walls exhibited diagonal tension failure with the same ductility as the solid infill frames. The opening aspect ratio did not affect the stiffness degradation and it was close to the elastic behavior. Also, the frames with openings experienced the same cumulative dissipated energy regardless of the opening aspect ratio[12].

Wang C. (2017), five scaled specimens, four masonry infilled reinforced concrete (RC) frames and one steel frame are tested for strength and out-of-plane behavior. Varying infill openings, prior in-plane damage, and frame-to-beam or column interface gaps are experimental parameters. Results show that the infill-top beam gap is worse than the infill-column gap and that out-of-plane strength decreases linearly with in-plane damage. Door openings lose more strength than window openings. The analytical estimates of RC and steel frame strength were inconsistent. The study emphasizes the need for improved analytical methods to predict irregular masonry infill strength under different conditions[13].

Altin S. et al. (2017), experimentally applied lateral loads on nonductile reinforced concrete (RC) frames with RC infills. Six one-third scaled, two-storey nonductile specimens were tested under reversed cyclic lateral loads to address common practice deficiencies. Infills increased frame strength and stiffness. Infilled frames showed the negative effects of lap splices in column longitudinal reinforcement.

This deficiency was addressed by adding continuous longitudinal reinforcements in infill boundary elements, building new columns on both sides of infill walls, and welding column lap splices. These strengthening methods prevented local failure in frame column splices and increased infilled frames' lateral strength, stiffness, and energy dissipation. The most practical and effective method for dissipating energy and improving seismic performance was welding column lap splices with external confinement. Initial stiffness predictions were slightly different in analytical studies, supporting the findings. This study illuminates infill wall strengthening of nonductile RC frames.[14]

Noh M. et al. (2017), improved the traditional material model to simulate concrete and masonry behavior in the simulation of lateral load response of the infilled RC frames. Researchers modeled frames from literature and found that the conventional available material models can successfully produce the backbone curve of the seismic event. While the developed model can represent the pinching behavior and accurately represent the hysteretic behavior of all tested infill RC frames[15].

Adnan S. et al. (2022), studied the lateral load response of masonry infilled reinforced concrete frames. A series of experimentally tested specimens showed clearly the shared axial forces between the boundary RC frame and the infill walls. The failure mechanism changed according to the specimens’ details that started with flexure failure of the bare frame to the combined failure of both the RC frame and the infill as gradual crack propagation in masonry that extended between the major shear cracks in the RC columns at loaded corners corresponding to sliding of the wall-frame interface as presented in figure 2-2 [16].

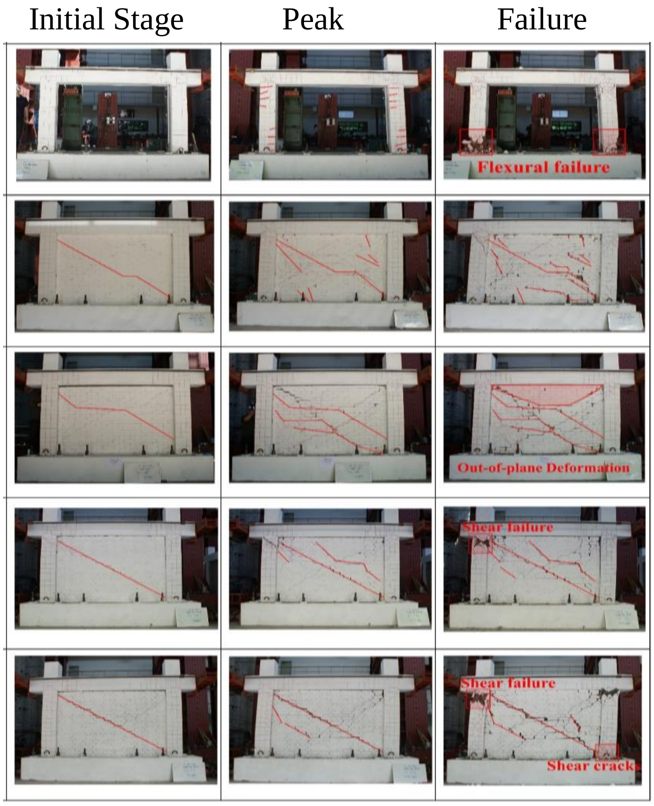


Figure 2 2 Cracking propagation during lateral loading of fully infilled RC frames Adnan S.et al.,2022)[16]

Comparative analyses of findings across these studies have uncovered key implications for structural performance. They highlight the role of cracking in reducing the stiffness and load-carrying capacity of RC frames subjected to horizontal loading. Cracks serve as weak points that can lead to the concentration of stress and deformation. The introduction of infill materials, such as concrete or masonry, has been found to be an effective strategy for mitigating the adverse effects of cracking by providing additional support and enhancing the overall resistance to lateral loads. Furthermore, the application of innovative strengthening techniques, including the use of Fiber-Reinforced Polymers (FRP), such as Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP), has been shown to improve the structural performance of RC frames by increasing their lateral stiffness, ductility, and energy dissipation capacity. These insights are invaluable for engineering practice, enabling professionals to make informed decisions when designing and retrofitting structures to withstand horizontal loading scenarios, contributing to the safety, resilience, and longevity of built environments.

3. Strengthening with Infilling

Infill materials play a critical role in structural engineering and construction by serving as integral components in reinforcing and rehabilitating various types of structures. These materials are commonly employed to bridge gaps, restore continuity, and enhance the load-carrying capacity of structural members, particularly in scenarios involving cracked or damaged Reinforced Concrete (RC) frames. Infill materials encompass a wide range of options, including concrete, masonry, and various composites, each offering distinct engineering properties and advantages. In the construction industry, these materials are vital for extending the service life of existing structures and ensuring their resilience in the face of dynamic and static loads and environmental stressors.

3.1. Full and Partial Infilled Frames

In the construction industry, infill materials have become invaluable tools for engineers and architects seeking to rehabilitate and reinforce existing structures while adhering to economic and environmental constraints. Infill materials offer a cost-effective and sustainable alternative to full-scale demolition and reconstruction, reducing both the financial burden on infrastructure owners and the environmental impact associated with new construction. This approach aligns with the industry's drive towards sustainability and resource efficiency. Additionally, infill materials are highly adaptable, making them suitable for addressing a wide spectrum of structural issues, from crack repair in RC frames to the enhancement of masonry walls.[17] The versatility and performance attributes of these materials contribute to their growing significance in the construction field, where engineers continuously seek innovative and practical solutions to enhance the safety, resilience, and longevity of infrastructure.

The literature provides a comprehensive review of studies exploring the application of concrete and masonry infill materials in the context of Reinforced Concrete (RC) frames subjected to differential settlement [18]. These studies consistently highlight the effectiveness of such infill materials in addressing structural issues associated with cracking and settlement.

Concrete is widely recognized for its high compressive strength, durability, and compatibility with existing RC structures. It is often used to fill gaps in cracked walls and frames, restoring structural continuity and distributing loads more uniformly. The engineering details in these studies emphasize the role of concrete in enhancing the load-carrying capacity of RC frames under both vertical and horizontal loading conditions. Furthermore, masonry infill materials, including bricks and blocks, have been employed in various structural rehabilitation projects. These studies demonstrate that masonry infill materials can significantly contribute to the shear resistance and stiffness of walls and frames, thereby improving the overall structural performance.

In the reviewed literature, the effectiveness of partial infill is underscored by its potential to offer cost savings and reduce material usage. By focusing on selectively reinforcing critical areas of a structure, engineers can target their resources more efficiently.[19] For instance, when dealing with RC frames with localized cracking or deficiencies, partial infill can be strategically applied to provide additional support only where it is required, leaving other areas untouched. This approach aligns with principles of sustainability and resource efficiency in the construction industry. Conversely, complete infill is favored when uniform strengthening is necessary throughout the entire structure, particularly in situations where there is extensive damage, and where global improvements in load-carrying capacity, stiffness, and resistance to deformation are needed. Both methods play crucial roles in engineering practice, as they offer flexibility in addressing a spectrum of structural conditions and are valued for their contributions to the construction industry, where the efficient use of resources and cost-effective rehabilitation are highly regarded objectives.[20] Figure 3-1 shows both cases of full/partial infill masonry.

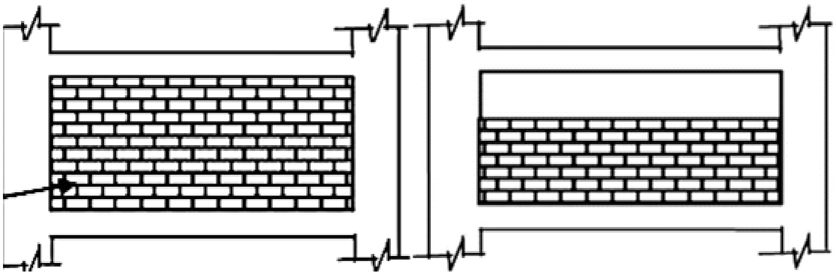


Figure 3-1 The full and partial infilled frames

Concrete is a widely used infill material with exceptional compressive strength and durability in the literature, it is frequently noted for its effectiveness in restoring the structural integrity of cracked RC frames by providing mechanical support and distributing loads more evenly across affected members.

This study introduces a seismic retrofit method for nonductile reinforced concrete frames with unreinforced masonry infills. Experimental tests included an un-retrofitted infill (UW) and three engineered cementitious composites (ECC) retrofitted infills (EW-25, EWBD-40, EWUD-40). Brittle failures reduced lateral capacity by 60% in specimen UW. Specimen EW-25, with a 0.5-inch ECC layer and steel mesh (0.25% cross-section), had 18% and 20% higher strength and stiffness but frame column shear failures. Specimen EWBD-40 with shear dowels increased lateral strength 87% and stiffness 61%. Shear dowels failed, but the specimen remained ductile.

Unbonded shear dowels improved strength and stiffness (58% and 34%) in specimen EWUD-40, which remained ductile after failures. These tests revealed potential failure mechanisms and showed that the ECC retrofit improves ductility and lateral strength, especially with shear dowels and bonding agents. Future research should examine different configurations and failure modes for practical use.[21]

Murty C. et al. (2000), examined the seismic behavior of RC frames with masonry infills, including stiffness, strength, ductility, and energy dissipation. Infills, especially reinforced ones, increase lateral stiffness and strength. Reinforced mortar thickness may reduce stiffness and strength. Prevention of out-of-plane collapse is improved by post-cracking reinforcement. In multistorey buildings in developing countries, masonry infills improve seismic performance when detailed. However, robust seismic design should address short-column and soft-storey effects[22].

Al-Chaar G. et al (2002), studied the behavior of the Masonry-infilled reinforced concrete frames in high seismic zones. These structures were designed for gravity loads without considering lateral loads, resulting in conservative designs. Infilled RC frames have higher ultimate, residual, and initial stiffness than bare frames while maintaining ductility, according to experiments on five half-scale, single-storey models of different bay configurations. Bay count affects peak and residual capacity, failure modes, and shear stress distribution, emphasizing the importance of nonuniform shear stress in multi-bay structures. Concrete frame failure mechanisms depend on shear strength, compressive strength, and infill geometry.[23]

Anil O. et al. (2007), focuses on experiments examining the behavior of ductile reinforced concrete (RC) frames with cast-in-place reinforced concrete infills, especially those with window or door openings, under cyclic lateral loading. Nine one-bay, one-storey specimens were tested with different infill wall aspect ratios and placements as shown Figure 3-2. Results showed that partially infilled RC frames had 3.73 to 7.37 times higher ultimate strength and initial stiffness than bare frames. Infills connected to columns and beams performed best. The study showed that infills as wing walls strengthen and that infill aspect ratio affects storey drift ratio and energy dissipation[24].

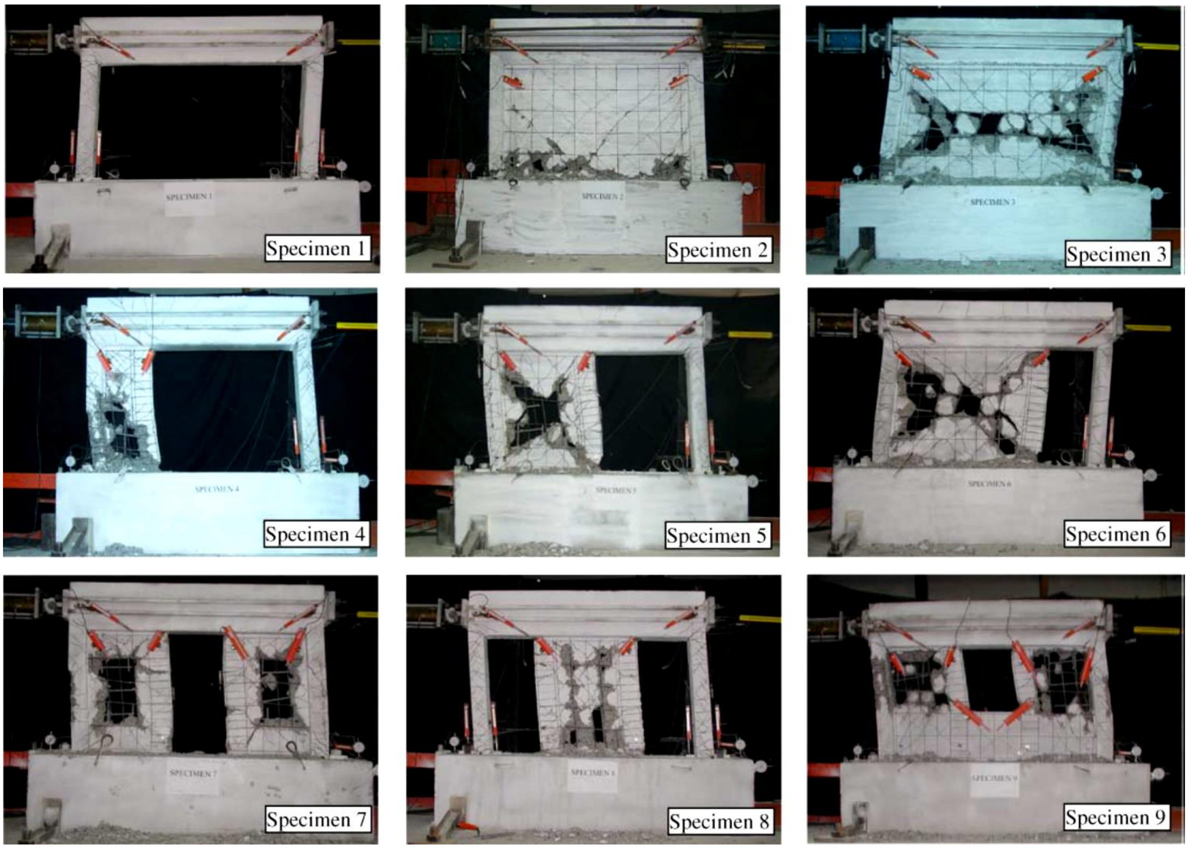


Figure 3-2 lateral load response of full/partial RC frames at failure (Anil O. et al. ,2007) [24]

Sattat S. et al. (2010), studies seismic performance by experimentally testing a set of bare, partially infilled, and fully infilled masonry-infilled (RC) frames. For seismic assessment, incremental dynamic analysis is performed on nonlinear models with two compressive strength-only nonlinear strut elements representing infill panels. Pushover analysis shows that infilled frames have higher initial stiffness, strength, and energy dissipation than bare frames, despite brittle infill failure modes. Dynamic analysis shows that earthquake-induced collapse is in bare frames and minimal in fully infilled frames. A median collapse capacity variation of 1.3 to 2.5 across configurations is found. Work is underway to incorporate column shear failure models and analyze wall modeling parameter sensitivity. Initial findings indicate that maximum strength, post-capping slope, and residual strength are important. Masonry material types and frames with stronger walls and window and door infill openings will be studied in the future. This study illuminates seismic risk mitigation strategies for RC frames with masonry infills [25].

Zovkic J. et al. (2013), examined how different masonry infills affect reinforced concrete frames under lateral loads. 10 1:2.5-scale reinforced concrete frames with high-strength hollow clay bricks, medium-strength hollow clay bricks, and low-strength lightweight autoclaved aerated concrete blocks were tested. Composite "framed wall" structures had higher stiffness, damping, and initial strength than bare frames. Masonry infill bridged the load capacity gap from 0.05% to 0.75% drift before the frame took over. Despite severe damage at 0.75% drift, the infills contributed to system resistance until drifts of about 1%. The study recommends improving code provisions for masonry infills because they reduce expected damages by lowering drift levels, improving structural performance [26].

Porto F. et al. (2015), strengthened Brick/block masonry RC frames with weak clay brick infill walls using lime-based plaster, bidirectional composite meshes, and enhanced TRM in this study. Better plasters and reinforcing meshes improve in-plane behavior and post-peak stability, providing insights for seismic retrofitting older RC structures [27]

Akin A. et al. (2016), examined full brick infill walls seismic strengthening of reinforced concrete frame systems with low earthquake resistance using precast concrete panels to improve brick infill walls. The study used six 1/2 scale, two-storey, single-span test specimens to simulate building defects. The key findings came from the strengthening method, which did not evacuate building occupants. Precast panel reinforcement improved lateral loads, initial rigidity, and energy dissipation. The reference specimen had severe damage to the 1st-storey columns and beam connections, but strengthened walls had less damage. This strengthening method increased lateral load resistance and reduced infill wall damage. This study suggests a way to increase seismic resistance without evacuation for nearby structures.[28]

Baran M. et al (2016), examined the reinforced concrete (RC)-framed buildings under the effect of seismic loading. Researchers developed an economically viable and structurally effective strengthening method for earthquake-prone hollow brick infill buildings. Six two-storey, one-third scale RC frames were tested. High-strength precast concrete (PC) panels increased RC frame lateral load capacity and rigidity by 2.55 to 2.51 times in frames with continuous column bars. Unfortunately, lap splices with inadequate lengths on column longitudinal bars reduced lateral strength to 90% of continuous column bar frames. As required by seismic regulations, all specimens carried loads up to 0.35% drift. PC panels also reduced infill wall shear deformations, improving seismic performance. This strengthening method may be an occupant-friendly and cost-effective seismic retrofitting solution.[29]

The Equivalent Lateral Force Method is used to study the seismic behavior of reinforced concrete (RC) frame building models, including bare, infilled, and open first-storey frames. Significant insights emerge from analysis: First, seismic analysis of RC frames must include infill walls using the equivalent diagonal strut method for accuracy. Second, seismic regions prefer infilled first-storey frames over open ones because they reduce storey drift and structural collapse. Thirdly, infill walls strengthen and stiffen structures. Finally, analyzing RC bare frames can underestimate base shear, putting structures at risk of failure during earthquakes. Infill walls are essential for seismic design[30].

Li S. st al. (2016), A quasi-static test was performed on a one-third scaled, four-bay by two-storey reinforced concrete (RC) frame with full-height infill walls to assess progressive collapse. In the experiments, progressive collapse resistance force increased by 37% and initial stiffness by 42% compared to the bare frame. In exchange, beam ductility decreased. At the frame's peak resistance force, major infill wall cracks appeared at a minimal vertical displacement of the removed column. The frame collapsed in two phases: beam bending, shear capacities, compressive arch action in beams, and compressive strut action in infill walls, and catenary action in beams. The equivalent compressive strut model, used in seismic response analysis of infilled frames, accurately depicted the failure mechanism[31].

Baghi H. et al. (2018), conducted experimentation and computational analysis to examine how masonry infill walls affect full-scale reinforced concrete (RC) frames subjected to column failure. It shows that mortar quality and workmanship determine masonry shear strength. Traditional infill walls improve structural integrity, stiffness, load-carrying capacity, and energy absorption, making them essential for progressive collapse resilience. Numerical simulations show that longitudinal beam reinforcement increases load-carrying capacity and frame reinforcement details significantly impact performance. Artificial vision monitoring reveals the dynamic interaction between infill walls and RC frames, emphasizing their importance in structural resilience[32].

Yu J. et al. (2019), developed numerical models to study RC frames with concrete masonry infill walls after middle column removal. An infilled frame's load transfer mechanism combines frame action and truss mechanism from infill walls and frame members. This truss mechanism affects beam plastic hinge locations by increasing initial structural stiffness and peak resistance. Wall panel failure affects infill wall-frame shear stress. In partial-height infill frames, diagonal splitting fails, and wall height increases peak structural resistance faster. Infill walls with openings (IWHO) reduce peak resistance with central openings and increased opening areas, but opening shape barely affects peak resistance. Peak resistance increases with full-height infill walls on multi-storey frames. The study illuminates load transfer mechanisms and structural behavior, improving seismic design [33].

Baran M. et al (2021), This study compared seismic strengthening methods for seismically loaded non-ductile reinforced concrete (RC) frames. The experimental phase tested one-third scale, two-storey RC frames with hollow brick infill strengthened five ways. RC infill walls, precast RC plates, steel fiber reinforced mortar, and plain mortar strengthened the structure. These methods increased frame strength and stiffness by 57% to 189% and 186% to 486%, respectively. Precast RC plates and plain 2% steel fiber reinforced mortar were cost-effective and occupant friendly. Using these methods to increase lateral strength and stiffness could prevent collapse in low-strength RC buildings, according to numerical analysis. The methods were evaluated based on concrete compressive strength, application ease, and material costs.[34]

The choice between partial and complete infill should be guided by a comprehensive structural analysis and the specific requirements of the project. In the construction industry, the ability to make informed decisions regarding infill strategies is a testament to the flexibility and adaptability of engineering solutions. Such informed choices lead to cost-effective and sustainable strengthening of RC structures, aligning with industry goals and the principles of structural resilience and longevity. These engineering insights provided in the literature review serve as valuable references for industry professionals seeking to optimize their strengthening strategies and efficiently address structural deficiencies in RC frames.

3.2. Infilled Frames with Openings

The impact of openings or voids in infill materials is a significant aspect explored in the literature, particularly in the context of strengthening Reinforced Concrete (RC) frames. These studies reveal that the presence of openings or voids in infill materials can have a substantial influence on the structural response and behavior.

When infill materials contain openings, whether intentional for architectural features or due to utility penetrations, they introduce complexities in terms of load distribution and stress concentrations as shown in figure 3-3. Engineering analyses have shown that the presence of openings within infill materials may lead to localized stress concentrations around the openings, which can affect the overall structural performance. [20], [35]

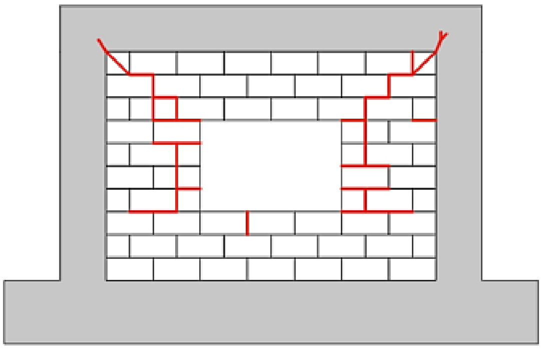


Figure 3-3 Impact of voids in infill.

In the construction field, understanding the impact of openings or voids in infill materials is critical to achieving the desired structural outcome while ensuring safety and durability. The literature underscores the importance of careful design and engineering considerations when dealing with openings in infill materials. Strategies to mitigate the effects of openings include the use of additional reinforcing elements or localized strengthening techniques around the openings. These considerations are particularly relevant when dealing with historical or heritage structures where architectural elements or utility installations must be preserved. By addressing the impact of openings or voids in infill materials, engineers and construction professionals can make informed decisions and implement effective strategies that maintain the structural integrity of RC frames. This knowledge and the engineering solutions it informs contribute significantly to the construction industry by allowing for more precise and adaptive strengthening methods, ensuring the long-term sustainability of structures with openings or voids in infill materials.[36]

The study includes bare RC frames and fully infilled walls with and without openings. While infill walls and openings did not affect specimen behavior, they did suffer significant damage at 1.25-2.50% storey drift ratios, posing risks. Walls with openings, especially eccentrically positioned ones, experienced additional damage. Due to inertia, deboned infill walls may fall, affecting combined in-plane behavior. High stability withstood 9% storey drifts in tests. Infilled walls with openings caused more damage, and Eurocode 8's 2.5% storey drift limit was considered safe. The study emphasizes the importance of understanding infill behavior in both in- and out-of-plane loading scenarios to avoid disjointed movement between frames and infill walls during seismic events[37].

Ten specimens under in-plane lateral loading and one bare frame specimen were tested to determine the behavior and capacity of concrete masonry infills in steel frames. Aspect ratio, grouting extent, infill openings, and frame-to-infill stiffness were considered. Corner crushing was the main failure mode for solid infills, while diagonal cracking was common in openings.

Grouting increased initial stiffness and ultimate load, while openings and gaps decreased them. Major axis column orientation increased initial stiffness and ultimate load, while minor axis orientation increased ductility. CSA S304 overestimates stiffness by 2.7 times and underestimates strength by 2.3 times, resulting in a conservative design.[38]

Masonry infill panels significantly impact the stiffness and strength of reinforced concrete frames. The absence of a standardized method for representing openings in infill walls poses a modeling challenge. Introducing a reduction factor (λ) to established equations for compression strut equivalent width facilitates the modeling of infill walls with openings. The study, utilizing a two-strut model calibrated on experimental results, assesses the influence of openings on vibration and inter storey drifts. Openings reduce the vibration period by a factor of nine in the fully infilled frame. Initially, the bare frame experiences inter Storey drifts twice as large, which triple during cyclic loading. Employing the proposed reduction factor for modeling infill frames with openings holds promise for validation and versatile applications[39].

Mondal G. et al. (2008), studied the structural behavior of the infilled reinforced concrete frames with central window openings. Initial stiffness when openings are present is calculated using a diagonal strut effective width reduction factor. Seven infilled frames with different opening sizes and configurations are analyzed. SAP 2000 is used for Finite Element (FE) analysis, and experimental results validate the reduction factor. The study suggests conditions for neglecting or considering openings' effect on initial lateral stiffness, setting a practical design guideline. Further research could examine how opening location and structural elements like lintel bands or stiffeners affect the proposed reduction factor [40].

Okail H. et al. (2014), investigated the behavior of confined masonry walls through both experimentation and numerical analysis. Six full-scale wall assemblies, incorporating various configurations such as solid and perforated walls with openings, different reinforcement ratios, and brick types, were subjected to lateral loads. Experimental results revealed shear failure in the confining elements after diagonal strut failure in the brick wall. Stepped bed joint cracks formed in the masonry panel. The numerical model, validated against experiments, conducted a parametric study on design configurations, showing that higher strength bricks, increased confining elements, and reduced perforation widths enhance lateral load capacity and ductility. The findings emphasize the significance of brick strength and the role of confining elements in influencing confined masonry wall behavior[41].

Cetisli F. et al. (2015), employed various analytical and numerical techniques, such as finite element analysis (FEA) and experimental testing, to examine the effects of openings or voids in infill materials. These investigations have provided valuable engineering insights. They highlight that the presence of openings, whether intentional for architectural design or for utility penetrations, can create stress concentration points and alter the load path within the structure. The size, shape, and location of openings have been found to influence the magnitude and distribution of stresses, as well as deformation patterns within the RC frames. Furthermore, researchers have identified that the introduction of openings may lead to reduced stiffness and reduced load-carrying capacity in localized regions [42]. Consequently, the reviewed studies emphasize the need for careful consideration of openings and the design of reinforcement strategies to mitigate the potentially adverse effects on the structural integrity of RC frames.

4. Strengthening with Steel Bracing

Steel bracing, as a strengthening technique in structural engineering, is a well-established method that has found extensive application in rehabilitating Reinforced Concrete (RC) frames subjected to differential settlement and other challenges. The use of steel bracing involves the introduction of steel elements, such as braces or trusses, within the structure to provide lateral stability and enhanced resistance to deformation and dynamic loads with no significant increase in building weight. These steel elements work by effectively redistributing loads, reducing sway, and improving the overall structural performance. Steel bracing is particularly effective in enhancing the resistance to lateral forces, such as wind or seismic loads, and has been a valuable tool in retrofitting existing structures to meet modern safety and performance standards[43]. Also, the steel bracings enable to accommodate required openings as well. Thus, steel bracings introduces both practical and economical retrofitting techniques. There are two main types of steel bracings: concentric bracing and eccentric bracing as shown in figure 4-1.

(a)Concentric bracings (b) eccentric Bracings

Figure 4-1 Types of steel bracings

4.1. Concentric Steel Bracing

The concentric system is the bracing when the steel members intersect at the same points of beams (midspan in most cases). This system is usually used when the frame spans are vertically aligned. This system increases the lateral stiffness of the frame with no significant effect on the cumulative dissipated energy. The lateral drift is reduced and the internal forces in frame columns as shear and bending moments are decreased corresponding to the increase of the compressive force in columns at points of intersections with braces. The literature has shown that the placement of CBFs influences their performance, with variations in bracing angles and locations impacting the overall structural response. Additionally, eccentrically braced frames[44]. This bracing system is the most common choice when strengthening the RC frames. Figure 4-2 shows the different types of concentric bracing systems that include:

X-Bracing: This method employs diagonal braces in an "X" pattern. It is simple, effective, and often used in buildings where architectural aesthetics are a concern. However, it may limit interior space.

V-Bracing: Like X-bracing but in a "V" shape. It provides stability while allowing for more open space. The choice between X and V depends on architectural and functional requirements.

Chevron Bracing or inverted V-bracing: Chevron braces form a pattern resembling an inverted "V." This method combines elements of both X and V-bracing, offering stability and architectural flexibility.

K-Bracing: In this configuration, diagonal braces form a "K" shape. It provides effective lateral stability and allows for larger open spaces, making it suitable for various architectural designs.

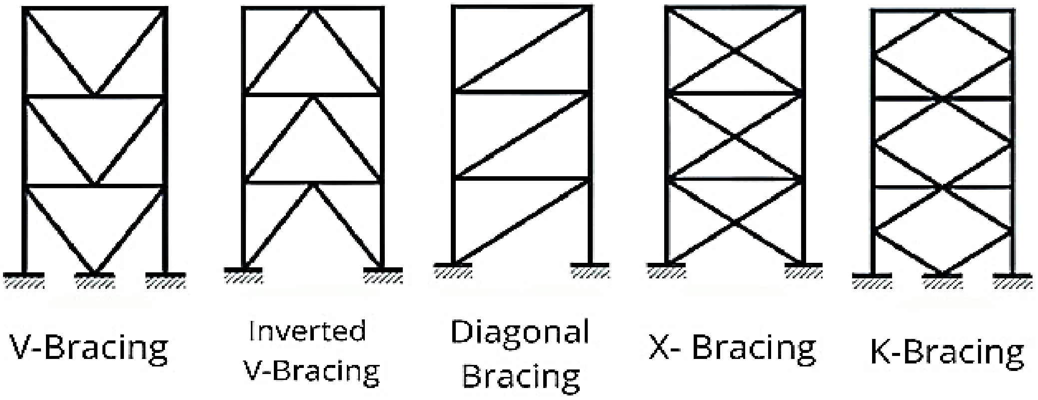


Figure 4-2 Types of concentric steel bracings

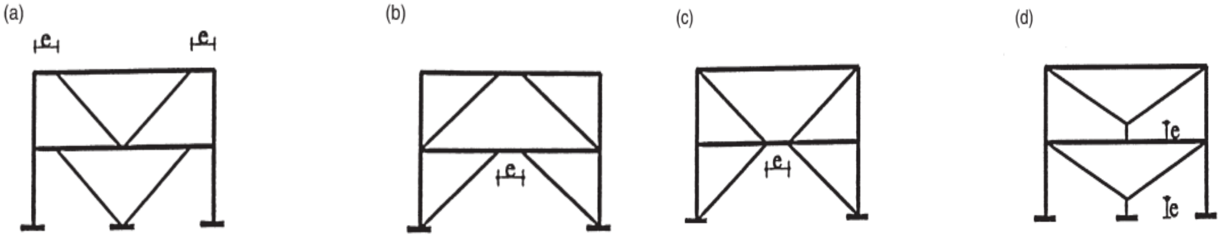
Massumi A et al. (2013), experimentally tested two 1/2.5-scaled concrete frame specimens: unbraced and braced with cross bracings. Bracing increases the system's strength, stiffness, and energy absorption, according to experimental results. Positive frame-bracing interaction increased the dual system's ultimate strength by 18.34%. The hybrid system's stiffness and energy dissipation increased significantly due to this interaction. The study stresses the importance of connection detailing for reinforced concrete frame bracing system efficiency. The researchers suggest designing or retrofitting RC frames to improve seismic performance with steel bracing and proper connection details. [45]

Qian K. Et al. (2019), tested five one-quarter-scale specimens, one bare frame and four braced frames under pushdown loading. The frames' first peak load and initial stiffness improved significantly with steel bracing. Tensile braces failed before catenary action mobilization, and compressive braces buckled severely, making braced specimens perform similarly to the bare frame. Braced frames had higher yield load (YL) by 24% to 44%, initial stiffness by 36% to 157%, and first peak load capacity (FPL) by 41% to 129% than bare frames. The findings show that steel bracing improves reinforced concrete frame load-resistance and stiffness, especially progressive collapse resistance[46].

Kafi M. et al. (2020), examined six concrete frame strengthening methods. The steel divergent bracing system with a steel link beam outperformed concrete frame X-bracing. Steel consumption dropped 10%–30% and base shear 20%. The existing-to-allowable stress ratio dropped to 35% for 20-storey buildings. Interestingly, higher buildings improved the steel braced frame system. Higher structures had 60% higher elastic hardness, 50% higher ductility, doubled behavior coefficient, and 25% higher base shear than shorter structures.[47]

4.2. Eccentric Steel Bracing

Eccentric Steel Bracing system enhances the dissipated energy that is a particularly good advantage while providing a good seismic behavior. On the other hand, the eccentric bracings reduce the lateral stiffness of the braced frame as the vertical force component in the bracings members produces lateral concentrated load at points of bracing-beam intersections. This type of bracings delays the damage and absorbs more energy than the concentric bracing system and is often used in high seismic zones. [48]



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

Figure 4-3 Various types of eccentrically braced steel frames (Ghobarah A. et al. (2001)

In addition, buckling-restrained braced frames. (BRBF) have gained attention for their capacity to provide stable and ductile response under seismic actions. These systems incorporate buckling-restrained braces, which limit brace buckling and control deformation, ensuring that the structure remains resilient during seismic events. Engineering details in the literature emphasize that the selection of the most appropriate steel bracing method is contingent on the specific project requirements, seismic risks, and structural conditions.[49]

Ghobarah A. et al. (2001), tested the effectiveness of the rehabilitation of non-ductile low rise RC framed building using the eccentric steel bracings by applying different seismic loading history. The researchers found that the eccentric exhibited lower deformations and damage when compared to the concentric bracing system. Also, the RC frames strengthened using eccentric steel bracings requires high attention to the factors controlling the design demand including the steel member inclination angle, connection details with the RC frame and the distribution of the steel bracing members along the building height[50].

The comparative analysis offered by these studies underscores the necessity of considering factors such as the expected loadings and the desired performance outcomes when deciding on the ideal bracing method for RC frame strengthening. By providing a comprehensive understanding of the engineering principles and effectiveness of these methods, the literature aids engineers and construction professionals in making informed decisions to ensure the structural resilience and safety of RC frames in diverse real-world scenarios.

5. Strengthening with Fiber Reinforcement Polymer (FRP)

A significant body of research in the literature has focused on the use of Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) Figure 5-1 materials for strengthening Reinforced Concrete (RC) frames to resist the challenges posed by differential settlement. GFRP and CFRP composites have emerged as innovative and versatile solutions in structural rehabilitation, owing to their exceptional tensile strength, corrosion resistance, and lightweight properties. These studies have consistently underscored the efficacy of GFRP and CFRP materials in enhancing the structural performance of RC frames, particularly in situations where differential settlement is a prevalent concern.[51]

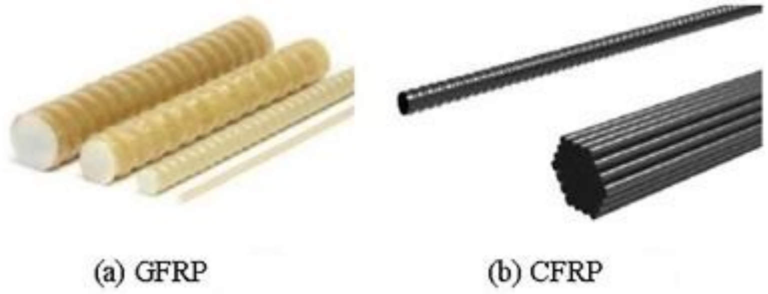

(a) GFRP (b) CFRP

Figure 5-1 (GFRP) and (CFRP)

Comprehensive analysis of Fiber Reinforced Polymers (FRP) in concrete reinforcement and repair. CFRP and GFRP are known for their high strength-to-weight ratios and tensile properties, with CFRP performing better. The study covers FRP materials, epoxy matrix components, and mechanical properties like tensile and flexural strengths

Figure 5-2. For seismic retrofitting, load-bearing capacity, and structure span extension, CFRP's tensile strength and lightweight make it ideal. GFRP is cheaper but improves structural integrity, especially in corrosive environments. Flexural strengthening increases load-bearing strength by 40%, as the paper discusses design and FRP retrofitting. This review highlights the transformative potential of FRP materials in modern construction, particularly in sustainable infrastructure rehabilitation. [52]

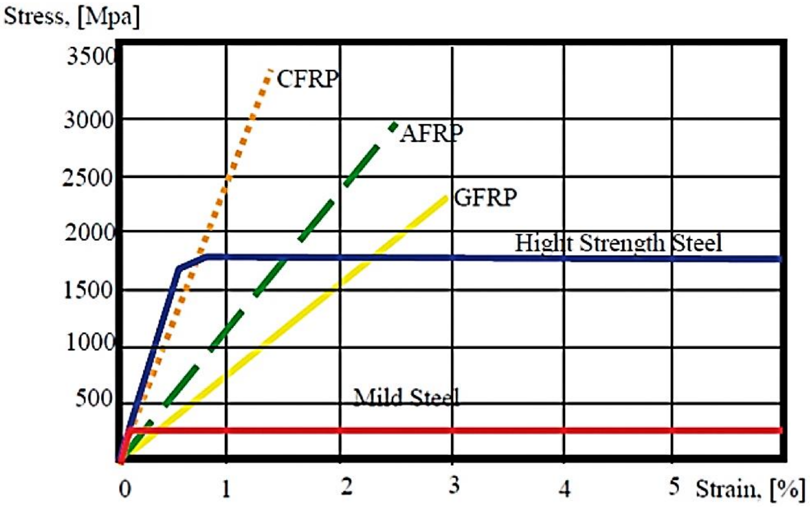


Figure 5-2 Stress–Strain Curves of some FRP composites {adapted from ref [53]}

5.1. Strengthening Using Glass Fiber Reinforced Polymers (GFRP)

The elastic and rigidity moduli (E&G) of GFRP poles are heavily influenced by sample size and shape, so the study aims to develop accurate measurement methods rather than using manufacturer values. The critical slenderness ratio (L/r) defines a 10% shear deformation contribution and sets an upper limit for E&G tests [54].

The engineering specifics outlined in these research investigations. reveal that GFRP and CFRP materials are typically applied in the form of externally bonded or near-surface mounted (NSM) reinforcement. Externally bonded reinforcement involves the application of GFRP or CFRP sheets or strips to the exterior of RC members, providing enhanced tensile strength and shear resistance. NSM reinforcement, on the other hand, involves the insertion of GFRP or CFRP bars or rods into grooves or channels in RC elements, offering a more concealed strengthening method. Researchers have conducted comprehensive experiments, including load tests and numerical simulations, to assess the effectiveness of these reinforcement techniques. The results consistently demonstrate that GFRP and CFRP materials can improve the load-carrying capacity, ductility, and resistance to cracking in RC frames subjected to differential settlement. Furthermore, the lightweight nature of these materials contributes to the ease of application, making them practical solutions for structural rehabilitation and retrofitting. The reviewed studies collectively highlight the contribution of GFRP and CFRP materials to the construction field, offering valuable insights into their engineering performance and their capacity to address the complex challenges associated with RC frames experiencing differential settlement[55], [56].

Awad Y. et al. (2023), focuses on strengthening GFRP poles with internal steel bracing bars and finding the best way to control lateral deflection. Different strengthening methods increased flexural stiffness by 44%, 66%, and 38%, with the external steel angle technique being the most effective [57].

As the utility industry uses more Fiber Reinforced Polymer (FRP) poles, this comprehensive review emphasizes their lightweight, high strength-to-weight ratios, and durability. Critical examination of manufacturing methods, testing procedures (static and dynamic), and modeling approaches shows that FRP can be customized for diverse applications. Selecting fibers, matrix materials, and geometrical properties helps engineers optimize products. [58]

5.2. Strengthening Using Carbon Fiber Reinforced Polymers (CFRP)

Altin S. et al. (2007), tested CFRP strip width on ten scaled-down RC frame specimens under cyclic lateral loading and found significant strength and stiffness improvements. The frames had 1.54 to 2.61 times greater ultimate lateral strength and 6.4 times greater initial stiffness than unmodified specimens. These gains were offset by storey drift ratios exceeding recommended limits, emphasizing the need for stiffness degradation and anchorage detailing. This study shows that CFRP strips can reinforce masonry-infilled RC frames, but design challenges must be addressed. [59]

Hudson J. et al. (2017), Analyzed how differential settlements affect Gothic barrel vault structural behavior and how FRP strengthens them. Unreinforced and FRP-reinforced model vaults were tested.

The unreinforced vault (BV1) collapsed after a 132 mm settlement (42% of vault rise) with rapid cracking and structural deformation. However, the reinforced vault (BV2) with a 33 mm carbon fiber braid performed better. The FRP increased stiffness and limited crack propagation, allowing it to withstand a 162 mm settlement (51% of the rise) with less crack formation. The study shows that FRP can strengthen historic masonry structures against differential settlements, making it a promising repair and strengthening method for culturally significant structures like Gothic barrel vaults. [60]

Erdem I. et al. (2006), tested two strengthening methods on 1/3-scale, two-storey, three-bay Turkish building frames. RC infill and CFRP hollow clay blocks strengthened one frame. Special transducers at exterior column bases measured strength, stiffness, and storey drifts under reversed cyclic quasi-static loading. Both strengthening methods increased stiffness and strength, with 500% lateral strength. CFRP strip strengthening does not require evacuation, but column bar slips limited specimen capacity. In conclusion, RC infills and CFRP strips strengthen masonry without frame member reinforcement if anchor dowels work [18].

Garcia R. et al. (2010), analyzed how Carbon Fiber Reinforced Polymer (CFRP) composites improve seismic resilience of reinforced concrete (RC) frames with poor detailing. Shake table tests were performed on a two-story RC building before and after CFRP retrofitting. The CFRP-strengthened frame sustained 65% less global damage than its original state during real earthquake excitations. This significant seismic performance improvement was due to improved beam-column joints. The study proves that CFRP composites can significantly reduce earthquake damage in RC frames, improving structural resilience and safety. [61]

Sebastian W. et al. (2016), compared the behavior of two reinforced concrete frames: one under-reinforced with 0.94% tension steel (control) and the other with 0.35% near-surface mounted tension CFRP. CFRP frames carried 37% more load than controls. RC nonlinear models showed distinct behavior. The CFRP frame unexpectedly failed at the midspan due to brittle separation of FRP bars from concrete in the peak positive moment zone, indicating unique performance differences. The control frame showed beneficial moment redistribution under higher loads to prevent cracking at lower loads. This pre-yield brittle separation failure mode's mechanics need further study [62].

Strengthening solutions restore structural integrity and resilience of cracked RC frames, emphasizing their importance. Infill materials, Fiber-Reinforced Polymers (FRP), and steel bracing systems are among these solutions, each with their own engineering benefits. Mechanical support and load redistribution from infill materials like concrete and masonry bridge cracks and restore structural continuity. GFRP and CFRP have high tensile strength and corrosion resistance, making them useful for increasing structural element load capacity. Lateral steel bracing reduces sway and improves structural performance. These strengthening solutions solve cracking and differential settlement problems and make RC structures safer and more durable.

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