Journal of Sustainable Civil Engineering and Technology
e-ISSN: 2948-4294 | Volume 3 Issue 2 (September 2024), 22-33
https://joscetech.uitm.edu.my
https://doi.org/10.24191/jscet.v3i2.22-33

Optimizing Steel Plate Shear Wall Performance: Influence of Infill Plate Thickness and Connection Length to Vertical Boundary Elements

Saidatul Assyura Rosman[1], Mohd Zamri Ramli[2*], Muhammad Farhan Mohd Fisol[3], Nur Izzaty Zulhazmi[4]

[1,2,3]Engineering Seismology and Earthquake Engineering Research (eSEER), Faculty of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia

[4]Faculty of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia

*Corresponding author: mohdzamri@utm.my

Received: 24 March 2024 / Accepted: 20 June 2024 / Published online: 4 September 2024

Abstract

The Steel Plate Shear Wall (SPSW) is widely used as a lateral force resisting system in areas prone to high seismic activity. This is because of its exceptional ductility and ability to dissipate energy. Previous studies have indicated that disconnecting the infill plate from the Vertical Boundary Element (VBE) can decrease the demands on the column. The observed outcomes lead to a decline in both the energy dissipation capability and the lateral load-bearing capacity. The primary goal of this investigation is to mitigate stress on the column while concurrently reducing both the energy dissipation and lateral force capacities. To accomplish this, a partial connection will be established between the infill plate and the Vertical Boundary Element. Thus, the overarching objective of this research is to identify the optimal connection length that minimizes the demands on the column while simultaneously curtailing the reduction in energy dissipation and lateral force capacities. Using Abaqus software, twenty models with different infill plate thicknesses and lengths of connection between the infill plate and Vertical Boundary Element were analysed. To determine the optimal length of connection between the infill plate and Vertical Boundary Element, the energy dissipation capacity, lateral load capacity, and column stresses were evaluated and compared. The maximum dissipation of energy occurs at a connection length of 75% between the infill plate and Vertical Boundary Element and an infill plate thickness of 12 mm. In contrast, the greatest lateral load capacity is achieved at connection lengths of 50% between a 25 mm infill plate thickness and a Vertical Boundary Element weight of 25%. The column stress reaches its minimum value when the infill plate measures 20 and 25 mm, and it reaches its maximum value when the infill plate measures 6 mm and 12 mm. By increasing the thickness of the infill plate and minimizing its connection to the Vertical Boundary Elements, the column stress in Vertical Boundary Elements can be decreased, while simultaneously enhancing lateral load capacity and maintaining an adequate level of energy dissipation.

Keywords: Infill steel plate; Vertical boundary elements; Steel plate shear wall; Energy dissipation; Lateral load capacity; Column stress

1. Introduction

In structural engineering, the overarching goals of any design are to ensure safety, optimize cost-efficiency, and maintain functional reliability. Currently, the Steel Plate Shear Wall system, commonly known as SPSW, is increasingly recognized as a cutting-edge solution for effectively withstanding lateral loads in both newly constructed and existing buildings, especially those with multiple storeys. This system stands out for its pronounced rigidity and stiffness, which facilitate precise monitoring of structural movements, enable a ductile failure response, and offer a high capacity for energy absorption. Within steel constructions, the SPSW system is frequently deployed to counteract lateral forces such as wind or seismic loads, as well as horizontal shear stresses within individual storeys. Moreover, it serves as a dependable mechanism for resisting overturning moments that could compromise structural integrity. A pivotal element of the SPSW system is the thin infill plate, commonly referred to as the web plate. These plates are encompassed by boundary elements, comprising both vertical components, known as columns, and horizontal components, termed beams. The interconnection between these structural elements is achieved through bolted or welded joints, as shown in Figure 1. Recent academic research and studies have underscored the promising potential of SPSWs as a viable alternative to conventional systems, particularly in regions characterized by frequent and severe earthquake activity. This growing interest can be attributed to the remarkable energy-dissipating properties exhibited by the web plate, which continue to demonstrate effectiveness even under extreme cyclic loading conditions.

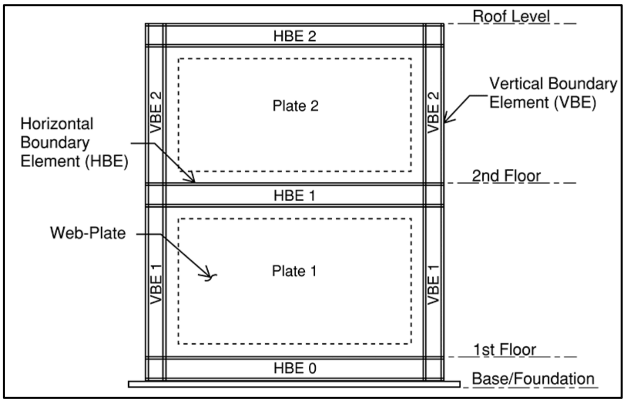


Figure 1. Steel plate shear wall system (Enright, 2014)

Countless lives have been tragically lost due to various disasters over the past few decades. Various seismic protection systems have been developed to enhance building performance and bolster reliability in the face of natural calamities. Nevertheless, a majority of these structural systems have failed to adequately address the issue of minimizing damages caused by the ineffective integration of ductility, stiffness, and overall structural performance. As an engineer research student, it is important to consider the impact of out of plane buckling of infill steel plate on the ability of the SPSW to effectively resist lateral load. The situation can be enhanced by incorporating stiffeners to increase the buckling capacity of the infill steel plate, which is influenced by its length.

Vertical boundary elements (VBE) need to be sufficiently strong to facilitate the yielding of the web plate and the development of a plastic hinge at the ends of the horizontal boundary elements (HBE). Due to the requirements of sustaining the pull in effect and resisting the overturning moment, VBEs have a large cross section. This is necessary to support the tension field of the web plate. Removing the link between the web plate and VBE resulted in the elimination of the pull-in force (Shekastehband et al., 2018). Despite this, the lateral load capacity and energy dissipation capacity experienced a decrease in the absence of a connection between the web plate and VBE, as observed in the study conducted by (Choi et al., 2009). Therefore, it is suggested to partially remove the link between the web plate and the VBE in order to reduce the impact on the lateral load capacity and energy dissipation capacity, as well as to reduce the strain on the VBE caused by the pull-in force on the web plate.

The ideal connection length between the infill plate and the Vertical Boundary Element (VBE) that effectively minimizes the bending moment and axial force exerted on the column remains undetermined. Furthermore, it is imperative to evaluate the effects on lateral load capacity, energy dissipation and ductility of the square Steel Plate Shear Wall (SPSW) when the connection between the infill plate and the VBE is not fully connected. This study aims to investigate the optimal connection length between the infill plate and the VBE. The primary objective is to reduce the axial force and bending moment experienced by the beam, all while maintaining the lateral load capacity, energy dissipation and ductility properties integral to the performance of the square SPSW.

2. Literature Review

Steel Plate Shear Walls (SPSW) represent an important form of Lateral Load Resisting System (LLRS) that present a multitude of performance benefits. These encompass their capacity to endure displacement, exhibit high elastic stiffness, and demonstrate consistent hysteresis behaviour (R. Vhatkar et al., 2018). The architectural composition of an SPSW includes vertical steel infill plates, which are strategically interconnected between beams and columns. These infill plates possess a singular storey height and span a single bay in width. Fabricated from A36 Steel, these plates are crafted from a material widely employed across diverse construction facets, ranging from columns and beams to decking and finishing components. Despite it is versatility, the ductility inherent to ASTM A36 Steel renders it unsuitable for applications requiring cables or reinforcement bars. On the other hand, the boundary elements are constructed from A992 steel, a prevalent structural steel variant extensively utilized in the construction sector. This steel variant is employed in crafting beams, expansive flanges, channels, plates, angles, and an assortment of other structural forms. Notably, A992 steel incorporates trace amounts of vanadium or columbium, in addition to copper, nickel, chrome, and molybdenum, enhancing its structural integrity and versatility.

The performance of Steel Plate Shear Walls (SPSW) is influenced by shear buckling and the subsequent formation of diagonal tension fields within the infill plate (Maleki et al., 2010). Chan et al. (2011) emphasize that infill panels are inherently stiff to counteract elastic shear buckling. SPSW stands out by offering high lateral stiffness as a viable alternative to bulkier reinforced concrete walls. Ductility, denoting a structure's capacity to deform without fracturing, plays a pivotal role. Structures with higher ductility can navigate inelastic zones and dissipate substantial energy. Moreover, extending the span length of the steel plate shear wall results in a notable enhancement in both ultimate shear strength and energy dissipation. However, this improvement is accompanied by a reduction in the system's ductility. A deterministic design technique has been introduced, wherein the target displacement ductility ratio (μt) serves as the design criterion (Gupta et al., 2009). Leveraging the ductility capabilities of SPSW systems proves to be highly effective. Energy wastage, often termed dissipation, refers to the loss of energy that does not transition to usable stores but instead dissipates into the environment. Energy dissipation systems, well-developed and rigorously tested, efficiently manage substantial energy dissipation (Santos Monteiro, 2011). To optimize energy dissipation in SPSW structures, it is essential for beams to yield before facing damage from columns and exhibiting ductile flexural damages. Implementing a "strong column - weak beam" design strategy effectively addresses these issues. This design principle entails reducing the bending moment capacity of beams while reinforcing columns to possess a higher bending moment capacity.

This term is crucial to structural engineering because it can be used to calculate the possible locations and amounts of bending that can happen when forces are applied. Steel links are responsible for transmitting three types of internal forces: axial force, shear force, and moment. Connections are commonly required to transmit multiple powers, and a structural steel link is often referred to as the primary load carried by the steel connection. Column axial requirements primarily arise from the need to withstand the moment of overturning, which can be significant in the case of multi-story SPSWs. The study found that stiffening the plate improved seismic performance, enhancing strength and energy dissipation, even when not meeting minimum column flexural stiffness requirement (He et al., 2022). The column axial requirements arise from the influence of the infill plate applying forces on the vertical component. These important SPSW column specifications will lead to the use of significant columns. This study demonstrated that central plate-to-column connections significantly enhance shear strength, with a 67% connectivity ratio nearly matching full connection strength, offering a more efficient design approach for steel plate shear walls (Yang et al., 2022). A standard steel plate shear wall (SPSW) has a structure of infill steel panels enclosed by vertical boundary elements (VBEs) on each side, and horizontal boundary elements (HBEs) above and below. SPSWs are commonly compared to cantilever vertical plate girders. If the VBEs deform excessively, the infill panel yield forces will not be able to anchor them (Bing et al., 2010). Non-uniform diagonal tension fields can be created by the VBEs, which can lead to inconsistencies in the design assumptions. However, previous research on SPSW was only concentrates on shear strength by varying connection conditions. This study to aims the most effective connection length between the infill plate and the column specifically in terms of reducing axial force and bending moment in the (VBE). In other hand, it is important to focus on energy dissipation, ductility, and stress distribution to provides a more holistic view of how partial connections impact the wall's behaviour.

3. Methodology

The square Steel Plate Shear Wall (SPSW) system has emerged as an innovative lateral load-resisting mechanism in building construction. This system comprises thin steel infill plates, commonly referred to as the web plates. These web plates are enclosed or bounded by boundary elements, which encompass both vertical components known as columns and horizontal components termed as beams, all interconnected through fixed connections. The boundary elements play a crucial role in preventing the steel plate from being subjected to excessive gravitational loads. The primary objective of implementing a steel plate shear wall is to counteract horizontal shear forces and to resist overturning induced by lateral loads. Consequently, due to these overturning moments, one vertical boundary element (VBE) experiences compressive forces while its counterpart undergoes tensile forces.

3.1 Models

The primary objective of this research is to determine the most effective length for the connection between the infill steel plate and the column in the context of a 4m tall square Steel Plate Shear Wall (SPSW). For the construction of the infill steel plate, A36 mild steel was employed, while the boundary elements were crafted using W14x176 beams and W14x257 columns, both fabricated from A36 mild steel. All SPSW models were securely fixed at their bases. A total of twenty models were developed, ensuring a fixed connection between the infill plate and the boundary. Variations were made in the spacing between the infill steel plate and the Vertical Boundary Element (VBE), as well as in the thickness of the infill steel plate. As shown in Figure 2, the example from Model A3 of the square SPSW demonstrates an infill plate connection ratio of 50% to the columns, originating from the center and extending with a complete connection to the beams. The connectivity ratio is computed by dividing the length of the connection line between the infill plate and the boundary elements by the overall length of the panel. Consequently, a conventionally fully connected steel plate shear wall achieves a connectivity ratio of 100%.

The SPSW models were subjected to lateral cyclic loading at their uppermost sections, with subsequent measurements taken of the lateral displacement of the SPSW and the stress experienced by the columns. Figure 3 shows the applied cyclic loading, adhering to the ATC24 - Guidelines for Cyclic Seismic Testing of Components of Steel Structures. The Finite Element Method (FFM) is a numerical technique that can be employed to resolve a wide range of engineering challenges, including those that are nonlinear, stable, transient, or linear (Rao, 2011). ABAQUS, one of the finite element method software packages, is widely recognized for its practicality in both academic and industrial research (Bathe, 1995). Additionally, finite element analyses of ductility, rigidity, and energy dissipation can be performed in ABAQUS. As a result, ABAQUS software is the optimal platform for this study, as numerous researchers in the past have utilized it.The square SPSW models underwent analysis using the ABAQUS software. The assessment of energy dissipation, involving the examination of the area encompassed by all loops in the hysteretic curve, and the determination of ductility, calculated as the ratio of the maximum lateral displacement to the displacement at yield, were performed using the data extracted from the hysteretic curve.

The ABAQUS finite element software was employed to meticulously mesh and model both the horizontal and vertical boundary components, in addition to the infill plate. This was achieved utilizing an 8-node reduced integrated shell element (S8R). To ensure greater accuracy in results and to optimize computational efficiency, the reduced integrated formulation was implemented. The dimensions of the infill plate were 19x19 cm. The steel employed was A36 mild steel, characterized by a Young's modulus (E) of 200 MPa and a Poisson's ratio of 0.3. The yield stress for the frame members stood at 385 MPa, whereas for the infill walls, it was 327 MPa. Consequently, the attributes of the twenty samples under examination are detailed in Table 1.

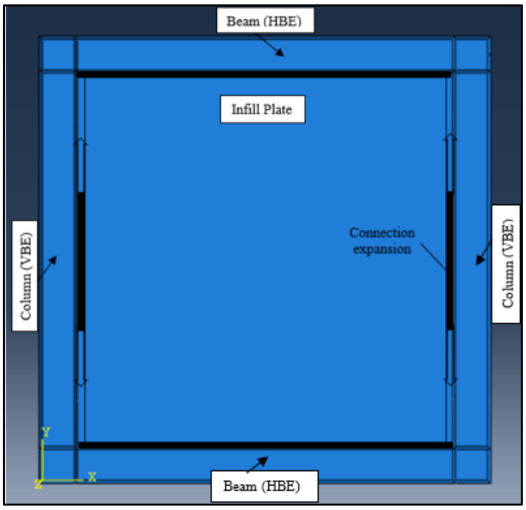


Figure 2. Square SPSW

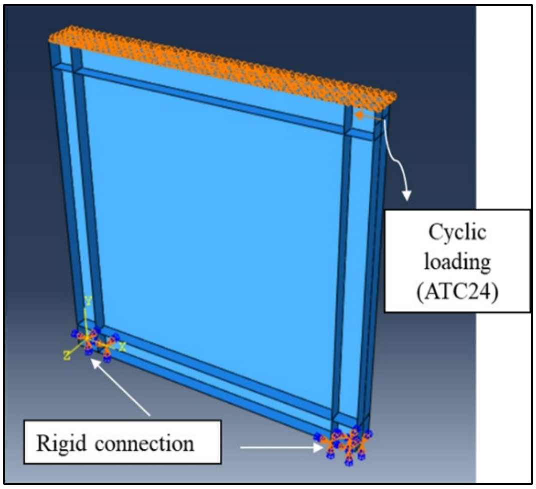


Figure 3. Loading and Boundary condition of Square SPSW

Table 1. The manipulated parameters of the SPSW models analysed

Model	Thickness of SPSW (mm)	Types Connection between Infill Plate to VBE	Connection detail of infill plate
A1	6	Fixed	Fully connected to column
A2	6	Fixed	75 percent connected to column
A3	6	Fixed	50 percent connected to column
A4	6	Fixed	25 percent connected to column
A5	6	Fixed	No connection to column
A6	12	Fixed	Fully connected to column
A7	12	Fixed	75 percent connected to column
A8	12	Fixed	50 percent connected to column
A9	12	Fixed	25 percent connected to column
A10	12	Fixed	No connection to column

Model	Thickness of SPSW (mm)	Types Connection between Infill Plate to VBE	Connection detail of infill plate
A11	20	Fixed	Fully connected to column
A12	20	Fixed	75 percent connected to column
A13	20	Fixed	50 percent connected to column
A14	20	Fixed	25 percent connected to column
A15	20	Fixed	No connection to column
A16	25	Fixed	Fully connected to column
A17	25	Fixed	75 percent connected to column
A18	25	Fixed	50 percent connected to column
A19	25	Fixed	25 percent connected to column
A20	25	Fixed	No connection to column

3.2 Test Verification

The model developed by Abdi and Abdoli Yazdi (2018) was used to validate the modelling process in this article. As shown in Figure 4, the findings of a study on the buckling behavior of a single-story, single-bay unstiffened SPSW with rigid beam-column connections were compared with the findings of the present study to validate under lateral loading. Various wall aspect ratios (L/h=1, 1.5, 2, 2.5, and 3) and infill plate thicknesses (tw= 3, 5 and 7 mm) were utilised in the SPSW.

The results in Table 2 show a satisfactory agreement between closest increment with maximum shear stress values in S12 and using a deformation scale factor of 1 obtained from the Abaqus analysis by validated data according to Rahim Abdi and Nader Abdoli Yazdi. The error rates for the different plate thicknesses of 3mm, 5mm, and 7mm are 1%, 2%, and 1% respectively.

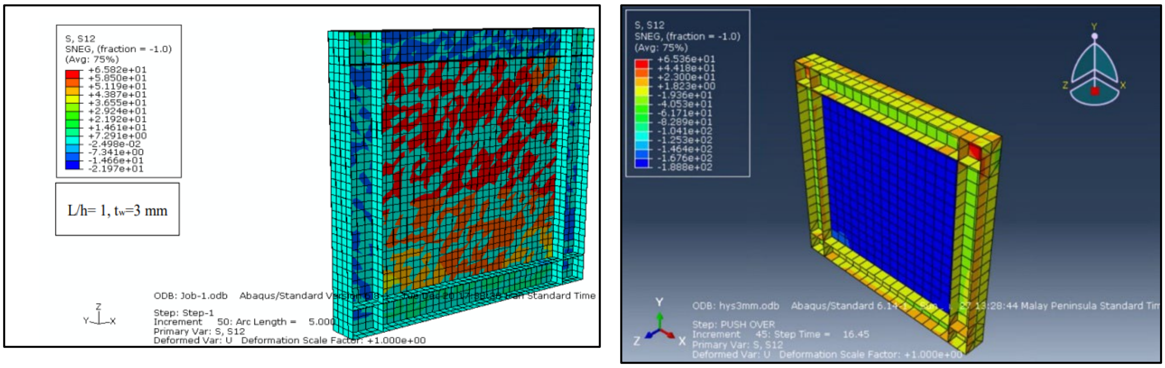


Figure 4. ABAQUS FE of SPSW system between model [9] and current research

Table 2. Comparison of maximum shear stress in square SPSW system with rigid connection between Abdi and Abdoli Yazdi (2018) and current study

Infill Plate Thickness (mm)	Shear Stress (ton/m2) (Abdi & Abdoli Yazdi, 2018)	Shear Stress (ton/m2) (Current Study)	Error Rate (%)
3	6582	6665	1
5	7102	7248	2
7	7424	7362	1

4. Results and Discussion

4.1 Hysteresis Behavior

The hysteresis curve results for models A6 to A10 are shown in Figure 5. This selection offers a more appropriate comparison for evaluating the extent to which the structural performance of the SPSW is affected by varying infill plate thicknesses and connection lengths. After examining the hysteresis curves of these models, it is clear that although the curves have similar forms, there are slight variations in the performance measures. More precisely, a reduction in the proportion of connections is associated with a slight increase in energy dissipation and ductility, as evidenced by the area contained by the hysteresis loops and the maximum displacement observed. While the enhancements may not be immediately evident based just on the curves, they are really significant when examining the total structural response to cyclic loads. Furthermore, the consistent symmetry seen in the hysteresis paths across all models indicates that the SPSWs were stable throughout cyclic loading, without any noticeable effect of shear buckling in the infill plates. The results show that the selected connection designs and material qualities successfully reduced shear buckling, even when the different connection was changed. The shear stress simulations of SPSW models with rigid beam-to-column connection was shown in Figure 6.

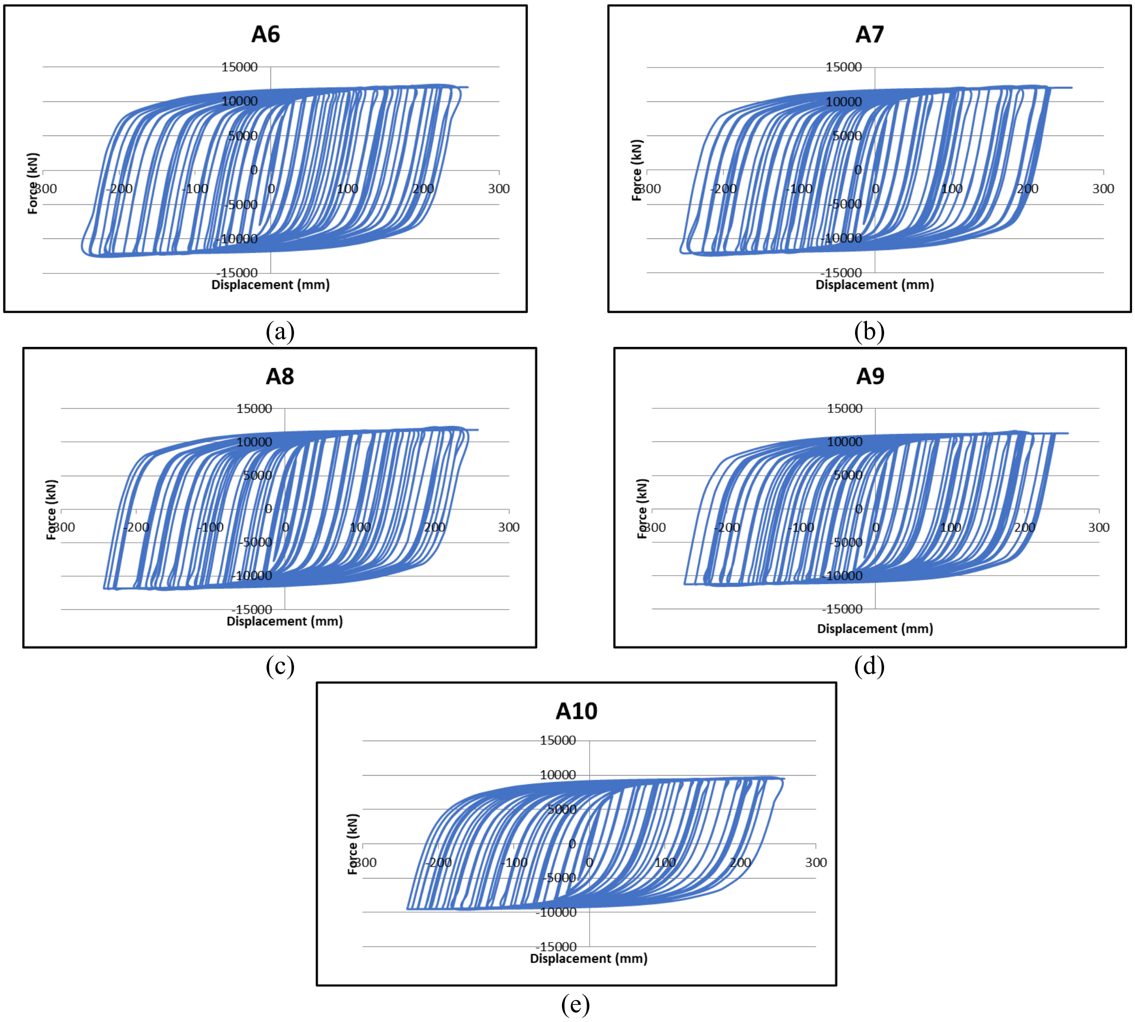
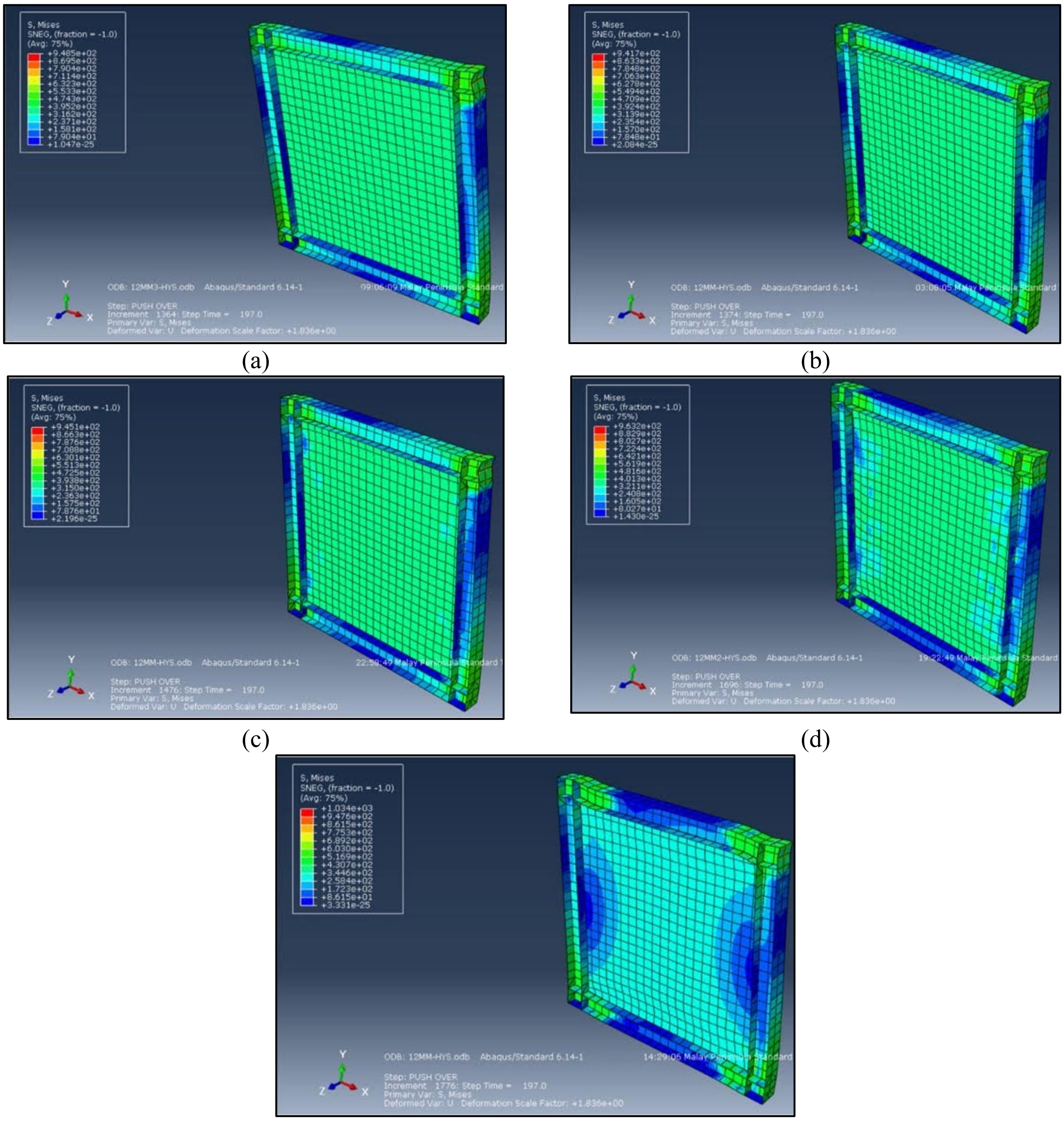


Figure 5. (a) Hysteretic curve for Model A6; (b) Hysteretic curve for Model A7; (c) Hysteretic curve for Model A8; (d) Hysteretic curve for Model A9; (e) Hysteretic curve for Model A10



(a) (b) (c) (d) (e)

Figure 6. Shear stresses simulation with the corresponding Von Mises stresss (a) Model A6; (b) Model A7; (c) Model A8; (d) Model A9; (e) Model A10

4.2 Energy Dissipation

The total energy dissipation for all models was calculated and presented in Table 3, and it was also graphically shown in Figure 7 based on the total area in the hysteresis loops. The study shows that infill plate thickness affects energy dissipation. Infill plates with thicknesses of 6 mm and 12 mm dissipated the most energy at 100% and 75% connection lengths. Above these lengths, energy dissipation stabilized. In contrast, energy dissipation rose with connection length for the 25 mm thick infill plate but subsequently declined and stayed constant beyond 50%. Results of infill plate stiffness and strength, energy dissipation patterns vary. Thicker infill plates, such 25 mm ones, are less flexible, which impacts energy dissipation through connection and infill contact. For infill plates thicker than 12 mm, such 25 mm, energy dissipation does not improve with longer connections due to their rigidity and less plasticity. Plastic deformation also depends on infill plate thickness. According to the stiffness, thicker infill plates have lower plastic deformation and different energy dissipation than thinner plates. This explains reason the 12 mm thick infill plate dissipated the most energy at connections larger than 16% and the 25 mm thick plate at connections less than 16%.

Table 3. Energy dissipation

Model	Energy Dissipation (kNm)	Model	Energy Dissipation (kNm)
A1	47.54	A11	28.31
A2	42.45	A12	32.07
A3	25.97	A13	38.13
A4	19.93	A14	35.29
A5	12.26	A15	39.52
A6	59.56	A16	32.20
A7	58.47	A17	31.07
A8	50.62	A18	31.66
A9	39.90	A19	34.82
A10	24.83	A20	38.44

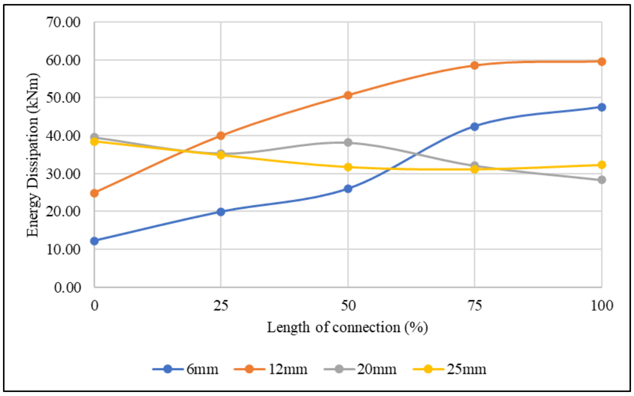


Figure 7. Energy Dissipation vs Length of connection of different models of SPSW

4.3 Lateral load capacity

The lateral load capacity is the maximum force that may be exerted on the SPSW model. The lateral load capacity values for all models were listed in Table 4 and graphed in Figure 8. The lateral load capacity increased as the connection length increased. The lateral load capacity reached its maximum value and became constant when the connection length reaches 25% for infill plates that are 20 mm and 25 mm thick. The lateral load capacity of the infill plate reached its maximum when the connection length was 50% for both the 6 mm and 12 mm thick plates. Thicker infill plate such as 20 mm and 25 mm infill plate are capable to withstand larger lateral load as its stress is smaller due to its larger cross-sectional area. Larger lateral load than the one applied to thinner infill plate is required to enable the 20 mm and 25 mm to reach ultimate stress. As a results, it has higher lateral load capacity. SPSWs typically collapse like plastic hinges at these maximum load capacities at the connection length values studied. Instead, the connection length and infill plate thickness interact to determine capacity, resulting in stable load capacities without collapse mechanisms. However, a basic mechanical model may estimate lateral load capacity based on connection ratios, but it must account for structural behaviour and failure mechanisms in the individual types.

The highest load capacity was achieved with infill plates of 20 mm and 25 mm thicknesses. Increasing the infill plate's thickness naturally boosts its stiffness, subsequently elevating the overall stiffness of the entire structure and, consequently, the lateral load capacity. The stiffness of the infill plate plays a pivotal role in enhancing the structure's lateral load capacity. A more rigidly constructed building can effectively minimize earthquake-induced damages. Based on these findings, a 20 mm thick infill plate is recommended to maximize lateral load capacity. Figure 8 illustrates that the lateral load capacity curves for the 20 mm and 25 mm thick infill plates are overlapped, while the 6 mm thick plate exhibits the lowest lateral load capacity.

Table 4. Lateral load capacity

Model	Force (kN)	Model	Force (kN)	Model	Force (kN)	Model	Force (kN)
A1	7732.28	A6	12134.78	A11	15978.60	A16	16008.93
A2	7695.11	A7	12084.56	A12	15981.55	A17	15982.10
A3	7574.18	A8	11855.65	A13	15954.37	A18	15992.79
A4	7260.23	A9	11270.24	A14	15681.84	A19	15941.56
A5	6367.40	A10	9493.37	A15	11672.65	A20	12432.13

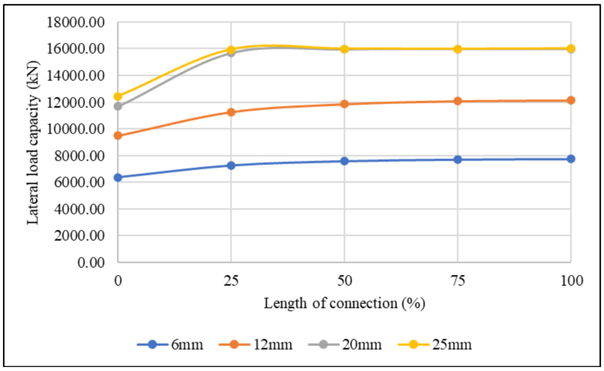


Figure 8. Lateral load capacity vs Length connection Infill Plate of different models of SPSW

4.4 Column Stress

The vertical component of the inclined tension field in the infill plate causes axial force in the column, resulting in the development of normal stress, which is calculated by dividing the axial force by the cross-sectional area of the column. The lateral cyclic load causes an overturning moment, resulting in the development of normal bending stress. The column stress values are presented in Table 5 and shown in Figure 9. Column stress remained almost constant throughout all connection lengths using a 12 mm infill plate. Both the 20 mm and 25 mm thick infill plates showed the minimum value of column stress at 50% of the connection length. As the length of the connection extended, the 6 mm thick infill plate also increased in thickness until it reached a constant value at a connection length of 50%. Figure 9 shows that the 6 mm and 12 mm thick infill plates had the highest column stress, whereas the 20 mm and 25 mm thick infill plates had the lowest column stress.

The differences in column stresses and energy dissipation trends in Figure 7 may be due to various factors. Energy dissipation is controlled by hysteretic behaviour and deformation, although column stresses are principally driven by axial forces and bending moments from infill plate contacts and applied loads.

Journal of Sustainable Civil Engineering and Technology
e-ISSN: 2948-4294 | Volume 3 Issue 2 (September 2024), 22-33
https://joscetech.uitm.edu.my
https://doi.org/10.24191/jscet.v3i2.22-33

Table 5. Column stress

Model	Stress (N/mm2)	Model	Stress (N/mm2)	Model	Stress (N/mm2)	Model	Stress (N/mm2)
A1	595.872	A6	566.15	A11	464.636	A16	468.665
A2	585.023	A7	564.192	A12	465.058	A17	465.058
A3	571.532	A8	562.63	A13	488.341	A18	485.099
A4	558.279	A9	559.227	A14	557.73	A19	513.037
A5	514.934	A10	594.553	A15	622.73	A20	617.05

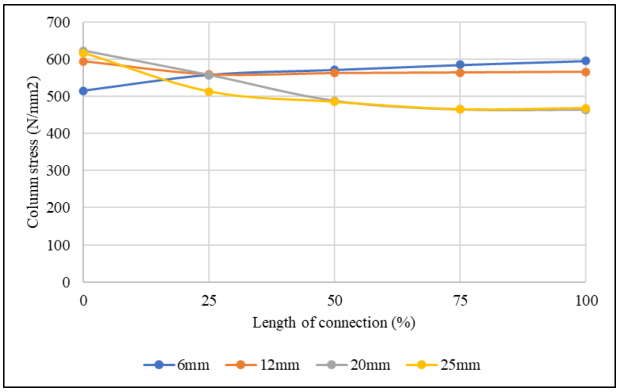


Figure 9. Column Stress vs Length connection Infill Plate of different models of SPSW

From the results and analysis, thinner infill plate will yield faster due to its smaller cross sectional area which causes it to have higher stress compared to thicker infill plate, and achieves yield stress faster than thicker infill plate. As a result, it will displace further than thicker infill plate which causes higher energy dissipation which is the larger the area under the force-versus-displacement graph. As a result, higher stress is also transmitted by thinner infill plate to the VBE compared to thicker infill plate.

Thicker infill plate such as 20 and 25 mm infill plate are capable to withstand larger lateral load as its stress is smaller due to its larger cross sectional area. As a results, larger lateral load than thinner infill plate is required to enable the 20 and 25 mm to reach ultimate stress. As a results, it has higher lateral load capacity.

5. Conclusion

This study investigated the effects of reducing the thickness of the infill plate and the length of connection between the infill plate and the vertical boundary elements on the structural performance of steel plate shear walls. Based on the findings of this study, the following conclusions have been reached;

1. Energy dissipation capacity of various SPSW models was determined by plotting hysteresis curves for different lengths of connection between the infill plate and vertical boundary condition. The energy dissipation capacity reached its maximum when the infill plate had a thickness of 12 mm and covered 75% of the length of the connection. However, it shown the highest column stress.
2. The maximum lateral load capacity was achieved when the infill plate had a thickness of 20 mm and 25 mm, covering 50% of the length of the connection. In addition, the infill plates with thicknesses of 20 mm and 25 mm showed the lowest column stress.

3. Using a 6 mm thick infill plate is not advisable due to its limited lateral load capacity and high column stress. However, it exhibited greater energy dissipation compared to the infill plates that were 20 mm and 25 mm thick when the connection was at 100% length of connection.
4. By increasing the thickness of the infill plate and reducing the infill plate connection, the column stress in VBEs can be effectively reduced. Based on the findings, it was determined that a connection length of 50% is the most optimal for connecting the infill plate to the vertical boundary elements. This length resulted in minimized column stress, maximized lateral load capacity, and an acceptable level of energy dissipation capacity for all infill plate thicknesses, with the exception of the 6 mm thick infill plate.

Acknowledgements

The author would like to acknowledge Universiti Teknologi Malaysia for the financial support provided through HiCOE grant, RJ130000.7822.4J223.

Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

References

Abdi, R., & Abdoli Yazdi, N. (2018). Effects of Aspect Ratio and Plate Thickness on the Behavior of Unstiffened Steel-Plate Shear Walls with Pinned and Rigid Connections. *Civil Engineering Journal*, 4(6), 1383. doi: 10.28991/cej-0309180.

Bathe, K. J. (1995). *Finite Element Procedures*. http://archives.umc.edu.dz/handle/123456789/116606

Bing, Q., & Michel, B. (2010). *Behavior of Vertical Boundary Elements in Steel Plate Shear Walls*. American Institute of Steel Construction.

Chan, R., Albermani, F., & Kitipornchai, S. (2011). Stiffness and Strength of Perforated Steel Plate Shear Wall. *The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction,* 14, 675-679.

Choi I.R, and Park H.G. (2009). Steel Plate Shear Walls with Various Infill Plate Designs, *Journal of Structural Engineering*, Vol. 135, No. 7, July 1, 2009.

Enright, J. (2014, June). *Efficient design of steel plate shear walls*. STRUCTURE magazine. https://www.structuremag.org/?p=2586.

Gupta, MK; Kharmale, SB; Ghosh, S. (2009). Ductility-based Seismic Design of Steel Plate Shear Walls: Practical Application using Standard Sections. *International Journal of Advanced Structural Engineering*, 1(2), 93-110.

He, J., Li, Y., Lin, S., Dong, X., & Chen, S. (2022). Effect of column flexural stiffnesses on the seismic performance of stiffened steel plate shear walls. *Buildings*, 12(11), 1965. https://doi.org/10.3390/buildings12111965.

Maleki, A., Donchev, T., Hadavinia, H., & Cheah, A. (2010). Behaviour of steel shear wall systems with cut-outs and stiffeners. *In Structures & Architecture* (pp. 151-152). https://doi.org/10.1201/b10428-71

R. Vhatkar, S., & D. Jadhao, P. (2018). Steel plate shear wall – a 20th century review. *International Journal of Engineering & Technology*, 7(4.5), 617. https://doi.org/10.14419/ijet.v7i4.5.21170

Rao, S. S. (2011). Finite element analysis using Abaqus. *The Finite Element Method in Engineering*, 631–662. https://doi.org/10.1016/b978-1-85617-661-3.00021-0

Santos Monteiro, M. (2011). *Energy Dissipation Systems For Buildings* (pp. 1-10). Lisbon: Technical University of Lisbon – Portugal.

Shekastehband, B., Azaraxsh, A. A., & Showkati, H. (2018). Experimental seismic study on shear walls with fully-connected and beam-only-connected web plates. *Journal of Constructional Steel Research*, 141, 204–215. https://doi.org/10.1016/j.jcsr.2017.11.013.

Yang, Y., Mu, Z., & Zhu, B. (2022). Study on shear strength of partially connected steel plate shear wall. *Metals*, 12(7), 1060. https://doi.org/10.3390/met12071060.