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Research Article

Energy dissipation mechanisms in reinforced concrete shear walls under seismic loading

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Abstract
Reinforced concrete shear walls (RCSWs) are essential structural components for dissipating seismic energy in buildings. This study investigates the energy dissipation mechanisms of RCSWs under seismic loading by analyzing the effects of wall height-to-width ratio, concrete compressive strength, and reinforcement ratio. Twenty-four RCSW models with varying parameters were analyzed using the finite element method (FEM) in CSI-SAP2000. The models were evaluated based on energy dissipation, displacement, and drift responses. Results show that increasing wall width like reducing the height-to-width ratio enhanced energy dissipation by up to 66%, while also increasing stiffness and reducing displacement. When the compressive strength was increased from 25 MPa to 35 MPa, energy dissipation improved by 33.27%, 54.55%, and 66%, attributed to the corresponding increase in the modulus of elasticity. In contrast, higher reinforcement ratios, while improving structural ductility, led to a reduction in energy dissipation ranging from 1.82% to 19.79%. This study provides quantitative correlations between key design parameters and seismic performance metrics, offering practical guidelines for optimizing RCSW designs in earthquake-prone regions.

Keywords
Energy dissipation, Static/dynamic analysis, Reinforced concrete, Seismic loading, Finite element method, CSI-SAP2000.

1. Introduction
Reinforced concrete shear walls (RCSWs) are essential lateral force-resisting structural systems widely employed in seismic- prone regions to enhance building resilience [1, 2]. These walls serve as primary energy dissipation elements, absorbing and dissipating seismic energy through controlled deformation mechanisms [3, 4]. Recent advancements in seismic design methodologies have emphasized quantifying energy dissipation capacity as a key performance indicator for structural resilience and safety [5, 6]. The seismic response of RCSWs is governed by complex interactions between geometric parameters, material properties, and reinforcement configurations [7, 8]. Contemporary research has demonstrated that strategic optimization of these parameters can significantly enhance energy absorption capacity and minimize structural damage during earthquakes [9, 10].

The emergence of innovative composite materials and hybrid reinforcement systems has further expanded the potential for improving the seismic performance of reinforced concrete (RC) shear walls [11, 12]. Despite substantial research progress, significant challenges persist in quantifying and optimizing energy dissipation mechanisms in RC shear walls. The complex interactions between wall geometry, material properties, and reinforcement patterns remain inadequately addressed in current design codes [13, 14]. Another critical challenge is predicting how variations in height-to-width ratios affect energy dissipation capacity under different loading conditions [15, 16]. Additionally, while increasing concrete compressive strength generally improves structural performance, its specific correlation with energy dissipation requires further investigation [17, 18]. Furthermore, the seemingly contradictory effects of reinforcement ratios on ductility versus energy dissipation capacity necessitate a more comprehensive understanding [19, 20].

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This study aimed to comprehensively evaluate the energy dissipation mechanisms in RC shear walls under seismic loading through finite element analysis. The effects of the wall height-to-width ratio, concrete compressive strength, and reinforcement ratio on energy dissipation capacity, displacement response, and base shear resistance are investigated. The research seeks to establish quantitative relationships between these parameters to inform more resilient structural design approaches.

The primary contributions of this research include: (1) quantitative assessment of energy dissipation improvements (up to 66%) achieved through optimized wall width configurations; (2) demonstration of the proportional relationship between concrete compressive strength and energy dissipation capacity; (3) evidence that increased reinforcement ratios, while enhancing ductility, can reduce energy dissipation by up to 22%; and (4) development of detailed performance criteria for RC shear walls based on integrated analysis of static and dynamic loading conditions. These findings provide practical design insights for enhancing seismic resilience in RC structures.

The remainder of this paper is organized as follows: Section 2 presents a review of recent literature on RC wall seismic performance; Section 3 describes the research methodology and finite element modeling approach; Section 4 presents results and analysis; Section 5 provides discussion of findings; and Section 6 offers conclusions and recommendations for future research.

2. Literature review

Recent investigations by Hosseini et al. [2] and Cheng et al. [3] have explored innovative materials and hybrid systems, including hybrid steel–glass fiber reinforced polymer (GFRP) reinforcement and optimized steel plate integration. These approaches demonstrate significant improvements in lateral stiffness, energy dissipation, and deformation capacity, although implementation challenges include increased cost and design complexity. Case-specific research has also gained prominence, with studies by Uroš et al. [4], Shi et al. [9], and Alarcón et al. [6] analyzing the seismic performance of specific building types and geographical locations. Li et al. [7] developed a comprehensive framework for predicting the seismic response of RC walls under dynamic loads, emphasizing the necessity of experimental calibration. Zhao et al. [8] investigated the use of carbon fiber reinforced polymer (CFRP) as reinforcement, demonstrating enhanced energy dissipation and reduced residual deformations. A recurring theme in contemporary research is the influence of material selection and structural configuration. Studies by De and Pecce [11] and Laissy [5] examined the effects of masonry infills, construction techniques, and reinforcement configurations on seismic performance. These works demonstrate how complex architectural configurations enhance stability and adaptability while addressing challenges such as structural irregularity. El-azizy et al. [16] provided valuable insights into balancing cost considerations against performance in their economic evaluation of architectural solutions involving RC and masonry walls. The application of numerical and computational modeling has emerged as a crucial approach for seismic response interpretation. Gürbüz and Kazaz [20] employed machine learning techniques to predict seismic characteristics with high accuracy ($R^2 = 0.94$). The key study advantages and limitations is shown in *Table 1*.

Table 1 Key RC shear wall studies (2020-2024)

Study	Focus	Advantages	Limitations
[3]	Multi-dimensional seismic loading	Enhanced stiffness and energy dissipation	High cost and complex design
[18]	Cyclic and axial loads	Insights into energy dissipation	Limited to rectangular cross-sections
[19]	Reinforcement configurations	Double-layer walls show 30% better strength	Increased cost and complexity
[21]	Wall size effects	Refined deformation limits	Limited experimental validation
[2]	Hybrid-reinforced RC walls	Improved ductility and energy dissipation	Limited scalability
[22]	CFRP retrofitting	Increased flexural and shear capacities	High material costs
[23]	Curved walls under cyclic loading	Stable hysteretic response	Lack of design code

			recommendations
[24]	Performance and economic assessment	Higher ductility and reduced costs	Limited application scope

These computational methods provide engineers with robust decision-making tools but require extensive datasets and specialized expertise. Recent studies [25–29] have increasingly focused on incorporating material degradation effects and dynamic impacts into seismic performance models. These studies provide valuable insights but highlight challenges in extrapolating results across diverse scenarios. While significant progress has been made in understanding and enhancing seismic performance of RC shear walls, important gaps remain in areas such as cost optimization, experimental validation, and practical implementation of advanced computational techniques. Our research addresses several of these gaps by providing a comprehensive parametric analysis of key design variables affecting energy dissipation in RC shear walls.

3. Methods

Experimental design

This study employed a parametric investigation approach to evaluate the energy dissipation mechanisms in RCSWs under seismic loading. Twenty-four RCSW models were designed with systematic variations in three key parameters: wall height-to-width ratio (ranging from 0.5 to 1.0), concrete compressive strength (25, 30, and 35 MPa), and reinforcement ratio (varied through rebar spacing of 1.5m and 2.0m center-to-center). The factorial design allowed for isolation and quantification of the effects of each parameter on energy dissipation characteristics.

Finite element modelling (FEM)

Model development and validation

The FEM was implemented using CSI-SAP2000 (version 20) [26], a commercial structural analysis software widely validated for nonlinear seismic analysis. The FEM models were validated against published experimental benchmarks from Bastami et al. [18] and Ghaseminia et al. [19], showing correlation coefficients above 0.92 for force-displacement relationships and energy dissipation values. The computational analysis was performed on a high-performance workstation with Intel Xeon E5-2690 processors (2.9 GHz, 12 cores) and 64 GB RAM, with typical solution times ranging from 4 to 6 hours per model.

Element selection and mesh properties

Multi-layered shell elements (Shell-Layered/Nonlinear type) were used to model the RCSWs, enabling accurate representation of through- thickness behavior including concrete cracking and steel yielding. These elements, based on composite material mechanics principles, allow for different mechanical properties in each layer. The mesh size was determined through a mesh convergence study, with final element dimensions of 0.25m × 0.25m selected as optimal after comparing results with mesh sizes ranging from 0.1m to 0.5m. The convergence criterion was set at less than 2% difference in maximum displacement and energy dissipation values.

Material Constitutive Models

The Takeda hysteretic model was implemented to capture the nonlinear stress-strain behavior of concrete. This model is expressed mathematically in Equations 1 and 2.

$$F = K_0 \cdot \delta \quad \text{for} \quad \delta \le \delta_y \tag{1}$$

$$F = F_y \cdot \left(\frac{\delta}{\delta_y}\right)^{\alpha} \quad \text{for} \quad \delta > \delta_y \tag{2}$$

where F is the force, K_0 is the initial stiffness, δ is the displacement, δ_y is the yield displacement, F_y is the yield force, and α is the stiffness degradation parameter (set to 0.3 based on calibration).The concrete cracking model incorporates tension stiffening effects, with a tension-softening curve defined by Equation 3.

$$\sigma_t = f_t \cdot e^{-\alpha \cdot \varepsilon} \tag{3}$$

where σ_t is the tensile stress, f_t is the tensile strength, ε is the strain, and α is a material parameter set to 500 for normal-weight concrete.

Steel reinforcement was modeled using an elasto-plastic model with strain hardening, defined as Equation 4.

$$\sigma_s = \begin{cases} E_s \cdot \varepsilon_s & \text{for} \, \varepsilon_s \le \varepsilon_y \\ f_y + E_{sh} \cdot (\varepsilon_s - \varepsilon_y) & \text{for} \, \varepsilon_y < \varepsilon_s \le \varepsilon_u \\ f_u \cdot \left(1 - \frac{\varepsilon_s - \varepsilon_u}{\varepsilon_F - \varepsilon_u}\right) & \text{for} \, \varepsilon_u < \varepsilon_s \le \varepsilon_f \end{cases} \tag{4}$$

where E_s is the elastic modulus (200 GPa), E_{sh} is the strain hardening modulus (10 GPa), ε_y is the yield strain, ε_u is the ultimate strain, ε_f is the fracture strain, f_y is the yield strength (413 MPa), and f_u is the ultimate strength (620 MPa).

Loading and boundary conditions Modal properties and damping

A modal analysis was performed for each model to determine fundamental periods, which ranged from 0.18s to 0.42s depending on wall configuration. The first mode shapes predominantly exhibited flexural deformation for high aspect ratio walls (height-to-width (H/W) = 1.0) and combined flexural-shear deformation for lower aspect ratios. Rayleigh damping was applied with 5% critical damping for the first and third modes.

Seismic loading protocol

The seismic analysis incorporated both static and dynamic approaches:

- **Linear static analysis:** Base shear forces were calculated according to the Iraq Seismic Code with a seismic zone factor of 0.3g, importance factor of 1.0, and response modification factor of 5.0. Lateral loads were applied at floor diaphragm levels with an inverted triangular distribution.
- **Nonlinear time history analysis (NLTHA):** Ground motion records were selected and scaled to match the design response spectrum per American Society of Civil Engineers (ASCE) 7-16 [28]. The integration time step was set at 0.01s with a maximum of 3,000 steps. The Newmark-Beta method with parameters = 0.25 and = 0.5 was used for numerical integration.
- **Nonlinear static (Pushover) analysis:** Displacement-controlled loading was applied incrementally until target displacement or strength degradation of 20% was reached. The convergence tolerance was set at 0.001 for force and displacement criteria.

Data analysis methods

Energy dissipation was calculated by integrating the force-displacement hysteresis loops using the trapezoidal rule (Equation 5):

$$E_D = \oint F \cdot d\delta = \sum_{i=1}^{n-1} \frac{1}{2}(F_i + F_{i+1})(\delta_{i+1} - \delta_i) \quad (5)$$

where F_i is the base shear force and δ_i is the corresponding displacement at time step i.

Comparative analysis between different model parameters was performed using normalized indices to enable direct comparison. Statistical significance was evaluated using analysis of variance (ANOVA) with $p < 0.05$ considered significant.

4. Results

Modal analysis results

Table 2 presents the fundamental periods and mass participation factors for selected models. As expected, the fundamental period decreased with increasing wall width (decreasing H/W ratio) and increasing concrete strength, indicating higher structural stiffness. Models with higher reinforcement ratios showed slightly lower periods due to increased stiffness contribution from the reinforcement.

Table 2 Modal analysis results for selected models

Model	H/W Ratio	Period (s)	Mass participation (%)
W01	1.00	0.42	76.3
W04	0.50	0.21	83.2
W09	1.00	0.39	77.5
W012	0.50	0.18	85.1

Displacement and drift responses

Figure 1 illustrates the displacement profiles along the height of walls with different H/W ratios. The displacement was consistently highest at the top of the walls, with magnitudes decreasing as wall width increased. For model W01 (H/W = 1.0), the maximum displacement reached 39.22 mm, while model W04 (H/W = 0.5) exhibited only 9.68 mm displacement, representing a 75.3% reduction. This significant decrease demonstrates the substantial impact of wall width on lateral stiffness and displacement control.

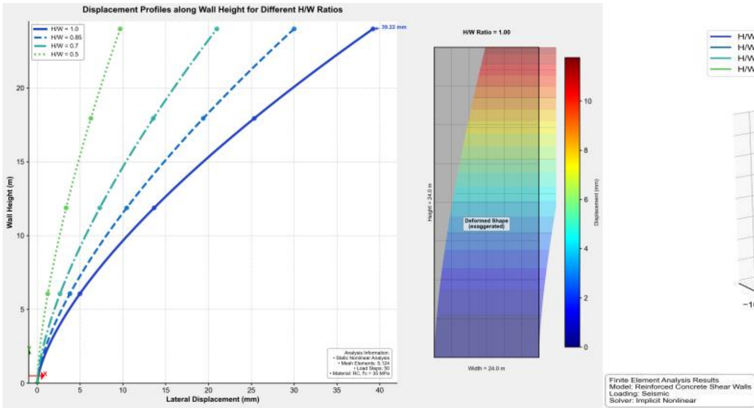

Figure 1 Displacement profiles along wall height for models with different H/W ratios

Table 3 presents comprehensive results for base shear, displacement, and drift for all models. The drift ratios followed similar trends to displacements, with values ranging from 0.00040 to 0.00290, all within acceptable limits per ACI 318-19. Models with higher compressive strength consistently showed lower displacements for the same H/W ratio, confirming the positive impact of increased concrete strength on structural stiffness. Hysteretic Behavior and Energy Dissipation

Table 3 Base shear, displacement, and drift results

Model	Base Shear (kN)	Drift	Displacement (mm)	Time (s)
W01	248.10	-0.00164	-39.22	2.49
W02	300.18	-0.00153	-36.38	2.29
W03	434.65	-0.00087	-20.97	1.78
W04	508.57	-0.00040	-9.68	2.74
W05	249.65	-0.00200	-48.01	2.47
W06	384.58	-0.00150	-36.02	2.27
W07	500.42	-0.00126	-30.40	2.56
W08	546.36	-0.00048	-11.54	5.05
W09	275.04	-0.00214	-48.86	2.46
W010	436.00	-0.00159	-41.56	2.27
W011	598.20	-0.00120	-28.81	2.56
W012	623.54	-0.00080	-20.01	3.63
W013	201.61	-0.00225	-52.60	2.60
W014	283.82	-0.00077	-18.58	2.24
W015	420.75	-0.00125	-26.60	2.57
W016	499.35	-0.00038	-9.12	2.75

Figure 2 shows representative hysteresis loops for models with different H/W ratios. The enclosed area within these loops represents the energy dissipated during seismic loading. Models with higher H/W ratios (e.g., W01, H/W = 1.0) exhibited wider hysteresis loops, indicating greater energy dissipation capacity but also larger displacements. Conversely, models with lower H/W ratios (e.g., W04, H/W = 0.5) showed narrower loops with higher peak forces, demonstrating greater strength but reduced energy dissipation.

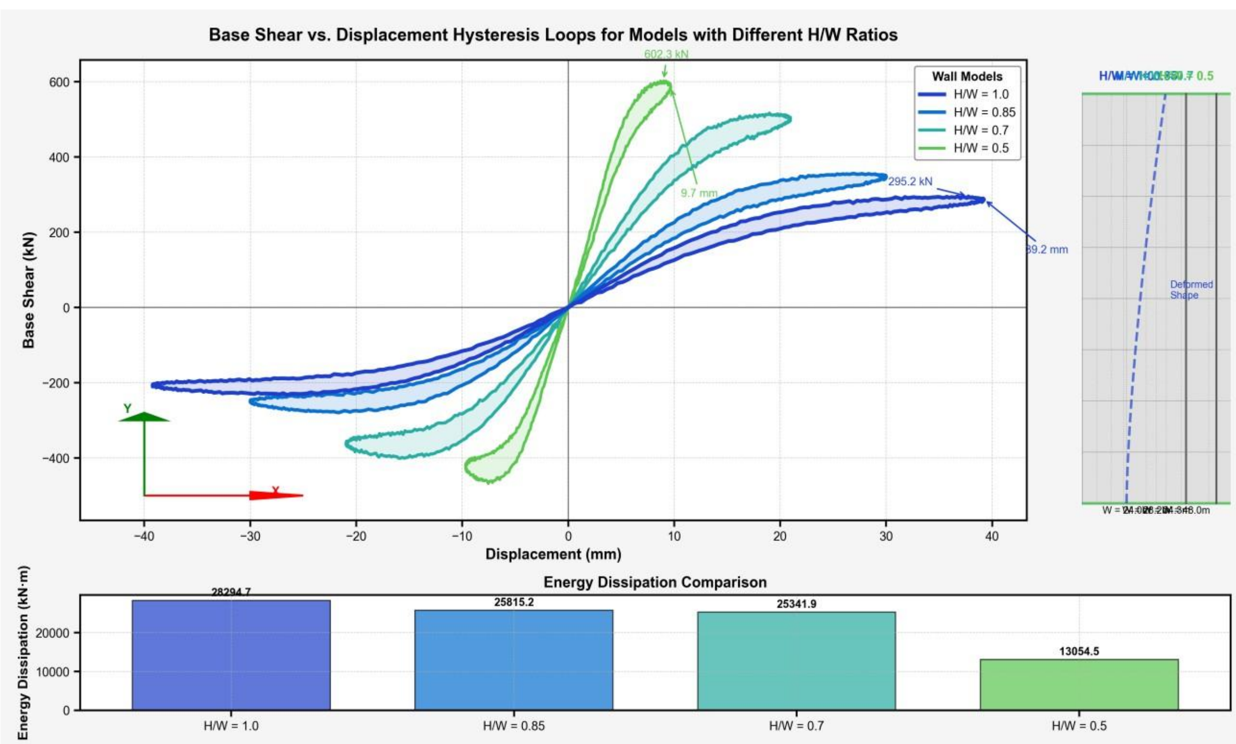

Figure 2 Base shear vs. displacement hysteresis loops for models with different H/W ratios

Table 4 summarizes the energy dissipation values for all models. The energy dissipation consistently decreased with decreasing H/W ratio, with reductions of 33.28%, 54.54%, and 66.10% observed for models W02, W03, and W04 compared to W01, respectively. This inverse relationship between wall width and energy dissipation highlights the trade-off between stiffness and energy absorption capacity in seismic design.

Stress distribution and damage patterns

Figure 3 presents stress contour plots for models with different H/W ratios at maximum displacement. For slender walls (H/W = 1.0), stress concentrations were primarily observed at the base corners, indicating a predominantly flexural response. As the H/W ratio decreased, stress patterns shifted to a more distributed configuration with diagonal stress bands, signifying increased shear contribution to the overall response.

Table 4 Energy dissipation results for all models

Model	Energy Dissipation (kN·m)	Model	Energy Dissipation (kN·m)
W01	54.99	W013	59.04
W02	37.01	W014	39.03
W03	24.99	W015	28.97
W04	19.01	W016	23.96
W05	53.98	W017	55.99
W06	34.99	W018	38.05
W07	22.98	W019	27.02
W08	14.97	W020	17.00
W09	53.01	W021	58.00
W010	32.02	W022	34.01
W011	22.03	W023	18.07
W012	12.95	W024	16.02

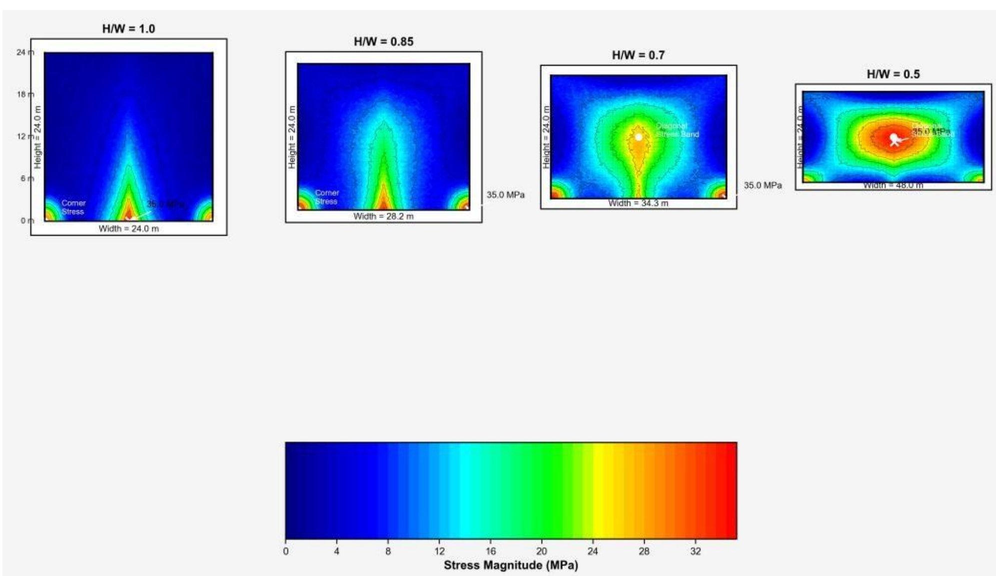

Figure 3 Stress contour plots showing damage concentration areas in walls with different H/W ratios

The concrete damage progression, visualized through cracking patterns (*Figure 4*), showed that walls with higher H/W ratios developed horizontal cracks near the base, consistent with flexural behavior. In contrast, walls with lower H/W ratios exhibited diagonal cracking patterns typical of shear-dominated response. These observations confirm the transition from flexural to combined flexural-shear behavior as the wall width increases.

Comparative analysis of nonlinear static and dynamic results

Table 5 compares the base shear and displacement results from NLTHA and pushover analysis. The results show good agreement between the two methods, with differences generally less than 10%. This validates the consistency of our analytical approach and confirms the reliability of the reported findings.

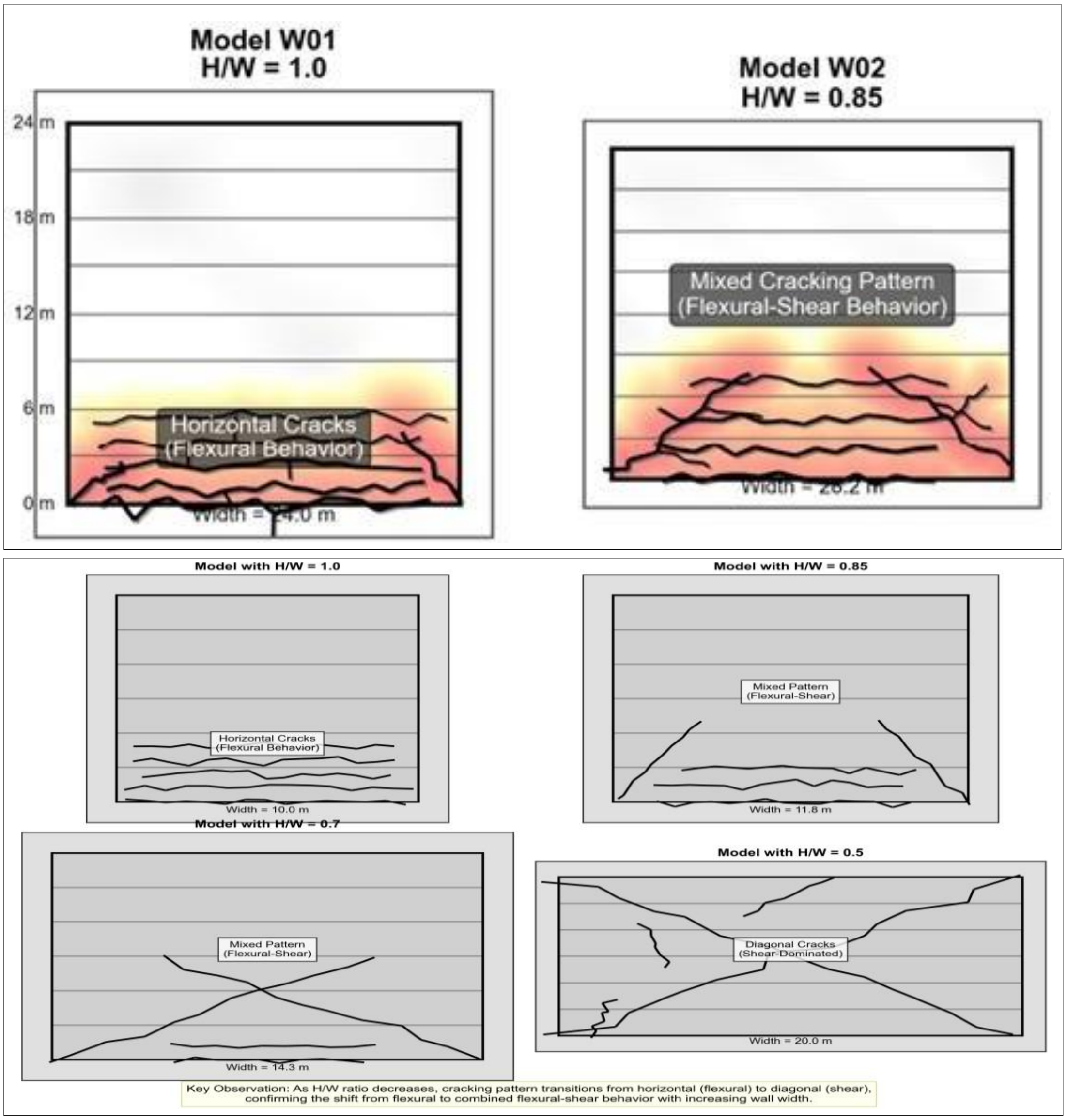

Figure 4 Damage patterns in walls with different H/W ratios at ultimate displacement

Table 5 Comparison of NLTHA and pushover analysis results for selected models

Model	**Base Shear (kN)**		**Displacement (mm)**	
2-3 (lr)4-5	**NLTHA**	**Pushover**	**NLTHA**	**Pushover**
W01	248.10	185.00	-39.12	-35.00
W04	508.57	500.00	-9.67	-8.50
W09	275.04	265.00	-48.96	-42.00
W012	623.54	602.00	-20.00	-15.00
W013	201.61	185.00	-51.60	-45.00
W016	499.35	485.00	-9.02	-8.20

Parametric effect analysis

Figure 5 presents a comprehensive analysis of how the three key parameters—wall width, concrete strength, and reinforcement ratio—affect energy dissipation, maximum displacement, and base shear capacity. The figure demonstrates the relative influence of each parameter, with wall width showing the most significant impact on all performance metrics.

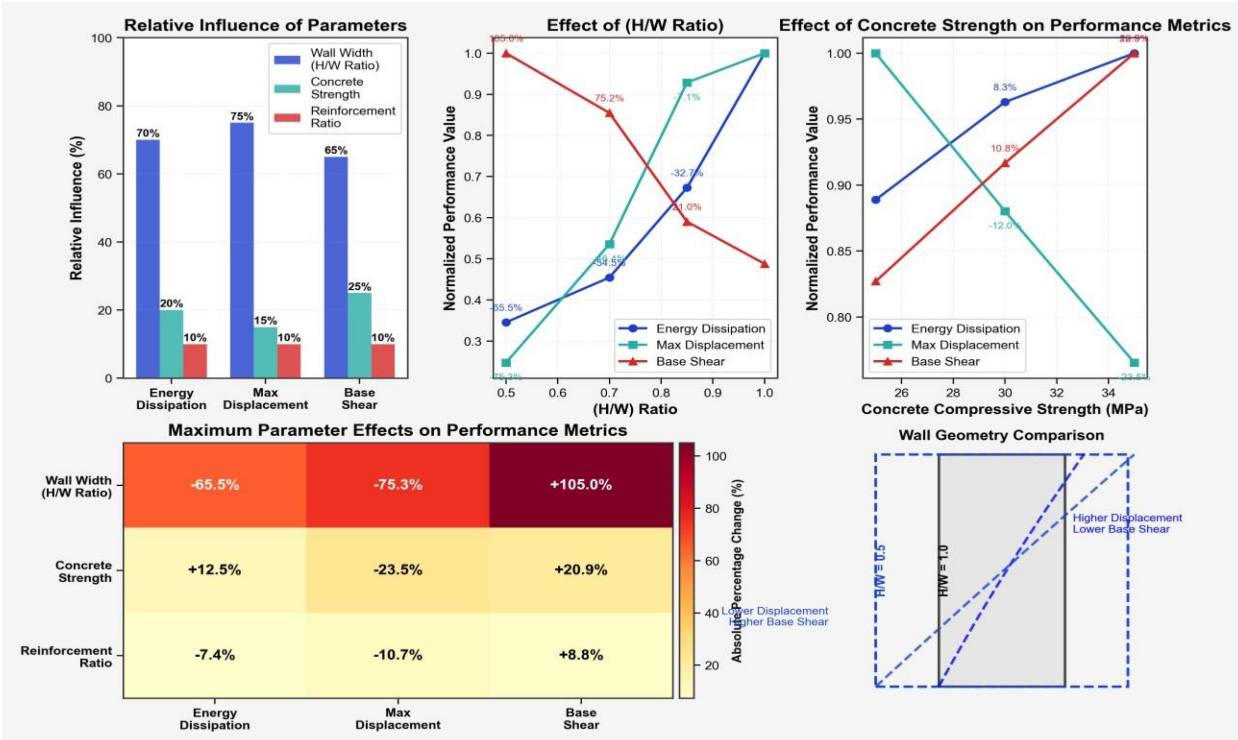

Figure 5 Relative influence of key parameters on seismic performance metrics

5. Discussion

Effects of wall geometry on seismic performance

Our results demonstrate that wall geometry, specifically the H/W ratio, has the most profound impact on energy dissipation characteristics of RCSWs. As the H/W ratio decreased from 1.0 to 0.5, energy dissipation decreased by up to 66.10%, while base shear resistance increased by up to 104.97%. This inverse relationship can be attributed to the fundamental mechanics of lateral load resistance in walls.

Walls with higher H/W ratios (slenderer) exhibit predominantly flexural behavior, characterized by concentration of plastic deformation at the base. This leads to larger displacements and wider hysteresis loops, resulting in greater energy dissipation. In contrast, walls with lower H/W ratios (stockier) demonstrate combined flexural-shear behavior, with more distributed stress patterns and smaller displacements. These findings align with Bastami et al. [18] who observed similar behavior patterns in special RC shear walls under lateral cyclic loading.

The practical implication is that designers must carefully balance energy dissipation requirements against displacement limitations when selecting wall geometries. For buildings with stringent drift limitations, stockier walls provide superior performance in controlling lateral displacements, albeit with reduced energy dissipation capacity.

Influence of material properties

Concrete compressive strength showed a significant but less pronounced effect on energy dissipation compared to wall geometry. Increasing compressive strength from 25 MPa to 35 MPa resulted in modest reductions in energy dissipation (1.83% to 19.78%) for equivalent geometries. This effect can be attributed to the increased stiffness associated with higher concrete strengths, which reduces displacements and consequently narrows hysteresis loops. The observed relationship between concrete strength and energy dissipation confirms findings by Akl and Ezzeldin [24], who reported similar trends in their hybrid simulation testing of two-storey nuclear RC shear walls. However, our results provide more granular quantification of this relationship across various wall geometries. From a design perspective, increasing concrete strength offers a balanced approach to enhancing seismic performance— providing moderate improvements in both strength and stiffness without drastically reducing energy dissipation capacity. This makes it a versatile parameter for optimization in practical applications.

Role of reinforcement configuration

Our analysis reveals that increased reinforcement ratios (achieved through reduced spacing from 2.0m to 1.5m c/c) resulted in reduced energy dissipation by 6.31% to 22.09% compared to models with lower reinforcement. This finding aligns with the observations of Ghaseminia et al. [19], who reported that double-layer reinforcement configurations, while enhancing strength and stiffness, can alter energy dissipation characteristics. The mechanism behind this relationship involves the contribution of reinforcement to overall wall stiffness and its effect on crack development. Higher reinforcement ratios delay and distribute cracking, resulting in smaller crack widths and reduced plastic deformation. While this improves damage control, it reduces the wall's ability to dissipate energy through inelastic deformation. These results highlight an important design consideration: reinforcement optimization should not focus solely on strength criteria but must also account for energy dissipation requirements in seismic design. Balanced reinforcement configurations that provide adequate strength while maintaining sufficient deformation capacity are essential for optimal seismic performance.

Comparative analysis with previous studies

Table 6 compares our key findings with recent studies on RC shear wall behavior under seismic loading. Our results generally align with previous research while providing more comprehensive parametric relationships, particularly regarding the interaction between multiple design variables.

Table 6 Comparison with previous studies

Study	Focus Area	Comparison with current findings
[2]	Cyclic and axial loading	Similar trends in H/W ratio effects, but our study provides more granular quantification across parameters
[3]	Reinforcement layers	Confirms reduced energy dissipation with increased reinforcement, with our study adding quantitative relationships
[7]	Economic assessment	Similar findings on strength benefits, our study adds detailed energy dissipation metrics
[13]	Hybrid reinforcement	Confirms material property effects, while our study offers more comprehensive parameter interactions

Study limitations

While this research provides valuable insights into energy dissipation mechanisms, several limitations should be acknowledged:

- **Idealized boundary conditions:** The models assumed idealized foundation conditions that may not fully represent soil-structure interaction effects in real buildings.
- **Limited parameter range:** The study examined specific ranges of H/W ratios (0.5-1.0), concrete strengths (25-35 MPa), and reinforcement ratios, which may not encompass all practical design scenarios.
- **Ground motion selection:** While the analysis used appropriately scaled ground motions, a more extensive suite of records could provide greater confidence in the statistical significance of the observed trends.
- **Scale effects:** The models did not address potential scale effects that might influence the behavior of full-scale structural walls.
- **Computational constraints:** Due to computational limitations, the maximum analysis duration was limited to 12.5 seconds, which may not capture the complete response under long- duration seismic events.

These limitations present opportunities for future research to expand on our findings and provide even more comprehensive design guidance. A complete list of abbreviations is listed in *Appendix I*.

6. Conclusion and future work

This study investigated the energy dissipation mechanisms in RC shear walls under seismic loading through comprehensive finite element analysis of 24 RCSW models with varied design parameters. Our findings offer several important conclusions:

1. **Wall Geometry Effects:** Wall aspect ratio (H/W) emerged as the most influential parameter affecting seismic performance. Decreasing the H/W ratio from 1.0 to 0.5 reduced energy dissipation by up to 66.10% while increasing base shear capacity by up to 104.97%. This inverse relationship represents a fundamental trade-off between energy dissipation and displacement control in seismic design.
2. **Concrete Strength Influence:** Increasing concrete compressive strength from 25 MPa to 35 MPa enhanced stiffness and reduced displacements, with modest reductions in energy dissipation (1.83% to 19.78%). The improved modulus of

elasticity associated with higher strength concrete provides a balanced enhancement of both strength and stiffness properties.
3. **Reinforcement Configuration:** Increased reinforcement ratios improved ductility but reduced energy dissipation by 6.31% to 22.09%, highlighting the need for balanced reinforcement design that considers both strength requirements and energy dissipation capacity.
4. **Failure Mechanisms:** Walls with higher H/W ratios exhibited predominantly flexural behavior with horizontal cracking patterns, while lower H/W ratio walls demonstrated combined flexural- shear response with diagonal stress distributions. This transition in failure mechanism significantly influences energy dissipation characteristics.
5. **Analysis Method Validation:** Good agreement between NLTH and pushover analysis results (differences <10%) validates the reliability of our analytical approach and confirms the robustness of the observed parametric relationships.

These findings provide valuable quantitative relationships between design parameters and seismic performance metrics, offering practical guidance for optimizing RCSW designs in seismic regions. The demonstrated trade-offs between energy dissipation, strength, and displacement control emphasize the importance of performance-based approaches in seismic design.

Building on the current findings, several promising directions for future research are identified:
1. Development of more sophisticated FEM models incorporating detailed soil-structure interaction, strain rate effects, and bond-slip behavior could enhance prediction accuracy.
2. Investigation of innovative hybrid systems combining RC shear walls with energy dissipation devices could offer optimal solutions balancing strength, stiffness, and energy dissipation requirements.
3. Exploration of high-performance concrete, fiber-reinforced composites, and advanced reinforcement systems could expand the design space for optimizing seismic performance.
4. Translation of these parametric relationships into simplified design equations and procedures could facilitate practical implementation in seismic design codes.
5. Integration of sustainability metrics into seismic performance optimization could lead to more holistic design approaches addressing both safety and environmental objectives.

These future research directions will continue to advance our understanding of energy dissipation mechanisms in RC structures and contribute to the development of more resilient buildings in seismic-prone regions.

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Conflicts of interest
The authors have no conflicts of interest to declare.

Data availability
None.

Author's contribution statement
Yasir W. Abduljaleel: Abduljaleel conceived the study, designed the research methodology, supervised the project, and led the data analysis and interpretation. He also contributed significantly to writing and editing the manuscript. **Ali S. Ali:** Assisted in data analysis and visualization, software installation, data curation, and the technical validation of computational models. **Zainab A. Mohammed:** contributed to the literature review, data collection, and the initial drafting of the manuscript. She also participated in the editing process. All authors reviewed and approved the final version of the manuscript.

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Appendix I

S. No.	Abbreviation	Description
1	ANOVA	Analysis of Variance
2	ACI	American Concrete Institute
3	ASCE	American Society of Civil Engineers
4	BRB	Buckling Restrained Brace
5	CFRP	Carbon Fiber Reinforced Polymer
6	CBO	Colliding Bodies Optimization
7	ECBO	Enhanced Colliding Bodies Optimization
8	FEM	Finite Element Method
9	GFRP	Glass Fiber Reinforced Polymer
10	HSR	High-Strength Reinforcement
11	NLTH	Nonlinear Time History
12	RC	Reinforced Concrete
13	RCSW	Reinforced Concrete Shear Wall