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Comprehensive study of load distribution and ductility in reinforced composite shear walls under seismic performance

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ABSTRACT

Steel shear walls are frequently employed in seismically resilient steel structures to enhance the efficacy of structural systems. In the elastic range, steel shear walls can buckle because of their unique shape. One kind of resistant structure is a composite shear wall, which is made up of layers of reinforced concrete and steel plates. This structure needs to combine the properties of ductility, stiffness, and strength. A steel plate in a shear wall improves system seismic performance by increasing stiffness, energy dissipation, load-bearing capacity, and preventing steel plate fracture. The purpose of this research is to find out how to use composite shear walls to make the system more seismically resistant and to prevent the steel plate from collapsing. 25 full-scale models of shear walls made of steel and composite materials, measuring 5 meters in length and 3.5 meters in height, were created for this specific purpose. Openings in the shear wall significantly influence its structural behavior. In this study, the behavior of the composite shear wall was examined using nonlinear static analysis. The variables of interest were ultimate strength, dissipated energy, stiffness, and ductility coefficient. Various factors are considered, including the steel plate's thickness (with values of 10, 12, and 15 mm), the kind and percentage of aperture, and whether or not the steel plate is covered with reinforced concrete. According to the results, a reduction of 18–83% in strength, 15–71% in dissipated energy, 20–91% in stiffness, and 20–28% in ductility coefficient occurs as the proportion of aperture in the composite shear wall increases.

Keywords: seismic behavior, composite shear wall, opening, and concrete-reinforced steel plate.

INTRODUCTION

Resisting lateral forces caused by earthquakes and wind is a fundamental requirement in building design, particularly for multi-story structures. Shear walls are among the most effective structural systems used to enhance a building's resistance to such forces due to their capacity to withstand shear forces, bending moments, and axial loads (Gharaei-Moghaddam et al., 2023; Haridas and Rasal, 2021; Singhal et al., 2019; Vahidi and Moradi, 2019). For decades, reinforced concrete (RC) shear walls were the only widely used type. However, under cyclic loading, they exhibited weaknesses due to concrete cracking, localized crushing, and eventual reductions in stiffness and load-bearing capacity (Mo et al., 2021). To address these limitations, alternative systems such as steel shear walls (SSWs) have been developed. These have demonstrated high efficiency in resisting seismic loads, particularly in seismic-prone countries like Japan and the U.S. Steel shear walls are lightweight and reduce material usage, but suffer from early plate buckling under lateral loads, which significantly impairs their strength, stiffness, and energy dissipation capabilities (Moradi and Vahidi, 2018).

Composite shear walls, which combine steel plates and reinforced concrete, have emerged as a promising solution to overcome the limitations of RC and SSW systems. These walls benefit from the high ductility of steel and the confinement and buckling prevention provided by concrete encasement, thus enhancing seismic performance (Aydin and Bayrak, 2021; Hao et al., 2017). Composite shear walls are generally categorized into two types: RC shear walls reinforced with steel elements, and steel plate shear walls encased in concrete-the focus of this study (Afefy, 2020; Chang, 2015). Numerous experimental and numerical studies have evaluated the seismic performance of composite shear walls. For instance, (Wang et al., 2018) tested sixteen steel-reinforced RC shear wall specimens and found that this system significantly improved ductility and damping capacity compared to conventional RC walls. Similarly, (Arabzadeh et al., 2011) demonstrated that encasing steel plates with concrete enhanced the strength and energy dissipation of the specimens under cyclic loading.

However, despite the growing body of research, limited attention has been given to the simultaneous effects of steel plate thickness and the presence of openings (e.g., doors and windows) on the seismic performance of composite shear walls. Although (Meghdadian et al., 2020) highlighted the influence of openings on wall stiffness and buckling resistance, the interaction between plate thickness and opening configuration remains understudied. Therefore, this study aims to fill this knowledge gap by investigating the combined effect of steel plate thickness and opening characteristics on the seismic performance of composite steel–concrete shear walls. Using validated finite element models in Abaqus, this research analyzes the influence of these parameters on lateral strength, stiffness, ductility, and energy dissipation capacity. Figure 1 represents a flowchart of the research methodology.

NUMERICAL VALIDATION

To assess the modeling approach and the reliability of the obtained results, validation is essential. This study aimed to achieve validation by analyzing three reinforced steel shear wall examples constructed by (Meghdadian et al. 2020). These walls featured steel plates covered with reinforced concrete on one side. The specimens were categorized into three groups: one without any openings, one with a rectangular opening measuring 150 × 200 mm, and one with a rectangular opening of the same dimensions, reinforced with a 45-degree rebar mesh around the edges to mitigate the negative impact of the opening. The specimens were modeled in Abaqus software at a quarter scale and subjected to cyclic loading, with the results analyzed accordingly. Figure 2 illustrates the composite steel shear wall specimen, which has a length of 530 mm and a height of 730 mm. The concrete and steel specifications and properties can be found in Tables 1 and 2, as provided by (Moradi and Vahidi, 2021).

The dimensions and characteristics of the open-ended models were selected based on the experimental specimens without openings. This selection allows for a comparison of a system with openings with the responses of the same system without openings. The test specimens were subjected to horizontal loading in accordance with the displacement control technique outlined in the ATC-24 (ATC-24 1992). The type of static loading

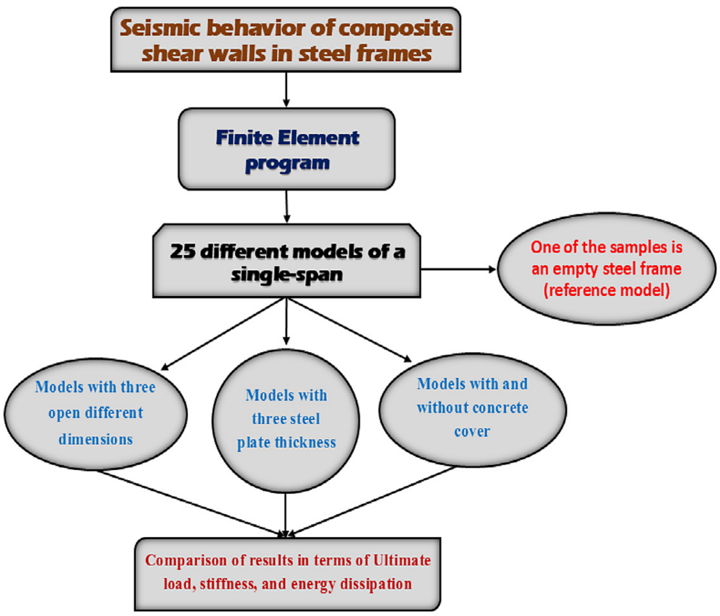


Figure 1. Represents a flowchart of the research methodology

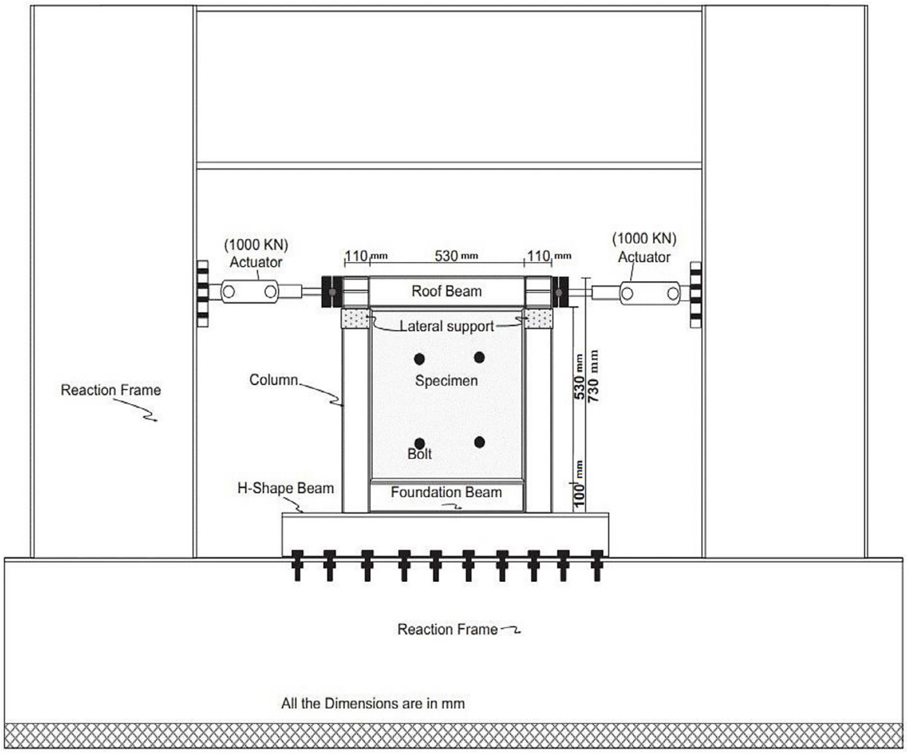


Figure 2. Characteristics of the experimental specimen (Meghdadian et al., 2020)

Table 1. Concrete and concrete cover specifications (Meghdadian et al., 2020)

Modulus of elasticity [MPa]	Cubic compressive strength [MPa]	Cylindrical compressive strength [MPa]	Thickness [mm]
30819	47	43	30

Table 2. Experimental specimen steel member characteristics and dimensions (Meghdadian et al., 2020)

Elements	Details	Modulus of elasticity [MPa]	Ultimate stress [MPa]	Yielding stress [MPa]
Columns	2IPE300+2PL300X5	203000	510	361
Beams	2IPE300	203000	510	361
Steel plate	Thickness 2 mm	203000	415	268
Shear connector	Φ20	203000	492	336
Reinforcement	Φ3	203000	510	361

was nonlinear (Owaid et al. 2025). The Abaqus model created for the specimen without openings and open-ended before and after analysis is shown in the Figures 3 and 4. The load-displacement hysteresis curves derived from the experimental data are displayed in Figure 5, while the numerical model's equivalent curves are displayed in Figure 6. The findings demonstrate that the models were correct since the numerical results and the experimental data agree to a satisfactory degree.

Because in this study, the maximum frame strength in numerical models has been compared, one of the main criteria in showing the accuracy of numerical modeling of the experimental model is the maximum steel frame strength. Consequently, the accuracy of numerical modeling has been assessed in this work using both the quantitative index of the steel frame's ultimate strength and the qualitative indicator of the hysteresis diagram. In Table 3, the ultimate strength of numerical models and experimental models has been compared.

The difference between the experimental and numerical results is 5–8%, as shown in Table 3. The geometric discrepancy between the experimental and numerical models, the differences in

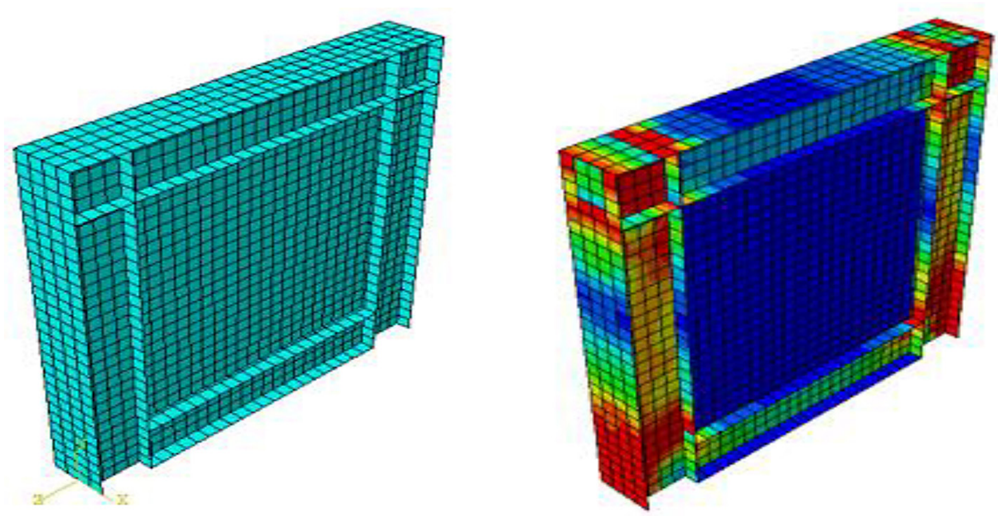


Figure 3. Abaqus model created for the sample without opening before and after analysis

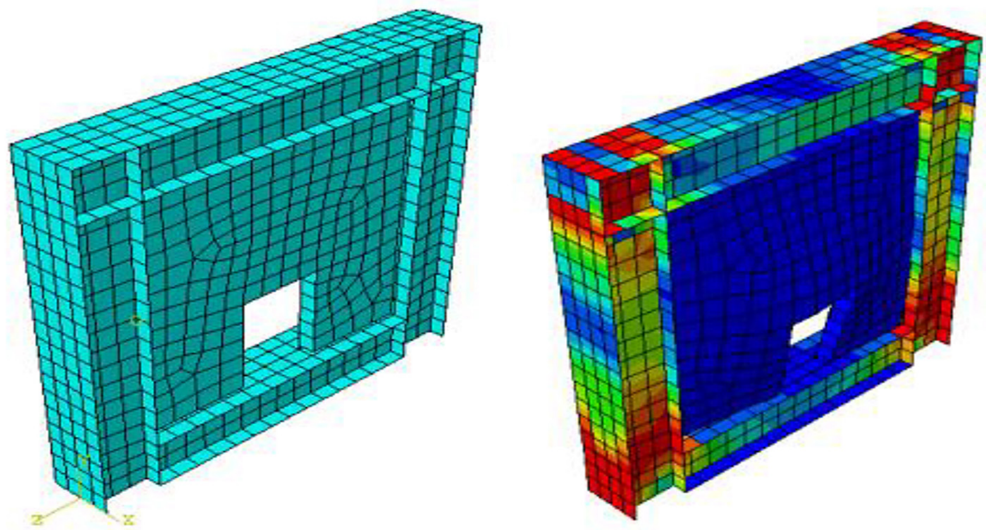


Figure 4. Abaqus model created for the open-end specimen before and after analysis

the loading conditions between the two models, the size of the elements in the numerical model, the assumptions made to make the prediction of the nonlinear behavior of the materials easier, the differences in the boundary conditions between the two models, human error, etc. are some of the factors that contribute to the percentage difference between the numerical and experimental results.

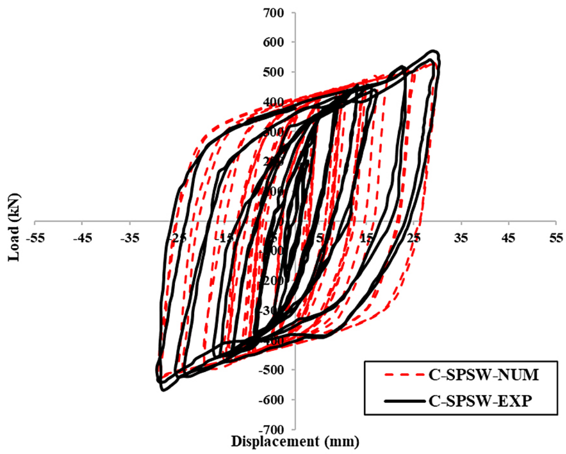
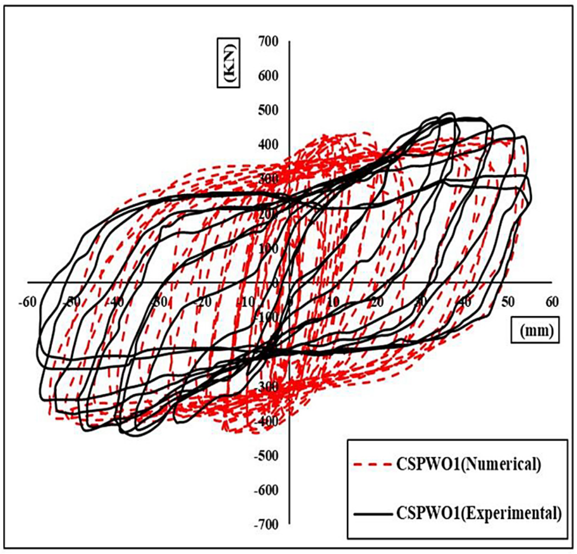


Figure 5. Experimental and numerical hysteresis diagrams compared without opening

VALIDATION OF FINITE ELEMENT MODELING ACCURACY

To verify the reliability and accuracy of the finite element modeling (FEM) approach in



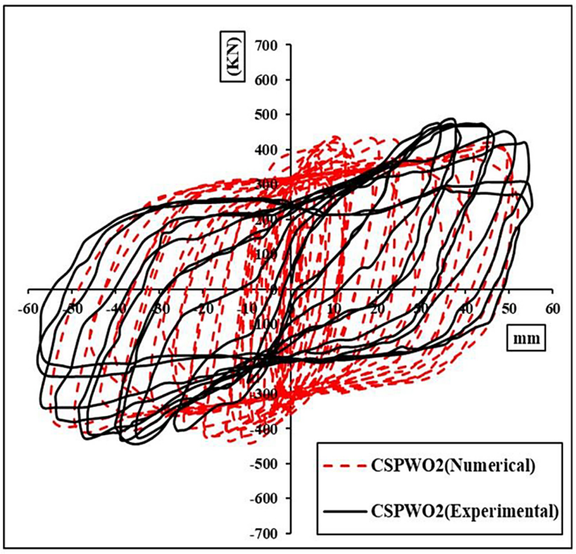


Figure 6. Hysteresis diagrams of the detector's first and second modes compared with numerical and experimental models

Table 3. Comparison of the ultimate load of the experimental specimen with the numerical model

Parameter	Experimental ultimate load [kN]	Numerical ultimate load [kN]	Different [%]
C-SPSW	557.6	530.6	4.8
C-SPWO1	473	449	5
C-SPWO2	465	428	8

simulating the behavior of composite steel–concrete shear walls, this chapter presents a validation process comparing numerical results with reliable experimental data.

Experimental program used for comparison

The numerical results obtained from the Abaqus software were compared with experimental data published by (Meghdadian et al., 2020) for three composite shear wall specimens:

- C-SPSW – a wall without an opening,
- C-SPWO1 – a wall with a rectangular opening of 150 × 200 mm,
- C-SPWO2 – a wall with the same rectangular opening, reinforced with a 45° rebar mesh around the perimeter.

The specimens were modeled at a quarter scale using Abaqus, and were subjected to quasi-static cyclic loading according to the displacement-controlled loading protocol described in ATC-24 (ATC-24 1992). The material properties used in the numerical models are detailed in Tables 1 and 2.

Modeling results and validation

The finite element models prior to and following the analysis are displayed in Figures 3 and 4. The load-displacement hysteresis curves from the computational calculations and the experimental testing are shown in Figures 5 and 6. A quantitative evaluation was conducted using two statistical metrics:

- root mean square error (RMSE) – represents the average deviation between the experimental and numerical load values,
- correlation coefficient (R) – measures the strength of the linear relationship between the experimental and numerical responses.

Quantitative analysis and comparison

The results demonstrate a high level of agreement between the numerical and experimental data, as shown in Table 4. RMSE values are relatively low, and the correlation coefficients exceed 0.94 for all specimens, confirming the accuracy and reliability of the finite element models in capturing the cyclic behavior of composite shear

Table 4. RMSE and correlation coefficient for load–displacement response

Specimen	RMSE [kN]	Correlation coefficient [R]
C-SPSW	15.4	0.976
C-SPWO1	18.6	0.963
C-SPWO2	22.9	0.948

walls. Minor discrepancies can be attributed to differences in boundary conditions, simplifications in material modeling, and mesh discretization in the numerical simulations.

In addition to the quantitative analysis, a qualitative visual comparison was performed for the failure patterns and strain distribution using strain maps from the numerical model and experimental failure images. The results showed that the general failure pattern-including diagonal cracks, localized crushing at the base of the wall, and stress concentration areas around the openings-was accurately represented in the numerical model.

In the C-SPSW model, the results showed a symmetrical distribution of diagonal strains, reflecting a shear failure mode, while in the C-SPWO1 model, high stresses were recorded at the corners of the opening, indicating local weakness caused by the opening. In contrast, the C-SPWO2 model exhibited a more uniform strain distribution due to the reinforcement mesh, which improved ductility and delayed failure initiation.

Based on this, the validation results confirm that the numerical model used is capable of accurately representing the real structural and mechanical behavior of composite shear walls under cyclic loading, both in terms of global response and local details, thus supporting its use in future analytical studies.

In this study on composite steel–concrete shear walls, a mesh convergence study was conducted to verify the independence of the results from the mesh size. The element size was gradually reduced, and results such as displacements and stresses were compared each time. The results showed a clear stabilization in the responses after mesh refinement, indicating that the results became independent of the mesh size.

To further validate the accuracy of the numerical model, hysteresis load-displacement curves were compared, showing a good agreement between the numerical and experimental results. Additionally, quantitative indicators such as the RMSE, which was found to be 18.3 kN, and the Correlation Coefficient (R), ranging from 0.94 to 0.97, confirmed a high level of accuracy in the numerical representation of the structural behavior.

Therefore, it can be confirmed that the numerical model used in this study provides an accurate representation of the structural behavior without being affected by changes in the mesh size.

RESEARCH METHOD

Given the importance and need of research in the field of seismic behavior for composite steel-concrete shear walls, the primary goal of this study is to investigate the impact of steel plate thickness and opening features on the seismic response of composite steel shear walls with reinforced concrete cladding. To achieve this goal, new articles and reliable sources were first studied, and then the research method was determined. The research method in this paper is as follows: First, a three-story steel building with a completely regular plan was designed based on American codes and using the ETABS software. In the design of the structure, a dead load of 7 kN/m^2 and a live load of 2 kN/m^2 were assumed. As shown in Figure 7, after selecting one of the side frames of the building, a single-story span frame located in the middle span of the frame was selected for analysis in Abaqus software. After determining the beam and column details for a single-story span frame, it was analyzed and examined in Abaqus software in four different cases, as shown in Figure 8, namely, an empty steel frame (reference model), a steel frame with a composite shear wall without an opening, a steel frame with a composite shear wall with a regular door opening, a steel frame with a composite shear wall with a large door opening, and a steel frame with a composite shear wall with a window opening.

This research has attempted to employ the most common apertures because one of its goals is to examine how openings affect the seismic behavior of composite steel shear walls. This is why the window opening in the center of the frame, which is 1200 mm long and 1600 mm high, has been taken into consideration. Furthermore, it has been estimated that the door opening in the center of the frame is 900 mm in length and 2100 mm in height. The percentage of windows and doors that open is 1.15%, which is about equal. Additionally, a big door opening with dimensions of 3000 x 2500 mm, whose opening percentage is around 60 percent, has been investigated in this study to

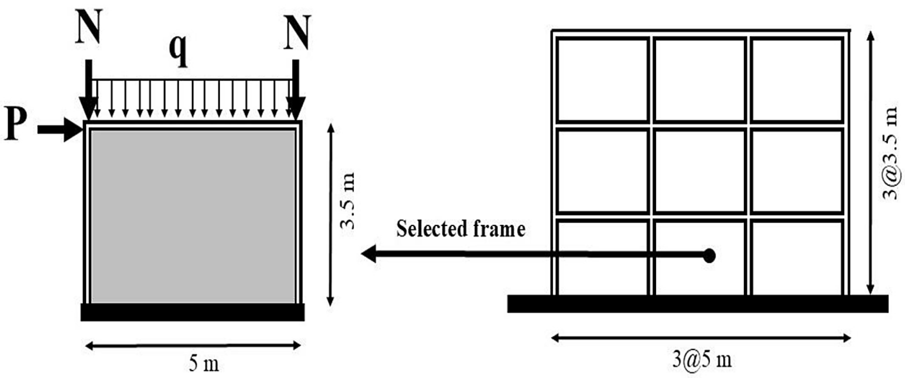


Figure 7. Selected single-span-single-story frame

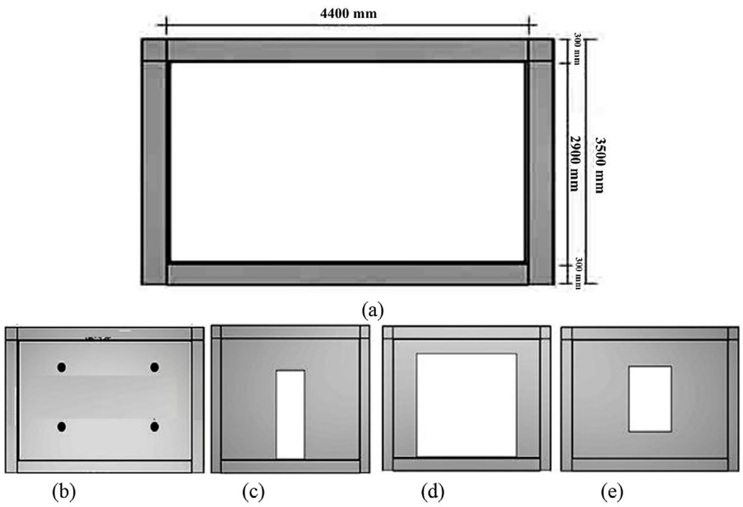


Figure 8. (a) Empty steel frame (reference model), (b) steel frame with composite shear wall without opening, (c) steel frame with composite shear wall with normal door opening, (d) steel frame with composite shear wall with large door opening, and (e) steel frame with composite shear wall with window opening

examine the impact of increasing the percentage of opening on the seismic activity of composite steel shear walls. Therefore, considering the main objective of the research, which is to investigate the effect of opening type, concrete cover, and steel plate thickness on the seismic behavior of composite shear walls, 25 different cases of a single-span, single-story steel frame, whose specifications are shown in Table 5, have been analyzed in finite element software, and finally, the ultimate strength, stiffness, ductility, and other important parameters are discussed and investigated.

Also in this research, the thickness of the reinforced concrete cover on the steel plate of the numerical specimens of the composite shear wall is considered to be 100 mm and concrete with a cylindrical strength of 40 MPa and an elastic modulus of about 2800 MPa has been used for it. The idea of attaching the concrete cover to the steel plate using a shear clamp has been explored. The minimum thickness for the steel plate in this research is 10 mm, and thicknesses of 12 and 15 mm have been considered to investigate the effect of increasing the thickness of the steel plate. This is because plates with a lower thickness (below 10 mm) need special and additional criteria and measures, and because the thickness of the steel plate in the composite steel shear wall shouldn't be chosen that is less than 10 mm. Thus, three distinct thicknesses of 10, 12, and 15 mm have been taken into consideration for the steel plate of the composite shear wall in this study. Table 6 displays the cross-sectional and material parameters of the single-span, single-story frame that was chosen, as depicted in Figures 7 and 8. Axial load is given to the columns in accordance with the loading depicted in Figure 7. After that, a linear spread load is applied to the beam, which exerts a

Table 5. Model naming and specifications

Model name	Thickness of reinforced concrete cover [mm]	Thickness of steel plate [mm]	Opening		
			Position	Percentage	Dimension [mm]
Ef (Reff model)	-	-	-	100	-
C10	100	10	-	0	-
C12	100	12	-	0	-
C15	100	15	-	0	-
S10	0	10	-	0	-
S12	0	12	-	0	-
S15	0	15	-	0	-
C10D15	100	10	Middle	15	900 × 2100
C12D15	100	12	Middle	15	900 × 2100
C15D15	100	15	Middle	15	900 × 2100
S10D15	0	10	Middle	15	900 × 2100
S12D15	0	12	Middle	15	900 × 2100
S15D15	0	15	Middle	15	900 × 2100
C10D60	100	10	Middle	60	3000 × 2500
C12D60	100	12	Middle	60	3000 × 2500
C15D60	100	15	Middle	60	3000 × 2500
S10D60	0	10	Middle	60	3000 × 2500
S12D60	0	12	Middle	60	3000 × 2500
S15D60	0	15	Middle	60	3000 × 2500
C10W15	100	10	Middle	15	1200 × 1600
C12W15	100	12	Middle	15	1200 × 1600
C15W15	100	15	Middle	15	1200 × 1600
S10W15	0	10	Middle	15	1200 × 1600
S12W15	0	12	Middle	15	1200 × 1600
S15W15	0	15	Middle	15	1200 × 1600

Table 6. Cross-section specifications used in modeling the frames

Elements	Modulus of elasticity [MPa]	Yielding stress [MPa]	Ultimate stress [MPa]	Details
Columns	203000	361	510	2IPE300+2PL300 × 5
Beams	203000	361	510	2IPE300
Steel plate	203000	268	415	Thickness 10 mm Thickness 12 mm Thickness 15 mm
Shear connector	203000	336	492	Φ20
Reinforcement	203000	361	510	Φ3

compressive force. Applying cyclic lateral load is the final step. According to the ATC24 code, the lateral load is applied up to 100 mm. The loading technique is displayed in Figure 9.

NUMERICAL MODELING ASSUMPTIONS

The numerical model used in this study incorporates several assumptions and limitations that should be critically discussed. One of the key assumptions is the use of a flexible damage model for steel members, which, while useful in capturing the behavior of steel under cyclic loading, may not fully represent the complex nonlinear interactions in real-world materials (Vahidi and Moradi 2019). Similarly, the plastic concrete damage model employed for concrete captures its brittle behavior under reciprocating and unidirectional loading, but may not completely reflect the

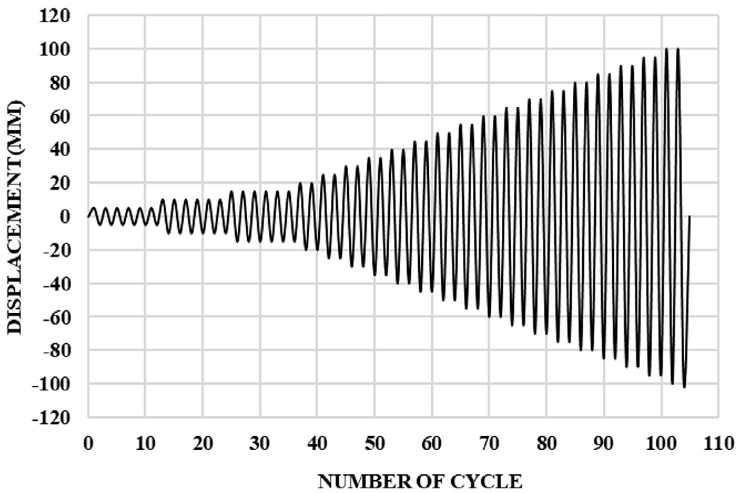


Figure 9. Loading protocol used in this research

nuances of concrete behavior, particularly under varying stress conditions, environmental factors, or in more complex load scenarios (Moradi and Khalilzadeh Vahidi 2018).

The choice of parameters in the plastic concrete damage model, such as the dilation angle, eccentricity, and viscous parameter, are based on prior studies (Hsu and Hsu 1994) but might not account for all possible variations in concrete performance, especially in different types of concrete mixes or under different environmental conditions. For instance, the assumed dilation angle of 31 degrees and the set eccentricity and viscous parameters may limit the model's ability to predict performance in extreme seismic events or under unusual loading conditions.

Moreover, the use of static analysis, while appropriate for many structural analyses, may not fully capture the dynamic effects of seismic forces, such as inertial effects or higher mode vibrations. The lateral load is applied in a reciprocating manner, simulating cyclic loading, but it does not replicate the full complexity of dynamic seismic forces, which could include varying frequencies, amplitudes, and durations.

Another important assumption is the use of idealized meshing and element types for modeling the structural components. While solid elements (C3D8R) are used for modeling the concrete cover, and shell elements (S4R) are used for the steel plates, beams, and columns, this simplification might not accurately represent the interaction between these materials under real-world loading. The meshing technique, which uses only two nodes at each shear end, may also neglect potential variations in stress distribution and failure modes, particularly at the interfaces where material transitions occur. Furthermore, the assumption that the steel plate is directly attached to the frame, without incorporating edge-clips or joints commonly used in real-world structures, could affect the model's accuracy in simulating the behavior of the infill plate under lateral loading. The choice of high-strength concrete for the model, while reducing the risk of cracking in the concrete cover, may not fully reflect the performance of lower-strength concrete, which is more commonly used in construction. Additionally, the reinforcement applied in a single layer constituting only 0.01% of the concrete volume might not capture the effects of different reinforcement configurations or densities typically used in practice.

In conclusion, while the numerical model presented offers valuable insights into the seismic behavior of composite shear walls, it is important to recognize these limitations and assumptions. Future research should consider more refined modeling approaches, including dynamic analysis, more representative material models, and a wider range of reinforcement configurations, to better capture the complexities of real-world seismic behavior.

RESULTS AND DISCUSSION

Studying the effect of the percentage and type of opening

For this purpose, four examples were chosen: one without an opening, one with a modest door opening, and one with a garage door. All of these models had a steel plate thickness of 10 mm. The control model was also included in this set. The selected models and the impact of the opening on ultimate strength, dissipated energy, stiffness, and ductility coefficient are displayed in Tables 7 and 8, respectively. We divide the values of the other models by the value of the control model, which is one, to make comparisons easier. The control model is normalized.

According to Table 7, the presence of a composite shear wall increases the ultimate strength by about 12 times. Furthermore, the ultimate strength of a composite steel-concrete shear wall with a window opening (15%) is approximately 9.5 times that of the reference model, which is an empty frame without a shear wall. Similarly, the ultimate strength of a composite steel-concrete shear wall with a door opening (15%) is approximately 4.6 times. That example, if both openings are in the middle and the opening % is the same for both, the ultimate strength of a shear wall with a window opening is around 1.5 times that of a shear wall with a door opening. It seems that the reason for this phenomenon is the change in the state of the force transmission mechanism. In other words, when we have a window opening, the compressive forces are transferred to the lower floors through the compression arms, but when we have a door opening, the force transmission mechanism is not well formed. Additionally, the composite shear wall's ultimate strength drops by roughly 70% when the proportion of door opening is increased from 15% to 60%.

Also, according to Table 7, the dissipated energy in the numerical model with 15 percent window opening and in the numerical model with 15 percent door opening was about 6 and 4 times that of the reference numerical model (numerical model without shear wall), respectively. In other words, the dissipated energy in the numerical model with window opening is about 1.5 times that of the numerical model with door opening. Also, increasing the percentage of opening from 15 to 60 percent causes a 50 percent reduction in dissipated energy.

According to Table 8, the ductility in the numerical model with 15% window opening and in the numerical model with 15% door opening is 3 and 2.4 times, respectively, of the reference numerical model (numerical model without shear wall). Increasing the opening percentage from 15 to 60% has caused a 10% decrease in ductility.

Also, according to Table 8, the stiffness in the numerical model with 15% window opening and in the numerical model with 15% door opening is about 49 and 27 times, respectively, of the reference numerical model (numerical model without shear wall). While increasing the opening percentage from 15 to 60% has caused a significant decrease in stiffness by 85%.

Based on Tables 7 and 8, it can be said that adding a composite shear wall to a steel frame will increase the ultimate strength by about 12 times, increase the dissipated energy by 7 times, increase the stiffness by 48 times, and increase the ductility by three times compared to the empty frame. Therefore, it is advised to utilize

Table 7. Ultimate strength and dissipated energy based on the percentage and type of opening

Specimens	Energy dissipated [kN.m]	E_i/E_{ef}	Ultimate load [kN]	Fu_i/Fu_{ef}
Ef (Reff Model)	142361.51	1	655.66	1
C10	998695.35	7.01	7957.03	12.13
C10W15	847475.14	5.95	6275.88	9.58
C10D15	562498.03	3.95	4221.64	6.43
C10D60	282968.02	1.98	1354.51	2.06

Table 8. Stiffness and ductility, based on the percentage and type of opening

Specimens	Ductility	D_i/D_{ef}	Stiffness [kN/mm]	S_i/S_{ef}
Ef (Reff model)	2.7	1	12.31	1
C10	8.14	3.02	600.99	48.85
C10W15	15.22	5.64	480.68	39.07
C10D15	6.52	2.41	331.72	26.96
C10D60	5.9	2.18	50.059	4.06

a composite shear wall to enhance the behavior of the structure taking into account the positive impacts of the wall on the shear behavior. The ultimate strength, dissipated energy, stiffness, and ductility are all decreased by introducing an opening, and significant seismic parameters further fall as the percentage of opening increases, as shown in Tables 7 and 8. Furthermore, the seismic behavior of a steel frame with a composite shear wall is more negatively impacted by door apertures than by window openings, as indicated by the results displayed in Tables 7 and 8. Therefore, when designing steel frames with a composite shear wall, it is advised to employ smaller holes.

Small openings: The presence of small openings (such as ventilation holes or small windows) generally has a minimal impact on the seismic performance of the wall. However, they may lead to stress concentrations around the opening, potentially causing cracking or local failure. Large openings: Large openings have a more significant effect on the wall's structural response. Large openings, such as doors or wide windows, can reduce the wall's load-bearing capacity by decreasing the cross-sectional area contributing to shear resistance. They may also contribute to stress concentrations around the edges of the opening, increasing the likelihood of failure in these areas. Interaction effects: The interaction between plate thickness and opening configuration amplifies these effects. For example, large openings in a thick plate wall may create a locally weak area around the opening, while openings in a thin plate wall may contribute to faster failure due to the uneven stress distribution.

Studying the effect of steel plate thickness

This section aims to investigate how the thickness of steel plates affects the seismic behavior of composite shear walls. Therefore, numerical models of composite shear walls without openings with steel plates of thicknesses of 10, 12, and 15 mm are compared with the reference numerical model. According to Table 9, in numerical models without openings, increasing the steel plate's thickness from 10 to 12 mm and from 12 to 15 mm by roughly 0.5 percent increases the ultimate strength; however, increasing the steel plate's thickness from 10 to 12 mm increases the dissipated energy by roughly 10 percent, and increasing from 12 to 15 mm increases the dissipated energy by 1%.

Increasing the thickness of the steel plate in a composite shear wall significantly improves both stiffness and ductility. When the thickness was increased from 10 mm to 12 mm, a 17% increase in stiffness and a 27% increase in ductility were observed. When the thickness was increased from 10 mm to 15 mm, the increase was even greater, with stiffness rising by 30% and ductility by 45%. These improvements occur because a thicker steel plate provides greater resistance to displacement under lateral loads, which enhances the wall's ability to deform before failure. This aligns with the findings of (Elgaaly et al., 1993; Purba and Bruneau, 2015), who noted that increasing the steel thickness improves the wall's performance in resisting seismic forces.

A steel plate with a thickness of 15 mm exhibits the best seismic behavior of the numerical model of a composite shear wall without an opening, as shown in Tables 9 and 10. This is because the steel plate's stiffness, ductility, dissipated energy, and ultimate strength are all higher, and it performs better seismically during an earthquake. To improve the seismic performance, it is advised that steel plates that are 15 mm thick be used in the design of composite shear walls. Increasing the plate thickness: Increasing the thickness of the steel plate in shear walls may enhance the ability to resist lateral forces and reduce cracking and damage to the wall. A thicker plate provides greater shear resistance, leading to an increase in the wall's strength under loading. Decreasing the plate thickness: On the other hand, reducing the plate thickness may decrease the wall's ability to resist external forces, weakening its seismic response and causing an increase in deformations.

Table 9. Ultimate strength and dissipated energy based on steel plate thickness

Specimens	Energy dissipated [kN.m]	E_i/E_{ef}	Ultimate load [kN]	Fu_i/Fu_{ef}
Ef (Reff Model)	142361.51	1	655.66	1
C10	998695.36	7.01	7957.03	12.13
C12	1100799.1	7.73	8003.98	12.20
C15	1113079.44	7.81	8026.16	12.24

Table 10. Steel plate stiffness and ductility as a function of thickness

Specimens	Ductility	D_i/D_{ef}	Stiffness [kN/mm]	S_i/S_{ef}
Ef (Reff model)	2.7	1	12.31	1
C10	8.14	3.02	600.99	48.85
C12	10.36	3.84	706.07	57.3
C15	11.8	4.37	785.15	63.5

Investigating the effect of reinforced concrete cover

The influence of the reinforced concrete cover on the seismic behavior of the composite shear wall will be explored by comparing two cases: one with and one without the cover. The control model, one without openings, one with a small door opening, and one with a window opening, all with a steel plate thickness of 10 mm, will all be considered.

The ultimate strength of the composite shear wall is approximately 1.8 times greater than that of the conventional shear wall in the model without an opening, 1.7 times greater in the numerical model with a window opening, and 1.6 times greater in the numerical model with a door opening, as shown in Table 11. In other words, the composite shear wall's ultimate strength is greater than that of the traditional shear wall. This appears to be because the steel plate buckles later because of the reinforced concrete layer. Additionally, the dissipated energy of the numerical models with a composite shear wall is greater than that of the traditional shear wall, as indicates in Table 11. The early buckling of the steel plate and, consequently, the lack of energy dissipation by the shear wall appear to be the reasons for the comparable dissipated energy between the numerical models with and without openings and those with door and window openings in numerical models with a conventional shear wall.

According to Table 12, the initial stiffness of numerical models with composite shear walls is almost the same as that of models with conventional shear walls, with only a slight difference between them. The absence of participation of the reinforced concrete cover on the steel plate in supporting the lateral load appears to be the cause of this. Nevertheless, compared to numerical models with composite shear walls, the ductility

Table 11. Effects of reinforced concrete cover on ultimate strength and energy dissipation

Specimens	Energy dissipated [kN.m]	E_i/E_{ef}	Ultimate load [kN]	$Fu_i/F_{ue}f$
Ef (Reff model)	142361.51	1	655.66	1
C10	998695.36	7.01	7957.03	12.13
C10W15	847475.14	5.95	6275.88	9.58
C10D15	562498	3.95	4221.64	6.45
S10	388188	2.72	4370.58	6.66
S10W15	400335.17	2.61	3752.22	5.72
S10D15	302344.67	2.12	2603.35	3.97

Table 12. Variations in stiffness and ductility as a result of reinforcing the concrete

Specimens	Ductility	D_i/D_{ef}	Stiffness [kN/mm]	S_i/S_{ef}
Ef (Reff model)	2.7	1	12.31	1
C10	8.14	3.02	600.99	48.85
C10W15	15.22	5.64	480.68	39.07
C10D15	6.52	2.41	331.72	26.96
S10	9.17	3.39	566.5	46.05
S10W15	15.73	5.84	388.1	31.54
S10D15	9.27	3.43	280.26	22.36

of the conventional shear wall model is higher. This occurrence appears to be caused by the reinforced concrete cover that is attached to the steel plate via shear connectors, which stops the steel plate from pulling. Stated differently, the presence of the reinforced concrete cover on the steel plate, when fully integrated and attached to the steel plate using steel shear connectors, increases the tensile strength of the entire shear wall assembly and makes the shear wall behave brittle and fragile, which lowers the ductility in comparison to traditional steel shear walls.

The results presented in Tables 11 and 12 indicate that the addition of a reinforced concrete layer to steel shear walls, whether without openings or with openings, significantly improves the strength, stiffness, and dissipated energy, while reducing the ductility coefficient. This improvement can be attributed to the role of reinforced concrete in enhancing the wall's ability to resist lateral forces (shear) and better distributing the stresses. Increased Strength and Stiffness: For the steel shear wall without an opening, the results showed that the addition of a 10 mm reinforced concrete cover increased the strength by 82% and stiffness by 6%. This increase aligns with findings by (Yin et al., 2020), who stated that reinforced concrete improves the performance of walls against seismic forces by distributing stresses more effectively, thus enhancing the wall's load-bearing capacity.

The study also showed a 157% increase in dissipated energy for the steel shear wall without an opening, indicating that the reinforced concrete cover helps in absorbing seismic energy more effectively, reducing the negative effects on the structure. This result supports the work of (Yin et al. 2020), which highlighted that reinforced concrete improves energy dissipation in shear walls. Despite the improvements in strength, stiffness, and dissipated energy, there was a reduction in the ductility coefficient by 11% for the steel shear wall with the reinforced concrete cover without an opening. This reduction in ductility is a natural consequence of the increased stiffness provided by the concrete, which reduces the wall's ability to deform before failure. This finding is consistent with (Wang et al., 2018), who noted that adding concrete could increase stiffness while decreasing ductility. In the case of a steel shear wall with an opening (such as a window or door), the strength, dissipated energy, and stiffness were enhanced by 138%, 127%, and 23%, respectively. However, the ductility coefficient decreased by 4%. These results align with (Dey and Bhowmick, 2016), who pointed out that openings affect the wall's performance, as the presence of an opening reduces the effectiveness of reinforced concrete in improving the seismic resistance due to stress concentrations around the opening. For the steel shear wall with a small door opening, the strength, dissipated energy, and stiffness improved by 62%, 87%, and 21%, respectively, but the ductility coefficient decreased by 28%. This indicates that small openings have a greater impact on the wall's load-bearing capacity compared to walls without openings, which is consistent with findings from (Zhang et al., 2022), who confirmed that small openings lead to a more significant reduction in ductility.

These results suggest that adding reinforced concrete to steel shear walls significantly improves their structural performance, but with some trade-offs in ductility, particularly in the presence of openings.

PRACTICAL AND METHODOLOGICAL LIMITATIONS

While the current study provides valuable insights into the seismic performance of composite steel–concrete shear walls, it is important to acknowledge certain practical and methodological limitations. First, the analysis conducted is based solely on static nonlinear loading, without incorporating dynamic time-history or spectral analysis, which limits the understanding of the structure's response to real earthquake excitations. Dynamic effects such as frequency content, duration, and cumulative damage are therefore not captured. Second, the finite element simulations rely on idealized assumptions regarding material behavior-such as perfect plasticity and homogeneous, isotropic properties-which may not fully represent the complex, inelastic response of materials under cyclic and dynamic loading conditions.

Additionally, the study does not consider construction-related imperfections, residual stresses, or interaction effects between the steel plate and concrete due to possible debonding or imperfect composite action. These simplifications, although necessary to reduce model complexity and computational cost, may influence the accuracy and applicability of the results when extrapolated to full-scale, real-world structures. Therefore, while the findings contribute to the academic understanding of composite shear wall behavior, caution should be exercised when translating the results into practical engineering applications without further experimental and dynamic validation. The findings of this study emphasize the importance of design factors such as plate thickness, concrete cover, and the presence of openings in composite shear walls for seismic performance. Increasing the plate thickness from 10 to 15 mm significantly enhances the strength, energy dissipation, stiffness, and ductility of composite shear walls, especially in systems without openings. However, the presence of openings, whether in the form of windows or doors, reduces the wall's resistance, energy dissipation, stiffness, and ductility. The inclusion of reinforced concrete cover further improves the resistance and energy dissipation but may decrease ductility.

These results suggest that composite shear walls are highly effective in improving the seismic behavior of buildings, and their design should focus on optimizing plate thickness and concrete cover. For structures with openings, adjusting the plate thickness can help balance functionality and seismic performance. Future research should continue exploring methods to enhance energy dissipation and ductility to further improve the seismic resilience of these walls.

CONCLUSIONS

The conclusions drawn from this study focus on the impact of various factors on the seismic behavior of composite steel shear walls. The following key findings were observed:

- Effect of openings: The presence of an increased percentage of openings in composite shear walls reduces their resistance by (18–83%), dissipated energy by (15–71%), stiffness by (20–91%), and ductility coefficient by (20–28%).
- Impact of plate thickness: Increasing the steel plate thickness from 10 to 15 mm in a composite steel shear wall without openings enhances the ultimate strength by 2%, dissipated energy by 12%, stiffness by 30%, and ductility coefficient by 45%.
- Influence of plate thickness in aperture models: In composite shear walls with apertures, increasing the steel plate thickness from 10 to 15 mm results in increases in ultimate strength (12–19%), dissipated energy (7–22%), stiffness (28–35%), and ductility coefficient (11–27%).
- Performance with a 10 mm plate and openings: A steel shear wall with or without holes and a 10 mm plate shows significant increases in strength (62–138%), dissipated energy (87–157%), and stiffness (6–23%). However, the ductility coefficient decreases by 4% to 28%.
- Effect of reinforced concrete cover (12 mm Plate): The inclusion of reinforced concrete cover in steel shear walls, both with and without openings, increases resistance by 44 to 113%, dissipated energy by 31 to 90%, and stiffness by 3 to 19%. However, it reduces the ductility coefficient by 7 to 39%.
- Effect of reinforced concrete cover (15 mm Plate): The presence of reinforced concrete cover in steel shear walls with a 15 mm plate increases resistance by 33 to 80%, dissipated energy by 18 to 76%, and stiffness by 4 to 15%. However, it reduces the ductility coefficient by 11 to 51%.
- Comparison with bare frame: When compared to the bare frame, adding a composite shear wall increases ultimate strength by approximately 12 times, dissipated energy by 7 times, stiffness by 48 times, and ductility by 3 times. Therefore, the use of composite shear walls is highly recommended for enhancing the shear behavior of buildings.
- Optimal plate thickness for seismic performance: A steel plate with a thickness of 15 mm demonstrates the best seismic performance in composite shear walls without openings due to its superior stiffness, ductility, dissipated energy, and ultimate strength. Therefore, steel plates with a thickness of 15 mm are recommended for improving seismic performance.
- Future research: Further experimental studies focusing on enhancing the energy dissipation and ductility of composite shear walls are recommended for researchers aiming to improve the seismic behavior of these structures.

In conclusion, composite shear walls exhibit significant improvements in seismic behavior when appropriate design factors such as plate thickness and concrete cover are considered. Future research should continue to explore methods to enhance the energy dissipation and ductility to further improve the performance of these walls in seismic conditions.

REFERENCES

1. Afefy, H. M. 2020. Seismic retrofitting of reinforced-concrete coupled shear walls: A review. Practice Periodical on Structural Design and Construction, 2020; 25(3): 3120001. https://doi.org/10.1061/(ASCE)SC.1943-5576.0000489
2. Arabzadeh, A., Soltani, M. and Ayazi, A. Experimental investigation of composite shear walls under shear loadings. Thin-Walled Structures, 2011; 49(7): 842–854. https://doi.org/10.1016/j.tws.2011.02.009.
3. ATC-24. Guidelines for seismic testing of components of steel structures. Applied Technology Council., Report 1992; 24.
4. Aydin, A. C., and Bayrak, B. Design and performance parameters of shear walls: a review. Architecture, Civil Engineering, Environment, 2021; 14(4): 69–94. https://doi.org/10.21307/acee-2021-032
5. Chang, W.-S. Repair and reinforcement of timber columns and shear walls–A review. Construction and Building Materials, 2015; 97: 14–24. https://doi.org/10.1016/j.conbuildmat.2015.07.002.
6. Dey, S., and Bhowmick, A. K. Seismic performance of composite plate shear walls. Structures, 2016; 59–72.
7. Elgaaly, M., Caccese, V. and Du, C. Postbuckling behavior of steel-plate shear walls under cyclic loads. Journal of Structural Engineering, 1993; 119(2): 588–605.
8. Gharaei-Moghaddam, N., Meghdadian, M. and Ghalehnovi, M. Innovations and advancements in concrete-encased steel shear walls: A comprehensive review. Results in Engineering, 2023; 19: 101351. https://doi.org/10.1016/j.rineng.2023.101351
9. Hao, T., Cao, W., Qiao, Q., Liu, Y. and Zheng, W. Structural performance of composite shear walls under compression. Applied Sciences, 2017; 7(2): 162. https://doi.org/10.3390/app7020162
10. Haridas, A., and Rasal, D. S. A. Seismic behaviour of high rise building with composite shear wall: An overview. Available at SSRN 2021; 3856957: 6. https://doi.org/10.2139/ssrn.3856957
11. Hsu, L. S., and Hsu, C.-T. Complete stress—strain behaviour of high-strength concrete under compression. Magazine of Concrete Research, 1994; 46(169): 301–312.
12. Meghdadian, M., Gharaei-Moghaddam, N., Arabshahi, A., Mahdavi, N. and Ghalehnovi, M. Proposition of an equivalent reduced thickness for composite steel plate shear walls containing an opening. Journal of Constructional Steel Research, 2020; 168: 105985. https://doi.org/10.1016/j.jcsr.2020.105985
13. Mo, J., Uy, B., Li, D., Thai, H.-T. and Tran, H. A review of the behaviour and design of steel–concrete composite shear walls. Structures, 2021; 1230–1253.
14. Moradi, R., and Khalilzadeh Vahidi, E. Comparison of numerical techniques of masonry infilled RC frames for lateral loads. Journal of Concrete Structures and Materials, 2018; 3(2): 102–118. https://doi.org/10.30478/jcsm.2019.82172
15. Moradi, R., and Vahidi, E. K. General study of new ideas and practical of friction dampers for passive vibration control of structures. Karafan Journal, 2021; 17(4): 239–257. National University of Skills. https://doi.org/10.48301/kssa.2021.126575.
16. Owaid, A. M., Akhaveissy, A. H. and Al-Abbas, B. H. Retrofitting seismically designed exterior beam-column joints under lateral monotonic loading: A numerical analysis based on experimental testing. Journal of Rehabilitation in Civil Engineering. 2025. https://doi.org/10.22075/jrce.2024.33704.2043.
17. Purba, R., and Bruneau, M. Seismic performance of steel plate shear walls considering two different design philosophies of infill plates. II: Assessment of collapse potential. Journal of Structural Engineering, 2015; 141(6): 4014161.
18. Singhal, S., Chourasia, A., Chellappa, S. and Parashar, J. Precast reinforced concrete shear walls: State of the art review. Structural Concrete. 2019; 20(3): 886–898. https://doi.org/10.1002/suco.201800129
19. Vahidi, E. K., and Moradi R. Numerical study of the force transfer mechanism and seismic behavior of masonry infilled RC frames with windows opening. Civil Engineering Journal, 2019; 5(1): 61–73. https://doi.org/10.28991/cej-2019-03091225
20. Wang, W., Wang, Y. and Lu Z. Experimental study on seismic behavior of steel plate reinforced concrete composite shear wall. Engineering Structures, 2018; 160: 281–292. https://doi.org/10.1016/j.engstruct.2018.01.050
21. Yin, F., Xue, S.-D., Cao, W.-L., Dong, H.-Y. and Wu, H.-P. Behavior of multi-cell concrete-filled steel tube columns under axial load: Experimental study and calculation method analysis. Journal of Building Engineering, 2020; 28: 101099. Zhang, Y., Yuan, G., Shu, Q., Zhu, M. and Lu, L. Investigation on seismic behavior of RC shear walls with multiple post-construction openings based on experiment and simulation. Journal of Building Engineering, 2022; 46: 103707.