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REVIEW

Seismic Behavior of Squat Reinforced Concrete Shear Walls: A State-of-the-Art Review

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ABSTRACT

Squat reinforced concrete (RC) shear walls are essential structural elements in low-rise buildings, valued for their high strength and stiffness. However, research on their seismic behavior remains limited, as most studies focus on tall, slender walls, which exhibit distinct failure mechanisms and deformation characteristics. This study addresses this gap by conducting an extensive review of existing research on the seismic performance of squat RC shear walls. Experimental studies, analytical models, and numerical simulations are examined to provide insights into key factors affecting wall behavior during seismic events, including material properties, wall geometry, reinforcement detailing, and loading conditions. The review aims to support safer design practices by identifying current knowledge gaps and offering guidance on areas needing further investigation. The findings are expected to aid researchers and practitioners in refining seismic design codes, ultimately contributing to the development of more resilient squat RC shear walls for earthquake-prone regions. This research underscores the importance of improving structural resilience to enhance the safety and durability of buildings.

KEYWORDS

Seismic behavior; squat shear walls; reinforced concrete; earthquake resilience; structural performance

1 Introduction

Reinforced concrete (RC) shear walls play a fundamental role in the structural design of buildings, particularly in seismic regions [1,2]. These walls are critical for resisting lateral forces and enhancing the structural integrity and safety of buildings during seismic events [3,4]. Squat RC shear walls, with their low height-to-length ratio, are crucial in low-rise structures and buildings with limited vertical space. Their distinct structural characteristics necessitate a thorough understanding of their behavior under seismic loads to optimize their design and performance. The body of literature on the seismic behavior of squat RC shear walls is extensive, covering various aspects from experimental investigations to numerical simulations and analytical modeling. Choi [5] emphasized the significance of understanding the cyclic behavior of these walls to improve their seismic resilience. Li et al. [6,7] conducted cyclic tests on ultra-high-performance concrete (UHPC) squat shear walls, providing critical insights into their load-bearing capacity and deformation characteristics. Similarly, Chen et al. [8] explored enhancements in seismic behavior through innovative materials and construction techniques in one-sided concrete squat walls. In North America, El-Dakhakhni et al. [9] discussed the design of reinforced masonry and concrete walls, highlighting regional differences in design practices and their impact on wall behavior. Kim et al. [10] tested six squat walls under cyclic loading, contributing valuable data on failure mechanisms and deformation patterns. These findings align with those of Fathalla et al. [11], who also examined the seismic performance of squat walls under cyclic loads. The research by Akl et al. [12] further elaborate on collapse fragility functions for squat walls, while Arafa et al. [3] investigated the flexural and shear stiffness of these structures. Despite these efforts, existing literature lacks a review article that covers the experimental, analytical, and numerical studies of squat shear walls while also being systematic and bibliometrics. Accordingly, with the increasing frequency and intensity of earthquakes globally, there is an urgent need to enhance the understanding and design of these structural components. This study aims to conduct a comprehensive literature review on the seismic behavior of squat RC shear walls. By critical investigating findings from experimental, analytical, and numerical studies, the review will provide a detailed understanding of these walls' performance during seismic events. The study will evaluate the effectiveness of current modeling techniques and propose recommendations for improving design practices and guidelines. The comprehensive scope of this study includes a detailed analysis of various aspects of wall behavior, modeling techniques, and design procedures. The review will also cover the general seismic performance of squat shear walls, discussing performance metrics and common failure mechanisms. Key experimental findings will be integrated to highlight the influence of structural and material parameters on wall behavior. Additionally, the study will examine analytical modeling approaches, numerical simulation methods, and the validation and comparison of these models against experimental data. The review will also provide a biometric assessment of the current state of the art and will go through the design strategies of squat shear walls. By addressing the existing fragmentation in the literature and providing a detailed perspective on wall behavior, this review aims to contribute to the development of more effective and reliable strategies for enhancing the seismic resilience of squat RC shear walls. The rest of the paper is organized as follows: Section 2 discusses the seismic behavior of squat shear walls; Section 3 reviews modeling techniques; Section 4 evaluates current design procedures; Section 5 summarizes key findings, identifies gaps, and suggests future research directions.

2 Bibliometric Assessment

The bibliometric assessment of research on squat RC shear walls provides an insightful overview of scholarly activity in this specialized field. In order to perform the bibliometric assessment, a keyword search on the Scopus database identified about 110 directly related articles with squat shear walls mentioned in the title. These documents were then analyzed and reviewed in this study. Fig. 1 analyzes the publication trends over time and reveals a dynamic pattern in research output. The data shows periods of increased academic interest, particularly in recent years, which can be attributed to advancements in seismic design requirements and heightened awareness of structural resilience against natural disasters with respect to low-rise buildings. This trend underscores the growing importance of squat shear walls in the context of structural engineering and earthquake-resistant design.

A closer examination of the top journals, Fig. 2, reveals that the majority of influential studies are published in reputable sources such as Engineering Structures and ACI Structural Journal. The geographic distribution of research contributions, Fig. 3, highlights the global nature of scholarly work on squat shear walls. Leading countries, including the United States and China, are prominent due to their significant investments in infrastructure resilience and advanced research facilities. The presence of

European nations like Germany and Italy also reflects their long-standing tradition in civil engineering research and innovation. This global distribution points to a collaborative international effort to enhance the understanding and performance of squat shear walls in seismic applications. The keyword analysis, Fig. 4, further elucidates the core themes and focal points within this body of research. The frequent occurrence of terms such as shear walls, RC, seismic behavior, and high-strength materials indicates a concentrated effort to understand the mechanical and seismic performance of squat shear walls. These keywords also suggest a strong emphasis on material innovations and the development of design methodologies that improve the resilience of structures in earthquake-prone areas.

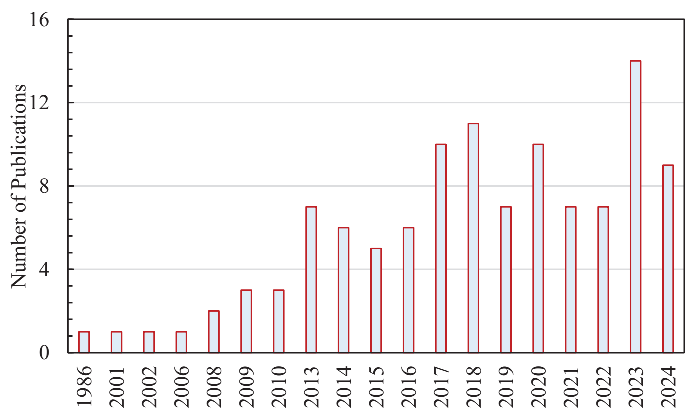


Figure 1: Number of publications over time

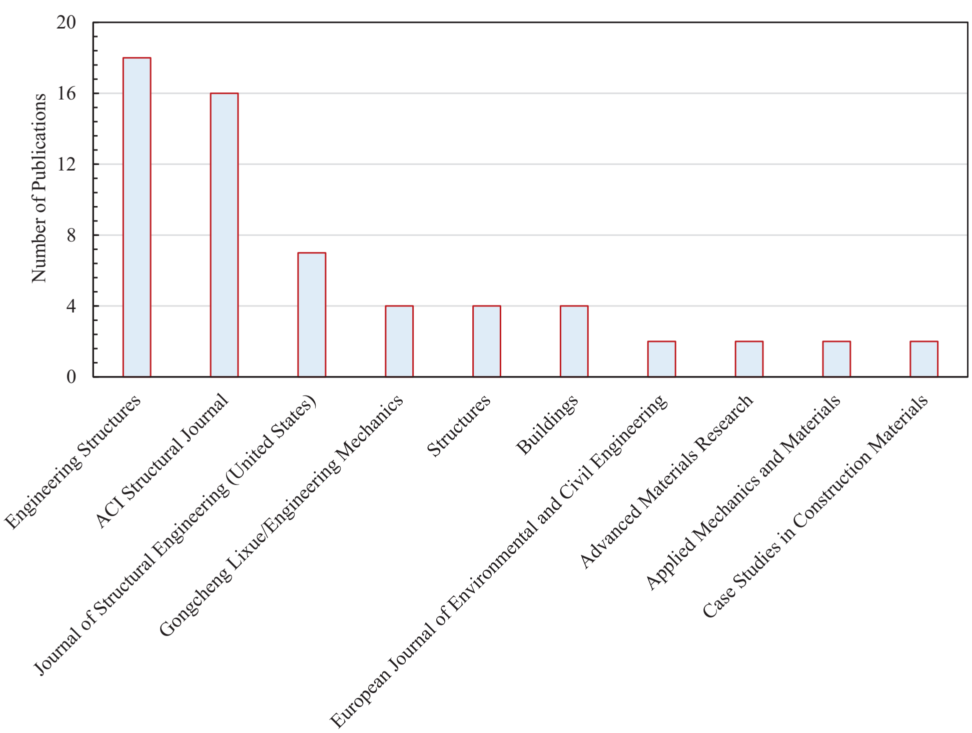


Figure 2: Top 10 journals with the heights number of publications on squat shear walls

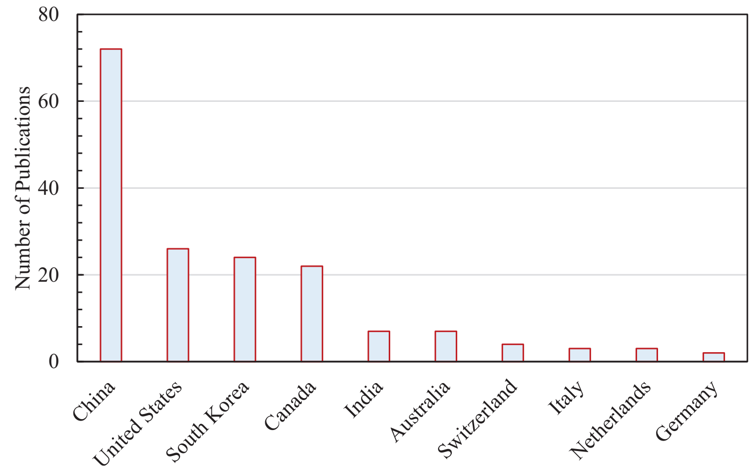


Figure 3: Countries with the highest number of publications on squat shear walls

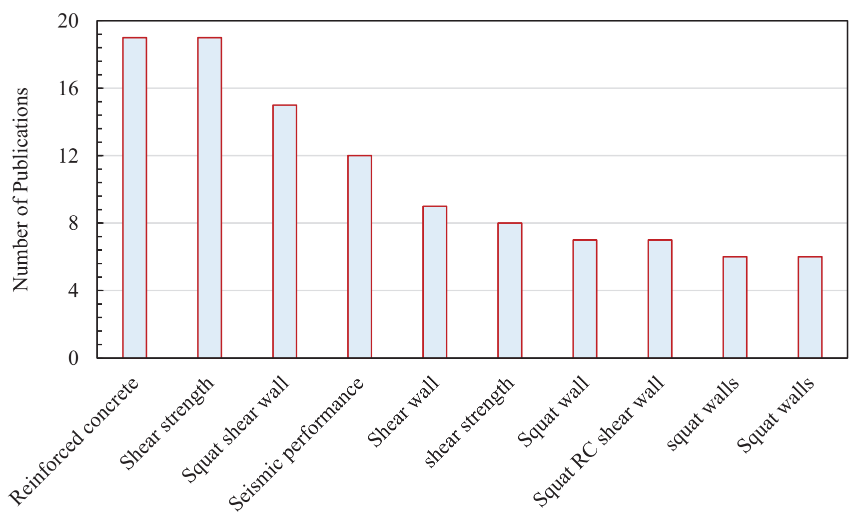


Figure 4: Most used keywords in squat shear walls research

3 Seismic Behavior of Squat Shear Walls

3.1 General Seismic Performance

The seismic performance of squat RC shear walls is a vital area of study in structural engineering, particularly for buildings in earthquake-prone regions [12,13]. These walls are characterized by a low aspect ratio (height-to-length ratio less than two). As a result, they behave differently under seismic loading compared to their taller, slender counterparts [14,15]. Squat shear walls are less typically used in low-rise buildings and are less understood compared to taller ones, especially regarding their unique mechanisms of failure and deformation during earthquakes [16–18]. Unlike slender walls dominated by flexural deformations, squat walls are governed by shear deformations, making them more vulnerable to shear failures, which are often brittle and catastrophic if not properly addressed in the design [19,20]. The seismic performance of squat shear walls is influenced by several factors, including material properties, wall geometry, reinforcement detailing, and loading conditions [21,22]. Understanding these factors is crucial for enhancing the seismic resilience of buildings relying on squat shear walls for lateral load resistance [23,24]. Early research on squat shear walls, such as the study by Hidalgo et al. [14], emphasized the importance of reinforcement detailing in preventing shear failures and improving ductility under cyclic loading. Subsequent studies explored various reinforcement strategies to enhance seismic performance, including the addition of steel plates to improve energy dissipation and shear strength [8]. Recent research has expanded to include environmental factors affecting the seismic behavior of squat shear walls. For example, studies by Rong et al. [16] examined the impact of frost damage and exposure to offshore atmospheric environments on these walls, highlighting the need to consider environmental degradation in their seismic design. Similarly, Eid et al. [25] and Tong et al. [26] investigated the impact of construction materials, such as low-performance concrete (LPC) and UHPC, on the shear capacity and overall seismic performance of squat shear walls, finding that LPC can reduce seismic performance while UHPC can enhance it. Advanced analytical and numerical modeling techniques have also contributed to the understanding of squat shear wall behavior. Research by Sivaguru et al. [21] and Hosseini et al. [27] found that openings could significantly weaken the walls' seismic resistance, emphasizing the need for careful reinforcement detailing around these openings. Environmental factors, such as chloride ion erosion and freeze-thaw cycles, also significantly affect the seismic performance of squat shear walls. Studies by Zheng et al. [23,28–30] and Yang et al. [31] demonstrated that environmental degradation could reduce the seismic capacity of these walls, underscoring the importance of incorporating such factors into the design and maintenance of squat shear walls. Similarly, chemical reactions within the concrete, such as alkali-silica reaction (ASR), can compromise the seismic resilience of these walls [32]. The role of boundary conditions and construction details in the seismic performance of squat shear walls has also been extensively studied. Research by Gulec et al. [15,33] provided insights into how boundary conditions influence shear strength and seismic performance. Different reinforcement materials have been explored for their impact on seismic performance as well. Studies by Yu et al. [18] and Lim et al. [34] found that steel fiber RC (SFRC) and strain-hardening cement composite (SHCC) can enhance shear strength and seismic resilience. The influence of wall geometry has also been a key area of research. Kim et al. [35] found that flanges can enhance seismic performance by providing additional lateral resistance. Yang et al. [36] emphasized the importance of considering geometric details in seismic design. Numerical simulations have become increasingly important in understanding the seismic behavior of squat shear walls. Tariq et al. [20] utilized gene expression programming to estimate the shear strength of RC squat walls, offering a novel approach to predictive modeling in seismic design. Akl et al. [12] conducted a seismic collapse risk assessment of low-aspect-ratio RC shear walls using FEMA P695 methodology, providing valuable insights into the probabilistic assessment of seismic performance. The integration of new materials, such as ultra-high-performance fiber-reinforced concrete (UHPFRC), has also been explored to enhance seismic performance. Nagib et al. [19,37] demonstrated that UHPFRC could significantly improve the seismic resistance and energy dissipation capacity of squat shear walls. Kang et al. [38] effect of cement matrix's type on the shear performance of lightly reinforced squat shear walls subjected to cyclic loading. Finally, the role of the horizontal reinforcement ratio in improving the seismic performance of BFRP-RC squat shear walls was studied by Miao et al. [39]. Accordingly, the seismic performance of squat RC shear walls is influenced by various factors, Table 1, including material properties, wall geometry, reinforcement detailing, environmental conditions, and loading scenarios. While significant advancements have been made in understanding squat wall behavior, there remain gaps that require further research, particularly concerning the long-term effects of environmental degradation and performance under extreme loading conditions.

3.2 Failure Mechanisms and Modes

Over the past decades, experimental methods have been used as the main approach for investigating the behavior of civil structures [40,41]. In this regard, the failure mechanisms and modes of squat shear walls, which are critical aspects that significantly influence their seismic behavior, have been mainly investigated experimentally at the element level [10,24,31]. In general, squat shear walls, characterized by their relatively short height-to-length ratios, are prone to various failure modes, particularly under seismic loading conditions [42,43]. The failure mechanisms in these walls include shear failure, flexural-shear failure, shear sliding failure, flexural cracking, diagonal cracking, concrete crushing, brittle failure, and ductile failure [44,45]. Each of these mechanisms presents unique challenges that must be addressed to ensure the structural integrity and resilience of squat shear walls during seismic events. Shear failure is one of the most critical failure modes in squat shear walls, characterized by the formation of diagonal cracks and subsequent crushing of concrete, leading to sudden and brittle failure. This failure mode can be prevented by incorporating adequate shear reinforcement, which helps in distributing shear stresses and preventing the initiation and propagation of diagonal cracks [46,47]. As shown in Table 2, the implementation of appropriate shear reinforcement is essential to mitigate this type of failure and enhance the wall's overall performance under seismic loads. Flexural-shear failure involves the simultaneous occurrence of flexural cracking at the wall's base and shear cracking along its height, resulting in complex and unpredictable failure patterns. In order to prevent this failure mode, the use of high-strength concrete and well-detailed reinforcement is recommended.

Table 1: Key factors influencing the seismic performance of squat RC shear walls

Factor	Study/Reference	Impact on seismic performance	Key findings
Wall geometry	[14,15,33]	Low aspect ratio influences shear-dominated behavior.	Squat walls are more prone to brittle shear failures compared to slender walls.
Material properties	[25,26,32]	Material quality affects shear strength and ductility.	Low-performance concrete and ASR reduce seismic resilience, while UHPC enhances it.
Reinforcement detailing	[8,21]	Proper detailing improves ductility and shear capacity.	Steel plates, careful reinforcement around openings, and SFRC improve performance under seismic loading.
Environmental conditions	[16,17,28,29,32]	Environmental degradation weakens seismic resistance.	Exposure to frost, chloride ions, and ASR reduces shear strength and ductility.
Loading conditions	[1,18,21]	Cyclic and extreme loading conditions stress the structural integrity.	Squat walls exhibit distinct hysteretic behavior under cyclic loading, necessitating robust design strategies.
External reinforcement	[19,34]	External reinforcement enhances seismic resistance.	UHPFRC and SFRC significantly improve shear strength and energy dissipation capacity.

Table 2: Failure mechanisms in squat shear walls

Failure mechanism	Description	Preventive measures	Reference
Shear failure	Characterized by diagonal cracks and concrete crushing, leading to sudden and brittle failure.	Adequate shear reinforcement to distribute shear stresses and prevent diagonal cracking.	[24,26,28,29,39,43–47]

(Continued)

Table 2 (continued)

Failure mechanism	Description	Preventive measures	Reference
Flexural-shear failure	Involves both flexural cracking at the base and shear cracking along the height, resulting in complex failure patterns.	High-strength concrete and well-detailed reinforcement are used to control both flexural and shear cracks.	[31,43]
Shear sliding failure	Horizontal cracks develop along the plane of maximum shear stress, leading to significant displacement.	Incorporation of transverse reinforcement to prevent horizontal crack propagation and shear sliding.	[48,49]
Flexural cracking	Cracks primarily at the base of the wall due to bending moments affect the wall's load-bearing capacity.	Proper reinforcement detailing at the base to manage bending moments and prevent flexural cracking.	[50,51]
Diagonal cracking	Diagonal cracks form due to high shear stresses, potentially leading to shear failure if not controlled.	Reinforcement placement and concrete strength optimization to control diagonal cracking.	[4,45,52–54]
Crushing of concrete	Localized crushing of concrete at points of high compressive stress, compromising structural integrity.	Ensuring sufficient concrete cover and quality to prevent localized crushing.	[5,49,53,55,56]
Brittle failure	Sudden failure without significant deformation, often due to inadequate reinforcement detailing.	Detailed reinforcement design to enhance ductility and prevent brittle failures.	[17,54]
Ductile failure	Failure with significant deformation is typically associated with well-detailed reinforcement and better energy dissipation.	Use of advanced materials like steel fibers to improve ductility and energy absorption.	[5,18,36,37,57]

These measures help control both flexural and shear cracks, thereby improving the wall's resilience against seismic forces [31,43]. Shear sliding failure is another significant concern, where horizontal cracks develop along the plane of maximum shear stress, leading to substantial displacement and potential structural collapse. The incorporation of transverse reinforcement is a key preventive measure for this failure mode, as it helps prevent the propagation of horizontal cracks and subsequent shear sliding [48–50]. Flexural cracking, which primarily occurs at the base of the wall due to bending moments, can severely compromise the wall's load-bearing capacity. Proper reinforcement detailing at the base is crucial to managing bending moments and preventing the onset of flexural cracking [31,50]. Additionally, diagonal cracking, caused by high shear stresses, poses a significant risk of shear failure if not adequately controlled. The strategic placement of reinforcement and optimization of concrete strength is necessary to control diagonal cracking and ensure the wall's stability [4,51,52]. Concrete crushing is a localized failure mechanism that occurs at points of high compressive stress, compromising the structural integrity of the wall. Ensuring sufficient concrete cover and maintaining high concrete quality are essential preventive measures against this type of failure [49,53–56]. Therefore, understanding the various failure mechanisms and modes of squat shear walls is essential for improving their seismic performance. By implementing appropriate preventive measures, such as enhanced reinforcement detailing and the use of advanced materials, the resilience of these walls against seismic forces can be significantly improved, ultimately leading to safer and more durable structures.

3.3 Influence of Structural and Material Parameters

The seismic behavior of squat RC shear walls is a complex phenomenon influenced by various structural and material parameters. The influence of these parameters has been extensively studied to understand how they affect the overall performance of these walls during seismic events. Concrete strength is one of the most critical factors determining the seismic behavior of squat shear walls. Higher concrete strength increases the load-bearing capacity and reduces crack propagation during seismic events. Table 3 summarizes the influence of material properties on the seismic behavior of squat shear walls. It highlights that higher concrete strength, appropriate reinforcement types, and the addition of steel fibers contribute to improved seismic performance.

Table 3: Influence of material properties on seismic behavior

Material property	Influence on seismic behavior	Key findings
Concrete strength	Higher concrete strength increases load-bearing capacity and reduces crack propagation during seismic events.	High-performance concrete with added steel fibers demonstrated increased concrete strength, significantly enhancing the first crack load, overall structural strength, and energy dissipation capacity under lateral cyclic loading [58]. Moreover, UHPC squat shear walls exhibited superior performance in cyclic tests, with higher load-bearing capacity and reduced lateral deformations [6,7].
Reinforcement type	The type of reinforcement (steel, GFRP, CFRP) affects the ductility and energy absorption capacity of the walls.	CFRP sheets effectively restored the in-plane strength of earthquake-damaged RC shear walls, significantly enhancing their load-bearing capacity and seismic performance [46]. Besides, GFRP-reinforced squat walls demonstrated the ability to resist lateral loads effectively, with the study highlighting the importance of considering concrete shear contribution and boundary element confinement for accurately predicting their ultimate flexural and shear strengths [3].
Steel fibers	Steel fibers enhance ductility, delay the onset of shear cracking, and improve energy absorption capacity.	Steel fibers at a volume fraction of 1% to 2% increased load-bearing capacity by 25% and energy absorption by 30% [58].
Reinforcement detailing	Detailed reinforcement improves energy dissipation and controls shear deformations, preventing brittle failures.	A transverse reinforcement ratio of 0.5% to 1% was found optimal for controlling shear deformations [32].

Moreover, reinforcement detailing plays a significant role in enhancing energy dissipation and controlling shear deformations, preventing brittle failures. Previously, Ganesan et al. [58] demonstrated that high-performance concrete with added steel fibers significantly enhances the first crack load, overall structural strength, and energy dissipation capacity under lateral cyclic loading. Similarly, UHPC squat shear walls exhibited superior performance in cyclic tests, with increased load-bearing capacity and reduced lateral deformations [6,7]. This aligns with findings from Chen et al. [59] and Chetchotisak et al. [60], who also highlighted the importance of concrete strength in seismic performance.

The application of high-strength concrete is further supported by the work of Liu et al. [43] where experimental and numerical investigations confirmed the enhanced seismic resilience of squat shear walls constructed with high-strength materials. The type of reinforcement used in squat shear walls plays a crucial role in influencing their seismic performance. Different types of reinforcement, such as steel, GFRP, and CFRP, affect the ductility and energy absorption capacity of the walls. Arafa et al. [3] emphasized that GFRP-reinforced squat walls demonstrated effective resistance to lateral loads, and their study highlighted the importance of considering concrete shear contribution and boundary element confinement for accurately predicting the ultimate flexural and shear strengths. Additionally, Woods et al. [46] found that CFRP sheets effectively restored the in-plane strength of earthquake-damaged RC shear walls, significantly enhancing their load-bearing capacity and overall seismic performance. These findings are consistent with those of Fathalla et al. [11], who observed that the type and detailing of reinforcement directly impact the energy dissipation and deformation characteristics of squat shear walls under seismic loads. Steel fibers, when added to concrete, further enhance the seismic performance of squat shear walls. Hosseini et al. [61] examined squat RC shear walls with steel and GFRP rebars. Testing six specimens, they found hybrid reinforcement improved seismic performance by modifying failure modes, enhancing energy dissipation, ductility, and load factors, and delivering superior hysteresis behavior compared to GFRP-only walls. Hybrid rebars proved effective in seismic applications.

Ganesan et al. [58] reported that steel fibers, at a volume fraction of 1% to 2%, increased the load-bearing capacity by approximately 25% and improved energy absorption by 30%. This improvement is attributed to the ability of steel fibers to delay the onset of shear cracking and enhance the ductility of the concrete, which is critical for preventing brittle failures during seismic events. Lim et al. [34] also supported these findings, noting that steel fibers contribute to the overall shear behavior of squat shear walls, particularly in configurations with vertical slits. Reinforcement detailing is another critical parameter that influences the seismic behavior of squat shear walls. Proper detailing, particularly the transverse reinforcement, is essential for controlling shear deformations and preventing brittle failures. Habibi et al. [32] found that a transverse reinforcement ratio of 0.5% to 1% was optimal for controlling shear deformations, thereby enhancing the energy dissipation capacity of the walls during seismic loading. This is consistent with the observations of Jin et al. [42] and Ma et al. [62], who emphasized the importance of reinforcement detailing in ensuring the structural integrity and seismic resilience of squat shear walls. The influence of structural parameters on the seismic performance of squat shear walls is further illustrated in Fig. 5, which shows variations in shear strength with design parameters such as aspect ratio, axial load ratio, boundary reinforcement ratio, and web reinforcement ratio [60]. This figure emphasizes the complex interplay between structural and material parameters in determining the overall seismic performance of squat shear walls, as also highlighted by Devine et al. [53] and Gondia et al. [63]. Additionally, the damage patterns of various squat shear wall materials, as depicted in Fig. 6, underscore the importance of material properties in influencing seismic behavior. Ultra-high-performance concrete and UHPFRC specimens exhibited distinct damage patterns under different shear stress demands, highlighting the role of material composition in determining the extent and nature of damage during seismic events [57]. These observations are corroborated by the experimental findings of Han et al. [4] and Hosseini et al. [27], which further reinforce the importance of understanding material behavior to optimize the seismic design of squat shear walls.

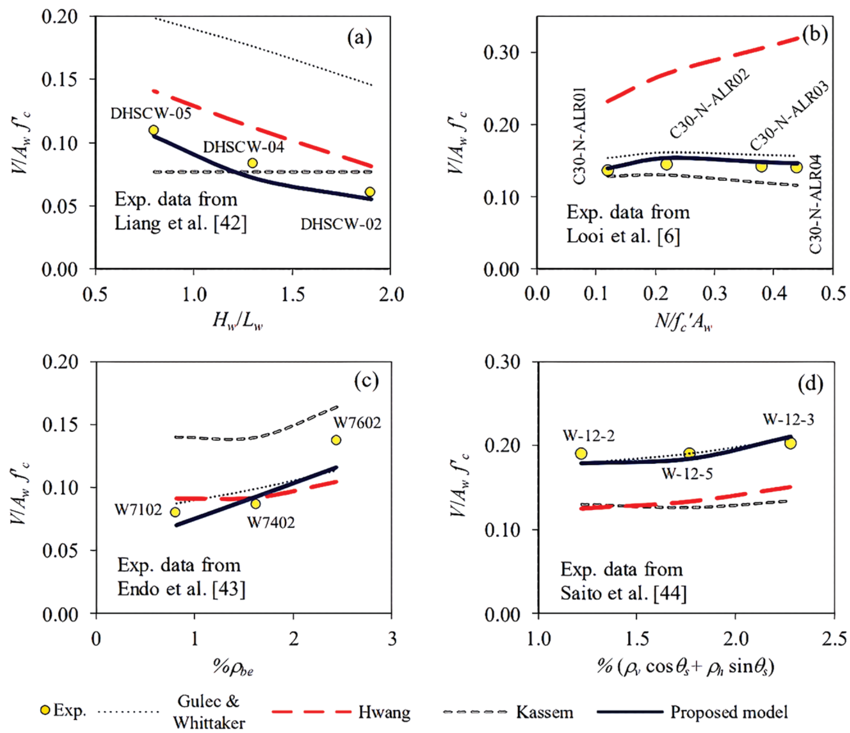
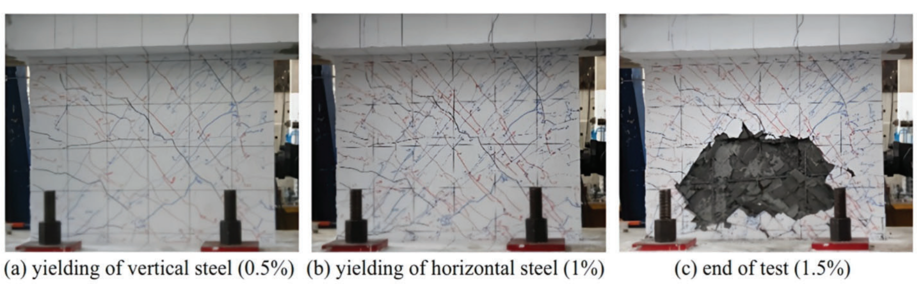
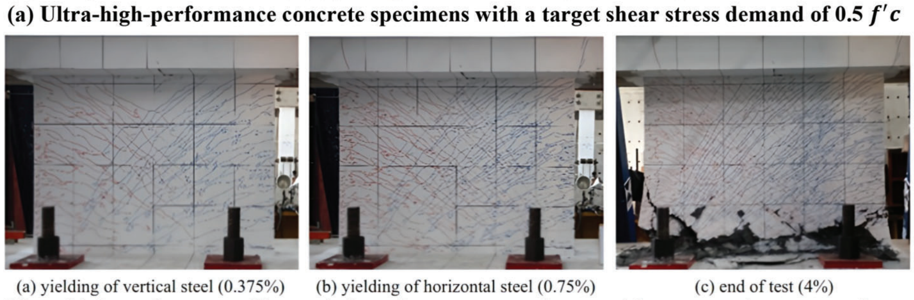


Figure 5: Variations in shear strength with design parameters: (a) aspect ratio; (b) axial load ratio; (c) boundary reinforcement ratio; (d) web reinforcement ratio (Reprinted with permission from Reference [60], Copyright 2024, Engineering Structures)

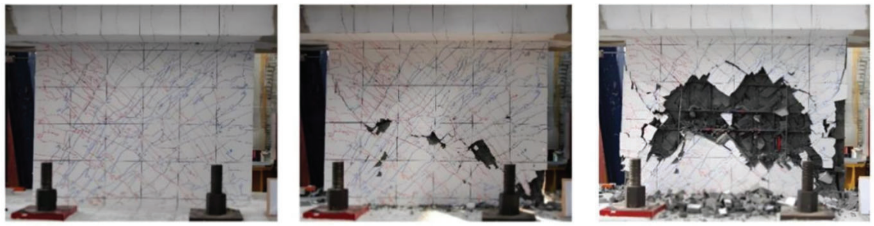


(a) Ultra-high-performance concrete specimens with a target shear stress demand of 0.5 $f'c$



(b) Ultra-high-performance fiber-reinforced concrete specimens with a target shear stress demand of 0.5 $f'c$

Figure 6: (Continued)



(a) yielding of vertical steel (0.75%) (b) yielding of horizontal steel (1%) (c) end of test (1.5%)

(c) Ultra-high-performance concrete specimens with a target shear stress demand of 0.83. $f'c$

(a) yielding of vertical steel (0.75%) (b) yielding of horizontal steel (2%) (c) end of test (3%)

(d) Ultra-high-performance fiber-reinforced concrete specimens with a target shear stress demand of 0.83. $f'c$

Figure 6: Damage patterns of various squat shear wall materials (Reprinted with permission from Reference [57], Copyright 2024, Engineering Structures)

4 Modeling Techniques for Squat Shear Walls

4.1 Analytical and Numerical Modeling Approaches

This section reviews the various modeling approaches employed in the literature, encompassing analytical models, numerical simulations, and machine learning techniques, all supported by extensive experimental validations, Tables 4 and 5. The strut-and-tie model is a widely adopted analytical approach for modeling the internal force distribution within squat shear walls. Chetchotisak et al. [60] developed a strut-and-tie model specifically tailored for predicting the shear strength of squat shear walls under earthquake loads, demonstrating its efficacy in capturing the complex force interactions as shown in Fig. 7. Similarly, Kassem [64] proposed a closed-form design formula based on the strut-and-tie model, enhancing the predictive capabilities for shear strength in squat walls. Massone et al. [65] further advanced this approach by modeling squat structural walls controlled by shear, providing a robust framework for shear response estimation. Massone [66] introduced a shear-flexure interaction model calibrated for squat structural walls, offering improved strength predictions by considering the interplay between shear and flexural forces. This approach was validated through experimental data, showcasing its reliability in practical applications. Chen et al. [59] developed an alternative shear strength equation for RC squat walls, emphasizing the importance of ensuring deformation capacity. This equation provides a simplified yet accurate method for estimating shear strength, facilitating easier design processes. Finite element modeling has been extensively utilized to simulate the behavior of structural components over the past [67–69]. In this context, Belletti et al. [70] employed a PARC-CL model to numerically predict the response of squat shear walls subjected to monotonic loading, achieving high accuracy in load-bearing capacity and deformation predictions. Damoni et al. [71,72] utilized nonlinear finite element analyses to simulate crack propagation and the transition from flexural to shear-dominated behavior, aligning closely with experimental observations. Gopalarathnam et al. [73] conducted nonlinear finite element dynamic analyses of squat shear walls with openings, highlighting the influence of openings on seismic performance. Similarly, Jin et al. [42] performed finite element modeling of squat shear walls under combined cyclic and high axial loads, providing insights into their complex loading responses. Liu et al. [43] investigated the seismic performance of RC squat shear walls with single post-openings reinforced by steel plates through both experimental and numerical methods, validating their finite element model results against empirical data. Kolozvari et al. [74] utilized OpenSees' capabilities for modeling nonlinear behavior in RC walls and columns, with a focus on combined shear and flexural responses. The paper introduced the shear-flexure interaction MVLEM (SFI-MVLEM) and the fixed-strut-angle model (FSAM) to more accurately capture these interactions. Additionally, new material models, ConcreteCM and SteelMPF, improve the representation of cyclic degradation and prevent stress overshooting. Validated against experimental data, these models enhance load capacity and stiffness degradation predictions, particularly for structures with notable shear-flexure interaction. Petrone et al. [75] presented a versatile numerical model capable of nonlinear analysis for squat-to-tall reinforced-concrete shear walls, accommodating a range of loading conditions and wall geometries. This comprehensive framework allows for the simulation of various failure modes and seismic responses. Additionally, Rasoolinejad et al. [76] examined the size effect on squat shear walls using the microplane model M7, providing insights into how scaling influences seismic performance. This is crucial for ensuring that models remain accurate across different wall sizes and configurations.

4.2 Machine Learning-Based Modeling Techniques

Machine learning techniques have gained prominence in predicting the properties and behavior of materials and structures [77–81]. In this context, the behavior of various materials [82,83] and structural elements [84–87] has been estimated. Chen et al. [13] utilized a hybrid artificial neural network-particle swarm optimization model to predict shear strength, demonstrating superior accuracy compared to traditional methods. Goh et al. [88] applied multivariate adaptive regression splines (MARS) and neural network models to forecast shear strength, further validating the potential of these approaches in structural engineering. Gondia et al. [63] introduced mechanics-guided genetic programming expressions for shear strength prediction, integrating physical principles with data-driven methodologies. Nguyen et al. [89] used machine learning-based formulations to predict the shear capacity of squat flanged RC walls, offering a novel approach to seismic design. The presence of openings in squat shear walls introduces additional complexities in their seismic performance. Feng et al. [90] developed an interpretable XGBoost-SHAP machine learning model, enhancing the transparency and reliability of shear strength predictions for squat RC walls. Le Nguyen et al. [91] conducted a comparative study of various machine learning approaches for lateral strength estimation of squat shear walls, highlighting their practical implications and effectiveness. Sulaiman et al. [92] examined the efficiency of the XGBoost algorithm for predicting the shear strength of squat RC walls, performing comprehensive parametric analyses to optimize model performance. Nguyen et al. [93] further improved data-driven models for estimating shear capacity, emphasizing enhanced predictive accuracy and robustness, particularly in the case of random forest (RF) and gradient boosting regression tree (GBRT). Finally, Kazemi et al. [94] introduced an advanced ensemble approach for seismic risk and probability assessment by combining multiple machine learning models with optimization techniques. This stacked model integrates algorithms like decision trees, support vector machines, and gradient boosting and utilizes optimization methods, such as Bayesian and genetic algorithms, to refine model choice and parameters for peak performance. Focused specifically on RC shear walls, it analyzes structural and material factors affecting resilience to earthquakes, achieving 99.1% accuracy for incremental dynamic analysis (IDA) and 99.4% for seismic fragility curves. For user convenience, the study includes a graphical interface (GUI) that displays performance levels and seismic curves and calculates mean annual frequency for seismic hazards, providing a practical tool to support improved seismic safety decisions for concrete structures.

4.3 Material Innovations and Reinforcement Techniques

Shabana et al. [95] investigated the shear strength of GFRP-RC squat walls using the strut-and-tie model, demonstrating significant improvements in seismic performance. Their study underscores the benefits of advanced reinforcement materials in enhancing the ductility and strength of squat shear walls. In addition to that, Shabana et al. [96] investigated the stiffness characteristics of squat walls reinforced with glass FRP (GFRP) bars method to estimate the post-cracking shear stiffness of squat shear walls. Nagib et al. [19] explored the cyclic behavior of squat RC shear walls strengthened with UHPFRC, showcasing enhanced durability and seismic resilience. This approach highlights the potential of fiber-reinforced materials in modern structural design. Kim et al. [10,56] focused on the shear strength modeling of flanged squat walls, particularly in nuclear power plants, emphasizing the critical role of boundary elements. Their models account for high-strength reinforcing bars and boundary flanges, providing accurate shear strength predictions under seismic loads. Kim et al. [97] investigated flanged squat walls reinforced with 690 MPa bars, and found that Incorporating flanges significantly boost shear strength by 40%. Additionally, high-strength bars perform comparably to conventional ones, and shear strength surpasses ACI 318-19 limits by 200%. Woods et al. [46] utilized image analysis methods in the seismic rehabilitation of squat RC shear walls using CFRP sheets, demonstrating effective strengthening strategies. This work highlights the integration of advanced materials and diagnostic techniques in enhancing structural resilience. Weng et al. [98] focused on predicting the lateral load-displacement curves for RC squat walls failing in shear, providing critical data for understanding their deformation characteristics under seismic loading. Finally, Ocampo-Escobar et al. [99] compared the analytical findings with experimental data to identify important parameters impacting the effective stiffness of RC squat walls. Fig. 8a illustrates the reinforcement of the wall with truss elements, while Fig. 8b shows the wall with brick elements and steel reinforcement embedded into the wall.

Looi et al. [100] developed ultimate drift prediction models for rectangular squat RC shear walls, facilitating better seismic performance assessments. Seif Eldin et al. [101] studied the seismic performance parameters of fully grouted reinforced masonry squat shear walls, while Faraone et al. [51] analyzed damage patterns in both squat and flexural RC shear walls, contributing to a deeper understanding of failure mechanisms. Massone et al. [102] developed a single-panel model for estimating the shear response of squat RC walls, simplifying the analysis while maintaining high predictive accuracy. This approach is particularly useful for preliminary design and assessment purposes. Many studies integrate multiple modeling techniques to enhance prediction accuracy and reliability. For instance, Damoni et al. [71,72] combined finite element methods with discrete element models to capture complex behaviors such as cracking and shear-flexure interactions. Fig. 9 shows the squat RC wall configuration setup, while Fig. 10 demonstrates the verification of the prediction model compared to tested high axial load ratio ALR squat walls.

Table 4: Summary of simulation model's performance

Model type	Predicted behavior	Experimental data	Validation outcome	Reference
Strut-and-tie model	Accurate prediction of diagonal struts and tie forces	Cyclic loading tests on squat shear walls	Good agreement with experimental observations	[60]
Finite element model	Accurate load-deformation behavior, crack patterns, and failure mechanisms	Tests on squat RC shear walls	Excellent agreement with experimental results	[91]
Coupled FEM model	Accurate prediction of reduced load-bearing capacity and increased deformations due to environmental degradation	Cyclic tests on squat shear walls exposed to harsh environmental conditions	Good agreement with experimental observations	[70]
Hybrid FEM-DEM model	Accurate transition from flexural to shear-dominated behavior	Tests on squat shear walls	Good agreement with experimental results	[71,72]
Finite element model	Accurate ductility, energy absorption, and crack patterns	Tests on steel fiber-reinforced squat shear walls	Close match with experimental behavior	[95]
Strut-and-tie model	Accurate stress distributions, load-deformation behavior, and failure mechanisms	Tests on squat shear walls	Excellent correlation with experimental data	[13]

Table 5: Utilized design codes and guidelines for research on squat shear walls in the existing literature

Design code/ Guideline	Description	Reference
ACI 318	American Concrete Institute code for structural concrete design.	[4,10,19,33,63,95,103,104]
Eurocode 8	European standard for the seismic design of buildings.	[101,105]
New Zealand standard	New Zealand code for seismic design and building construction.	[9]

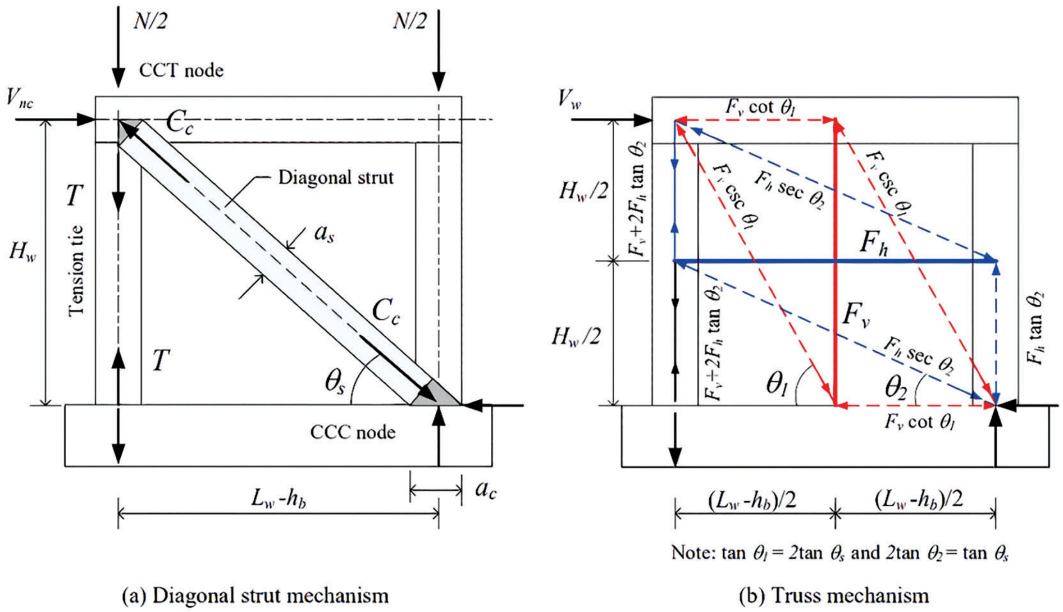


Figure 7: Force transfer mechanisms for squat shear walls (Reprinted with permission from Reference [60], Copyright 2024, Engineering Structures)

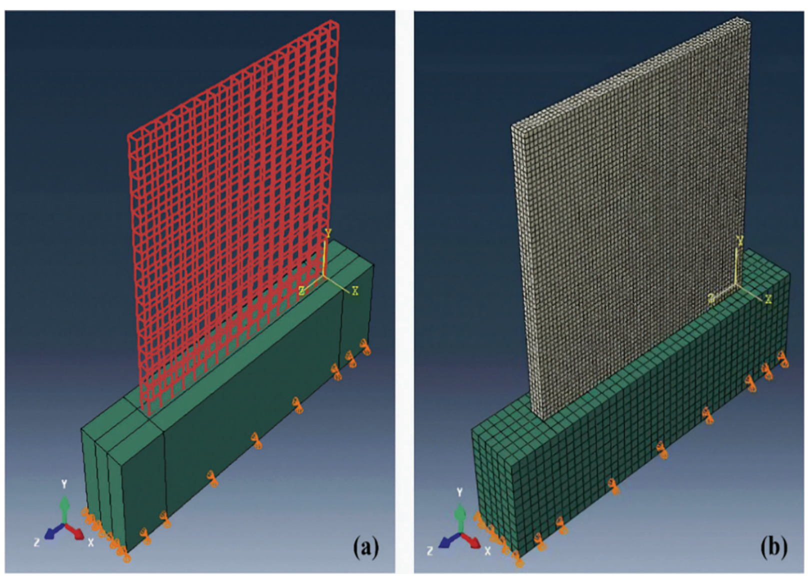


Figure 8: (a) Reinforcement of the wall with truss elements; (b) wall with brick elements and steel reinforcement embedded into the wall (Reprinted from Reference [99])

5 Future Research Recommendations

Despite the extensive research on squat shear walls, several gaps and unresolved issues remain that warrant further investigation. One critical area is the need for comprehensive experimental studies that focus on the use of non-conventional materials and innovative strategies in squat shear walls. Existing studies have provided valuable insights, but there is a lack of large-scale experimental programs that can capture the full range of behaviors and failure modes under various seismic scenarios. These studies should include advanced materials such as UHPC and FRPs to fully understand their impact on seismic resilience. Another significant gap is the integration of environmental factors into the analysis and design of squat shear walls. While some studies have highlighted the impact of environmental degradation on seismic performance, more research is needed to evaluate the use of advanced materials like UHPC and HPC in terms of their environmental impact, particularly CO_2 emissions and other gases. Developing models and design guidelines that account for long-term environmental exposure will be crucial for sustainable construction practices. The development of more accurate and realistic analytical models is also necessary. Current models often simplify the interactions between different types of reinforcement and concrete, which can lead to discrepancies between predicted and observed behaviors. Future research should focus on refining these models to improve design standards, incorporating the complexities of material behavior, and providing more reliable predictions of structural performance. Numerical simulations have proven to be invaluable tools, but there is a need to adopt advanced models such as artificial intelligence and machine learning to leverage the large amounts of accumulated data over time. These technologies can help develop more efficient algorithms and modeling approaches that provide accurate predictions with reduced computational effort. Additionally, validating these models against a broader range of experimental data is essential to ensure their reliability and applicability. Table 6 lists the future research recommendations on squat-RC shear walls.

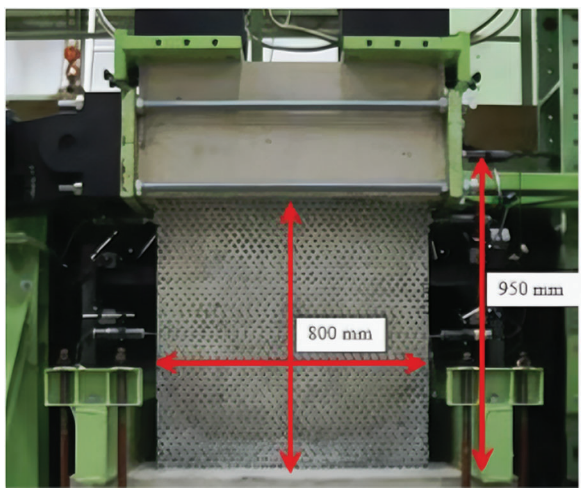


Figure 9: Squat RC wall configuration setup (Reprinted from Reference [100])

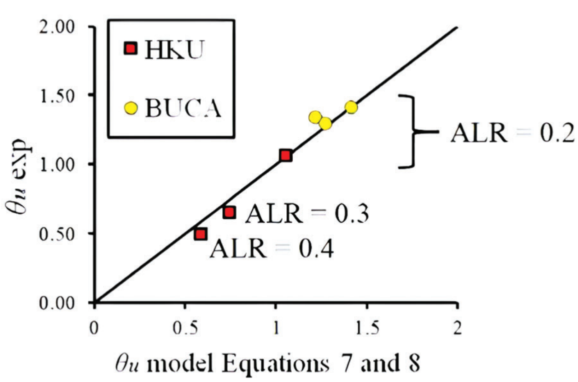


Figure 10: Verification of prediction model compared to tested high axial load ratio ALR squat walls (Reprinted from Reference [100])

Table 6: Future research recommendations on squat RC shear wall

Research area	Future research recommendations
Experimental studies	Focus on large-scale experimental programs using non-conventional materials and strategies in squat shear walls to capture a full range of behaviors and failure modes under different seismic scenarios.
Environmental factors	Evaluate the use of advanced materials like UHPC and HPC in squat shear walls and their impact on CO_2 emissions and other gases, developing models and design guidelines that account for long-term environmental exposure.
Analytical modeling	Continue to develop more accurate and realistic analytical models to improve design standards, accurately predicting the interaction between different types of reinforcement and concrete and incorporating complexities of material behavior.
Numerical simulations	Adopt advanced models such as AI and machine learning in numerical simulations to leverage large accumulated data over time, developing more efficient algorithms and validating models against a broader range of experimental data.

6 Conclusion

This study aimed to address the significant gap in the literature regarding the seismic behavior of squat RC shear walls, particularly under extreme earthquake conditions. Unlike tall, slender walls, squat walls exhibit unique failure mechanisms and deformation characteristics that are not well understood. Through a comprehensive literature review, this study synthesized current research findings from experimental investigations, analytical models, and numerical simulations to provide a detailed understanding of squat shear walls' performance during seismic events. The primary objective was to identify critical factors influencing their behavior and offer insights to guide the design and construction of more resilient structures in earthquake-prone regions. Based on the aforementioned statements, the following conclusions are drawn:

- Squat shear walls exhibit higher stiffness and lower deformability compared to slender walls, making them more suitable for low-rise buildings with space constraints. The inclusion of detailed reinforcement significantly improves energy dissipation and prevents brittle failures.
- The use of HPC and FRPs enhances the seismic resilience of squat shear walls. These advanced materials increase load-bearing capacity, improve ductility, and reduce deformations.
- Incorporating hybrid reinforcement techniques, seismic isolation systems, and the use of advanced materials like UHPC and steel fibers significantly improves the load-bearing capacity, energy dissipation, and overall seismic resilience of squat shear walls.
- Analytical models like the strut-and-tie model and frame analysis, along with numerical simulations such as the finite element method and discrete element method, have proven effective in predicting the seismic performance of squat shear walls. These models accurately simulate load-bearing capacity, deformation patterns, and failure mechanisms.

Despite the extensive research on this topic, several limitations and areas for future research were identified. There is a need for comprehensive experimental studies focusing on non-conventional materials and innovative strategies to capture the full range of behaviors and failure modes under various seismic scenarios. Additionally, integrating environmental factors into the analysis and design of squat shear walls is crucial for sustainable construction practices. Developing more accurate and realistic analytical models to predict the interaction between different reinforcement types and concrete will enhance design standards. Leveraging artificial intelligence and machine learning technologies can further refine numerical simulations, providing accurate predictions with reduced computational effort. Future research should also focus on validating these models against a broader range of experimental data to ensure their reliability and applicability.

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