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Numerical Analysis of Infill Plate Performance on Steel Plate Shear Wall (SPSW)

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ABSTRACT

Steel Plate Shear Wall (SPSW) is one of the systems that can be used to minimize the effect of earthquakes on buildings. The main energy-absorbing element of the steel plate shear wall system is on the thin steel plate that are located on the center of the steel frame. This thin steel plate is called infill plates. This infill plate will later experience buckling and form a series of tension field action. This paper will prove that the infill plates in the steel plate shear wall system provides significant strength contribution in resisting lateral loads.

The analysis was carried out by comparing the strength provided by steel plate shear wall system and simple beam-column steel frame system (without infill plate) with some aspect ratio (width per height) value variation that in accordance with AISC regulations. The material used for the infill plates was low yield strength (LYS) steel plate of 1.30 mm thick, while the column (vertical boundary element) used WF 400.200.8.12, and the beam (horizontal boundary element) used WF 350.175.7.11. The loading used a monotonic pushover loading of 2% drift (68.8 mm) for each specimen.

The analysis result proved that the steel plate shear wall system (frame with infill plates) had significant strength advantage compared to the plateless frame system. The aspect ratio (L/h) on infill plates were also affects the strength of the entire system, where the greater the aspect ratio, the greater the strength. The strength value of the SPSW specimen at 2% drift loading on aspect ratio L/h = 1.00, 1.50, 2.00, 2.50 respectively was 614.95 kN, 634.88 kN, 646.69 kN, and 688.03 kN. Meanwhile, the strength increment percentage between steel plate shear wall systems compared to plateless frame systems in each aspect ratio was 21.67%, 32.39%, 42.48%, and 54.20%.

1. Introduction

Earthquakes are destructive and cannot be predicted. Earthquakes can cause severe damage on building structures, so the building structures should be made in such a way to minimize the impact of the earthquake itself. One of the methods that can be used to minimize the impact of earthquakes on buildings is to install Steel Plate Shear Wall (SPSW). Steel plate shear wall (SPSW) is one of the lateral load-bearing systems in the form of a steel frame with thin steel plate attached in the center of the frame. The SPSW system consists of beams called Horizontal Boundary Element (HBE), columns called Vertical Boundary Element (VBE) and a steel plate called infill/web plate. SPSW is an effective system in resisting seismic loads because when subjected to cyclic deformation, SPSW showed high rigidity, high ductility, and high energy dissipation [1]. Research in SPSW behavior, design, and modeling has been carried out by previous researchers [2]-[10]. Design codes and specifications are regulated in SNI 7860:2020 [11], AISC 341-20 [12], AISC 358-16 [13], and AISC Design Guide 20: Steel Plate Shear Wall [1].

The design of SPSW follows the capacity design principle, accordingly SPSW must be designed to have high ductility when carrying lateral loads where the boundary elements (beams and columns) must be able to resist the tensile force from the infill plate. The boundary elements must remain in elastic state except at the ends, where the ends of the boundary elements are allowed to be plastic to form uniform plastic collapse mechanism. The lateral loads will be fully restrained by the infill plate without surrounding boundary elements strength contribution. Then the

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boundary elements will resist the tensile force from the infill plates that are assumed perfectly yielded, and the plastic hinge is prevented from occurring along the span of the boundary element.
The main-energy absorbing element of unstiffened SPSW is a steel plate that experience buckling and forms a series of tension field action in diagonal direction. The post buckling strength and tension field action mechanism on unstiffened steel plate shear wall has a concept where the infill plate is assumed not to carry gravitational load and only experiences shear deformation when the structure is given lateral load. When the lateral load charged to the infill plate creates compressive stress that exceeds the plate compressive strength, then the plate will buckle, forming a fold line on the plate perpendicular to the compressive stress direction (parallel to the principle tensile stress). Furthermore, the lateral force will be transferred trough the plate by the principle tensile stress.

The gravity frame system in buildings, including the boundary elements on SPSW have to be designed so that it can resist gravitational loads while ignoring the contribution from the infill plate. The infill plate on the SPSW should not be taken account as gravity load resistor. Infill plate must be able to resist 100% lateral load on the system, meanwhile the boundary elements must be able to resist minimum 25% of the system's shear capacity. The study about the characteristics of the load against the deformations in the SPSW system has been conducted by [2]. The researchers found that the width-thickness ratio variation did not give significant strength effect on the SPSW system, but the width-height ratio (aspect ratio) gave strength effect on the system. When the aspect ratio increased, the load when the plate yielded also increased when the post-buckling stiffness value remained the same.

To prove the contribution of the infill plate in resisting lateral load, this paper will present the result of the strength contribution that infill plate gives to the overall performance of SPSW system. The result will be compared between the SPSW system and the plateless beam-column frame system. Furthermore, the strength comparison between variations of aspect ratios on the specimens will also be presented. The results of this study can also be used to consider the most optimum steel plate shear wall aspect ratio to be implemented in buildings.

2. Methods

This research focused on the influence and contribution of infill plate towards the overall strength of SPSW system. The analysis was carried out numerically using Abaqus Software. The specimens used in this research was based on the specimen data by [10]. The specimens were single story SPSW with dimension and material data that have been validated with the results obtained by [10]. The flowchart of this research shown in Figure 1.

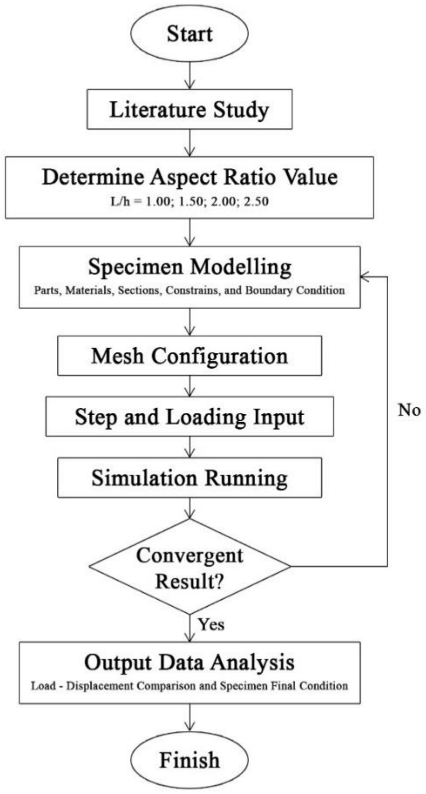


Figure 1. Research Flowchart

The material used in this study was steel. Steel was used because of its ductile behavior in resisting lateral loads. The steel material that was used in infill plate had yield strength value of 40 MPa, while for the boundary elements the steel's yield strength value was 340 MPa. The steel on the infill plate had lower yield strength than the steel on boundary elements in order to keep the boundary elements in elastic state when the infill plate already reach perfectly plastic state. The boundary elements must remain in elastic state except at the ends, where the ends of the boundary elements were allowed to reach plastic state. The steel specifications were obtained from tensile coupon test. Summary of the material properties that were used in this research shown in Table 1.

Table 1. Material properties [10]

Component	Yield Strength (MPa)	Ultimate Strength (MPa)	Rupture Strain (%)
Column (VBE)	340	455	22
Beam (HBE)	340	455	22
Infill plate	40	128	20

The infill plate on the specimen used low yield strength (LYS) steel plate of 1.30 mm thick. The column (VBE) used WF 400.200.8.12 steel, and the beam (HBE) used WF 350.175.7.11 steel. The four column-beam were connected using WUF-W (Welded Unreinforced Flange-welded Web) moment resisting connection. The plate dimension on the specimens were varied to acknowledge the effect of the aspect ratio (L/h) to the overall strength of the system. In accordance with AISC regulations, the recommended aspect ratio value for the infill plate is 0.8 ≤ L/h ≤ 2.5. Therefore, 4 specimens were taken varying in their infill plate aspect ratio. The aspect ratio used in this study was L/h = 1.00, 1.50, 2.00, 2.50, based on assumptions about the provisions stated in AISC regulations. The summary of the dimensions and aspect ratios of the specimens used were shown in Table 2.

Table 2. Infill plate dimensional ratio parameters of SPSW

Specimen Number	Width / L (mm)	Height / h (mm)	Ratio (L : h)	L / h
1	2500	2500	1 : 1	1.00
2	2500	3750	1.5 : 1	1.50
3	2500	5000	2 : 1	2.00
4	2500	6250	2.5 : 1	2.50

This study used monotonic pushover loading of 2% drift, or 68.8 mm displacement. All specimens will be loaded with this pushover load to see the strength of each model. The loading was given from the left top side of the specimen, on the confluence center line between the left column and the top beam on the model Figure 2.

The numerical analysis of this study was carried out using Abaqus Software. The modeling in Abaqus was done in several steps. The first step was to input parts, materials, and sections. The second part was to assemble all the parts according to the shape of the specimens, and then all the intersections between parts were given constrains. Then the third step was to mesh the model. Furthermore, the fourth step was to determine the step, and to input the loading to the model. The fifth step was to define the boundary conditions of the model. The sixth step was to run the simulation. If convergent results have been achieved then the research can be continued by analyzing the output data from Abaqus using the help of Microsoft Excel Software.

The type of element used for the entire model in this study was the S4R shell element. S4R is a conventional 4-node quadrilateral shell element with reduced integration. Reduced integration on the S4R element means that the S4R element only has 1 integration point, in contrast to the S4 element which has 4 integration points. The S4R type element was chosen in this study because it can reduce running time, but still present accurate results.

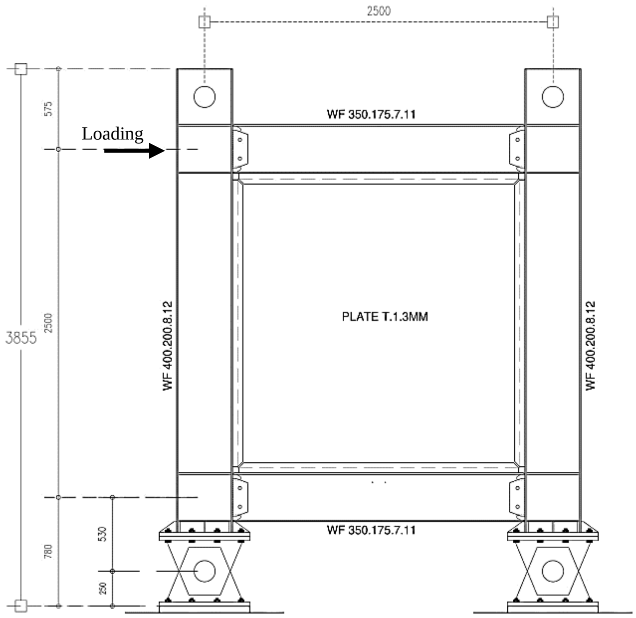


Figure 2. SPSW model details with aspect ratio L/h = 1.00 [10]

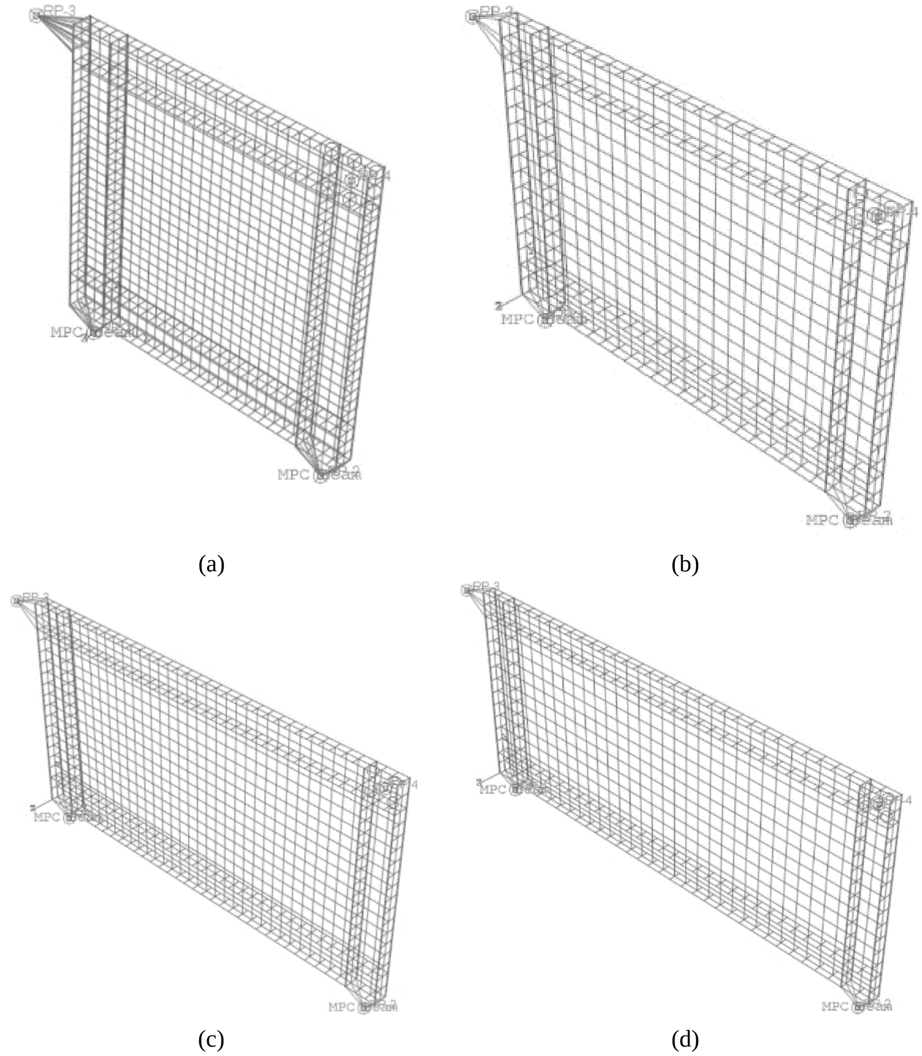
The idealization of the model's connections used merge/cut method, where this method unites several parts to become a single model and eliminate duplicated nodals on the edges of the bordering parts [14]. The meshing technique used in this model was structured meshing technique, where all specimens were meshed using quadrilateral elements so that all sides of the specimen had the same number of mesh area.

The pinned supports on the base of the specimens were idealized on the Abaqus using the CONN3D2 element (three-dimensional 2 node connector element). This joint element has total 6 degrees of freedom for each node (3 rotations and 3 displacements). The constraint type used on the supports was beam type MPC constraint. Furthermore, the pin boundary conditions were given to the constraints. The supports in this study were not idealized perfectly like in the experimental research where the supports used in experimental research were clevis hinges, further research is needed for better idealization of the supports.

The specimen loadings were idealized using kinematic coupling constraint. This type of constraint is able to resist the translational and rotational movements of the coupling node against a reference load. The reference point was placed at a distance of 500 mm to the left of the specimen. After the constraint was created, the boundary conditions in the form of displacement loading will be placed at this reference point.

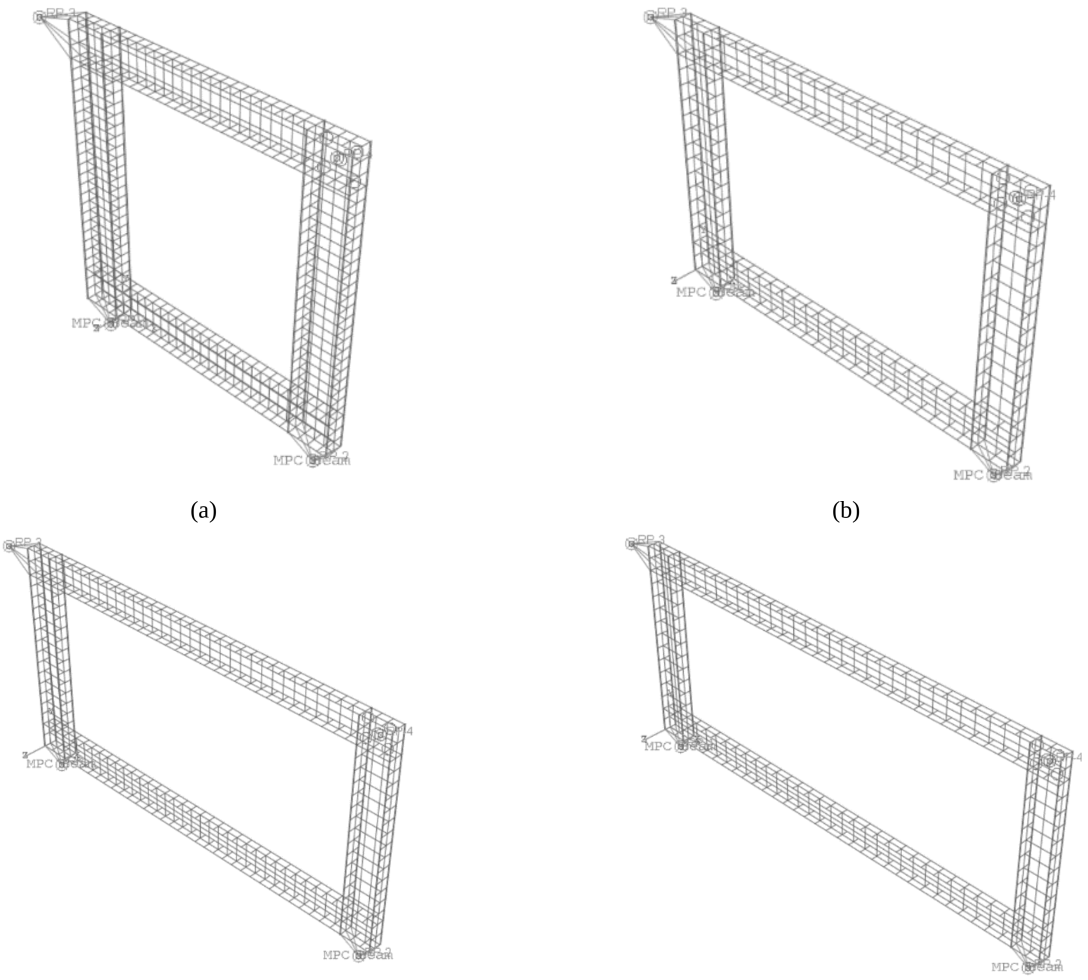
The result observed were the strength contribution provided by the infill plate to the overall strength of the specimens in resisting lateral load. This were observed by removing infill plate in the middle of the SPSW boundary frame. There were 2 specimens for each aspect ratio, where the first represented SPSW (frame with infill plate) and the second represented plateless beam-column frame. All specimens were given a 2% drift loading to see the strength for each model. The idealization of the SPSW specimens on Abaqus Software were shown in Figure 3, where Figure 3(a) shown SPSW specimen with aspect ratio L/h = 1.00, Figure 3(b) shown SPSW specimen with aspect ratio L/h = 1.50, Figure 3(c) shown SPSW specimen with aspect ratio L/h = 2.00, and Figure 3(d) shown SPSW specimen with aspect ratio L/h = 2.50.

Furthermore, the idealization of the plateless frame specimens on Abaqus software were shown in Figure 4, where Figure 4(a) shown plateless frame specimen with aspect ratio L/h = 1.00, Figure 4(b) shown plateless frame specimen with aspect ratio L/h = 1.50, Figure 4(c) shown plateless frame specimen with aspect ratio L/h = 2.00, and Figure 4(d) shown plateless frame specimen with aspect ratio L/h = 2.50.



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

Figure 3. Idealization of the SPSW specimen on Abaqus Software
(a) L/h = 1.00, (b) L/h = 1.50, (c) L/h = 2.00, (d) L/h = 2.50



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

Figure 4. Idealization of the plateless frame specimen on Abaqus Software
(a) L/h = 1.00, (b) L/h = 1.50, (c) L/h = 2.00, (d) L/h = 2.50

3. Results

The results of this study about the infill plate's strength contribution effect to the overall strength performance of the system were shown using load-displacement curve. The specimens of this research have been validated with experimental result by [10]. Figure 5 shown the comparison graph on specimen with aspect ratio L/h = 1.00 with the experimental results. The hysteresis curve of experimental research [10] was not symmetrical because of external factors, causing a slight difference between the numerical and experimental load value starting on 1% drift and above.

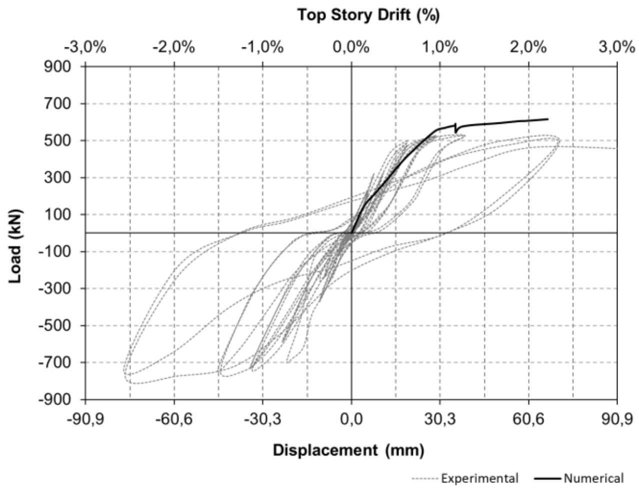


Figure 5. Load – displacement curve comparison between numerical and experimental analysis on L/h = 1.00 SPSW specimen [10]

Figure 6 shown detailed modeling result graph on specimen with aspect ratio L/h = 1.00. A load of 68.8 mm displacement was given to the specimen, and then the load value obtained on 2% drift was 614.96 kN. It could be seen on the curve that there was a drastic drop in the load value at 35 mm displacement. This happened when the infill plate was about to buckle.

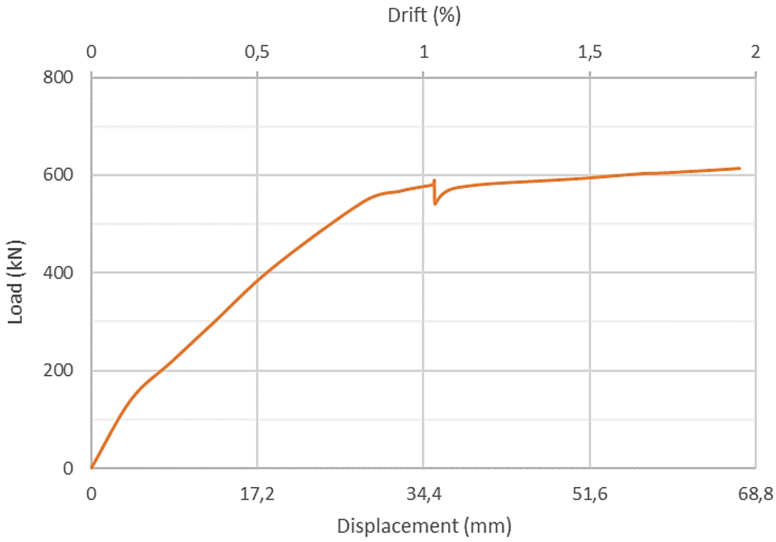
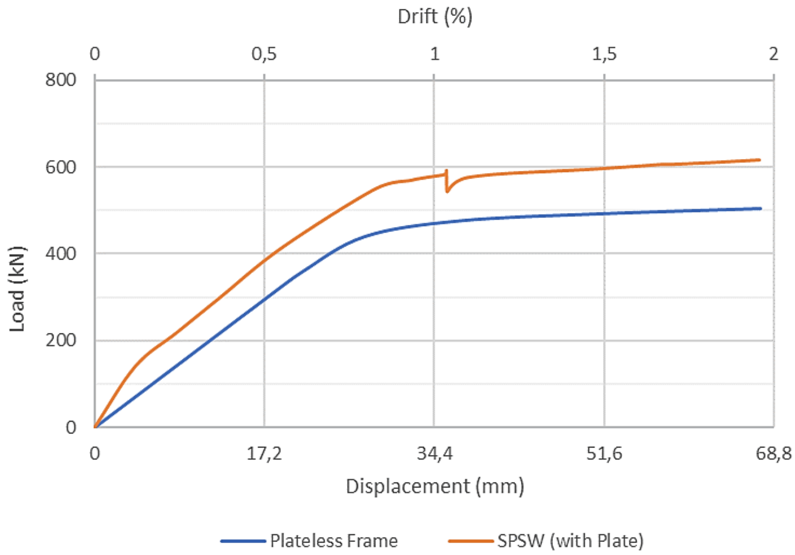
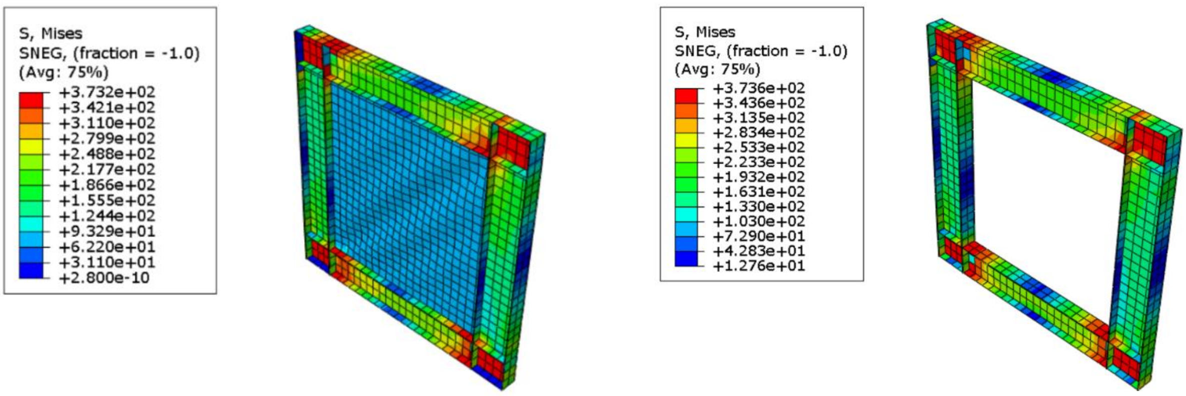


Figure 6. Load – displacement curve on L/h = 1,00



(a)



(b) (c)

Figure 7. Plate aspect ratio L/h = 1.00, (a) load vs displacement, (b) SPSW final condition, (c) plateless frame final condition

Strength comparison result graph on 2% loading of aspect ratio L/h = 1.00 between SPSW system and plateless frame system, as well as the final condition of each specimen were shown on Figure 7, where Figure 7(a) shown load – displacement curve, Figure 7(b) shown the SPSW specimen final condition, and Figure 7(c) shown the plateless frame final condition. Load value result on plateless frame at 2% drift was 505.43 kN, while the result on SPSW was 614.95 kN. Accordingly, the presence of the infill plate contributed strength increment of 109.52 kN or 21.67%.

Furthermore, the aspect ratio of the infill plate was varied as shown in Table 3. Strength comparison result graph between SPSW system and plateless frame system, as well as the final condition of aspect ratio L/h = 1.50 were shown on Figure 8, where Figure 8(a) shown load – displacement curve, Figure 8(b) shown the SPSW specimen final condition, and Figure 8(c) shown the plateless frame final conditions.

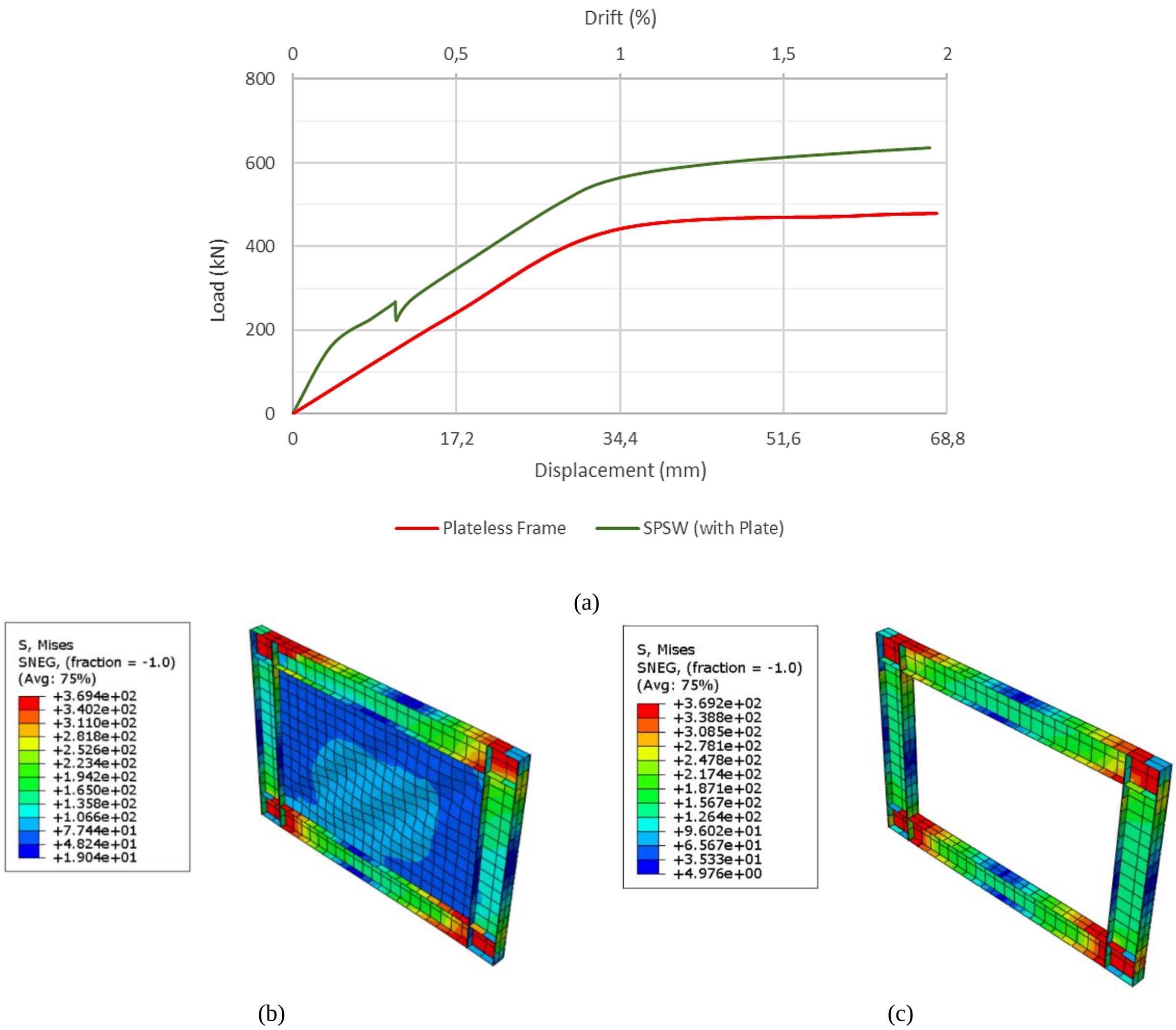
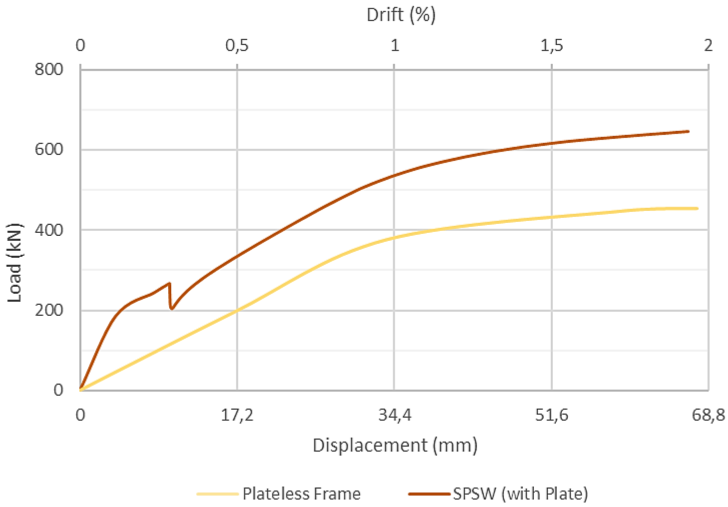


Figure 8. Plate aspect ratio L/h = 1.50, (a) load vs displacement, (b) SPSW final condition, (c) plateless frame final condition

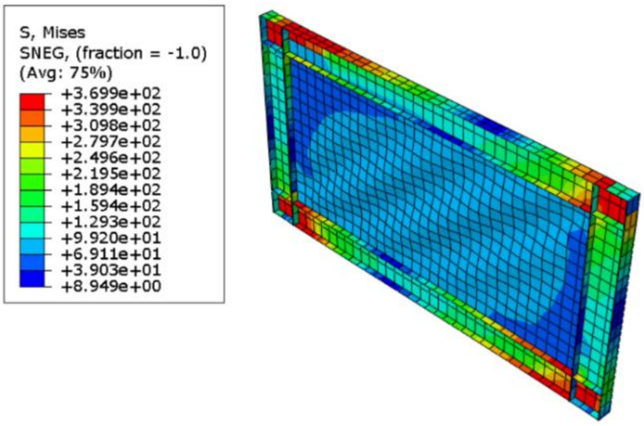
Then the strength comparison result graph between SPSW system and plateless frame system, as well as the final condition of aspect ratio L/h = 2.00 were shown on Figure 9, where Figure 9(a) shown load – displacement curve, Figure 9(b) shown the SPSW specimen final condition, and Figure 9(c) shown the plateless frame final condition.

Furthermore, the strength comparison result graph between SPSW system and plateless frame system, as well as the final condition of aspect ratio L/h = 2.50 were shown on Figure 10, where Figure 10(a) shown load – displacement curve, Figure 10(b) shown the SPSW specimen final condition, and Figure 10(c) shown the plateless frame final condition.

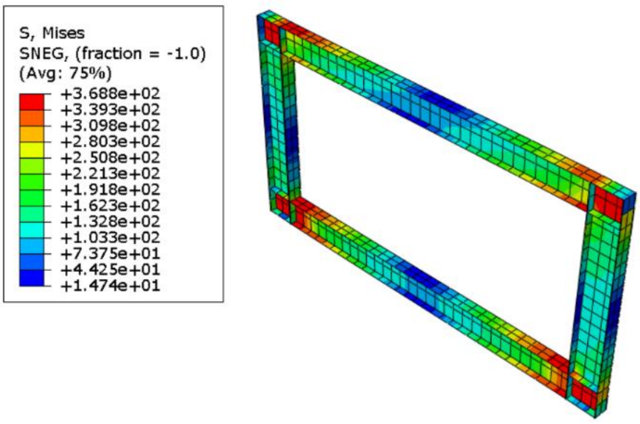
Summary of load value on 2% drift loading for every aspect ratio were shown on Table 4. The load value difference for L/h = 1.50 was 155.32 kN (increased 32.39% with infill plate), for L/h = 2.00 the load value difference was 192.80 kN (increased 42.48% with infill plate), and for L/h = 2.50 the load value difference was 241.84 kN (increased 54.20% with infill plate). The strength increment percentage of each aspect ratio is compared in Figure 11. The aspect ratio of the infill plate greatly affects the strength increment between plateless frame system and SPSW system. In specimens with larger aspect ratio, the strength increment percentage (load) increased significantly with the addition of infill plate in the frame system.



(a)

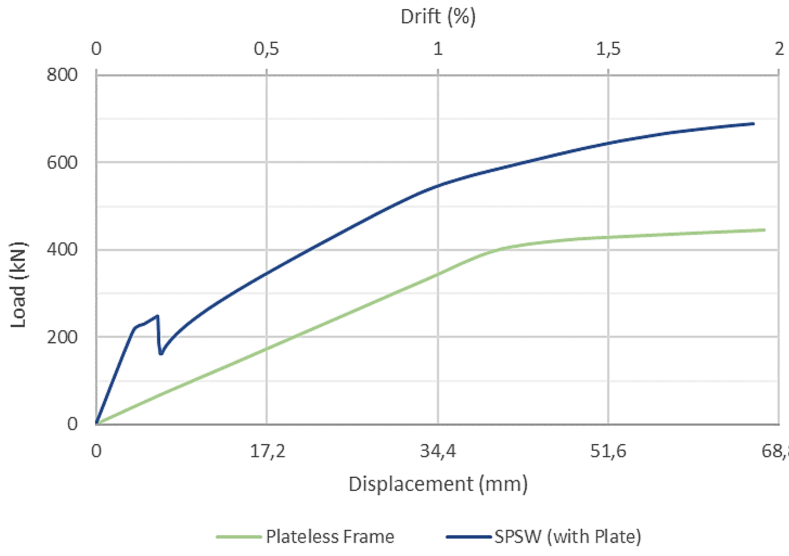


(b)

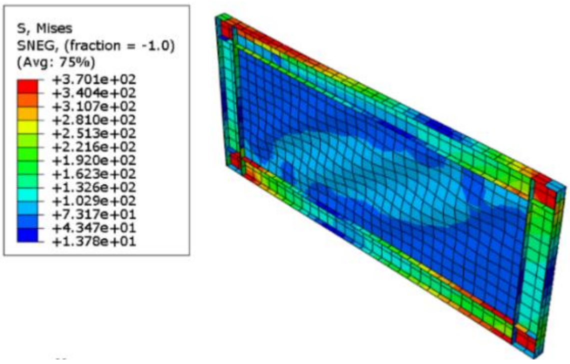


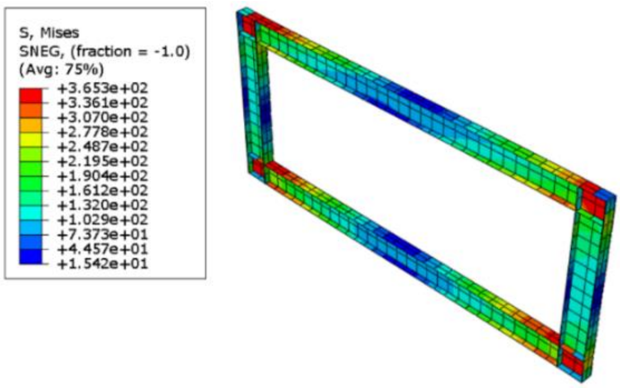
(c)

Figure 9. Plate aspect ratio L/h = 2.00, (a) load vs displacement, (b) SPSW final condition, (c) plateless frame final condition



(a)





(b) (c)

Figure 10. Plate aspect ratio L/h = 2.50, (a) load vs displacement, (b) SPSW final condition, (c) plateless frame final condition

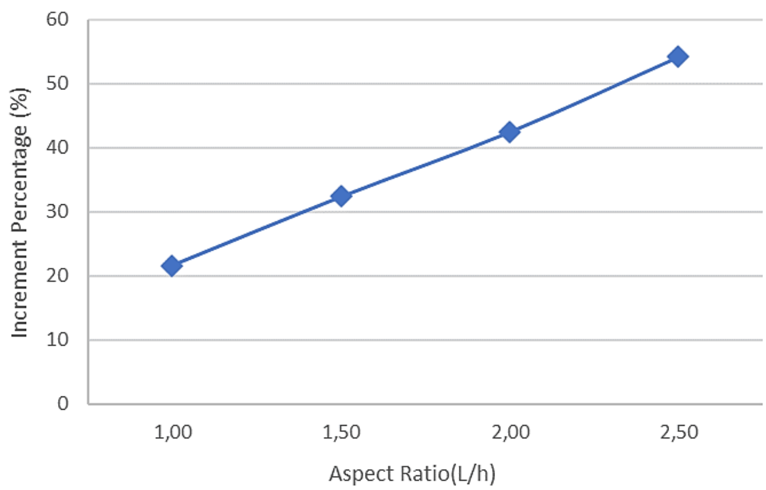


Figure 11. Strength increment percentage between plateless frame and SPSW system

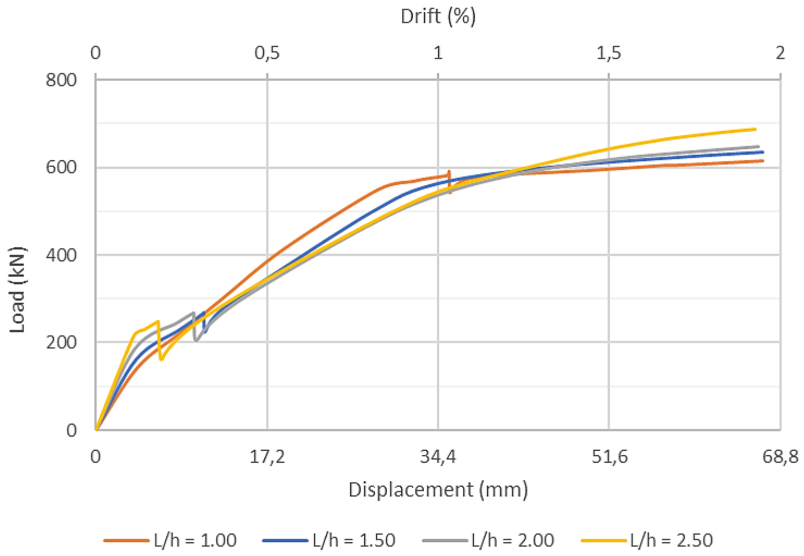


Figure 12. Respective load – displacement curve of aspect ratio specimens on SPSW

Table 3. Summary of strength value on 2% drift

L/h	Load (kN)		Strength Increment (kN)	Increment Percentage (%)
	Plateless Frame	SPSW		
1.00	505.43	614.95	109.52	21.67
1.50	479.56	634.88	155.32	32.39
2.00	453.90	646.69	192.80	42.48
2.50	446.18	688.03	241.84	54.20

Table 4 presents the SPSW system load values at 0.50%, 1%, 1.50%, and 2% drift. At 2% drift, the largest load value was obtained by specimen with aspect ratio L/h = 2.50. Figure 12 presents a load – displacement curve on each aspect ratio that has been analyzed.

Table 4. Summary of load value on SPSW specimens

L/h	Drift (%)			
	0.5	1	1.5	2
1	381.17	577.56	595.61	614.95
1.5	345.79	560.84	611.96	634.88
2	334.69	536.48	616.64	646.69
2.5	345.06	544.94	642.92	688.03

The strength of SPSW specimens using 1.50 aspect ratio experienced an increase of 3.24% compared to SPSW with 1.00 aspect ratio. For 2.00 and 2.50 aspect ratios respectively, the strength increment percentage compared to 1.00 aspect ratio were 5.16% and 11.88% It can be concluded that the greater the infill plate's aspect ratio (L/h) in SPSW, the greater the strength value.

The results obtained in this research were in accordance with previous studies, where the infill plate on the SPSW specimens were perfectly yielded, and experienced buckling in diagonal direction. The boundary condition remained in elastic state, while the column – beam connection reached plastic state. This behavior fitted the SPSW behavior caught in previous research, including [4], as well as [10]. In addition, the result of this research also validated the findings of [2] who stated that the aspect ratio of the infill plate gave strength effect on the SPSW system, where when the aspect ratio increased then the strength value was also increased.

4. Conclusions

This paper discusses about the infill plate strength contribution to the overall strength of steel frame system. The research was carried out numerically using Abaqus Software. This study used 4 SPSW specimens and 4 plateless frame specimens that were given 2% drift (68.8 mm displacement) loading to observe the strength difference of all these specimens. The result of this study proves that the placement of the infill plate between steel frames, or what is called SPSW system, can significantly increase the strength of the building in resisting lateral loads, or in this case earthquake loads. The aspect ratio (L/h) of the infill plate were also affected overall strength of the system, where the greater the aspect ratio, then the greater the strength (valid if the aspect ratio values were in accordance with AISC regulations).

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