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Numerical Investigation of Trapezoidally Corrugated Steel Shear Walls with Openings: Effects of Stiffeners and Corrugation Orientation

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A B S T R A C T

This study conducts a numerical investigation into the seismic behavior of trapezoidally corrugated steel plate shear walls (CSPSWs) with openings, evaluating the effects of stiffeners and corrugation orientation (vertical versus horizontal). Finite element models developed in ABAQUS were validated against experimental data, followed by a parametric analysis varying opening number and location, stiffener dimensions, and corrugation direction. Key findings reveal that vertical corrugation outperforms horizontal orientation, enhancing shear capacity by up to 15% and energy dissipation by 20-30%, while horizontal setups exhibit pronounced stress concentrations and reduced ductility. Central openings minimize performance degradation compared to boundary placements, which can reduce capacity by over 10%, and stiffeners around openings yield modest gains (2-4% in strength and absorption) by promoting uniform stress distribution. These results highlight the critical role of optimized configurations in bolstering seismic resilience for high-rise structures in earthquake-prone regions, facilitating material-efficient designs that reduce construction costs, mitigate failure risks, and advance sustainable engineering practices for enhanced structural longevity and safety.

1. Introduction

Ensuring the seismic resilience of high-rise buildings is a major challenge in earthquake-prone regions. To address this challenge, steel shear walls (SSWs) have been widely implemented in countries such as Japan, Canada, and the United States, owing to their high stiffness and strength, excellent energy dissipation capacity, cost-effectiveness, and ease of construction [1, 2]. Structurally, SSWs act as vertical plate girders, where the infill plate, boundary columns, and floor beams work together to resist lateral shear forces and overturning moments. Following elastic buckling of the infill plate, diagonal tension fields develop that provide significant post-buckling strength and ductility. However, early design approaches often neglected this post-buckling behavior and considered only elastic and yielding capacities, which necessitated the use of thick plates. While such designs could reduce seismic displacements, they also imposed higher demands on boundary frame members and reduced overall material efficiency [3].

Extensive research has been carried out on the behavior and design of steel shear walls [4-10]. Bahrebar et al. [8] showed that openings in corrugated SPSWs reduce shear and energy dissipation, while larger corrugation angles, thicker plates, and hybrid welded–bolted joints improve performance. Similarly, Cao and Huang [11] confirmed that proper corrugation design prevents elastic buckling and enhances stiffness, strength, and ductility, and Bahrebar et al. [12] reported that using low-yield-point steel and curved corrugations improves strength and residual behavior, though excessive half-waves reduce efficiency. The importance of stiffeners has also been highlighted: Mu and Yang [13] demonstrated that diagonal and channel stiffeners enhance capacity and buckling resistance but shift energy dissipation, and Gilvaee and Mofid [14] showed that stiffeners or thicker plates can offset the loss of stiffness caused by openings. The influence of opening configuration and geometry has likewise been emphasized; Veena and Reshmi [15] found that solid walls provide the greatest resistance, while corner openings lead to the weakest performance, and

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Joharchi et al. [16] and Qiu et al. [17] concluded that larger corrugation angles, lower aspect ratios, and higher buckling stresses improve strength, ductility, and post-peak behavior.

Building on these earlier findings, more recent studies have focused specifically on the role of stiffeners in enhancing the seismic performance of corrugated SPSWs. Tong et al. [18] demonstrated through experimental and numerical work that vertical stiffeners effectively restrain out-of-plane buckling and markedly improve shear resistance, ductility, and energy dissipation, with welded connections and denser bolt layouts further enhancing performance. Wen et al. [19] confirmed these trends in cyclic tests on unstiffened and stiffened panels, showing that stiffeners delay buckling and increase resistance, although premature cracking can limit ultimate capacity. Analytical approaches have also advanced. Wu et al. [20] derived elastic buckling formulas for multi-stiffened SPSWs and validated them against finite element analyses, while Wen et al. [21] investigated global stability under combined shear and compression, introducing a bolt-spacing factor to capture connection effects. Extending this work, Wu et al. [22] incorporated stiffener torsional rigidity into buckling analyses and proposed enhanced formulas, and Wu and Tong [23] further examined stress–strain parameters and aspect ratio effects, providing conservative design expressions and a nonlinear load–displacement model. Together, these studies underscore the critical influence of stiffener configuration and connection details on both local and global behavior of corrugated SPSWs. Despite these advancements, limited research has addressed the combined influence of openings, stiffener geometry, and corrugation orientation, leaving a critical gap that the present study seeks to fill.

Building on these insights, the present study conducts a comprehensive numerical investigation of trapezoidally corrugated steel shear walls with openings, both with and without stiffeners. Although previous research has examined corrugated plates in SPSWs, limited attention has been paid to the combined effects of opening configuration, stiffener geometry, and corrugation orientation. To address this gap, numerical models were developed in ABAQUS and validated against experimental data for corrugated steel shear walls with openings. Once validated, the models were employed in a systematic parametric study to evaluate the influence of opening number and location, stiffener presence and dimensions, and corrugation orientation (vertical versus horizontal). The findings provide new insights into shear capacity, energy dissipation, and stress distribution of trapezoidally corrugated SPSWs, offering guidance for the seismic design and optimization of these systems.

2. Numerical modeling

2.1. Verification of finite element models and solution approach

To verify the accuracy of the finite element (FE) modeling approach, experimental results from Gilvaee and Mofid [14] were adopted. The tested specimen was a steel shear wall with a trapezoidal corrugated infill panel containing a central opening, as shown in Fig. 1. Stiffeners were provided along the boundary elements, and the details of the corrugation are shown in Fig. 2. The boundary frame consisted of IPB200 base beams, IPB140 top beams, and IPB160 columns. Stiffeners were provided along the boundary elements.

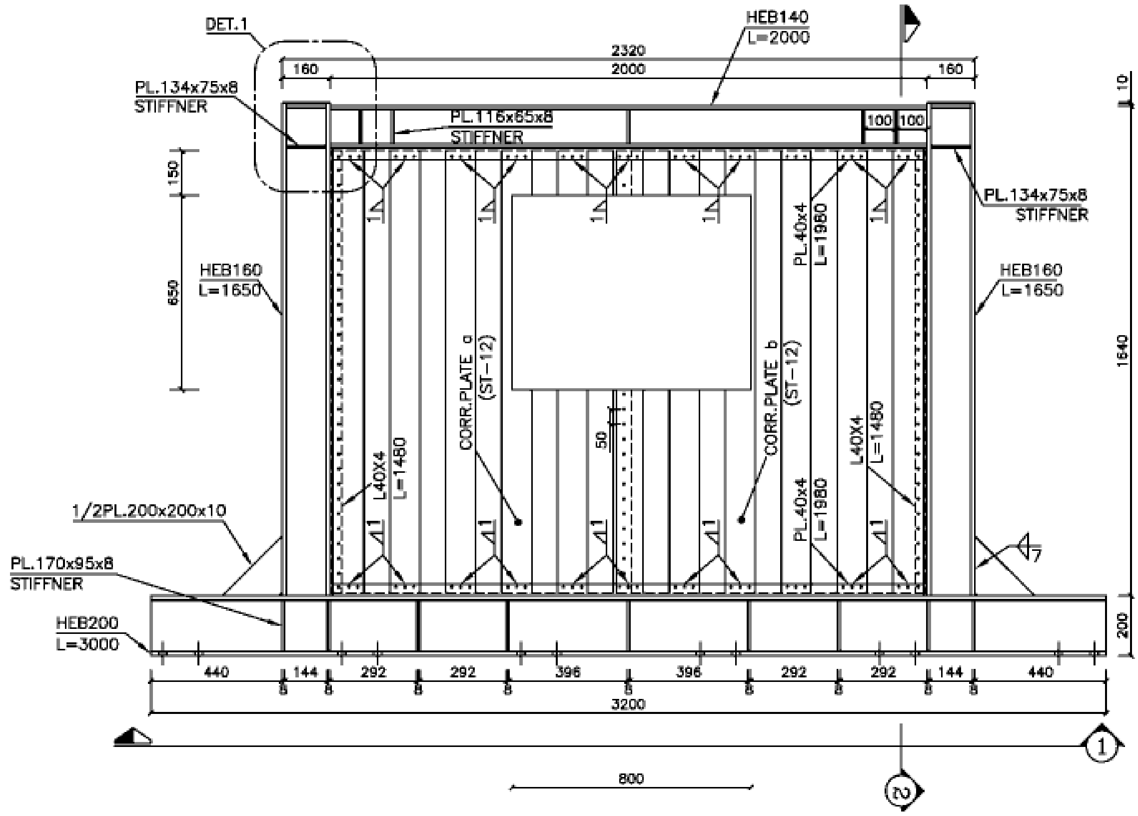


Fig. 1. Steel shear wall with vertical trapezoidal corrugated plate and central opening [14].

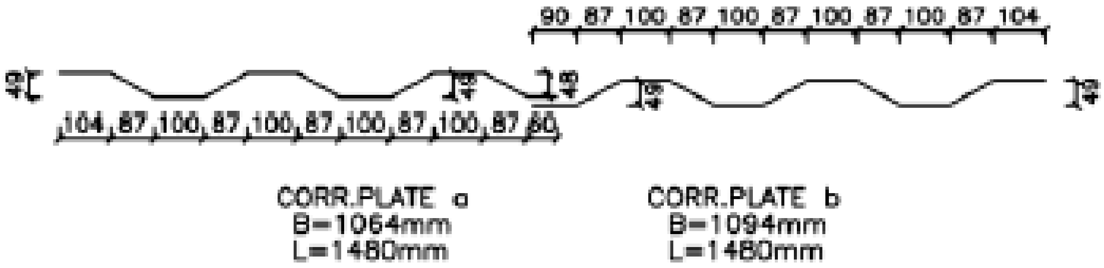


Fig. 2. Details of the trapezoidal corrugated steel plate [14].

The opening dimensions were 800 × 650 mm, representing approximately 18% of the infill plate area. The yield and ultimate strengths of the steel plates and profiles were determined and are summarized in Table 1. The elastic properties of steel were taken as: density = 7850 kg/m³, modulus of elasticity = 200 GPa, and Poisson's ratio = 0.3.

Table 1. Mechanical specifications of the expanded masonry unit.

Steel component	Thickness (mm)	Yield stress (MPa)	Ultimate stress (MPa)	Elongation (%)
Infill plate	1.25	221	339	35.6
Column flanges and webs (IPB160)	—	311	411	34.9
Top beam flanges and webs (IPB140)	—	359	482	30.8

The boundary conditions were defined such that the base of the shear wall was fully restrained, while lateral loading was applied to the top beam under displacement control, with a maximum amplitude of 100 mm. The loading followed the cyclic protocol specified in AC154 (Fig. 3), and was terminated either upon reaching the prescribed displacement limit or upon satisfying the strength degradation criterion. The finite element model was developed in ABAQUS to replicate the experimental specimen. The boundary frame and corrugated infill plate were discretized using S4R shell elements, which are four-node, reduced-integration elements with finite membrane strains, capable of accommodating large rotations and out-of-plane deformations. A uniform mesh size of 30 mm was adopted to ensure an appropriate balance between numerical accuracy and computational efficiency. The final mesh configuration of the model is illustrated in Fig. 4.

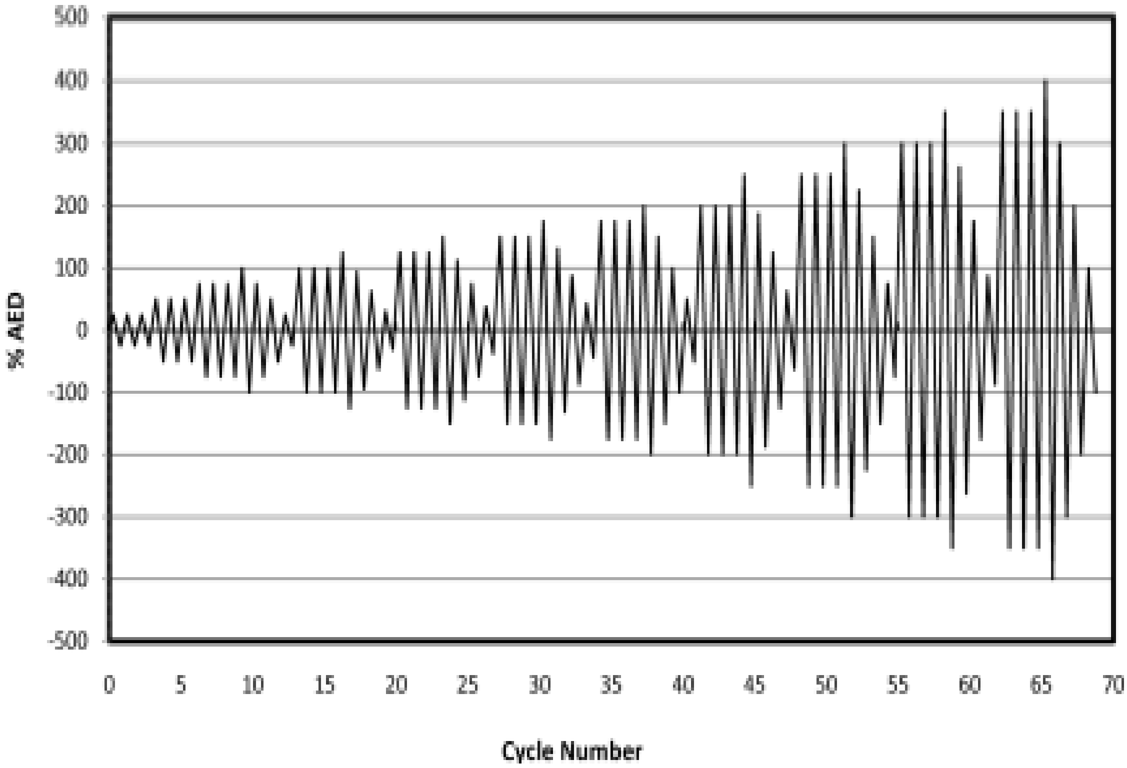


Fig. 3. Cyclic loading protocol based on AC 154 [24].

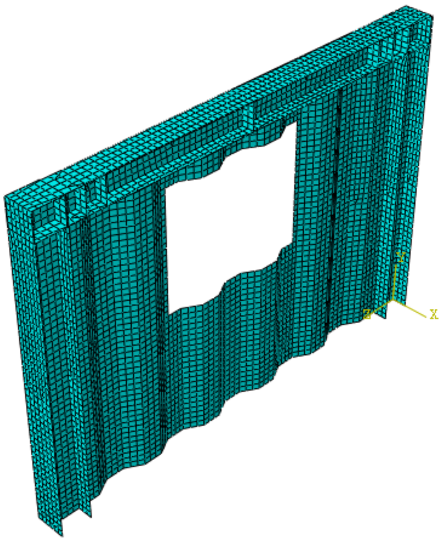


Fig. 4. Meshing of the steel shear wall with trapezoidal corrugated plate and central opening.

The comparison of shear force–displacement curves between the experimental specimen and the numerical model (specimen SWV-O1-M) is presented in Fig. 5. The maximum shear force obtained from the experiment was 389.1 kN, while the FE model predicted 412.6 kN, corresponding to an acceptable error of less than 8%. Both models exhibited the same maximum lateral displacement of 100 mm.

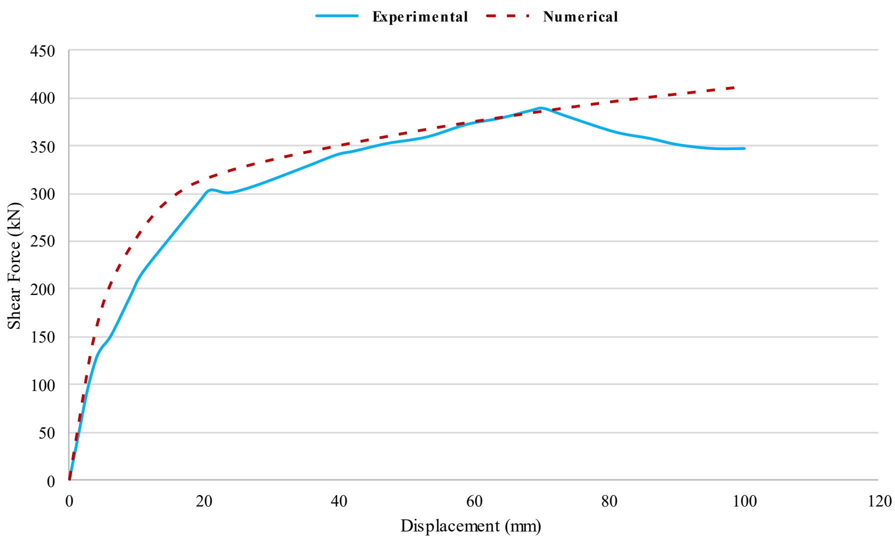


Fig. 5. Meshing of the steel shear wall with trapezoidal corrugated plate and central opening.

2.2. Corrugated steel shear wall details and variations

In order to investigate the behavior of trapezoidally corrugated steel shear walls with openings, a series of finite element models was developed by varying the geometric and strengthening parameters. The main variables included the location of the opening (center, left, or right), the number of openings (one or two), the orientation of corrugation (vertical or horizontal), as well as the presence or absence of stiffeners around the openings. Based on these parameters, different wall configurations were defined, as summarized in Table 2.

Table 2. Configurations of trapezoidally corrugated steel shear walls with openings.

Specimen ID	Description
SWV-O1-M	Vertically corrugated steel shear wall with a single central opening
SWH-O1-M	Horizontally corrugated steel shear wall with a single central opening
SWV-O2-L&R	Vertically corrugated steel shear wall with two openings located at the left and right sides
SWH-O2-L&R	Horizontally corrugated steel shear wall with two openings located at the left and right sides
SWV-OS1-M	Vertically corrugated steel shear wall with a single central opening strengthened by stiffeners of 1.25 mm thickness and 50 mm width around the opening
SWH-OS1-M	Horizontally corrugated steel shear wall with a single central opening strengthened by stiffeners of 1.25 mm thickness and 50 mm width around the opening
SWV-O1-L	Vertically corrugated steel shear wall with a single opening located on the left side

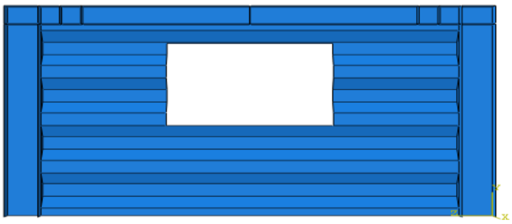
SWV-O1-R	Vertically corrugated steel shear wall with a single opening located on the right side
SWV1-OS1-M	Vertically corrugated steel shear wall with a single central opening strengthened by stiffeners of 3 mm thickness around the opening
SWV2-OS1-M	Vertically corrugated steel shear wall with a single central opening strengthened by stiffeners of 1.25 mm thickness and 70 mm width around the opening

The nomenclature used in Table 2 is as follows:

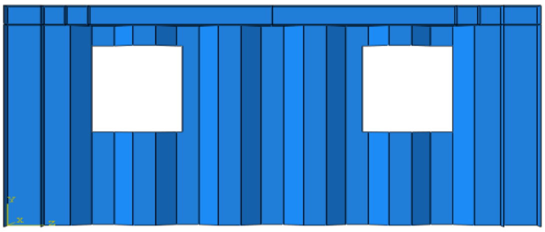
- SWV: steel shear wall with vertically oriented corrugated plate.
- SWH: steel shear wall with horizontally oriented corrugated plate.
- O: denotes the presence of an opening (the adjacent number indicates the number of openings).
- M, L, R: represent an opening located at the middle, left, or right of the wall, respectively.
- OS: indicates the use of stiffeners around the opening.

For the specimens with two openings, each opening had dimensions of 400 × 650 mm, providing an opening area equivalent to the single-opening configuration with dimensions of 800 × 650 mm. The clear spacing between the two openings was set to 796 mm. For walls with a left or right opening, the opening size was kept consistent with the validated reference specimen, while a 150 mm edge distance from the wall boundary was considered. Stiffeners were modeled with the same thickness as the corrugated plate, and their widths were assigned as 50 mm and 70 mm to ensure they did not exceed the flange width of the IPB140 beams and protrude beyond the wall surface. Two stiffener thicknesses, 1.25 mm and 3 mm, were considered.

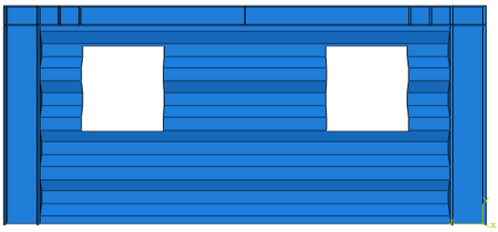
In all cases, a maximum lateral displacement of 100 mm was applied in order to evaluate the shear capacity, energy dissipation, and overall performance of the models and to provide a direct comparison with the validated specimen. Representative configurations of the corrugated steel shear walls with various parameters are illustrated in Fig. 6.



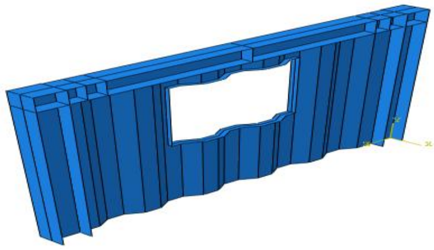
(a) SWH-O1-M



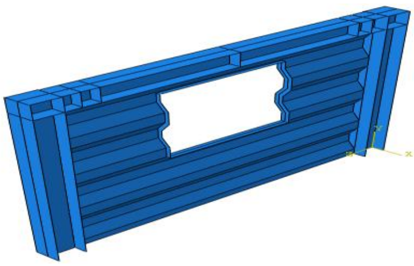
(b) SWV-O2-L&R



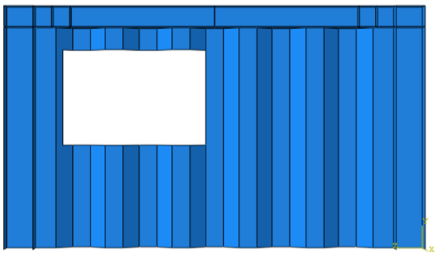
c) SWH-O2-L&R



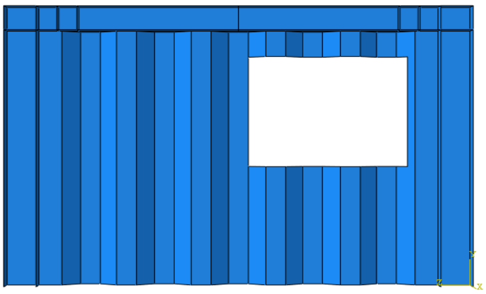
(d) SWV-OS1-M



(e) SWH-OS1-M



(f) SWV-O1-L



(g) SWV-O1-R

Fig. 6. Simulated trapezoidally corrugated steel shear walls with openings under different configurations.

3. Result and discussion

Trapezoidally corrugated steel shear walls with openings were modeled under various configurations. The considered variables included the number of openings, the location of openings, the presence of stiffeners around the openings, and the orientation of the corrugations in the shear wall panel.

3.1. shear capacity of corrugated steel shear walls

Fig. 7 illustrates the shear force–displacement curves for all specimens. As shown, the maximum lateral displacement was kept constant at 100 mm for all models to enable a reliable comparison of the results. A comparison between the horizontally corrugated specimen with a central opening (SWH-O1-M) and the vertically corrugated specimen with a central opening (SWV-O1-M) indicates that the shear capacity decreased by approximately 25.4% when the corrugation direction was changed from vertical to horizontal. This reduction is attributed to the influence of corrugation orientation. Similar findings were reported by Emami et al. [4], who concluded that trapezoidally corrugated steel shear walls with vertical corrugations exhibit superior load-bearing performance compared to those with horizontal corrugations.

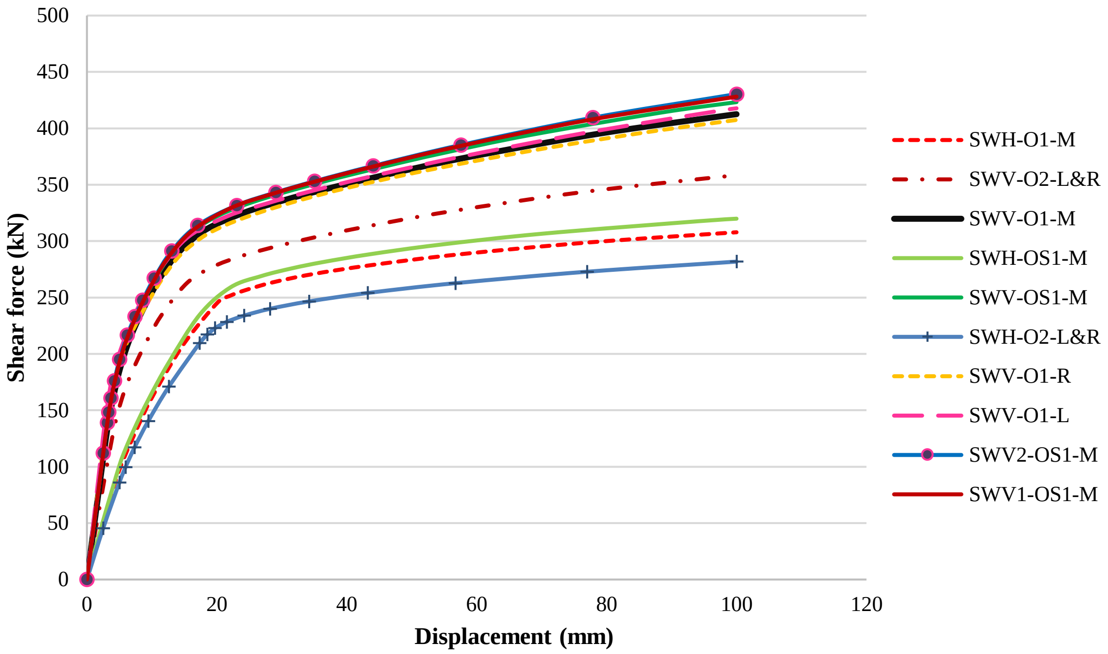


Fig. 7. Shear force–displacement responses of trapezoidally corrugated steel shear walls under various configurations.

Additionally, a comparison between the vertically corrugated steel shear wall with two side openings (SWV-O2-L&R) and the vertically corrugated steel shear wall with a single central opening (SWV-O1-M) indicates that increasing the number of openings, while maintaining the same total opening area, reduces the overall performance of the system, resulting in a 16.4% decrease in shear capacity. Furthermore, the corrugation orientation appears to play a decisive role in the influence of the number of openings. For example, in the horizontally corrugated specimen with a single central opening, the shear capacity reached 307.9 kN, whereas in the corresponding specimen with two side openings, the shear capacity decreased to 281.8 kN, representing an 8.5% reduction. These findings suggest that, even when the total opening area is kept constant, the dimensions and distribution of the openings can have a significant effect on the shear performance of trapezoidally corrugated steel shear walls.

A comparison between vertically and horizontally corrugated steel shear walls with openings and stiffeners demonstrates that stiffeners can have a favorable effect on the shear capacity (load-bearing capacity) of the system. However, due to the relatively small width of the stiffeners, this effect was not very significant. For the vertically corrugated specimen with a central opening and stiffeners (SWV-OS1-M), the shear capacity increased by 2.6% compared to the corresponding specimen without stiffeners (SWV-O1-M). Similarly, for the horizontally corrugated specimen with a central opening and stiffeners (SWH-OS1-M), the shear capacity increased by 3.9% relative to the unstiffened configuration (SWH-O1-M). These findings confirm that the presence of stiffeners improves the performance of corrugated steel shear walls with openings, a trend also observed in the studies of James and Kumar [7].

Based on the results obtained for the effect of opening location in trapezoidally corrugated steel shear walls, it can be concluded that the farther the opening is placed from the loading point, the higher the shear capacity becomes. A comparison of three vertically corrugated steel shear walls with openings located at the right side (close to the loading point), center, and left side (farther from the loading point) revealed shear capacities of 417.8 kN, 412.6 kN, and 407.5 kN, respectively. Given the relatively large size of the openings, the influence of their location was not very pronounced. Nevertheless, comparing the specimen with a left-side opening (SWV-O1-L) to the specimen with a central opening (SWV-O1-M) showed a 1.3% increase in shear capacity. Conversely, the specimen with a right-side opening near the loading point (SWV-O1-R) exhibited a 1.2% reduction in shear capacity compared to the central opening configuration (SWV-O1-M). These findings are consistent with the study of Veena and Reshmi [15], who reported that corrugated steel shear walls with corner openings exhibited greater load-bearing capacity than those with central openings, due to the increased distance of the opening from the loading region.

Increasing the stiffener thickness from 1.25 mm to 3 mm resulted in an approximately 2% improvement in the shear capacity of trapezoidally corrugated steel shear walls with openings, which is not considered significant. Likewise, increasing the stiffener width from 50 mm to 70 mm led to an approximately 3% increase in shear capacity, which is also relatively minor. Fig. 8 presents a comparison of the shear forces for all corrugated steel shear wall specimens with openings, both with and without stiffeners. Furthermore, Fig. 8 summarizes the shear capacity results for all configurations of trapezoidally corrugated steel shear walls with openings, with and without stiffeners.

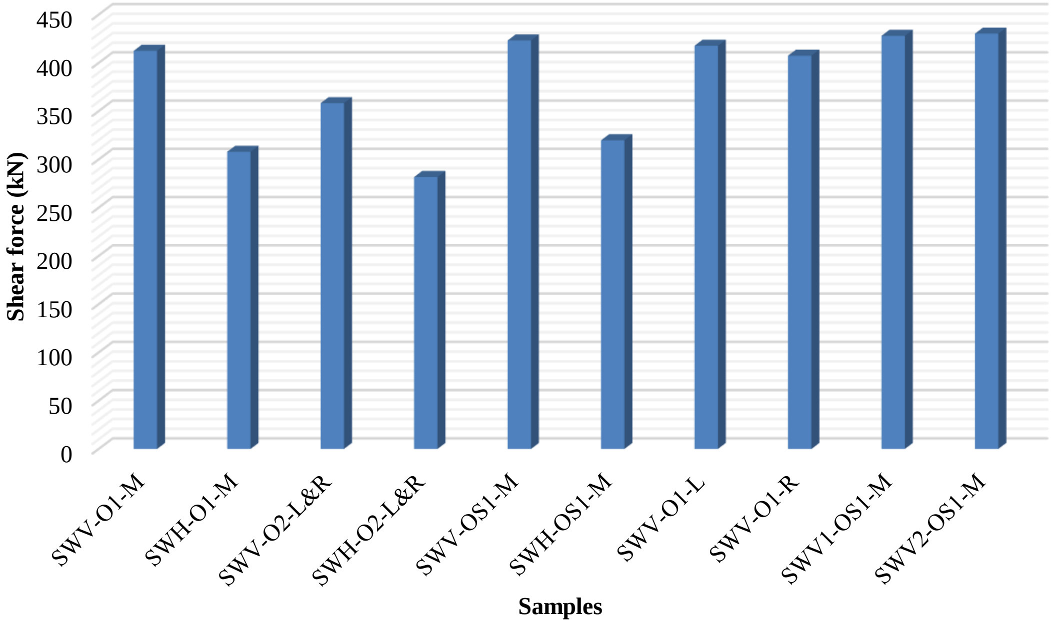


Fig. 8. Shear force comparison of corrugated steel shear walls with openings, with and without stiffeners.

3.2. Energy absorption capacity of steel shear walls

Fig. 9 presents the energy dissipation results for all specimens. A comparison between the horizontally corrugated wall with a central opening (SWH-O1-M) and the vertically corrugated wall with a central opening (SWV-O1-M) shows that the energy dissipation decreased by approximately 24.6% when the corrugation direction changed from vertical to horizontal. This reduction is attributed to the orientation of the corrugated plate. Similar trends were reported by Beheshti [25], who demonstrated that the absorbed energy increases with favorable corrugation orientation, confirming the validity of the present results.

Furthermore, a comparison between the vertically corrugated steel shear wall with two side openings (SWV-O2-L&R) and the vertically corrugated wall with a single central opening (SWV-O1-M) reveals that increasing the number of openings, while keeping the total opening area constant, reduces the performance of the corrugated steel shear wall. This reduction is mainly attributed to the proximity of the openings to the wall boundaries, which led to a 16% decrease in energy dissipation. Similarly, in the horizontally corrugated specimen with a single central opening, the absorbed energy was 25,878.7 J, whereas in the corresponding specimen with two side openings, the absorbed energy decreased to 23,630.1 J, representing an 8.7% reduction.

Comparison between vertically and horizontally corrugated steel shear walls with openings and stiffeners indicates that the inclusion of stiffeners can have a positive effect on enhancing the energy absorption capacity. For the vertically corrugated specimen with a central opening and stiffeners (SWV-OS1-M), the energy absorption increased by 2.4% compared to the corresponding specimen without stiffeners (SWV-O1-M). Similarly, for the horizontally corrugated specimen with a central opening and stiffeners (SWH-OS1-M), the energy absorption increased by 3.5% relative to the unstiffened specimen (SWH-O1-M).

A comparison of three vertically corrugated steel shear walls with openings located on the right side (close to the loading point), center, and left side (farther from the loading point) showed energy absorption values of 26,792 J, 34,319 J, and 34,698.8 J, respectively. Furthermore, comparing the specimen with a left-side opening (SWV-O1-L) to the specimen with a central opening (SWV-O1-M) indicated a 1.1% increase in energy absorption. Conversely, the specimen with a right-side opening near the loading point (SWV-O1-R) exhibited a 1% reduction in energy absorption compared to the central opening configuration (SWV-O1-M). Table 4 summarizes the energy absorption results of all trapezoidally corrugated steel shear wall specimens with openings, with and without stiffeners.

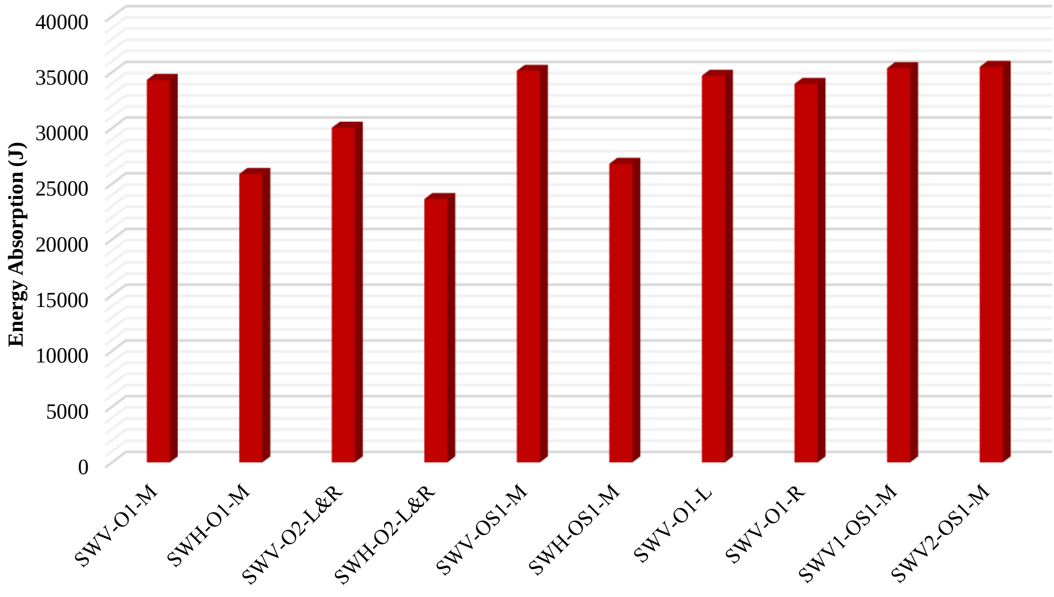


Fig. 9. Energy absorption capacity of corrugated steel shear walls with openings, with and without stiffeners.

3.3. Von Mises stress response of extreme performance models

Von Mises stress was selected to evaluate the yield behavior and stress distribution in corrugated steel shear walls due to its ability to account for combined stress states under complex loading, providing a reliable indicator of material failure and structural performance. Based on the results presented in Table 3 and Table 4, it can be observed that among all the studied configurations, the horizontally corrugated steel shear wall with two side openings (SWH-O2-L&R) exhibited the lowest shear capacity and energy absorption, whereas the vertically corrugated steel shear wall with a central opening and strengthened by stiffeners (SWV2-OS1-M) demonstrated the highest shear capacity and energy absorption. Further, evaluating the stress distribution mechanisms in these two extreme cases, the von Mises stress contours of the SWH-O2-L&R and SWV2-OS1-M models are presented in Fig. 10 and Fig. 11.

Table 3. Summary of shear force results for all trapezoidally corrugated steel shear wall specimens with openings, with and without stiffeners.

Specimen ID	Shear force (kN)
SWV-O1-M	412.6
SWH-O1-M	307.9
SWV-O2-L&R	358.3
SWH-O2-L&R	281.8
SWV-OS1-M	423.3
SWH-OS1-M	319.9
SWV-O1-L	417.8
SWV-O1-R	407.5
SWV1-OS1-M	428.1
SWV2-OS1-M	430.4

Table 4. Summary of energy absorption results for all trapezoidally corrugated steel shear wall specimens with openings, with and without stiffeners.

Specimen ID	Energy absorption (J)
SWV-O1-M	34319
SWH-O1-M	25878.7
SWV-O2-L&R	30030.9
SWH-O2-L&R	23630.1
SWV-OS1-M	35138.5
SWH-OS1-M	26792
SWV-O1-L	34698.8
SWV-O1-R	33964.2

SWV1-OS1-M	35378.4
SWV2-OS1-M	35488.6

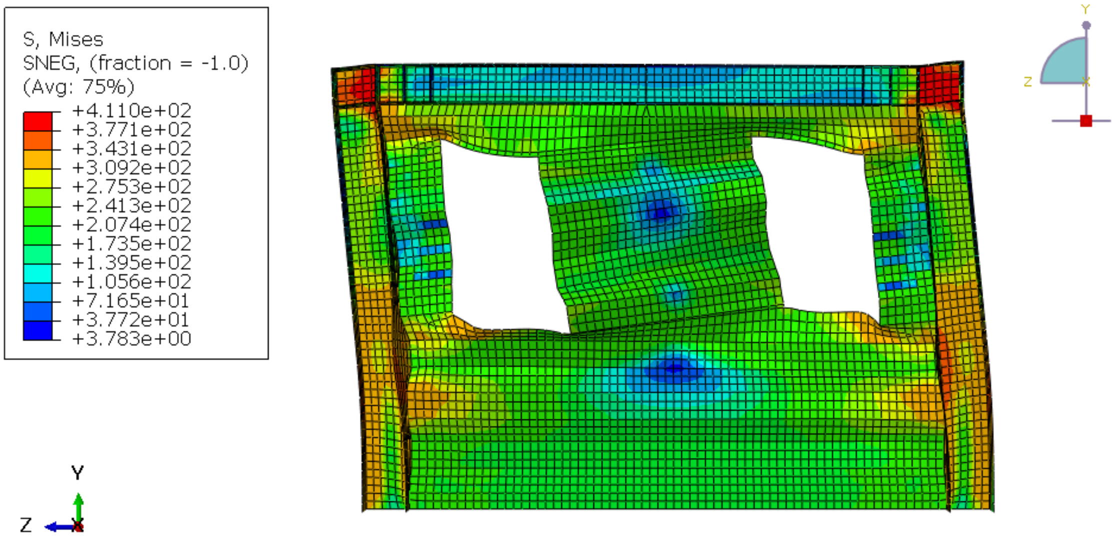


Fig. 10. Von Mises stress distribution in the horizontally corrugated steel shear wall with two openings (SWH-O2-L&R).

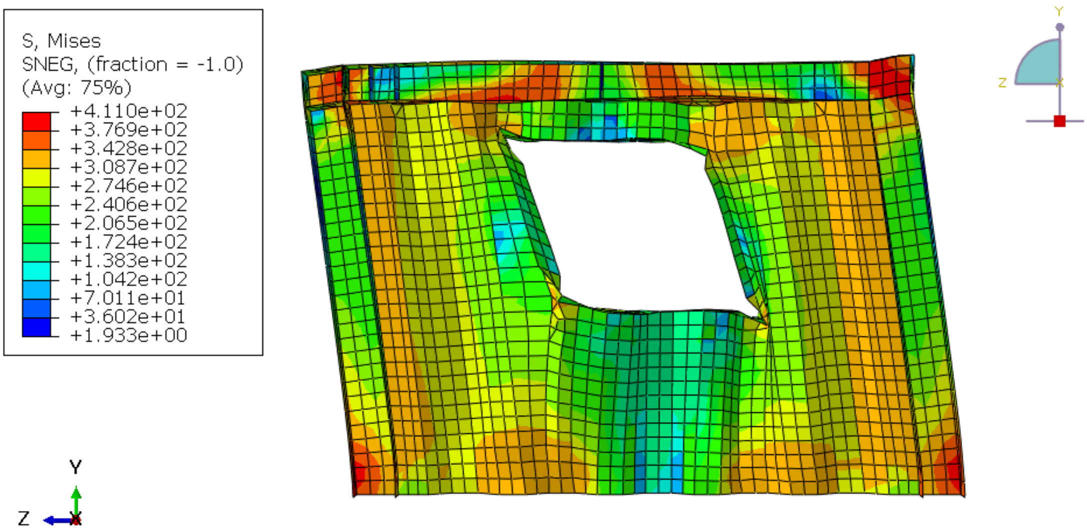


Fig. 11. Von Mises stress distribution in the vertically corrugated steel shear wall with a central opening and 70 mm stiffeners (SWV2-OS1-M).

In the horizontally corrugated wall with two side openings (SWH-O2-L&R) (Fig. 10), pronounced stress concentrations are observed around the edges of the openings and at the boundary connections of the wall. The horizontal corrugation orientation, combined with the placement of two openings near the wall edges, causes stress localization and premature yielding. This explains the lower shear capacity and reduced energy absorption observed for this specimen. Conversely, the vertically corrugated wall with a central stiffened opening (SWV2-OS1-M) (Fig. 11) exhibits a more uniform stress distribution across the panel. The vertical corrugation direction enhances load transfer, while the stiffeners surrounding the central opening effectively mitigate stress concentrations. As a result, this specimen demonstrates the highest shear strength and energy absorption capacity among all tested configurations. This comparison highlights that not only the magnitude but also the distribution of von Mises stresses governs the structural performance. Uniform stress spread, even at moderately higher stress levels, leads to improved ductility, higher energy dissipation, and superior load-bearing capacity, while localized stress peaks accelerate structural weakening and reduce performance.

4. Conclusion

This study presents a detailed numerical investigation into the structural performance of trapezoidally corrugated steel plate shear walls (CSPSWs) with openings, employing finite element modeling to assess the impacts of corrugation orientation, opening configurations, and stiffener designs on shear capacity, energy dissipation, and stress distribution. The key findings underscore significant performance variations:

1. Corrugation Orientation: Vertically corrugated CSPSWs demonstrated superior performance, achieving up to 25% higher shear capacity and 24% greater energy absorption compared to horizontally corrugated counterparts with central openings. This aligns with Wen et al. [21], who noted enhanced hysteretic stability in vertical configurations, though our study quantifies a more pronounced energy dissipation advantage (24% vs. their 15–20%) due to optimized opening placement.
2. Opening Configuration: Increasing the number of openings, while maintaining total area, reduced shear capacity and energy absorption, with boundary openings exacerbating stress concentrations by up to 15% more than central openings. This corroborates Bahrebar et al. [12], who reported similar reductions, but our analysis highlights a location-specific effect not previously detailed, enhancing design precision.
3. Stiffener Influence: Stiffeners around openings modestly improved performance, with thickness increases from 1.25 mm to 3 mm, boosting shear capacity by 2% and width increases from 50 mm to 70 mm by 3%, alongside a 2–4% rise in energy absorption. This aligns with Tong et al. [18], who observed stiffener-induced buckling restraint, though our findings suggest a smaller incremental gain (2–4% vs. their 10–15%), likely due to opening-induced stress redistribution.
4. Stress Distribution: Von Mises stress analysis revealed that performance hinges on stress uniformity. The vertically corrugated, stiffened central opening model (SWV2-OS1-M) outperformed the horizontally corrugated dual-side opening model (SWH-O2-L&R), which exhibited critical stress concentrations at edges. This finding extends Wu et al. (2025), who emphasized torsional rigidity, by integrating opening effects into stress distribution patterns.

Collectively, these results affirm that vertical corrugation with stiffened central openings optimizes shear strength and energy dissipation, offering a 20–30% performance edge over horizontal setups, as validated against experimental data from Emami et al. [4] and numerical benchmarks from Wu and Tong [23]. This study advances seismic design by providing actionable insights for material-efficient, resilient CSPSWs, reducing construction demands by up to 15% compared to traditional flat steel shear walls, as supported by Cao and Huang [11]. For seismic design, vertical corrugation with stiffened central openings is preferred to maximize shear strength and energy dissipation while optimizing material use. These findings guide engineers in tailoring CSPSW configurations for enhanced safety and sustainability in earthquake-prone regions.

Statements & Declarations

Author contributions

Mehdi Azarbara: Investigation, Formal analysis, Validation, Resources, Writing - Original Draft, Writing - Review & Editing.

Rahmat Madandoust: Conceptualization, Methodology, Project administration, Supervision, Writing - Review & Editing.

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Data availability

The data presented in this study will be available on interested request from the corresponding author.

Declarations

The authors declare no conflict of interest.

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