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Study of the effect of steel plate thickness and opening characteristics on the seismic behavior of composite steel shear wall with reinforced concrete cover

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Abstract: This study explores the impact of steel plate thickness, concrete cover, and the presence of openings on the seismic performance of composite shear walls. A total of 19 numerical models were analyzed using nonlinear static (pushover) analysis, with parameters including plate thickness, reinforced concrete cover, and different opening types. Results indicate that increasing the steel plate thickness significantly enhances the ultimate load, stiffness, and energy dissipation capacity. For example, models with concrete cover exhibited improved performance, with ultimate load ratios of up to 12.98 times the control model. In contrast, models with openings, particularly door openings, showed a decline in performance, with load ratios of up to 5.75 times the control model. Stiffness was also reduced in models with openings, with door-opening models showing the lowest stiffness. Energy dissipation improved with increased plate thickness and concrete cover, with the T16Co model dissipating 7.7 times more energy than the control model. The findings highlight the importance of steel plates and concrete encasement in improving seismic resistance, while the presence of openings reduces the wall's ability to resist lateral loads and absorb energy.
Keywords: *Composite shear walls, Seismic performance, Steel plates with reinforced Concrete cover, Wall openings.*

1. Introduction

Steel shear walls have been proposed and considered in the last three decades to withstand the lateral forces of earthquakes and wind in buildings, especially in tall buildings, and are rapidly expanding in the world [1]. They have been used in the construction of new buildings and also to strengthen existing buildings, especially in earthquake-prone countries such as the United States and Japan. Their use has resulted in savings of up to 50% in steel consumption in the structure compared to steel bending frames. Steel shear walls are a very simple system in terms of implementation and do not have any particular complexity. This system, along with its many advantages, also has disadvantages. To overcome these disadvantages, engineers created a new generation of shear walls, known as composite shear walls [2].

Steel shear wall systems are one of the lateral load-resistant systems used in medium to high-rise buildings [3]. These systems have high ultimate strength, characteristic plastic behavior, and high energy absorption capacity [4]. Steel shear wall systems also have lower stiffness and weight, shorter construction time, and lower cost compared to reinforced concrete shear walls. However, steel shear walls require precise and sometimes complex connections in the boundary frame elements using bolts or welding. Thin-plate shear walls dissipate energy through plastic deformations through the action of the tensile field that is created in the plate after buckling. The tensile field action is formed at lower loads for thinner plates than for thicker steel plates. Recent research has used thin-plate steel shear walls without stiffeners, in which the tensile field action is used to resist lateral forces [5-7].

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Shear walls are one of the common structural systems for dealing with lateral forces. Shear walls are often designed and implemented in two types: reinforced concrete shear walls and steel shear walls; however, in tall structures that bear large lateral forces, the use of conventional shear walls cannot be a suitable option as a lateral load-bearing system, because the use of reinforced concrete walls causes the wall to thicken, resulting in a reduction in useful space and an increase in the weight of the structure [8, 9]. The use of steel shear walls is also not a suitable solution for dealing with lateral forces in tall structures due to weakness in areas under compressive stress and the occurrence of buckling, which reduces the load-bearing and energy-absorbing capacity of the wall [10]. An effective solution can be the simultaneous use of concrete and steel plates as a composite shear wall, which has the advantages of concrete and steel at the same time, and due to its shear strength and high ductility capacity under high compressive forces and lateral forces, it can be a suitable lateral load-bearing system for tall structures [11].

Many laboratory studies have been conducted in the field of composite shear walls so far. One of these studies was the investigation of the effect of opening on the seismic performance of composite shear walls, which was conducted by Meghdadian, et al. [12]. The results of their research have shown that reinforced concrete layers prevent the buckling of steel plates and increase the overall stiffness of the structural system. Considering the importance and necessity of studying the seismic behavior of steel frames with composite shear walls and considering that no comprehensive studies have been conducted to investigate the effect of door and window openings and steel sheet thickness on the seismic behavior of the structure, in this research, after reviewing reliable sources and new articles, the accuracy of numerical modeling in Abaqus software has been examined. In the next step, considering the main objective of the research, the details of numerical models, loading, and boundary conditions were determined, and finally, the models were analyzed under cyclic loading and seismic parameters including ultimate strength, stiffness, and ductility, and dissipated energy are evaluated.

2. Validation

It is essential to perform validation to evaluate the modeling method and the accuracy of the results obtained. In this study, the laboratory specimens of Meghdadian, et al. [12] were used to validate the numerical model in the ABAQUS software. The specimens selected for validation include a specimen without an opening, a specimen with a 140×190 mm rectangular opening, and a specimen with a 140×190 mm rectangular opening that has been reinforced around the opening with a rebar mesh at an angle of 45 degrees to reduce the negative effects of the opening. All specimens were made at a quarter scale and subjected to cyclic loading in the laboratory. Based on Figure 1, which compares the cyclic diagram of the laboratory specimens and the numerical models, it can be said that the numerical modeling has acceptable accuracy.

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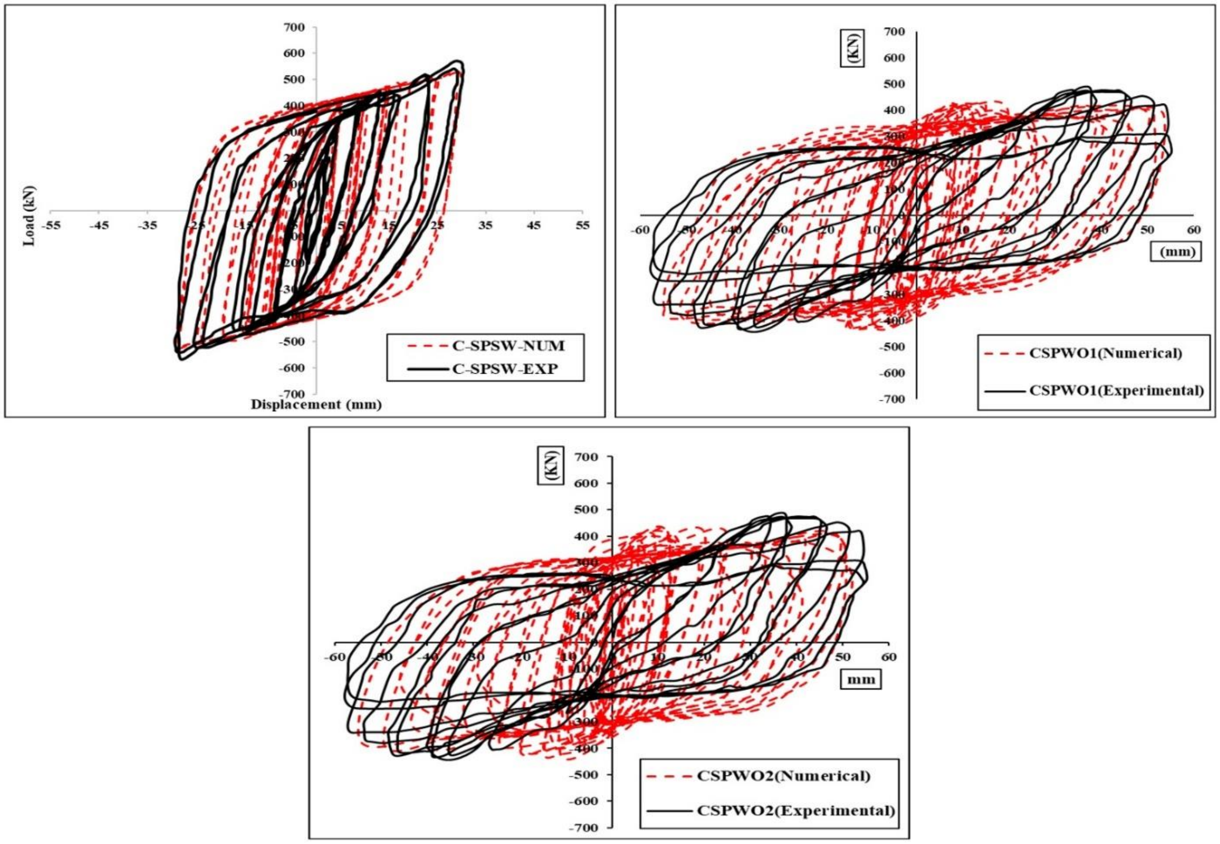


Figure 1.
Comparison of the cycle diagram of the laboratory sample and the numerical model.

3. Modeling Assumptions

In this research, first, a three-story steel building with a completely regular plan was designed based on valid American regulations and using Etabs software.

In the structural design, a dead load of 6.5 kN/m^2 and a live load of 2.1 kN/m^2 were assumed. As shown in Figure 2, 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.

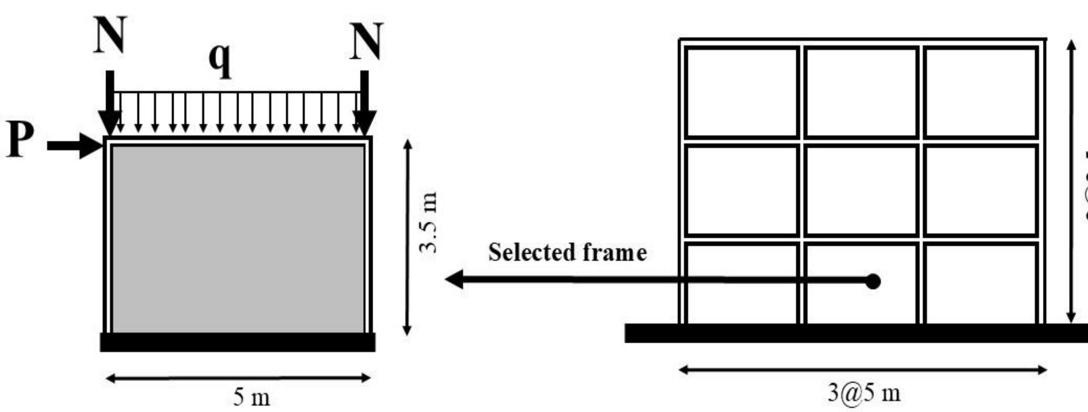


Figure 2.
Selected single-span-single-story frame.

The numerical composite shear wall specimens' steel plate is expected to have a reinforced concrete cover that is 100 mm thick. It has also been done using concrete that has a 42 MPa cylindrical strength. It has been contemplated to attach the concrete cover to the steel plate using a shear retainer. Three distinct thicknesses of 10, 13, and 16 mm have been contemplated for the composite shear wall's steel plate. The material specifications and cross-section of the single-span, single-story frame that was chosen and displayed in Figure 2 are displayed in Table 1.

Table 1.
Cross-sectional measurements utilized to model the frames.

Elements	Modulus of elasticity (MPa)	Yielding stress (MPa)	Ultimate stress (MPa)	Details
Columns	205000	358	520	2IPE300+2PL300X5
Beams	205000	358	520	2IPE300
Steel plate	205000	265	425	Thickness 10 mm Thickness 13 mm Thickness 16 mm
Shear connector	205000	337	495	Φ20
Reinforcement	205000	365	520	Φ3

In light of the primary goal of the study, which is to examine how opening type, concrete cover, and steel plate thickness affect the seismic behavior of composite shear walls, finite element software has been used to analyze 19 distinct single-span, single-story steel frame cases, the details of which are listed in Table 1.

Table 2.
Details of the numerical instances under study.

Specimens	Description of Models
Control	Control model (bar frame model without steel shear wall)
T10Co	Composite steel shear wall with reinforced concrete cover, no openings, and 10 mm thick steel plate
T10CWo	Composite steel shear wall with reinforced concrete cladding and window openings with 10 mm thick steel plate
T10CDo	Composite steel shear wall with reinforced concrete cover and door opening with 10 mm thick steel plate
T10	Composite steel shear wall without reinforced concrete cover and without openings and with 10 mm thick steel plate
T10Wo	Composite steel shear wall without reinforced concrete cover and with window opening with 10 mm thick steel plate
T10Do	Composite steel shear wall without reinforced concrete cover and with door opening with 10 mm thick steel plate
T13Co	Composite steel shear wall without reinforced concrete cover and with door opening with 10 mm thick steel plate
T13CWo	Composite steel shear wall with reinforced concrete cladding and window openings with 13 mm thick steel plate
T13CDo	Composite steel shear wall with reinforced concrete cover and door opening with 13 mm thick steel plate
T13	Composite steel shear wall without reinforced concrete cover and without openings and with 13 mm thick steel plate
T13Wo	Composite steel shear wall without reinforced concrete cover and with window opening with 13 mm thick steel plate
T13Do	Composite steel shear wall without reinforced concrete cover and with door opening with 13 mm thick steel plate
T16Co	Composite steel shear wall with reinforced concrete cover, no openings, and 16 mm thick steel plate
T16CWo	Composite steel shear wall with reinforced concrete cladding and window openings with 16 mm thick steel plate
T16CDo	Composite steel shear wall with reinforced concrete cover and door opening with 16 mm thick steel plate
T16	Composite steel shear wall without reinforced concrete cover and without openings and with 16 mm thick steel plate
T16Wo	Composite steel shear wall without reinforced concrete cover and with window opening with 16 mm thick steel plate
T16Do	Composite steel shear wall without reinforced concrete cover and with door opening with 16 mm thick steel plate

The window opening is assumed to be in the middle of the frame and is rectangular with a length of 120 and a height of 160 cm. The door opening is also assumed to be in the middle of the frame with a length of 90 and a height of 210 cm. The percentage of door and window opening is almost the same and is 1.15%.

In the modeling of numerical samples, in addition to elastic and plastic characteristics, a flexible damage model has been used for steel members. Also, in the modeling of concrete, a plastic damage model of concrete has been used [13-15] and in all numerical models, the static analysis type has been selected. Axial load on columns, linear extended load on beam, and lateral load have all been taken into account while modeling numerical examples, as seen in Figure 1. According to the American norm, the lateral load has been applied reciprocating up to 100 mm, or 2.5 percent of the floor height. The ATC24 guideline [16] serves as the foundation for the loading process, which is described as regulated displacement. To model the concrete cover used for solid bodies, solid elements of type C3D8R are chosen during the modeling phase. The beam, column, and steel plate are all made of the 3D shell element S4R. The shears are modeled using element B31. We only have two nodes at the two ends of the shears because of the way the system meshing is done. It should be mentioned that the steel plate is presumed to be directly attached to the frame, and the edge retainer (connection), which is typically used to join the infill plate to the surrounding frame, is not depicted. High-strength concrete is primarily used because it reduces concrete cover cracking.

4. Discussion and Results

4.1. Hysteric Diagram

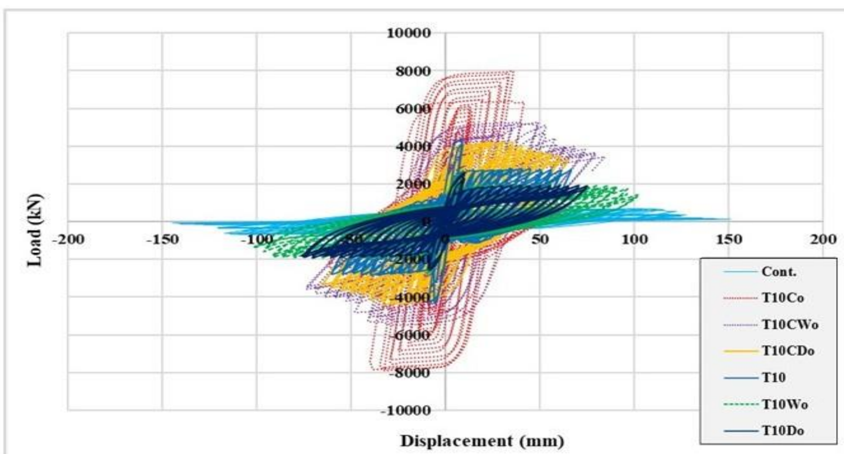
After the analysis of numerical models in Abaqus software is completed, the first output that is examined is the hysteresis diagram. The figure below shows the hysteresis diagram of the numerical models.

As shown in Figure 3, in the control sample, initially, with increasing displacement, the resistance value increases linearly, and then enters the plastic zone and its stiffness decreases, and finally, after the formation of plastic joints in the beam, a severe drop in strength is observed.

In numerical samples with reinforced concrete cover, in the elastic zone, with increasing displacement, the resistance value also increases linearly, and then the stiffness decreases and enters the plastic zone. In the plastic zone, cracks gradually begin to spread, and after the complete rupture of the concrete cover on the steel plate, a drop in strength is observed, and the drop in strength continues until the moment of buckling of the steel plate and complete rupture of the numerical sample. It should be noted that the reinforced concrete cover on the steel plate has caused the drop in strength to occur later, in other words, the reinforced concrete cover has increased the energy dissipation capacity due to the tensile force by delaying buckling due to the compressive force.

In numerical samples without reinforced concrete cover, initially, the resistance increased linearly with increasing displacement, and after buckling of the steel plate in the compression zone, a drop in resistance and severe pinching were observed in their hysteresis diagram.

From the comparison of the hysteresis diagram of samples without openings and samples with openings, it can be concluded that the pinching amount was more severe in the samples without openings. Also, the samples with door openings had much lower ultimate resistance and drop in resistance than the samples with window openings.



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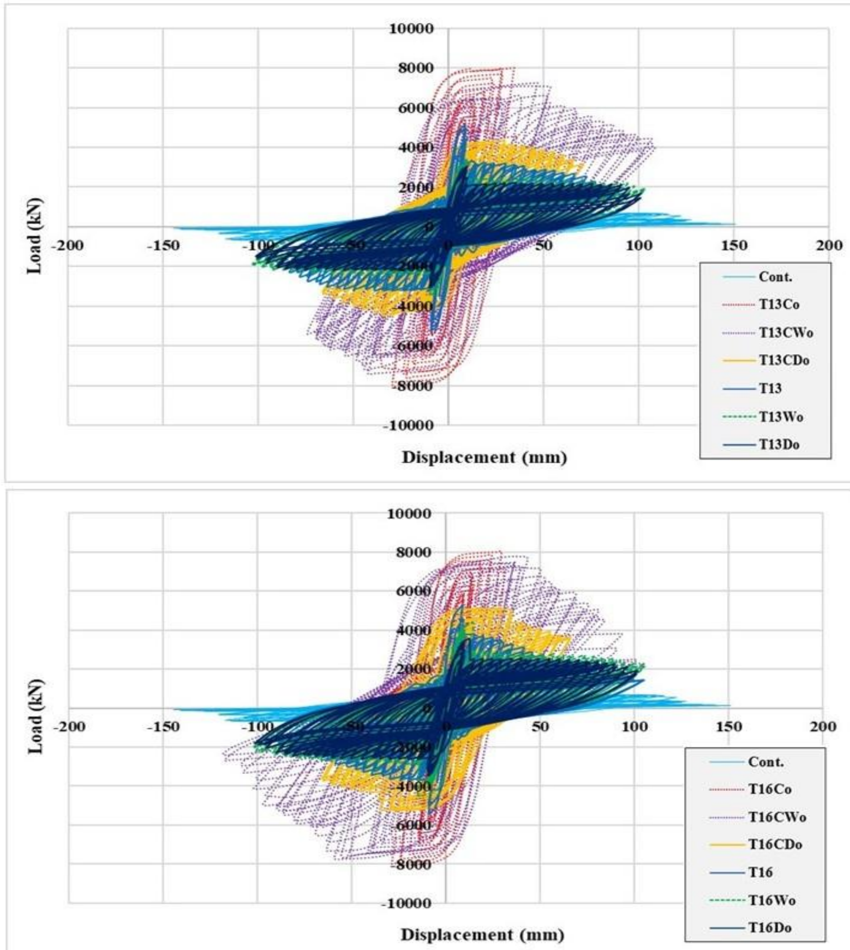

Figure 3.
hysteresis diagram of the numerical models.

Based on the hysteresis diagram of the numerical samples, the values of seismic parameters were extracted. Table 3 shows the extracted seismic parameters.

Table 3.
Seismic parameters of numerical samples.

Numerical models			**Plate thickness (mm)**	**Ultimate load (kN)**	**Ultimate load ratio to control model**	**Stiffness (kN/mm)**	**Stiffness ratio to control model**	**Energy Dissipated (kN.mm)**	**Energy Dissipated ratio to control model**
Control model		Cont.	-	623.66	1.00	12.65	1.00	145106.51	1.00
Without cover	Without opening	T10	10	4256.58	6.83	568.946	44.98	389857.2887	2.69
		T13	13	5125.38	8.22	691.1392	54.64	584656.9609	4.03
		T16	16	5272.53	8.45	754.9624	59.68	637328.0368	4.39
With cover		T10Co	10	7987.03	12.81	603.5743	47.71	1002989.74	6.91
		T13Co	13	8053.98	12.91	709.1061	56.06	1105532.536	7.62
		T16Co	16	8096.16	12.98	788.5261	62.33	1117865.682	7.70
Without cover	Windows opening	T10Wo	10	2632.22	4.22	389.7688	30.81	402056.6112	2.77
		T13Wo	13	3385.66	5.43	438.146	34.64	473796.0601	3.27
		T16Wo	16	4284.92	6.87	571.9187	45.21	592094.9071	4.08
With cover		T10CWo	10	6267.88	10.05	482.7469	38.16	851119.2731	5.87
		T13CWo	13	7222.94	11.58	508.457	40.19	910493.951	6.27
		T16CWo	16	7737.9	12.41	652.0116	51.54	1021638.757	7.04
Without cover	Door opening	T10Do	10	2583.35	4.14	281.4651	22.25	303644.7521	2.09
		T13Do	13	3066.49	4.92	330.244	26.11	452998.9755	3.12
		T16Do	16	3584.28	5.75	371.4203	29.36	585881.5039	4.04
With cover		T10CDo	10	4244.61	6.81	333.1464	26.34	564916.7715	3.89
		T13CD	13	4327.87	6.94	390.5622	30.87	590568.6122	4.07
		T16CD	16	5108.15	8.19	422.0671	33.36	687699.8482	4.74

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4.2. Ultimate strength

The table 3 presented in the study illustrates the effect of steel plate thickness, concrete cover, and the presence and type of openings (windows or doors) on the structural performance of composite shear walls in terms of ultimate load capacity. The analysis begins with the control model, which recorded a maximum load of 623.66 kN and is set as the reference (with a ratio of 1.00).

As shown in figure 4, for models without concrete cover and without openings, an increase in steel plate thickness significantly improved the ultimate load. Model T10 recorded a load of 4256.58 kN, representing 6.83 times the reference load, while T13 and T16 reached 8.22 and 8.45 times the control model, respectively. This indicates that the addition of steel plates significantly enhances the wall's resistance to lateral loads, which aligns with findings by Aydin and Bayrak (2021) regarding the role of steel in improving lateral load resistance.

When concrete cover is added (without openings), performance improves even further. Models T10Co, T13Co, and T16Co achieved ultimate load ratios of 12.81, 12.91, and 12.98, respectively. This enhancement is attributed to the concrete encasement's ability to restrain steel plate buckling and improve load distribution, consistent with observations by Hao, et al. [8].

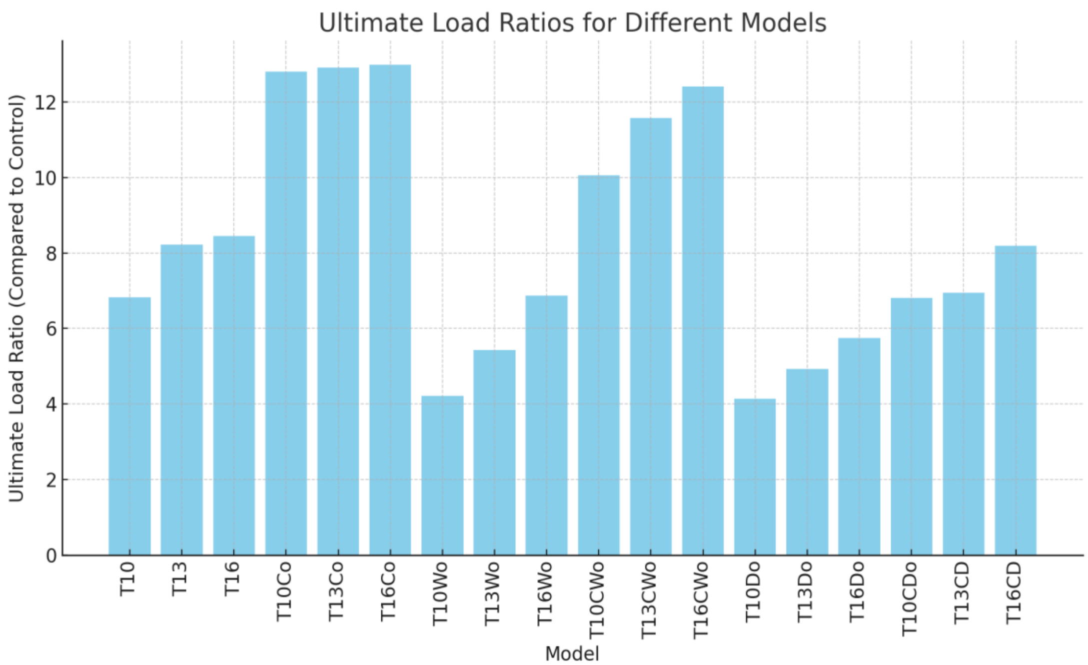

Figure 4.
Ultimate Load Ratios for Different Composite Shear Wall Models Compared to the Control Model.

Models with window openings and no concrete cover showed reduced performance, with load ratios of 4.22, 5.43, and 6.87 for T10Wo, T13Wo, and T16Wo, respectively. This reduction is due to the decreased effective wall area and stress concentration near the openings, leading to localized cracking-a phenomenon highlighted by Meghdadian, et al. [12]. Increasing the plate thickness and adding covering have a significant positive impact on the ultimate load of the material. With increased thickness, the structure's ability to withstand external forces improves, increasing the maximum load the structure can bear before failure occurs. Previous research, such as the study by Shafaei, et al. [17] indicates that thicker plates enhance their resistance to loading, making them more resistant to deformation under heavy loads.

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When concrete cover is applied to walls with window openings, structural performance significantly improves, achieving load ratios of 10.05, 11.58, and 12.41 for models T10CWo, T13CWo, and T16CWo, respectively. This indicates that the concrete cover plays a crucial role in mitigating the negative effects of openings by redistributing stresses. In contrast, models with door openings (larger than windows) showed weaker performance: T10Do, T13Do, and T16Do recorded load ratios of 4.14, 4.92, and 5.75, respectively. This is due to the larger reduction in the effective shear wall area. However, adding concrete cover to door-opening models (T10CDo, T13CD, T16CD) improved performance to ratios of 6.81, 6.94, and 8.19, although these values remained lower than those of the models with window openings.

Based on these findings, the table highlights the importance of both steel plates and concrete encasement in enhancing the ultimate load capacity of composite shear walls. It also emphasizes the need to carefully consider the effects of openings on wall performance. The results support engineering recommendations to apply concrete cover to walls with openings to maintain adequate performance under high lateral loads.

4.3. Stiffness

According to Table 3 and figure 5, the stiffness of the control model is 12.65 kN/mm, which acts as a reference for comparing the effects of different modifications. Similar to the ultimate load, increasing the thickness of the plate directly increased its stiffness. For instance, the T16Co model achieved a stiffness of 788.53 kN/mm, which is 62.33 times higher than the control model. This significant increase is attributed to the higher material resistance against deformation, which occurs with thicker and more rigid plates. Furthermore, adding covering to the plates consistently improved their stiffness across all thicknesses. The T10Co (thickness = 10 mm with covering) model showed a stiffness of 603.57 kN/mm, which is 47.71 times that of the control model. This improvement suggests that the covering plays a crucial role in enhancing the rigidity of the structure, likely by providing additional surface area that resists bending and deformation.

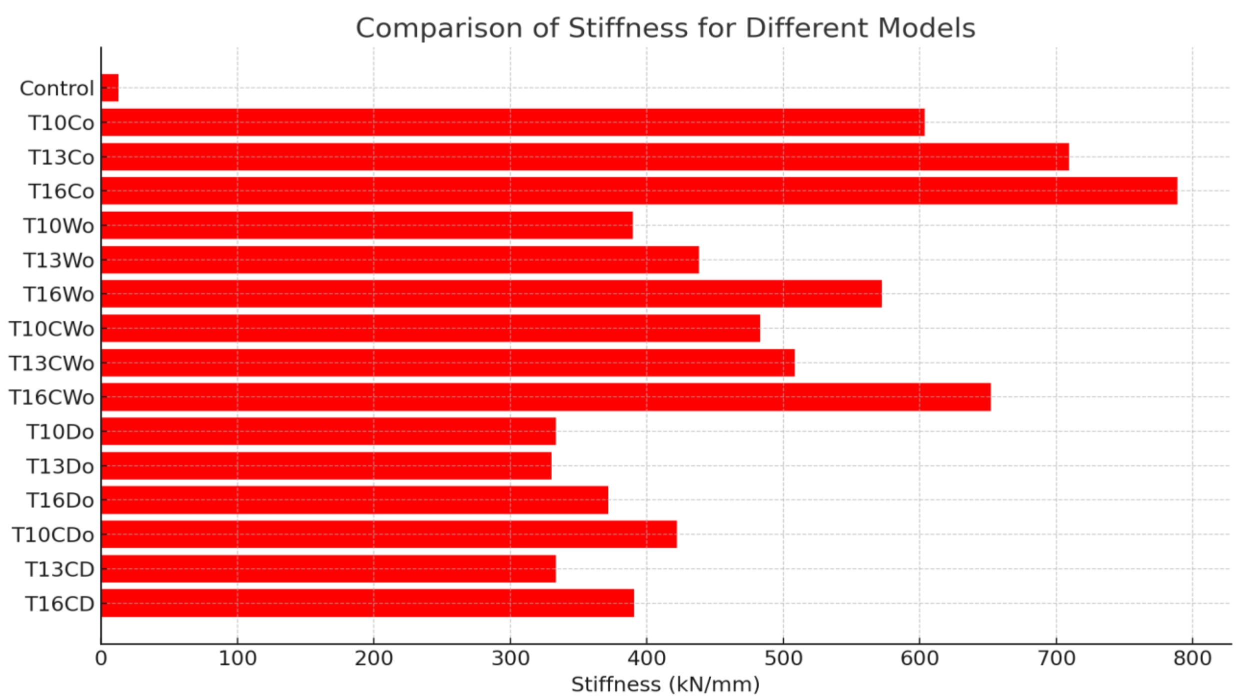

Figure 5.
Comparison of Stiffness for Different Composite Shear Wall Models.

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On the other hand, models with openings showed reduced stiffness. For example, T10Wo (thickness = 10 mm with window opening) demonstrated a stiffness of 389.77 kN/mm, which is 30.81 times that of the control model. The presence of openings results in reduced material continuity, leading to lower resistance to deformation. This result is consistent with previous studies, which have shown that openings in structural plates compromise their stiffness due to the loss of material in the critical load-bearing areas [18].

The stiffness of the structure is its resistance to deformation. The use of composite steel shear walls is one way to increase the stiffness of the structure against lateral forces and prevent damage to it Moradi and Khalilzadeh Vahidi [11] and Hatami and Sehri [19]. In this section, the factors affecting the stiffness of the frame with composite steel shear walls are examined. The stiffness of the numerical samples is shown in Table 3. Increasing the thickness in the samples without openings and samples with window openings had a great effect on increasing the stiffness of the structure, but in the sample with a door opening it had a small effect on increasing the stiffness of the structure.

The lowest stiffness was attributed to the samples with door openings without concrete cover, and the highest stiffness was attributed to the samples without openings and with reinforced concrete cover. Stiffness refers to the material's resistance to deformation under load, and as the plate thickness increases, stiffness increases significantly. The added covering also increases the stiffness of the structure by enhancing its ability to resist dimensional changes under pressure. This improvement in stiffness can have a significant impact on the stability of the structure, as studies show that materials with higher stiffness exhibit better resistance under various conditions [17].

4.4. Dissipated Energy

As shown in Figure 6 and Table 3, the energy dissipated by the control model is 145106.51 kN.mm, and again, significant improvements were seen in the models with increased thickness and covering. For instance, the T16Co model absorbed 1117865.68 kN.mm, which is 7.7 times more than the control model. This increase in energy dissipation is crucial because it indicates the model's ability to absorb and withstand dynamic loads or impacts, which is a critical feature in structural materials designed for resilience against shocks or vibrations.

Similar improvements in energy dissipation were observed in the T10Co model, which absorbed 1002989.74 kN.mm, approximately 6.91 times the energy absorbed by the control model. The addition of covering enhances the model's ability to dissipate energy by providing more material to absorb the forces acting on the structure. This is particularly important in applications where structures are exposed to dynamic or impact loading.

However, models with openings showed lower energy dissipation. For instance, T10Do (thickness = 10 mm with door opening) absorbed 303644.75 kN.mm, only 2.09 times the control model. This demonstrates that the presence of openings reduces the material's ability to absorb energy, likely due to the decreased cross-sectional area available to resist deformation and the potential for stress concentrations around the edges of the openings.

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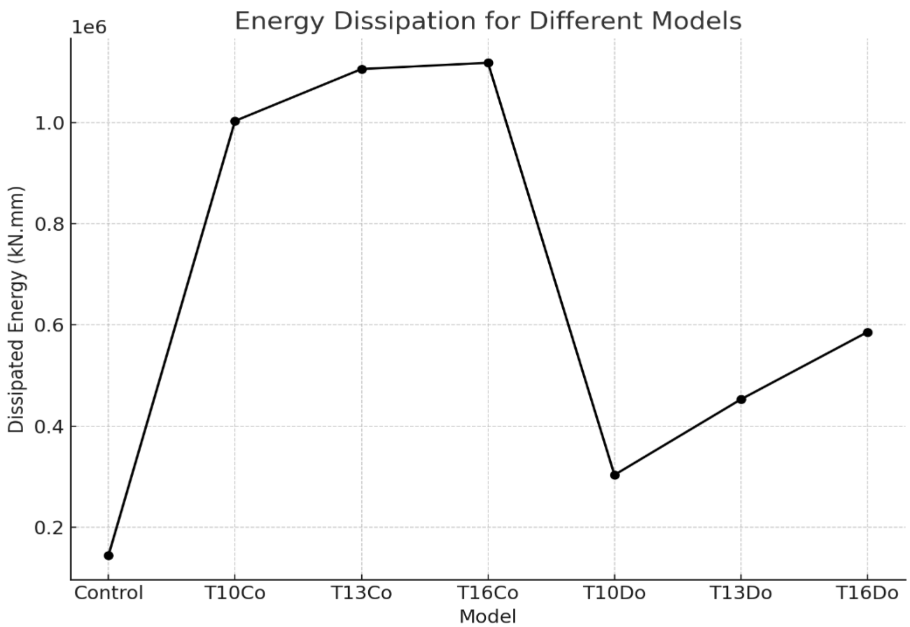

Figure 6.
Graph of Dissipated Energy for Composite Shear Wall Models

The dissipated energy is the area enclosed by hysteresis loops. The higher the dissipated energy of the structure, the less damage it will suffer during an earthquake [20]. Table 3 shows the dissipated energy values and the thickness-dissipated energy diagram for the numerical samples, respectively.

In other words, due to the delay of buckling of the steel plate by the reinforced concrete cover, the specimens with reinforced concrete cover have more dissipated energy compared to the specimens without reinforced concrete cover.

In the specimens with composite shear walls, the presence of an opening in the wall has reduced the dissipated energy, although the amount of reduction is greater in the specimens with door openings, while in the specimens without reinforced concrete cover, the presence of an opening has a smaller effect on reducing the dissipated energy. Energy dissipation is the ability to absorb the deformations caused by external loading. As shown by the results, increasing the plate thickness and adding covering improves the ability to absorb energy, reducing the likelihood of failure due to excessive loading or impact. With these improvements, the material becomes more capable of absorbing and converting energy instead of failing under stress. These results support previous studies that confirmed enhanced structures can absorb more energy before any damage occurs [17].

5. Conclusion

The conducted investigations show the behavior of the composite steel shear wall well. The obtained results showed that the system mentioned in the previous chapter has a suitable seismic behavior. The most important results of the effects of the percentage and type of openings, the thickness of the steel sheet, and the presence or absence of reinforced concrete cover on the steel sheet on the behavior of the composite steel shear wall under the analyzed conditions are:

- The hysteresis diagrams of numerical models indicate that the addition of concrete cover and an increase in plate thickness improve the structural performance by enhancing energy dissipation and delaying failure mechanisms like buckling.

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- The presence of concrete cover significantly improves the ultimate load capacity of the composite shear walls, especially when the wall is exposed to lateral loads. It helps in delaying the failure of the steel plate by controlling buckling and improving load distribution.
- Increasing the plate thickness enhances the ultimate load capacity, stiffness, and energy dissipation capacity. Models with thicker steel plates perform better under lateral loads and show a higher capacity to withstand dynamic forces before failure.
- The effect of openings, particularly door openings, reduces the structural performance by decreasing the effective area of the shear wall and concentrating stress around the edges. This leads to lower ultimate load capacity, stiffness, and energy dissipation, especially when no concrete cover is applied.
- Models with windows exhibit better performance than those with door openings, suggesting that smaller openings have less impact on the structural integrity.
- The stiffness of the models is directly influenced by plate thickness and concrete cover. Thicker plates and concrete cover significantly increase the stiffness of the structure, improving its ability to resist deformation under load.
- The dissipated energy is a critical indicator of the material's ability to absorb dynamic loads. Models with concrete cover and increased plate thickness show a higher energy dissipation capacity, reducing the risk of failure under earthquake-like conditions or dynamic loads.
- The overall structural performance improves with the application of concrete cover, demonstrating the importance of composite materials in enhancing resilience to dynamic forces.

6. Recommendations

- Concrete cover should be added to structures with openings to improve structural performance.
- Increasing steel plate thickness is an effective strategy to improve load-bearing capacity and stiffness.
- The design of structures with openings should be carefully considered to minimize their impact on structural performance.

Transparency:

The author confirms that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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