



Nonlinear Analysis Of The Behavior & Performance Of Multistory Steel Building Structures Without And With Steel Plate Shear Walls

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ABSTRACT

Indonesia, as a region highly susceptible to earthquakes, necessitates the construction of earthquake-resistant buildings, particularly multi-story steel structures. Steel Plate Shear Walls (SPSWs) offer an effective solution for resisting lateral loads. This research compares the behavior and performance of three (3) building models: an Open Frame (OF) Model, a Uniform Thickness Steel Plate Shear Wall (SPSW-UT) Model, and a Varied Thicknesses Steel Plate Shear Wall (SPSW-VT) Model. Linear analysis are running with equivalent static to get the structural behaviour & pushover for nonlinear analysis to get the structural performance. In terms of structural behavior, the inclusion of SPSWs in both the SPSW-UT and SPSW-VT models significantly enhances structural stiffness, evidenced by a drastic reduction in the fundamental period compared to the OF Model (without SPSW). The SPSW-UT Model reduces inter-story drift by up to 34.23% (X-direction) and 50.69% (Y-direction), while the SPSW-VT Model also shows similar reductions of up to 30.98% (X-direction) and 49.80% (Y-direction) compared to the OF Model. From a performance point perspective, the SPSW-UT Model increases the maximum base shear by up to 20.19% (X-direction) and 32.29% (Y-direction), while the SPSW-VT Model increases it by up to 13.34% (X-direction) and 25.96% (Y-direction) compared to the OF Model. Furthermore, both SPSW models achieve an Immediate Occupancy (IO) performance level for both pushover directions, whereas the OF Model only reaches IO in the X-direction and Damage Control (DC) in the Y-direction, demonstrating a significant performance improvement due to the use of steel plate shear walls.

Keywords: pushover, steel plate shear wall, structural behavior, structural performance

1. INTRODUCTION

Indonesia is situated within the Pacific Ring of Fire and the Trans Asiatic Earthquake Belt, making it a country with a high susceptibility to earthquakes. The elevated risk of earthquakes increases the likelihood of structural failure, especially if buildings are not properly designed. This necessitates the construction of buildings with superior seismic resistance, including multi-story steel structures. The capacity of steel buildings to withstand lateral loads, such as

earthquakes, depends on their overall strength. Building strength is determined by three characteristics: stiffness, damping coefficient, and building mass. According to SNI 1726-2019, one commonly used lateral load resisting system is the steel plate shear wall [1].

Prior research analyzed the performance of an office building with and without unstiffened steel plate shear walls (modeled using shell elements) linearly in SAP2000 software [2]. The results showed that the lateral displacement in the building with steel plate shear walls was at least two times (2x) smaller than in the building without shear walls. Furthermore, the internal forces generated in the building with steel plate shear walls tended to be smaller than in the building without them. However, linear analysis is limited to observing structural behavior only within the elastic range. In other words, the behavior and performance level of the structure when experiencing a nonlinear response cannot be accurately observed.

Therefore, this research will analyze the nonlinear performance and behavior of a hospital building in Denpasar using pushover analysis. The building will be modeled into three (3) configurations: Open Frame (OF) Model, Steel Plate Shear Wall-Uniform Thickness (SPSW-UT) Model, and Steel Plate Shear Wall-Variied Thicknesses (SPSW-VT) Model. The steel plate shear wall models will be simulated using diagonal tension strip elements.

2. THEORY AND METHODS

2.1 Theory

Steel Plate Shear Walls (SPSWs) & Tension Field Action Mechanism

Steel Plate Shear Walls (SPSWs) consist of a steel infill plate connected to surrounding beams (designated as Horizontal Boundary Elements (HBEs)) and columns (designated as Vertical Boundary Elements (VBEs)). The working mechanism of unstiffened steel plate shear walls utilizes the plate post-buckling strength. The plate is specifically designed to undergo shear buckling early on, after which it deforms to form a Tension Field Action that helps increase the load-carrying capacity before ultimately yielding [3]. The capacity design approach in standards like SNI 7860:2020 & newest AISC 341-22 mandates that HBEs and VBEs remain elastic while the plate yields, except at certain designated ends where plasticity is permitted [4], [5]. This mechanism has been substantiated by various studies and is recognized in international building codes.

Modeling of Strip Diagonal Plate Elements

The diagonal strip method, used in the macro-modeling of steel plate shear walls (SPSWs), idealizes the steel infill plate into several diagonal segments, each with a specific inclination angle and uniform cross-sectional area, forming a strip element. These strip or frame elements are generally defined as tension-only elements, a concept notably popularized by [6]. Modeling steel plate shear walls using the tension-only diagonal strip method requires adherence to several criteria or limitations, including slenderness ratio [7], aspect ratio (length-to-height ratio) [8], minimum moment of inertia for Vertical Boundary Elements (VBEs) [9].

Nonlinear Static Pushover Analysis

Pushover analysis is an approximate method that applies incrementally increasing lateral loads to a structure until components yield or fail. The model is updated to reflect reduced stiffness from yielding, and the process continues until a target roof displacement or instability

is reached. The resulting base shear (V) versus displacement (Δ) curve illustrates the structure's nonlinear behavior [10].

Structural Loading

Structural loading adheres to the SNI 1726:2019 for seismic loads and their load combinations. Meanwhile, PPPURG 1987 [11] and SNI 1727:2020 [12] are utilized for gravity loading.

Plastic Hinges Modelling

In SAP2000, plastic hinges can be modeled in two ways. Firstly, beam (M3) and column (P-M2-M3) plastic hinges can be assigned using the "Auto Hinges Assignment" feature, where the moment-curvature values are based on ASCE 41 design code provisions. Secondly, axial plastic hinges for strip elements are modeled using the "user-defined" option, allowing for manual input of their force-deformation relationships.

Structural Performance Levels

The objective of evaluating structural performance levels is to describe the potential structural and non-structural damage that may occur due to a planned seismic load. The structural performance level is assessed based on the classifications outlined in ATC-40 guidelines, which utilize the drift ratio as the primary indicator for determining the performance level of a structure. The maximum drift is calculated using Equation 1, with the maximum drift of the structure at the performance point (D_t) obtained from SAP2000 software using ATC-40 and FEMA 356 methodologies [13] [14]. The symbol "H" represents the structural height.

$$\frac{D_t}{H} \quad (1)$$

2.2 Methods

This research uses SAP2000 software to analyze the seismic behavior of a 5-story hospital building in Denpasar. Each floor is 4 meters high, and the building has a 30x30 m² footprint. The research flowchart can be seen in Figure 1, material data is in Table 1, and geometric data is in Figure 2. Low-yield steel is utilized for the Steel Plate Shear Wall (SPSW) plates to enhance ductility and prevent brittle fracture, aligning with a design philosophy that prioritizes plate yielding for seismic energy dissipation, keeping the main frame elastic. The SPSW placement follows findings from "Study on Non-Linear Behavior of Unstiffened Steel Plate Shear Walled Building Frames." [15].

Table 1. Material data of building

Component & Material	Material Grade (MPa)	Elasticity Modulus (MPa)
Column & Beam (BJ 41 Steel)	Fy = 250	2 x 10 ⁵
	Fu = 410	
Roof & Floor Slab (Concrete)	F'c = 30	25742.960
Slab Reinforcement (Steel Reinforcement)	Fy = 420	2 x 10 ⁵
	Fu = 546	
SPSW Plate (Low Yield Steel)	Fy = 165	2 x 10 ⁵
	Fu = 300	

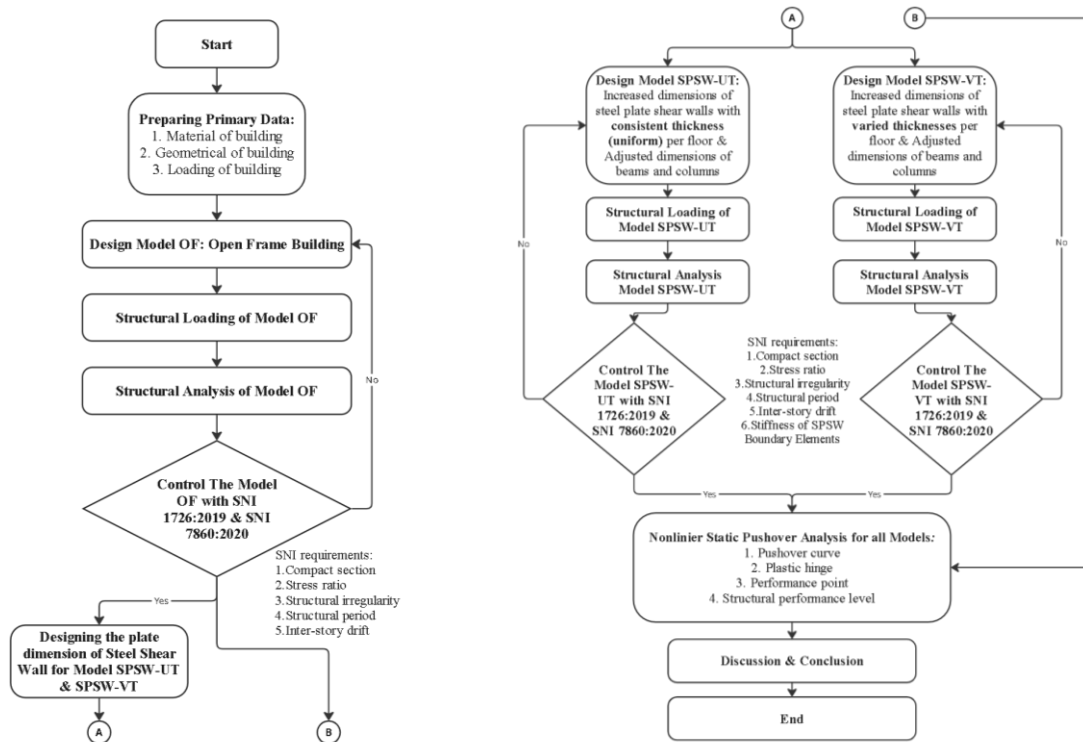
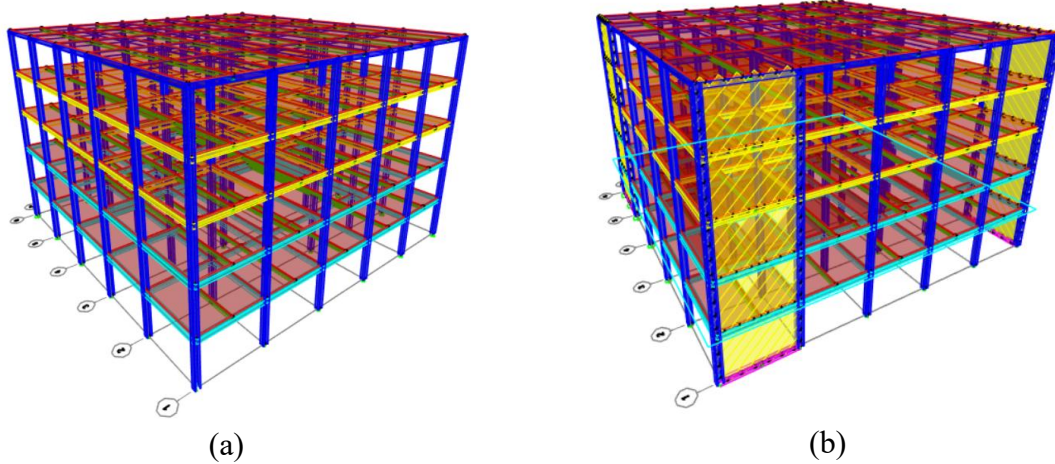


Figure 1. Flowchart of the research methodology



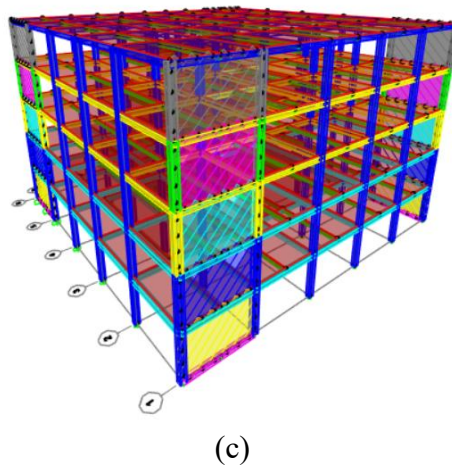


Figure 2. 3D view of all buildings (a) Open Frame (OF) Model, (b) SPSW-UT Model, (c) SPSW-VT Model

3. RESULTS AND DISCUSSION

Section Properties Used

The Model OF, Model SPSW-UT, and Model SPSW-VT have all undergone structural capacity checks, with all three models demonstrating stress ratio values of ≤ 1 . The section properties used for Model OF are presented in Table 2. The section properties for the SPSW Models can be found in Table 3 and Table 4.

Table 2. Section used for Model OF

Structural Component	Section Used
Column	W360X509
Main Beam (Girder)	Story 1-2 = W360X162
	Story 3-4 = W360X110
	Story 5 = W360X64
Secondary Beam (Joist)	W250X80
Floor Slab Thickness	130 mm
Roof Slab Thickness	100 mm

Table 3. Section used for Model SPSW-UT

Structural Component	Section Used
HBEs SPSW-UT	Ground Story = W360X196
VBEs SPSW-UT	W360X900
Plate Thickness of SPSW-UT	11.6 mm

Table 4. Section used for Model SPSW-VT

Structural Component	Section Used
HBEs SPSW-UT	Ground Story = W360X196
VBEs SPSW-UT	Story 1-2 = W360X900
	Story 3 = W360X744
	Story 4 = W360X551
	Story 5 = W360X463
	Story 1 = 11.6 mm
Plate Thicknesses of SPSW-UT	Story 2 = 10.8 mm
	Story 3 = 9.1 mm
	Story 4 = 6.2 mm
	Story 5 = 4.9 mm

Dual System Requirements Check

Adherence to SNI 1726:2019 requires the implementation of a dual system, where the moment-resisting frame is mandated to resist at least 25% of the seismic load. This provision ensures secondary resistance against lateral earthquake forces. Verification is performed by comparing the seismic load resisted by the frame system with that resisted by the shear walls. As stated in Table 5, compliance with this requirement is observed for both Model SPSW.

Table 5. Dual system requirements check of both Model SPSW

Model	Direction	SPSW System Support	Frame System Support
		Reaction (%)	Reaction (%)
SPSW-UT	X	62.39	37.61
	Y	71.65	28.35
SPSW-VT	X	62.62	37.38
	Y	71.78	28.22

Structural Period Check

Model SPSW-UT and Model SPSW-VT show significantly smaller structural periods compared to Model OF, as detailed in Table 6. This indicates superior structural stiffness in the SPSW models. For the SPSW models, the dominant mode shapes (modes 1-3) are consistently Y-translation, X-translation, and RZ-rotation, which aligns with SNI 1726:2019 clause 7.7.3 recommendations. In contrast, Model OF's second mode is translational, requiring an irregularity check to assess its behavior.

Table 6. Structural period check of all buildings

Model	Period (second)	Dominant Mode Shape
Open Frame (OF)	1.174586	Mode 1 = Y-translation
		Mode 2 = RZ-rotation
		Mode 3 = X-translation
SPSW-UT	0.64327	Mode 1 = Y-translation
SPSW-VT	0.661349	Mode 2 = X-translation
		Mode 3 = RZ-rotation

Structural Weight and Base Shear Check

As presented in Table 7, Model SPSW-VT's seismic weight and base shear are 0.992 times those of Model SPSW-UT. Compared to Model OF, Model SPSW-UT shows a 1.016 times greater seismic weight and a 1.610 times greater base shear, while Model SPSW-VT has a 1.009 times greater seismic weight and a 1.599 times greater base shear. These increases in seismic weight and base shear for the SPSW models are attributed to the additional mass from the VBEs sections and steel shear wall plates.

Table 7. Static analysis of all buildings

Model	Structural Weight (kN)	Base Shear (kN)
Open Frame (OF)	50548.7	4240.3
SPSW-UT	51334.2	6871.9
SPSW-VT	50922.6	6816.8

Structural Irregularity Check

The structural irregularity check in Table 8 specifically focuses on torsional irregularity types 1a and 1b. Generally, no structural irregularities were observed in Model OF or in either of the SPSW Models. The ratio (R) of the maximum displacement to the average displacement at each story level and for both earthquake directions (X and Y) remained below 1.3.

Table 8. Irregularity check of all buildings

Model	$R = \Delta_{max}/\Delta_{avg}$	Check $R \leq 1.3$
Open Frame (OF)	1	OKE
SPSW-UT	1	OKE
SPSW-VT	1	OKE

Inter-story Drift Check

Based on Figure 3, both Model OF and the SPSW Models exhibit inter-story drift values that are below their respective allowable drift limits. The difference in the allowable drift limit values is based on the distinct structural resisting systems: Model OF is a pure Special Moment Resisting Frame (SMRF), while Model SPSW-UT and VT are Dual Systems. The inter-story drift in Model SPSW-UT shows a maximum reduction of 34.23% in the X-direction and 50.69% in the Y-direction compared to Model OF. Similarly, Model SPSW-VT also achieves a maximum reduction of 30.98% in the X-direction and 49.80% in the Y-direction when compared to Model OF.

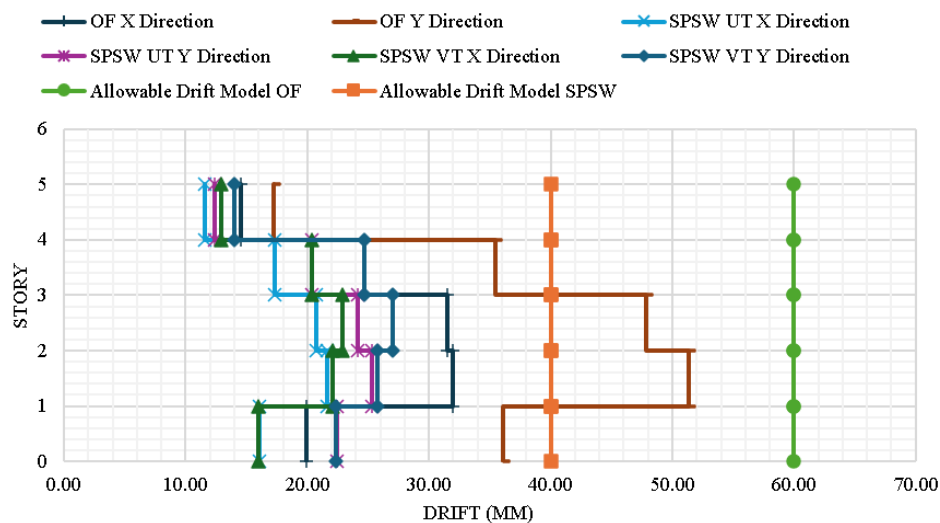


Figure 3. Inter-story drift of all buildings

Pushover Curve Analysis

Figure 4 illustrate the comparison of pushover curves for Model OF, Model SPSW-UT, and Model SPSW-VT in both the X and Y directions. The pushover curve analysis results for both X and Y directions clearly demonstrate that the SPSW (Steel Plate Shear Wall) models provide enhanced capacity compared to Model OF. This is evidenced by the pushover curves yielding larger base shear values, coupled with a longer "tail" of the curve, which signifies superior energy dissipation capability.

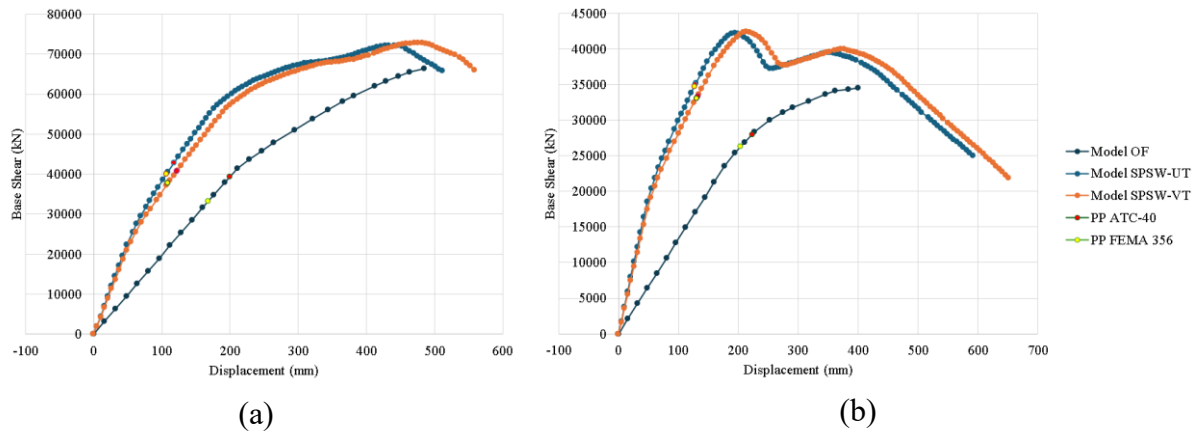


Figure 4. Pushover curve of all buildings (a) X-direction, (b) Y-direction

Based on the Performance Point (PP) values, Model SPSW-UT shows an increase in base shear compared to Model OF, with maximum increases of 20.19% for Push X direction and 32.29% for Push Y direction, according to FEMA 356. Furthermore, Model SPSW-UT demonstrates a significant reduction in displacement compared to Model OF, with maximum reductions of 40.99% for Push X direction and 42.49% for Push Y direction, according to ATC-40. Model SPSW-VT experiences similar, albeit slightly smaller, improvements when compared to Model OF. These percentages clearly indicate the expected performance enhancement in both Model SPSW-UT and Model SPSW-VT. Conversely, comparing Model SPSW-VT to Model SPSW-UT, there is a reduction in base shear of 5.70% for Push X and 4.79% for Push Y, as per FEMA 356. Additionally, Model SPSW-VT exhibits a slight increase in displacement compared to Model SPSW-UT, with maximum increases of 3.57% for Push X and 3.16% for Push Y, according to ATC-40.

Plastic Hinge Analysis

Regarding the plastic hinge mechanism at Figures 5 to 7, Model OF, Model SPSW-UT, and Model SPSW-VT, at the performance point for all models, plastic hinges only formed at the beam ends and/or at the column bases. There were no plastic hinges observed at the beam-column joints, indicating that these models did not experience a soft story mechanism. When comparing the number of plastic hinges that form relative to the total number of hinges, the results are as follows: Model OF pushover X: 292 out of 960 plastic hinges, Model OF pushover Y: 158 out of 960 plastic hinges, Model SPSW-UT pushover X: 326 out of 1168 plastic hinges, Model SPSW-UT pushover Y: 155 out of 1168 plastic hinges, Model SPSW-VT pushover X: 382 out of 1168 plastic hinges, Model SPSW-VT pushover Y: 183 out of 1168 plastic hinges.

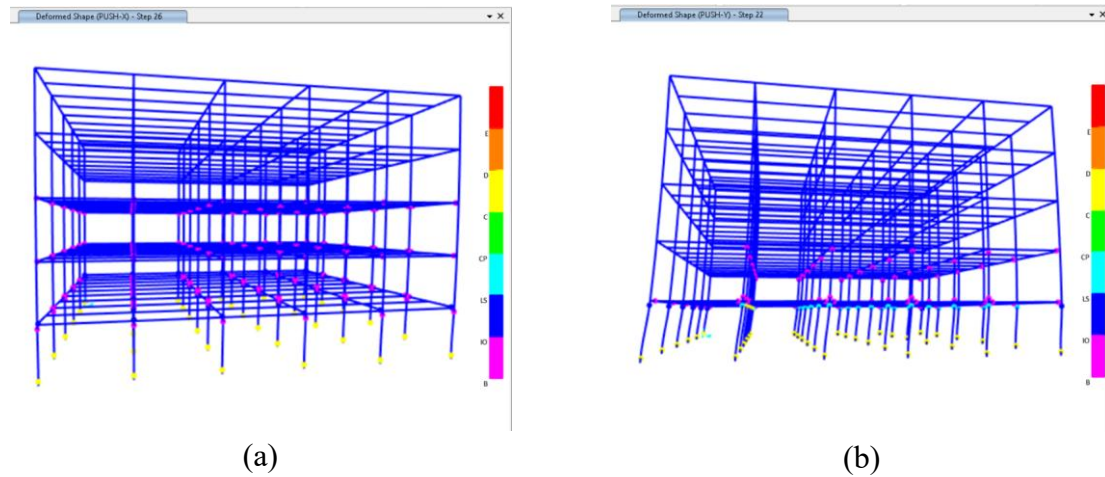


Figure 5. Last plastic hinge step Model OF (a) X-direction, (b) Y-direction

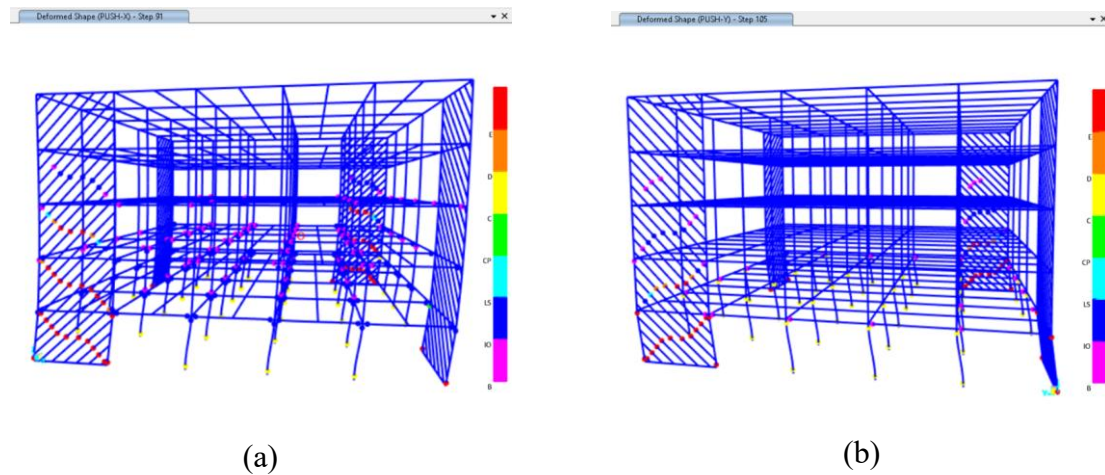


Figure 6. Last plastic hinge step Model SPSW-UT (a) X-direction, (b) Y-direction

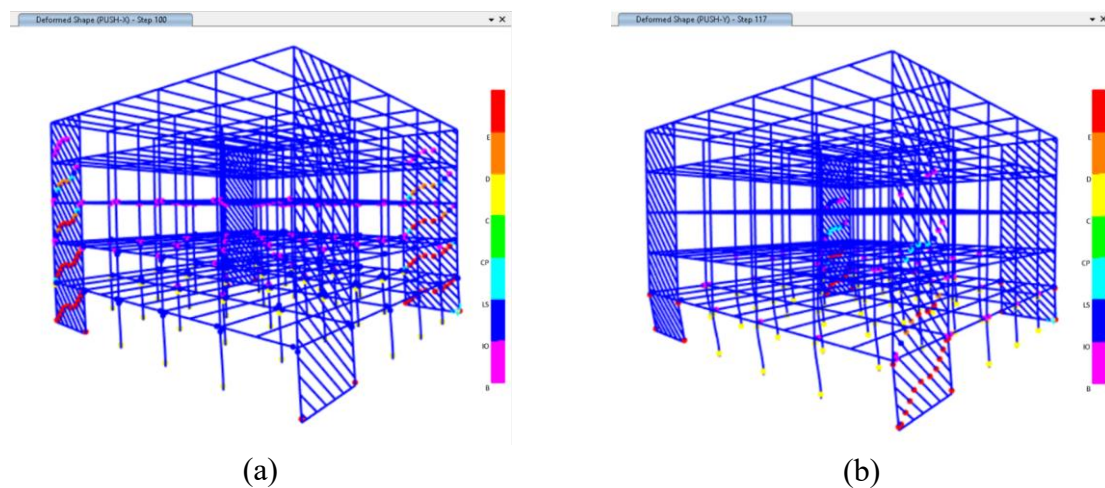


Figure 7. Last plastic hinge step Model SPSW-VT (a) X-direction, (b) Y-direction

Structural Performance Level Check

Model OF

For the ATC-40 Method:

$$Drift_x = \frac{0.199}{20} = 0.00995 \rightarrow (immediate\ occupancy)$$

$$Drift_y = \frac{0.223}{20} = 0.01115 \rightarrow (damage\ control)$$

For the FEMA 356 Method:

$$Drift_x = \frac{0.168}{20} = 0.0084 \rightarrow (immediate\ occupancy)$$

$$Drift_y = \frac{0.204}{20} = 0.0102 \rightarrow (damage\ control)$$

Model SPSW-UT

For the ATC-40 Method:

$$Drift_x = \frac{0.118}{20} = 0.0059 \rightarrow (immediate\ occupancy)$$

$$Drift_y = \frac{0.128}{20} = 0.0064 \rightarrow (immediate\ occupancy)$$

For the FEMA 356 Method:

$$Drift_x = \frac{0.107}{20} = 0.00535 \rightarrow (immediate\ occupancy)$$

$$Drift_y = \frac{0.127}{20} = 0.00635 \rightarrow (immediate\ occupancy)$$

Model SPSW-VT

For the ATC-40 Method:

$$Drift_x = \frac{0.122}{20} = 0.0061 \rightarrow (immediate\ occupancy)$$

$$Drift_y = \frac{0.132}{20} = 0.0066 \rightarrow (immediate\ occupancy)$$

For the FEMA 356 Method:

$$Drift_x = \frac{0.109}{20} = 0.00545 \rightarrow (immediate\ occupancy)$$

$$Drift_y = \frac{0.130}{20} = 0.0065 \rightarrow (immediate\ occupancy)$$

4. CONCLUSIONS

Here are the key conclusions from this study:

1. Model SPSW demonstrated superior stiffness, evidenced by shorter periods compared to Model OF.
2. Both SPSW Models showed a significant reduction in inter-story drift, with a maximum reduction of up to 50.69% for Model SPSW-UT and 49.80% for Model SPSW-VT compared to Model OF.
3. In the pushover curves and at the performance point, SPSW Models produced higher base shear values, with maximum increases of up to 32.29% for Model SPSW-UT and 25.965% for Model SPSW-VT relative to Model OF.
4. Model SPSW-VT exhibited the best energy dissipation capability, indicated by a plastic hinge distribution of 382/1168 for the X-direction and 183/1168 for the Y-direction.
5. Both SPSW Models achieved an Immediate Occupancy (IO) performance level for both pushover directions. In contrast, Model OF only reached IO in the X-direction and Damage Control (DC) in the Y-direction, highlighting the significant performance improvement gained from using steel plate shear walls.

5. SUGGESTIONS

For future research, it's recommended to consider pin supports ideally suited for steel structures and varying the orientation of steel section axes to achieve optimal performance in both principal directions. It's also crucial to employ cyclic loading through either response spectrum analysis or time history analysis as an idealized seismic load, and to incorporate notional loads to account for additional lateral forces due to geometric imperfections.

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