

# Cyclic Nonlinear Behavior of Steel Plate Shear Walls with Plane Infill Panel

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**Abstract**— Steel plate shear wall (SPSW), which consists of boundary frame elements and steel infill panel, have several advantages over the concrete walls and braced steel walls such as better seismic behavior, higher ductility, and energy dissipation capacity. In this paper, finite element models were validated by using the previous experimental study. Then, five models were established. The parametric study includes the effect of plate thickness and panel width on seismic behavior. The lateral base shear, hysteretic curves, strength degradation, stiffness degradation, and energy dissipation capacity for whole models were fully compared. The results show that finite element modeling gives a good prediction for the seismic behavior, reducing plate thickness by about 40% decreases system lateral strength by about 11%, whereas increasing panel width by about 50% increases lateral load capacity by about 20%.

**Index Terms**—backbone curve, energy dissipation capacity, hysteretic behavior, steel plate shear wall, seismic behavior.

## I. INTRODUCTION

The lateral load resisting systems developed from conventional system of using reinforced concrete walls and steel braced frames to a new system called steel plate shear wall (SPSW) due to its several advantages such as better seismic behavior, higher strength capacity, higher ductility, less own weights of structure, less footing depth, and increasing usable floor area. SPSW system has been used in high-intensity seismic zones such as United States, Canada, China, Japan, and Korea. As, steel boundary frame provide a good anchor for the plate, “Tension Field” action completely forms. Although local buckling of infill panel forms under low level of drift, SPSW still has high lateral strength capacity due to “Tension Field” action. SPSW can be constructed with several structural details, including SPSW with a horizontal, vertical, cross, or diagonal stiffeners, SPSW with holes, openings, or slits, as shown in Fig 1.

Several works conducted on SPSW system to improve its seismic behavior, carry load capacity and energy dissipation capacity as in [1], [2], [3], [4], [5], [6], [7], [8], [9], and [10].

It was found that thin SPSW can achieve high post-buckling strength and good seismic behavior which can be attributed to tension field action. It was found that using thin SPSW instead of thick SPSW produces early tension field action that can dissipate more energy by acting as a plastic hinge, as in [2].

Researchers experimentally studied single span with three-story SPSW. They studied the effect of panel thickness and span-to-height ratio under cyclic load. It was found that the thickness of the infill panel has a great influence on seismic behavior, as in [11]. Cyclic test of four-story thin unstiffened steel plate shear wall was conducted. The results

showed good seismic performance, as story drift reached to 4% before reached to failure and high energy dissipated capacity. In addition, various researchers studied the effect of different construction details on SPSW such as openings[4]. Vian, D., Bruneau, M., Tsai, K. C. and Lin, Y.-C conducted three experimental models with reduced anchor beam section. The first model was without opening, the second model with an upper corner opening, a third model with several opening. The hysteretic behavior between top displacement and the total shear base was drawn. It was found that all specimens resisted up to drift ratio 3% and models with an opening have less stiffness than the solid model by about 22 and 15%. ABAQUS software was used to simulate the same three models. The results were verified with the experimental results. It was found that the results of the finite element models have good agreement with the tested specimens [1]. In order to improve SPSW seismic behavior, researchers studied the effect of using vertical slits with SPSW [6]. The tests include 42 SPSW subjected to monotonic and cyclic lateral loading. It was found that SPSW with vertical slits can reach 3% lateral drift without failure when the ratio between width and thickness in the flexural links is less than 20. Using steel with low initial yield strength improves seismic behavior, energy dissipation capacity and ductility, as given by [12], [7].

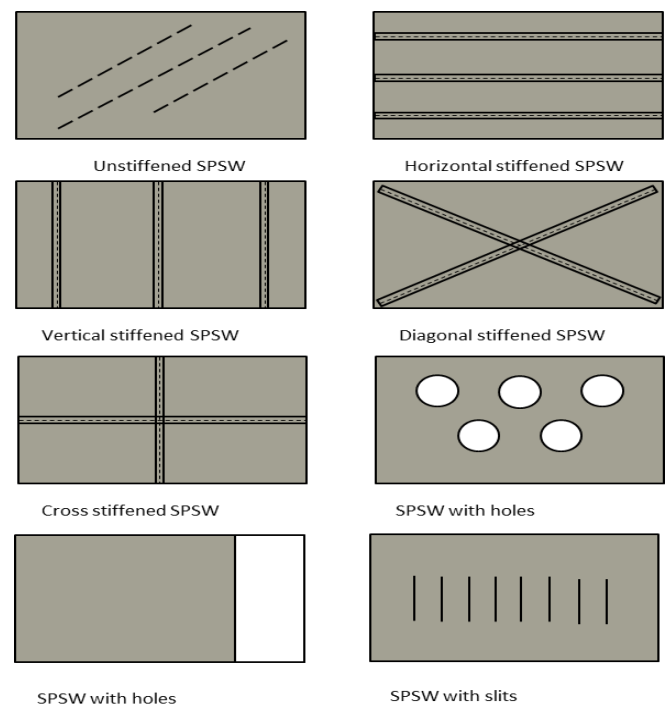


Fig 1: SPSW with several construction details.

In this research, due to the high cost of experimental work, finite element modeling is widely used. Firstly, previous experimental tests were validated using numerical simulation by ABAQUS software[13]. The results of finite element modeling were compared with the results of the experimental tests. It was found that finite element simulations can be used to predict the behavior of SPSW, lateral strength capacity, energy dissipation capacity, out of plane deformation. Then, based on the validated numerical simulation, five finite element models were established. The Geometric and material nonlinearity should be taken into consideration. The initial defect of the panel, which occurs during the storage process, should be simulated by using “imperfection” command to modify the coordinates of the panel’s nodes. The hysteretic behavior, load carrying capacity, initial stiffness, energy dissipated, strength and stiffness degradations for each model were fully compared.

## II. STRUCTURAL MODELING

Five models for SPSW with one story and single bay were studied using ABAQUS software. SPSW1 represents the reference model, in which the panel height, width, and thickness was 3000 mm, 3000 mm, and 5 mm, respectively. Infill height, width for SPSW2 and SPSW3 were 3000 mm, and 3000 mm. Panel thickness for SPSW2 and SPSW3 were 4 mm, and 3 mm, respectively. SPSW4 and SPSW5 studied the effect of panel width on seismic behavior. Height of panel for SPSW4 and SPSW5 was 3000 mm. Infill width for SPSW4 and SPSW5 were 2400 mm, and 4500 mm, respectively. In each model, the steel plate shear wall has the same boundary frame sections for comparison requirements. The case study includes (a) the effect of panel thickness; and (b) the effect of panel width.

Boundary frame elements were designed according to AISC Design Guide 20 [14], and [15]. The beam and column sections were HM500\*300\*11\*15 and HW400\*400\*13\*21, respectively. The infill panel has a height of 3000 mm. The panel thickness and width for the infill panels are shown in Table II-1.

Table II-1: The Panel Dimensions for the infill panels

Model	Wall			Boundary section	Parameter
	Height (mm)	Width (mm)	thickness (mm)		
SPSW1	3000	3000	5	Column HW400*400*13*21 Top and bottom beam HM 500*300*11*15	Reference model
SPSW2	3000	3000	4		Panel thickness
SPSW3	3000	3000	3		
SPSW4	3000	2400	5		Panel width
SPSW5	3000	4500	5		

The yielding strength for panel and boundary frame elements was 235 Mpa and 345 Mpa respectively. The elastic modulus  $E = 206000$  Mpa. Poisson ratio  $\nu = 0.3$  and

hardening modulus  $E_h = 1/100E$ . The 4(four)-node shell element S4R was used for structural modeling. Material and geometric nonlinearity was taken into consideration in the analysis.

Initial out-of-plane defect due to storage or installing was set as 1/1000 of the panel height by using “imperfection” command using first buckling modes.

The column base nodes had a fixed boundary condition. All nodes of the top beam center line and the beam-column connection had the out-of-plane constraint to consider the floor system. The lateral story drifts were assumed to be 0.25%, 0.5%, 1%, 1.5%, 2%, 2.5%, 3%, and 4%. Every drift was repeated twice, as shown in Fig 2.

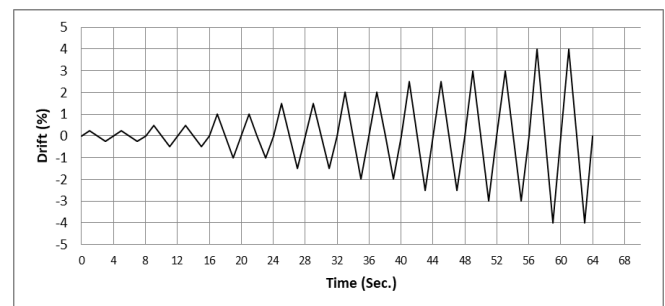


Fig 2: Cyclic Drifts

## III. VERIFICATION OF THE PARK’S TEST

Park’s experimental study was conducted on the cyclic behavior of SPSW [16]. Park studied five steel plate shear walls with single bay and three stories. Specimen SC6T was selected for finite element simulation validation. Finite element modeling was shown in Fig 3. The plate height, width, and thickness were 1000 mm, 1500 mm, and 6 mm, respectively for all stories. The section of the internal beams, top beam, and column were H200\*200\*16\*16 mm, H400\*200\*16\*16, and H250\*250\*20\*20, respectively. The material of plates and boundary frame was SM490 with yield stress  $f_y = 330$  Mpa. The cyclic hardening parameters were used as following

$$Q_\infty = 21, b = 2.1$$

$$C_1 = 7993N/mm^2, \gamma_1 = 175$$

$$C_2 = 6773N/mm^2, \gamma_2 = 116$$

$$C_3 = 2854N/mm^2, \gamma_3 = 34$$

$$C_4 = 1450N/mm^2, \gamma_4 = 29$$

The bottom of the model was fixed. The nodes in the middle of the upper column had an out-of-plane constraint. The initial out-of-plane defect was assumed to be 1/1000 height of steel panel, due to the absence of experimental data. The finite element simulation was shown in Fig 3.

The load-Horizontal displacement curve for experimental test SC6T and present finite element modeling was compared in Fig 4 which shows a good agreement with the experimental results. Fig 4 indicates that present simulation has higher initial stiffness than an experimental test by about 6% and

higher shears capacity by about 4%. This might be attributed to the assumed values for the cyclic hardening parameters. Thus, finite element modeling can be used for prediction of seismic behavior, and load carrying capacity.

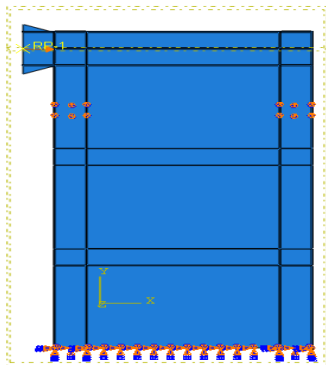


Fig 3: Finite element modeling of SC6T

IV. PARAMETRIC STUDY

A. Effect of Panel Thickness

In order to study the influence of plate thickness on seismic behavior, three finite element models, with single bay and one story were conducted. The plate dimensions were 3000 mm \* 3000 mm. The boundary frame for whole models remains the same for comparison reasons. In this study, SPSW1, SPSW2, and SPSW3 have thickness 5 mm, 4 mm, and 3 mm, respectively

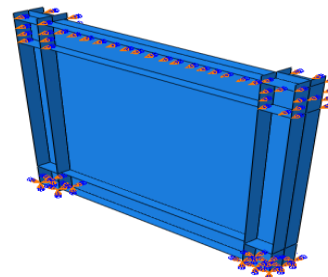


Fig 5: Finite element modeling for SPSW1.

1) Hysteretic and Backbone Curves of Systems

Hysteretic curves for SPSW1, SPSW2, and SPSW3 were fully compared, as shown in Fig 7, in which the drift ratio (%) and the base shear force (kN) was represented on the x-axis and y-axis, respectively. From Fig 7, it is clear that plate thickness has a great effect on load carrying capacity and shear base, especially in early cyclic stages. At 0.25% lateral story drift, SPSW1 has higher lateral capacity than SPSW2, and SPSW3 by about 37.5%, and 50.4%, respectively. At -0.25% lateral drift SPSW1 has greater capacity than SPSW2, SPSW3 by about 46.7%, and 56%, respectively.

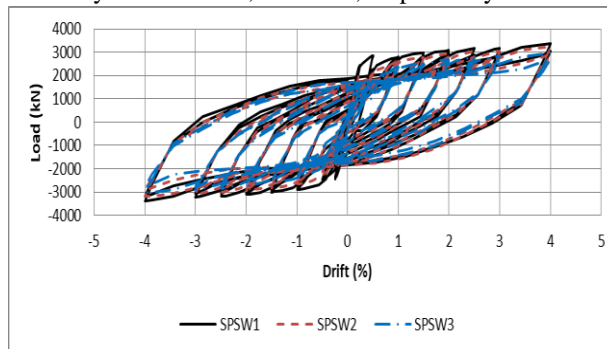


Fig 6: Hysteretic curves for SPSW1, SPSW2, and SPSW3

Symmetric backbone curves for SPSW1, SPSW2, and SPSW3 were concluded from hysteretic curves, as shown in Fig 7. Seismic characteristics and feature points were extracted from backbone curves, as shown in

Table IV-1. Yield point can be defined as a point, in which system reaches to plastic deformations.

Model	Load direction	Initial stiffness (kN/mm)	$\Delta y$ (mm)	V y (kN)	$\Delta m$ (mm)	Vm (kN)
SPSW 1	push -	300.76826	16	2479.5	130	3267.17
	pull +	299.90943	16	2855.2	130	3203.386
SPSW 2	push -	205.03413	8	2038.2	130	3068.573
	pull +	217.99893	8	2029.4	130	3075.035
SPSW 3	push -	192.62687	8	1621.8	130	2902.705
	pull +	199.50129	8	1612.8	130	2836.899

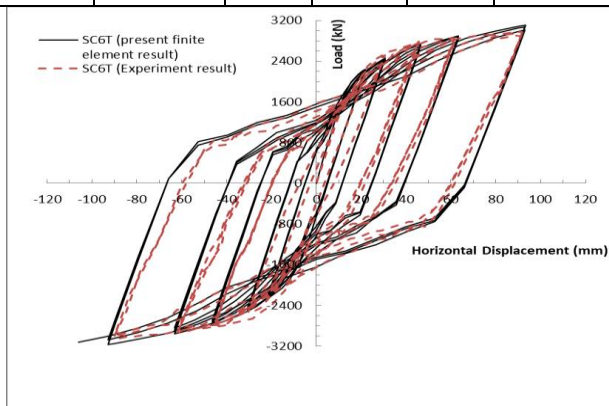


Fig 4: Load-Horizontal displacement curve for the experimental test and finite element result

Table IV-1 shows values for yield displacement ( $\Delta y$ ), yield

directions. SPSW3 has lower strength capacity than SPSW1 by about 11% in pull and push directions.

Model	Load direction	Initial stiffness (kN/mm)	$\Delta y$ (mm)	$V_y$ (kN)	$\Delta m$ (mm)	$V_m$ (kN)
SPSW 1	push -	300.76826	16	2479.5	130	3267.17
	pull +	299.90943	16	2855.2	130	3203.386
SPSW 2	push -	205.03413	8	2038.2	130	3068.573
	pull +	217.99893	8	2029.4	130	3075.035
SPSW 3	push -	192.62687	8	1621.8	130	2902.705
	pull +	199.50129	8	1612.8	130	2836.899

load ( $V_y$ ), maximum displacement ( $\Delta m$ ), and maximum load ( $V_m$ ) in pull and push directions. From Fig 7 and

Table IV-1, it is clear that SPSW 2 has lower initial stiffness

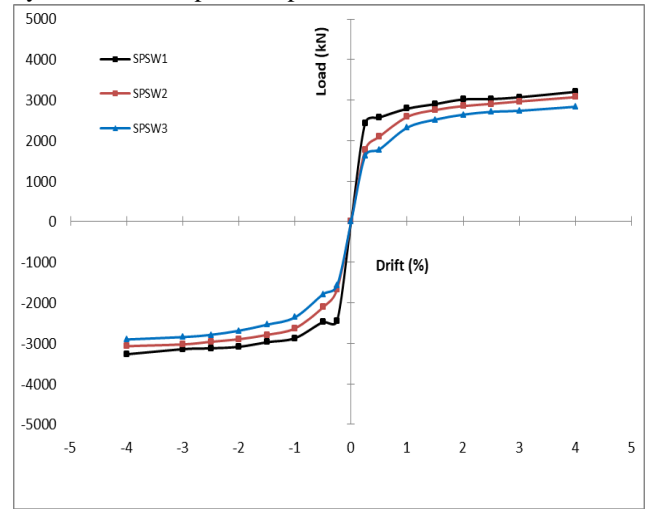


Fig 7: Backbone curves for SPSW1, SPSW2, and SPSW3  
Table IV-1: Cyclic analyses results of SPSW1, SPSW2, and SPSW3

Model	Load direction	Initial stiffness (kN/mm)	$\Delta y$ (mm)	$V_y$ (kN)	$\Delta m$ (mm)	$V_m$ (kN)
SPSW 1	push -	300.76826	16	2479.5	130	3267.17
	pull +	299.90943	16	2855.2	130	3203.386
SPSW 2	push -	205.03413	8	2038.2	130	3068.573
	pull +	217.99893	8	2029.4	130	3075.035
SPSW 3	push -	192.62687	8	1621.8	130	2902.705
	pull +	199.50129	8	1612.8	130	2836.899

than SPSW1 by about 31% and 27% in the push and pull directions, respectively. SPSW2 has lower lateral strength capacity than SPSW1 by about 6% and 4% in the push and pull directions. Fig 7 and

Table IV-1 also show that SPSW3 has lower initial stiffness

### 2) Strength Degradation

Strength degradation is one of the seismic characteristic behaviors, which reflects the structural damages occur during the cyclic loading process. Strength degradation can be defined as (the ratio between the lateral base shear capacity for the second cycle and the lateral base shear capacity for the first cycle for the same lateral story drift).

Fig 8 shows strength degradation ratios for SPSW1, SPSW2, and SPSW3. From Fig 8, it is clear that the lateral strength degradation for different systems is close to each other and varying between 0.85 and 1. Fig 8 indicates also that lateral strength degradation ratio increase with the increase of lateral story drift.

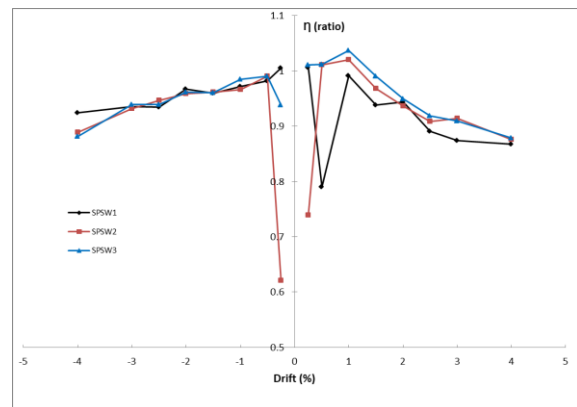


Fig 8: Strength degradation ratios for SPSW1, SPSW2, and SPSW3

### 3) Stiffness Degradation

Cyclic stiffness ( $K_i$ ) describes the stiffness degradation during the cyclic process. Cyclic stiffness can be calculated method in [17], as shown in Eq. 1, Where,  $P_j^i$  is peak lateral shear capacity in each cycle and  $\Delta_j^i$  is peak displacement for each cycle drift.

than SPSW1 about 36% and 33% in the push and pull

Fig 9 shows the stiffness degradation for SPSW1, SPSW2, and SPSW3. From Fig 9, it is clear that SPSW1 has higher initial stiffness than SPSW2, and SPSW3. Figure 6 indicates also that, SPSW1 has higher cycle stiffness than SPSW2, and SPSW3. SPSW1 has higher stiffness than SPSW2 by about 18% and 15% in pull and push directions at drift ratios 0.5% and -0.5%. SPSW1 has higher stiffness than SPSW3 by about 30% and 28% in pull and push directions at story drift 0.5% and -0.5%. The difference between cyclic stiffness decreases with increasing of internal story drift ratio. This might be attributed to plastic deformation and local buckling, which occurs in systems. This is meaning that the panel thickness parameter has a great impact on system stiffness.

$$K_i = \sum_{j=1}^n P_j^i / \sum_{j=1}^n \Delta_j^i$$

Eq. 1

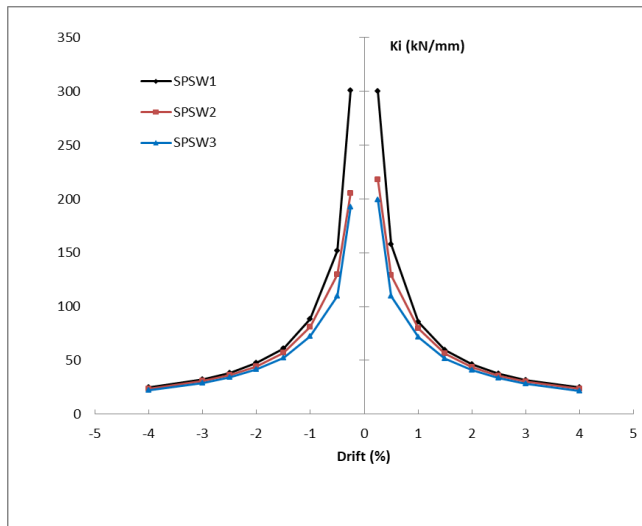


Fig 9 : Stiffness degradations for SPSW1, SPSW2, and SPSW3

#### 4) Energy Dissipation Capacity

Energy dissipation capacity is one of the most important seismic characteristics to describe the system seismic performance. Energy dissipation capacity is equal to the enclosed area of the hysteretic curve.

Fig 10 and Fig 11 show the accumulated energy dissipation capacity at cyclic drift number (N) for SPSW1, SPSW2, and SPSW3. From

Fig 10 and Fig 11, it can be concluded that SPSW2, and SPSW3 has lower energy dissipation capacity than SPSW1 by about 8% and 16.5%, respectively.

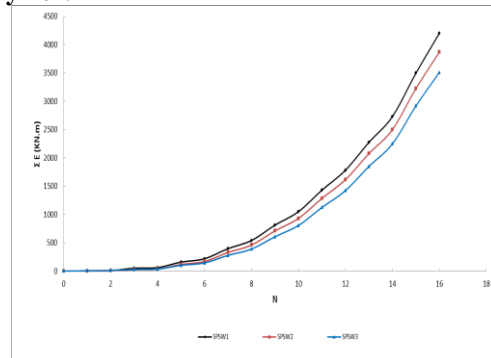


Fig 10: Accumulated energy dissipation capacity curves for SPSW1, SPSW2, and SPSW3

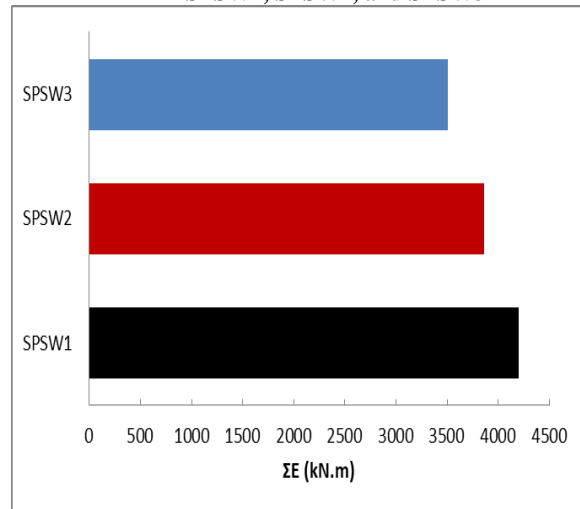


Fig 11: Accumulated energy dissipation capacities charts for SPSW1, SPSW2, and SPSW3

#### B. Effect of Panel width

In this section, the effect of the panel width was studied. In this study, SPSW1, SPSW4, and SPSW5 have width 3000 mm, 2400 mm, and 4500 mm, respectively. The height of panels for systems was 3000 mm. The plate thickness and boundary frame elements remain the same for comparison reasons.

##### 1) Hysteretic and Backbone Curves of Systems

Fig 12 shows the hysteretic curves for SPSW1, SPSW4, and SPSW5. From Fig 12, it can be concluded that the steel plate width has a great effect on carrying load capacity and seismic behavior. The higher panel width is, the higher lateral strength capacity of the system is. This might be attributed to the increasing resisting section, which is parallel to lateral drifts.

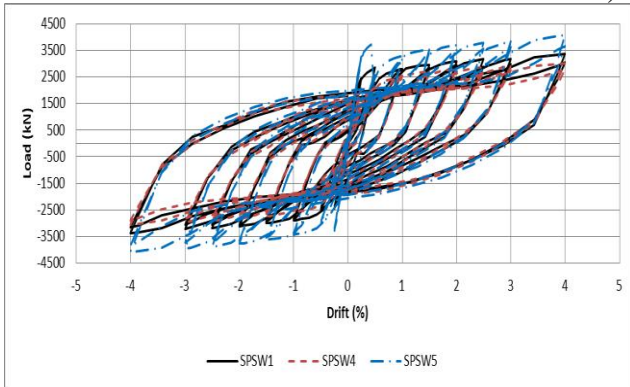


Fig 12: Hysteretic curves for SPSW1, SPSW4, and SPSW5.

Backbone curves for SPSW1, SPSW4, and SPSW5 were extracted from hysteretic curves, as shown in Fig 13. Feature points, lateral strength capacity, and initial stiffness for systems were concluded from backbone curves, as shown in Table IV-2. From Fig 13 and Table IV-2, it is clear that SPSW4 has lower initial stiffness than SPSW1 by about 32% and 28% in the push and pull directions and lower base shear capacity of about 9%. Fig 13 and Table IV-2 shows also that, SPSW5 has higher initial stiffness than SPSW1 by about 34% and higher lateral strength capacity by about 20%.

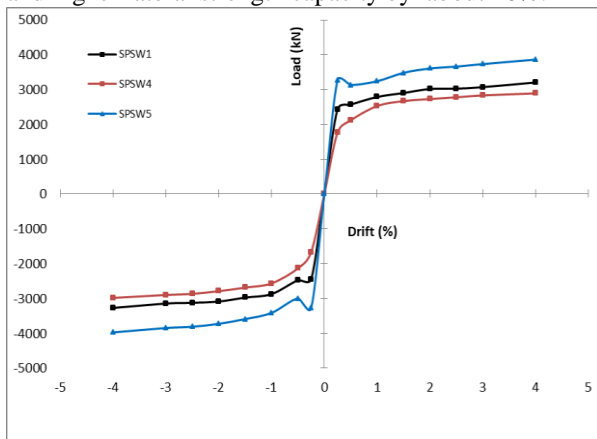


Fig 13: Backbone curves for SPSW1, SPSW4, and SPSW5.

Table IV-2: Cyclic analyses results of SPSW1, SPSW4, and SPSW5

Model	Load direction	Initial stiffness (kN/mm)	$\Delta y$ (mm)	$V_y$ (kN)	$\Delta m$ (mm)	$V_m$ (kN)
SPSW1	push -	300.7683	16	2480	130	3267.1
	pull +	299.9094	16	2855	130	3203.3
SPSW4	push -	204.6644	7	1950	130	2979.12
	pull +	217.3935	8	2053	130	2891.5
SPSW5	push -	402.9742	8	3279	130	3970.3
	pull +	402.2617	14	3704	130	3862.61

2) Strength Degradation

Fig 14 shows the strength degradation ratios for SPSW1, SPSW4, and SPSW5. It is clear that lateral strength ratios for the systems varying between 0.85 and 1.0, except for SPSW4

at drift ratios 0.25%, and -0.25% and for SPSW5, in which strength degradation ratio is under 0.7 at a drift ratio 0.5%.

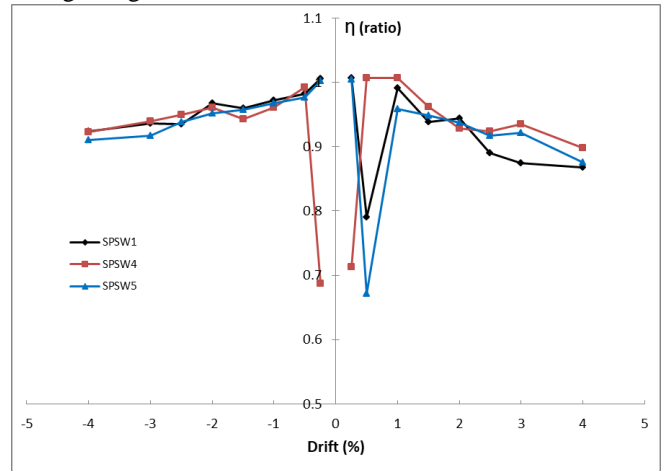


Fig 14: Strength degradation ratios for SPSW1, SPSW4, and SPSW5.

3) Stiffness Degradation

Fig 15 shows cyclic stiffness and stiffness degradation for SPSW1, SPSW4, and SPSW5. From Fig 15, it is clear that steel plate shear wall with higher plate width has higher cyclic stiffness, especially for early cyclic stages. SPSW1 has higher stiffness than SPSW4 by about 18% and 14% in pull and push directions at drift ratio 0.5% and -0.5%. SPSW5 has higher cyclic stiffness during drifts 0.5% and -0.5% than SPSW1 by about 22% and 21% in pull and push directions. For the last cyclic stages at drift ratios 4% and -4%, the cyclic stiffness for SPSW1, SPSW4, and SPSW5 was very close to each other. This might be attributed to local buckling, which occurred in all systems.

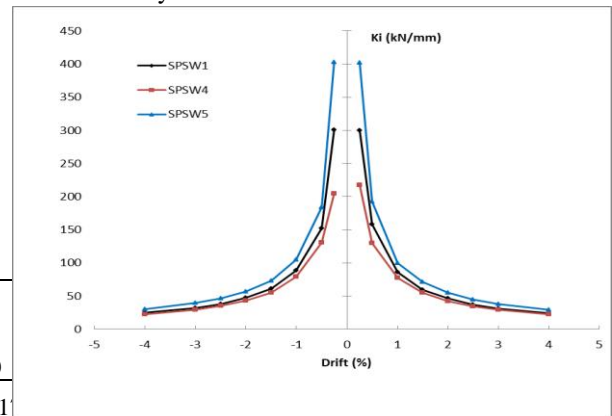


Fig 15: Stiffness degradations for SPSW1, SPSW4, and SPSW5.

4) Energy Dissipation Capacity

Fig 16 and Fig 17 show energy dissipation capacity for SPSW1, SPSW4, and SPSW5. From Fig 16 and Fig 17, it is clear that steel plate shear wall with a panel width equal to 2400 mm (SPSW4) has a lower energy dissipation capacity than SPSW1 by about 3%. SPSW5, in which panel width equal to 4500 mm, has higher energy dissipation capacity than SPSW1 by about 11%.

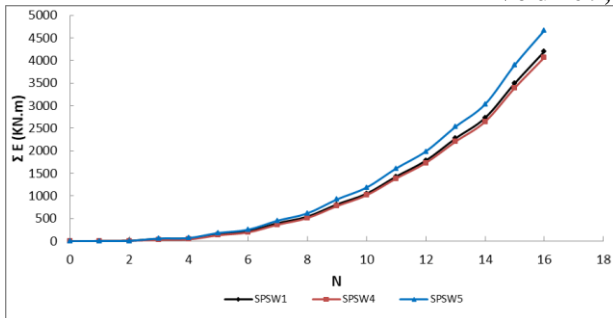


Fig 16: Accumulated energy dissipation capacity curves for SPSW1, SPSW4, and SPSW5.

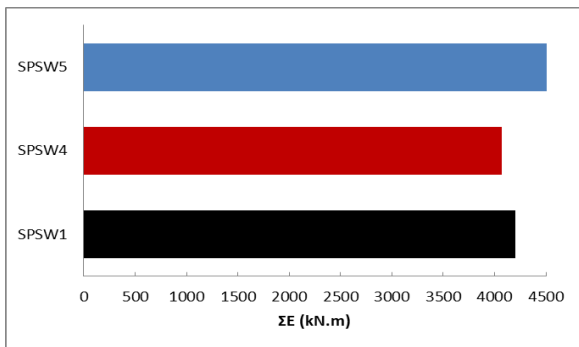


Fig 17: Accumulated energy dissipation capacities charts for SPSW1, SPSW4, and SPSW5.

## V. CONCLUSIONS AND RECOMMENDATIONS

In this study, based on previous experimental work validation, five finite element models were established, in order to investigate the carrying load capacity, cyclic stiffness, energy dissipation capacity, and strength degradation. The parametric study includes the effect of panel thickness and panel width. The numerical simulations results can be concluded as follows:

1. Finite element modeling can predict seismic behavior, initial stiffness with a percentage error of 6%, and lateral strength capacity with an error of 4%.
2. The thickness of the infill panel is an important parameter for seismic behavior, base shear capacity, initial stiffness, and energy dissipation capacity. Reducing panel thickness by about 40% leads to a decrease in initial stiffness, lateral strength capacity, and energy dissipation capacity by about 36%, 11%, and 16.5%, respectively.
3. The panel width has a great impact on seismic behavior. As reducing the width by about 80%, decreases initial stiffness, lateral load capacity, and energy dissipation capacity of about 32%, and 9%, and 3% respectively. Steel plate shear wall with plate width 4500 mm (SPSW5) has greater initial stiffness, base shear capacity, and energy dissipation capacity than steel plate shear wall with panel width 3000 mm (SPSW1) about 34%, 20%, and 11%, respectively.

Based on the present work and the obtained results, the following may be valid points for future research:

- 1-Experimental and finite element analyses for multi-story SPSW will be recommended to understand the behavior of this system deeply.
- 2-Studying the effect of boundary frame stiffness
- 3-Studying the effect of stiffeners with different directions
- 4-Studying the effect of opening positions and dimensions.

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