Structural Performance of SPSWs with Unstiffened Slender, Moderate, and Stocky LYP Steel Infill Plates

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SUMMARY:
Infill plates in steel plate shear walls (SPSWs) may be categorized as slender, moderate, and stocky, depending on their geometrical buckling and material yielding behaviour. In slender infill plates, buckling precedes yielding, while in stocky infill plates yielding occurs before buckling. Moderate infill plates, on the other hand, undergo simultaneous buckling and yielding. In order to improve the buckling stability, energy absorption capacity, and serviceability of thin-webbed SPSW systems, stiffened and/or relatively thick infill plates typically need to be employed. However, such lateral load resisting systems made of conventional steel may not be economical in terms of fabrication and construction costs. Use of low yield point (LYP) steel with extremely low yield stress and high elongation properties may enable the design of economically sound SPSW systems with improved structural, seismic, and serviceability characteristics. On this basis, the behaviour and performance of SPSWs with unstiffened slender, moderate, and stocky LYP steel infill plates are investigated in this paper through finite element analysis. The limiting plate thickness corresponding to concurrent geometrical-material bifurcation is accurately determined, and accordingly SPSWs with infill plates having various slenderness ratios are studied. The results and findings of this study indicate that the use of LYP steel results in desirable and improved structural and hysteretic performance of SPSWs so they can be used as efficient lateral load resisting systems.

Keywords: Steel plate shear wall; LYP steel; Plate slenderness; Buckling; Structural and hysteretic performance

1. INTRODUCTION

During the past three decades or so, SPSW systems have been used as the primary or part of the primary lateral force-resisting system in low- and high-rise buildings. In consideration of cost, performance, and design, these relatively new and efficient lateral-force resisting systems offer many advantages over other conventional systems, and hence have been increasingly used in retrofit of existing structures and new constructions.

SPSWs are composed of infill plates, horizontal and vertical boundary frame members, i.e. beams (HBEs) and columns (VBEs). Infill plates are the primary stiffening and damping components in such systems, whose stability and performance are characterized by geometrical buckling and material yielding. Based on their slenderness parameter, material yielding may occur either before or after or even at the same time as buckling. Hence, steel plates may be qualitatively and quantitatively divided into slender, moderate, and stocky categories. Slender plates undergo elastic buckling and then yield in the post-buckling stage. Moderate plates, on the other hand, undergo simultaneous buckling and yielding, while stocky plates yield first and then undergo inelastic buckling (Gheitasi and Alinia, 2010).

SPSWs have been used with two different design philosophies as well as detailing strategies. One approach employs heavily-stiffened and/or stocky infill plates to ensure that the wall panel achieves its full plastic strength prior to out-of-plane buckling. Such systems are current practice in Japan, where the high fabrication cost is tolerated in order to achieve high seismic and structural performance. North American practice, on the other hand, is to use unstiffened and slender-web SPSWs. Such relatively cost-effective systems undergo early elastic buckling and the lateral loads are resisted through development of diagonal tension-field action within the infill plate in post-buckling stage (Esfandiar and Barkhordari, 2008). Use of LYP steel with extremely low yield stress and high elongation properties provides the possibility to take advantage of merits of both stiffened and unstiffened configurations and balance between structural and economical considerations. Application of LYP steel infill plates has been shown to improve the buckling stability, serviceability, and damping capability of SPSW systems in a number of experimental studies, e.g. Tsai and Lin (2005) and Chen and Jhang (2006 and 2011), and numerical investigations, e.g. Bruneau and Bhagwagar (2002) and Mistakidis (2010), and the respective research is still underway.

This paper aims to present a numerical study on structural behaviour of several code-designed SPSWs with unstiffened slender, moderate, and stocky LYP steel infill plates under monotonic and cyclic loading. To achieve the objectives of this paper, the limiting thickness corresponding to simultaneous buckling and yielding of the moderate plate is first determined via theoretical and numerical approaches, and accordingly discussion is made on practical determination of this specific plate thickness in SPSW systems. The structural performances of SPSW systems with various thicknesses in comparison to the limiting plate thickness are evaluated in detail subsequently. The results demonstrate the desirable and improved performance when LYP steel infill plates are used.

2. DESIGN OF SPSW MODELS

In this study, six single-story, single-bay, and full-scale steel shear walls with 2000×3000, 3000×3000, and 4500×3000 mm LYP steel infill plates of various slenderness ratios are designed based on the capacity-design principles, so that the infill plates can yield in tension prior to plastic hinging of the boundary frame members. The performances of these systems largely depend on the thickness of the infill plate. A limiting plate thickness corresponding to concurrent geometrical-material bifurcation condition is defined and estimated first.

Considering that the infill plates in SPSW systems are largely subject to shear stress along the edges, the limiting thicknesses ($t_{p\text{-}limit}$) of the unstiffened and LYP100 steel infill plates are estimated by setting the critical buckling shear stress (τ_{cr}) of a clamped plate equal to the plate shear yield stress ($\tau_{yp} = \sigma_{yp}/\sqrt{3}$) determined by considering the von Mises yield criterion. It consequently leads to:

$$t_{p\text{-}limit} = b \times \sqrt{\frac{12 \times (1 - v^2) \times \sigma_{yp}}{(8.98 + 5.6/(a/b)^2) \times \pi^2 \times E \times \sqrt{3}}} \quad (2.1)$$

in which, E (=200000 MPa), v (=0.3), and σ_{yp} (=100 MPa) are Young's modulus, Poisson's ratio, and plate yield stress, respectively. In addition, a and b are taken as the respective maximum and minimum values of length (l) and height (h) of the infill plate. In order to evaluate the accuracy of predictions of Eqn. 2.1, the exact values of the limiting plate thickness are also obtained through a numerical iterative process in which nonlinear finite element analyses are repeatedly performed in order to reach a concurrent geometrical-material bifurcation condition, i.e. $P_y / P_{cr} = 1.0$ where P_y is the lateral load corresponding to plate's first yield point and P_{cr} is the critical buckling load of the SPSW model. The estimated values of the limiting plate thickness are tabulated in Table 2.1.

As it is seen in the table, agreement between predictions of Eqn. 2.1 and exact values of the limiting plate thickness is quite satisfactory. Another possible approach in determining the limiting thickness of the infill plate is to interpolate between the cases for simple and clamped support conditions as the boundary condition of the plate in a SPSW system is partially clamped. However, the excellent agreement shown in Table 2.1 indicates that the assumption of clamped support condition provides reliable estimates for the limiting plate thickness and can be confidently applied in practice provided that the boundary frame members are properly designed and are of sufficient stiffness and strength. The simultaneous geometrical buckling and material yielding of SPSW systems employing plates with limiting thicknesses ($t_{p\text{-}limit}$) is demonstrated numerically in the next section.

Table 2.1. Limiting thicknesses of unstiffened moderate LYP100 steel infill plates

$l \times h$ (mm)	Finite Element Model	$t_{p\text{-}limit}$ (mm)	
		Eqn. 2.1	Exact
2000×3000	SPSW1	10.6	10.3
3000×3000	SPSW4	14.0	13.5
4500×3000	SPSW6	15.8	16.0

One could also use Eqn. 2.1 to compute the limiting thickness for conventional steel by just using the respective yield stress (σ_{yp}). It is important to note that use of LYP100 steel with extremely low yield stress compared to the conventional steel results in relatively smaller limiting thickness values for unstiffened infill plates. Hence, LYP steel plates with thicknesses within the practical limits (in terms of economical considerations) can be employed to ensure early yielding and effective dissipation of the earthquake input energy.

Furthermore, boundary frame members for SPSW systems are designed in accordance with the strength and stiffness requirements specified in the latest AISC 341-10 (2010) design code, and ASTM A572 Gr. 50 steel with 345 MPa yield stress is selected for these components. Specifications of the code-designed SPSW models are provided in Table 2.2 along with their respective performance characterization as slender, moderate or stocky plates.

Table 2.2. Specifications of the code-designed SPSW models

Model	Infill Plate		Beam (HBE)	Column (VBE)
	$l \times h \times t_p$ (mm)	Type		
SPSW1	2000×3000×10.6	Moderate	W14×120	W14×311
SPSW2	3000×3000×4.7	Slender	W14×120	W14×132
SPSW3	3000×3000×9.3	Slender	W14×233	W14×257
SPSW4	3000×3000×14.0	Moderate	W14×311	W14×342
SPSW5	3000×3000×18.7	Stocky	W14×398	W14×426
SPSW6	4500×3000×15.8	Moderate	W30×391	W14×370

It is noted that according to the AISC 341-10 (2010) design requirements, boundary columns shall have moments of inertia (I_c) not less than $0.0031 t_p h_s^4 / l_s$, and boundary beams shall have moments of inertia (I_b) not less than $0.0031 l_s^4 / h_s$ times the difference in web plate thicknesses above and below, where l_s is the distance between column centerlines and h_s is the distance between beam centerlines. According to the findings of this study, these stiffness criteria seem to be fairly stringent in controlling the design in most cases. Hence, further research is required to evaluate the effectiveness of the specified stiffness criteria.

3. FINITE ELEMENT MODELLING AND ANALYSIS

ANSYS 11.0 (2007) is used in this study for developing and analyzing the finite element SPSW models. Infill plate and boundary beam as well as column components of SPSWs are modelled by Shell181 element. This four-node element with six degrees of freedom at each node is suitable for analyzing thin to moderately-thick shell structures and is also well-suited for linear, large rotation, and/or large strain nonlinear applications. Typical finite element models of the SPSWs with various aspect ratios are shown in Fig. 3.1.

As it is seen in the figures, both columns are fully fixed at their bases and all HBE-VBE intersections are laterally braced. Moreover, HBEs in SPSW6 model are also braced at their midspan against lateral displacement. Fig. 3.2 shows the stress-strain relationships as well as mechanical properties of the steel material applied in finite element modelling. In addition, von Mises yield criterion is used for material yielding, and isotropic and kinematic hardening rules are incorporated in the respective nonlinear pushover and cyclic analyses.

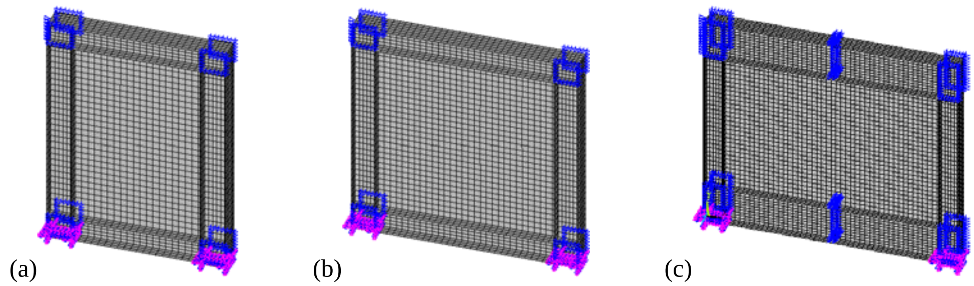


Figure 3.1. Finite element models: (a) SPSW1; (b) SPSW4; (c) SPSW6

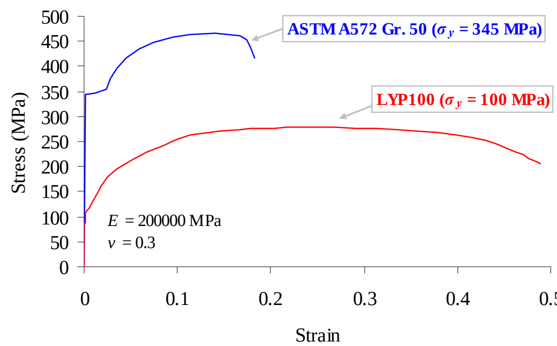
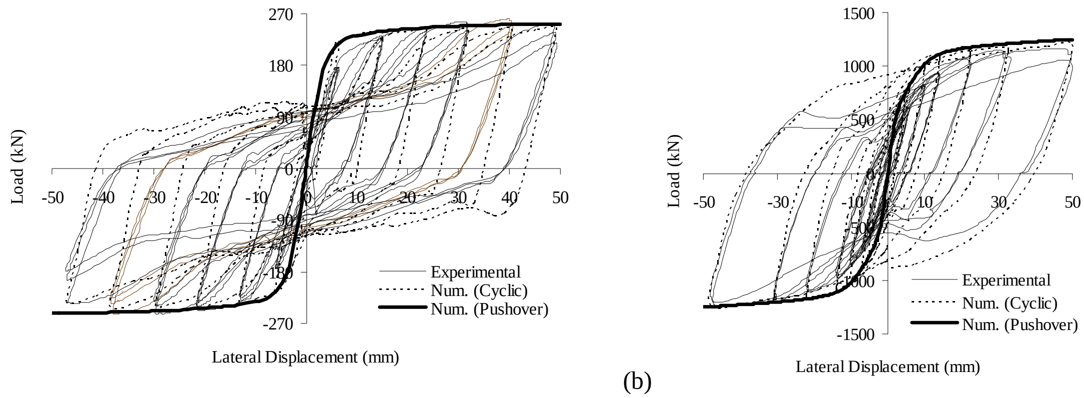


Figure 3.2. Material properties of the SPSW components

In order to account for initial imperfections, very small out-of-plane deformations of about $\sqrt{l \times h}/1000$ and proportional to the lowest eigen-mode shape of elastic buckling are introduced to the SPSW models, which are smaller than 1% of $\sqrt{l \times h}$ limit proposed by Behbahanifard et al. (2003). In-plane lateral load is applied to the beam-column connection, as shown in Fig. 3.1, in a displacement-controlled and incremental manner, and both geometrical and material nonlinearities are considered in the finite element analyses.

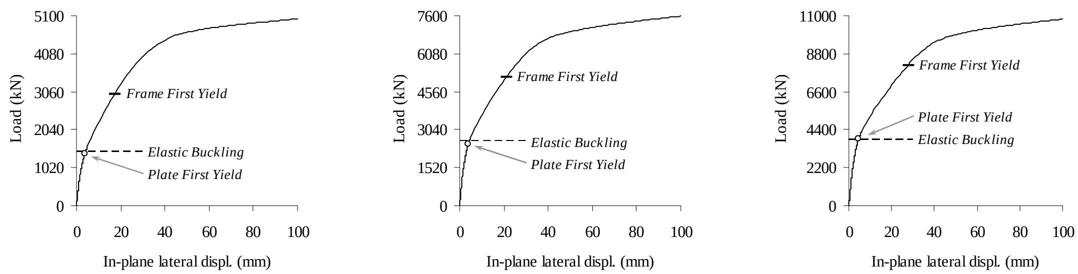
Numerical modelling of SPSWs is validated by considering two sets of test results reported by Lubell (1997) and Chen and Jhang (2006) representing SPSWs with respective slender (825×825×1.5 mm, hot-rolled steel) and stocky (1250×1250×8.0 mm, LYP100 steel) infill plates. The comparison results illustrated in Figs. 3.3(a) and 3.3(b) indicate that the agreement between numerical and experimental results is quite satisfactory in both cases.

Fig. 3.4 also plots the load versus in-plane displacement for SPSW1, SPSW4, and SPSW6 models as tabulated in Table 2.2. These three SPSW models with different aspect ratios have infill plates with limiting thicknesses predicted using Eqn. 2.1. As it is seen in Fig. 3.4, all three models have the plate first yield occurring simultaneously with the elastic buckling. This again indicates the accuracy of Eqn. 2.1 in determining the limiting plate thickness.



(a) (b)

Figure 3.3. Validation of numerical modelling: (a) Lubell (1997); (b) Chen and Jhang (2006)



(a) (b) (c)

Figure 3.4. Buckling and yielding of SPSW models with limiting plate thicknesses determined using Eqn. 2.1: (a) SPSW1, $t_p = 10.6$ mm; (b) SPSW4, $t_p = 14.0$ mm; (c) SPSW6, $t_p = 15.8$ mm

4. DISCUSSION OF RESULTS

In this section, the structural and hysteretic behaviours of SPSW models with 3000×3000 mm unstiffened and LYP steel infill plates of various slenderness ratios (h/t_p) as well as buckling and yielding characteristics are investigated. Employment of LYP steel plates may result in SPSW systems with low yielding and relatively high buckling capacities. Hence, the objective of this study is to identify and investigate the structural characteristics and performance of shear wall systems with slender, moderate, and stocky infill plates with improved buckling as well as energy dissipation capacities, and serviceability.

Lateral load versus out-of-plane displacement curves representing the buckling stability of the SPSW models are illustrated in Fig. 4.1. Shown in Fig. 4.2 are also the lateral load versus drift ratio curves which, in turn, represent the in-plane behaviour of the SPSW models. Elastic buckling capacities of the SPSWs denoted by *E.B.*, and plate as well as frame first yield points denoted by *P.Y.* and *F.Y.*, respectively, are also shown in the figures.

First of all, it is important to note that in all cases, yielding of the LYP steel infill plate occurs before frame yielding. This is mainly attributed to the fact that boundary frame members are properly designed based on the capacity-design principles, and accordingly elastically resist the development of the full expected yield strength of the infill plate. However, the effective role of low yield stress of the LYP steel is of great significance in this regard as well, since with lower yielding strength of the infill plate, it is easier to design the system to let the infill plate yield prior to that of the surrounding frame and to ensure that the frame would not collapse before the wall reaches its ultimate strength (Chen and Jhang, 2006). As a result, it may be concluded that the low yield strength provides better strength ratio between the infill plate and the surrounding frame with good arrangement of capacities.

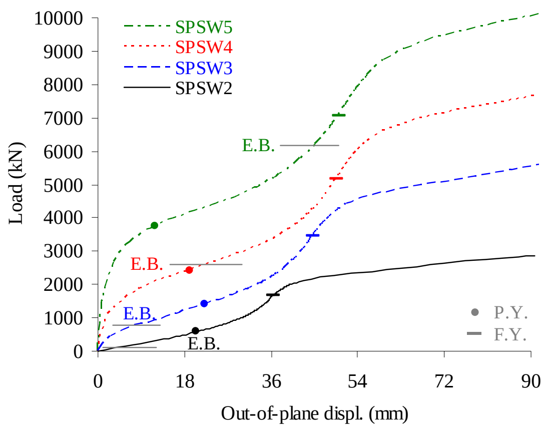


Figure 4.1. Buckling stability of SPSW models

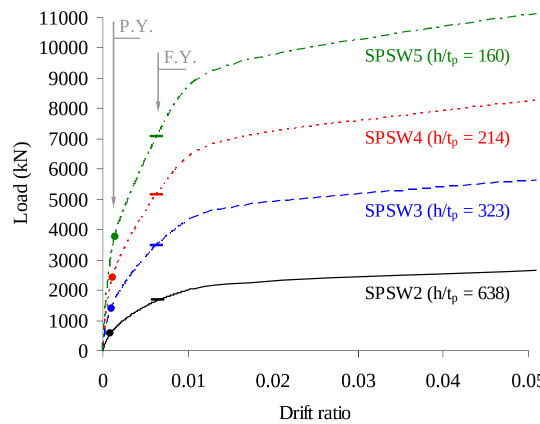


Figure 4.2. In-plane behaviour of SPSW models

Fig. 4.1 shows that SPSW models with slender, moderate, and stocky infill plates exhibit various buckling and yielding sequences. It is notable that the moderate fill plate in SPSW4 model undergoes simultaneous buckling and yielding, as expected. In addition, from Fig. 4.1, it is clear that increase of plate thickness results in a considerable increase in buckling strength and decrease in out-of-plane deformation which is, in turn, indicative of improved serviceability. Fig. 4.2 also shows that the strength and stiffness of the SPSW system under in-plane lateral load are enhanced due to the decrease of plate slenderness ratio (h/t_p). Stiffness performance of the SPSW models is further demonstrated in Fig. 4.3.

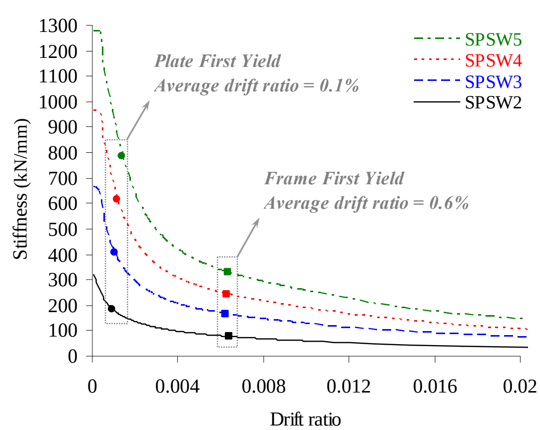


Figure 4.3. Stiffness performance of SPSW models

As it is seen in Fig. 4.3, all four SPSW models possess similar and stable stiffness performance in the elastic and inelastic ranges of structural response. The stiffness of the SPSW models decays as the drift ratio increases. However, most of the stiffness reduction occurs at lower drift ratios due to yielding and buckling of the LYP steel infill plate. Furthermore, as it is shown in Figs. 4.2 and 4.3, the plate and frame first yields occur at 0.1% and 0.6% average drift ratios, respectively. It is believed that the stable stiffness performance of all SPSW models is mainly contributed by the LYP steel material properties and also the proper design of the boundary frame members.

Fig. 4.4 shows the von Mises stress contour plot of SPSW4 model with moderate LYP steel infill plate at 3% drift ratio. As it is observed in Fig. 4.4, the infill plate of SPSW4 model is fully yielded at 3%

drift ratio which is accompanied by partial yielding of the boundary frame members due to the effect of diagonal tension-field action within the web-plate. From the figure, it is evident that yielding of the LYP steel material is spread over the entire infill plate which, in turn, ensures a very large global energy dissipation capability. This indicates that LYP steel infill plates can effectively act as seismic energy dissipation conduit without major involvement of the frame structure.

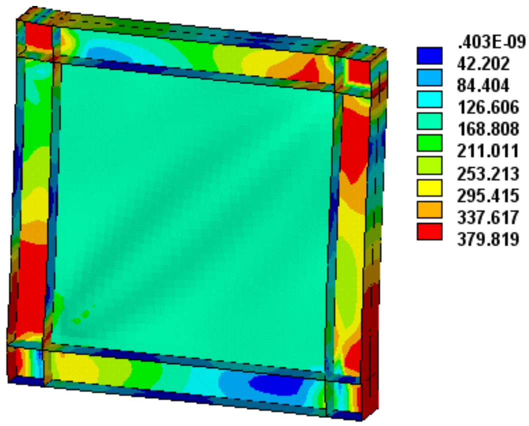


Figure 4.4. von Mises stress contour plot of SPSW4 model at 0.03 drift ratio

Cyclic behaviour of the SPSW models with unstiffened LYP steel infill plates of various slenderness ratios is also investigated here by means of nonlinear finite element analysis. The cyclic loading protocol is given in Table 4.1, and also the hysteresis curves of the SPSW models are shown in Fig. 4.5. Due to the early buckling phenomenon in thin unstiffened steel infill plates and regardless of the rigidity of the boundary members, unstiffened thin-webbed SPSWs do not possess great energy dissipation capacity. Hence, use of stiffeners in mild (conventional) steel infill plates is the most common method to prevent pinching of the hysteresis curves and consequently increase energy dissipation capacity (Alinia and Dastfan, 2007).

Table 4.1. Cyclic loading protocol

Cycle No.	1	2	3	4	5	6	7	8	9
Drift ratio	0.001	0.0025	0.005	0.01	0.015	0.02	0.03	0.04	0.05

Evaluation of hysteresis curves of the code-designed SPSW models with unstiffened LYP steel infill plates of various slenderness ratios, as shown in Fig. 4.5, demonstrates stable and ductile behaviour as well as desirable cyclic performance in all cases. However, from the figures it is apparent that decreasing of infill plate slenderness ratio (h/t_p) improves the hysteretic behaviour of the SPSW system by improving the buckling stability and decreasing the severity of pinching effect in the hysteresis loops resulting in the change of shape of the hysteresis loops from "S" shape to "spindle" shape. The variations of the cumulative dissipated energy (CDE) of the SPSW models at various cycles are also shown in Fig. 4.6.

Fig. 4.6 shows that the energy dissipated by the SPSW system increases as the thickness of the infill plate increases. From the figure it is also found that employment of LYP steel infill plates with low yielding strength results in early yielding and energy dissipation of the SPSW system from the initial stages of loading process.

Lastly, it is well known that stiffness, strength, and energy dissipation capacity are three important properties of every lateral force-resisting system which are indicative of its structural and seismic performance. On this basis and in order to make an overall and quantitative assessment of structural and seismic characteristics of the studied SPSW models with unstiffened LYP steel infill plates, the infill plate thickness (t_p), initial stiffness (K_i), strength at 0.05 drift ratio ($P_{DR=0.05}$), and total cumulative dissipated energy ($(CDE)_t$) values of the SPSW models are captured and summarized in Table 4.2. These quantities are also presented in a normalized manner by dividing each by the corresponding quantities of the SPSW2 model.

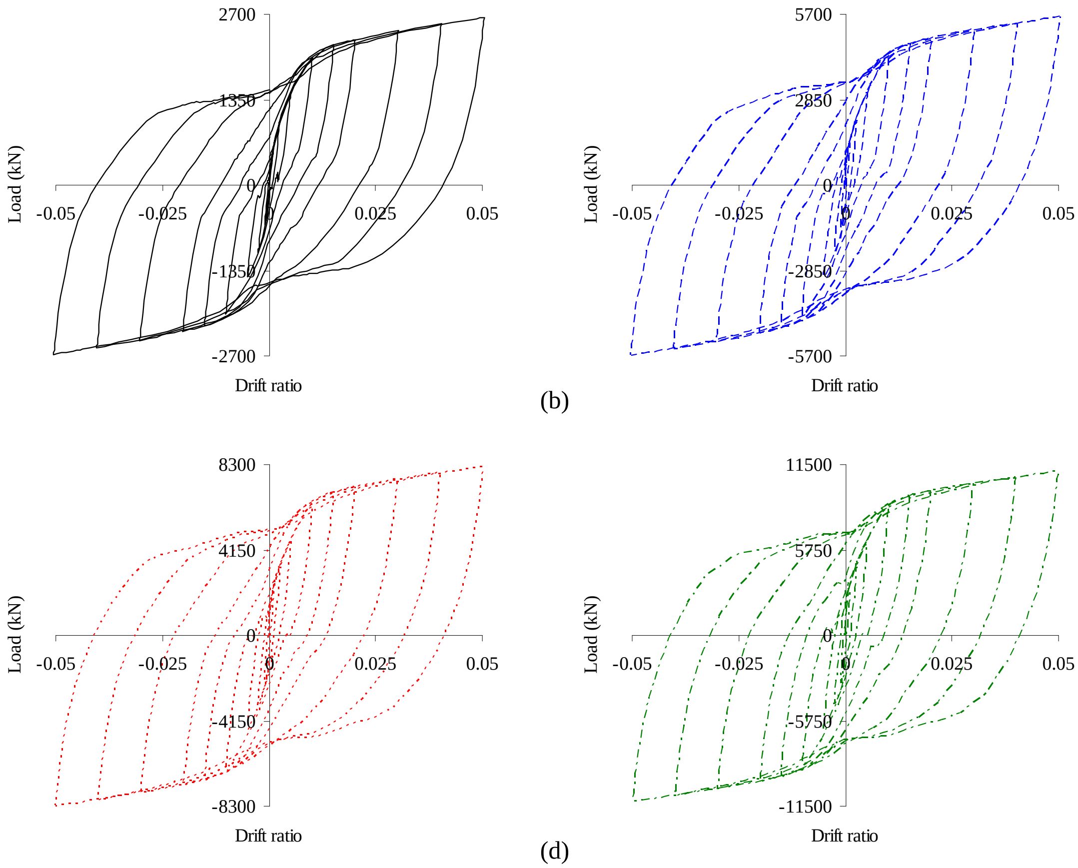


Figure 4.5. Hysteresis curves of SPSW models: (a) SPSW2; (b) SPSW3; (c) SPSW4; (d) SPSW5

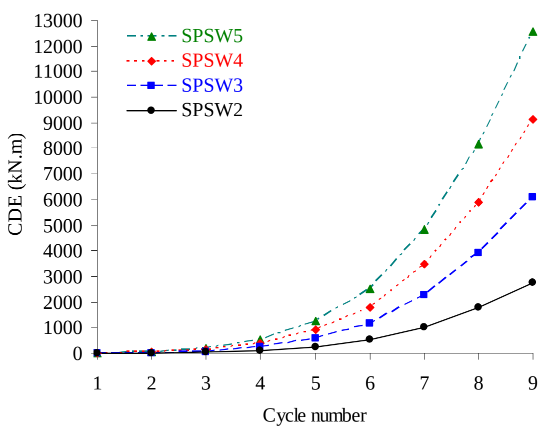


Figure 4.6. Variations of cumulative dissipated energies of SPSW panels

Table 4.2. Summary of structural and seismic properties of SPSW models

Model	t_p (mm)	t_p / $t_{p\text{-}SPSW2}$	K_i (kN/mm)	K_i / $K_{i\text{-}SPSW2}$	$P_{DR=0.05}$ (kN)	P / P_{SPSW2}	$(CDE)_t$ (kN.m)	$(CDE)_t$ / $(CDE)_{t\text{-}SPSW2}$
SPSW2	4.7	1.00	322.5	1.00	2653.2	1.00	2756.2	1.00
SPSW3	9.3	1.98	664.7	2.06	5606.4	2.11	6074.6	2.20
SPSW4	14.0	2.98	967.7	3.00	8198.9	3.09	9111.5	3.31
SPSW5	18.7	3.98	1275.2	3.95	11042.1	4.16	12563.0	4.56

The tabulated results in Table 4.2 indicate that stiffness, strength, and energy dissipation capacity values increase almost proportionally with the increase in infill plate thickness values. It is also found that the CDE ratios possess the highest rate of increase compared to stiffness and strength ratios. Overall, these findings are indicative of desirable structural characteristics as well as damping capabilities of SPSW systems with unstiffened LYP steel infill plates, which consequently qualify them as efficient lateral force-resisting and energy dissipating systems.

5. CONCLUSION

Application of unstiffened and thin-webbed SPSW systems with low buckling capacity, on the one hand, may result in reduced strength, stiffness, energy absorption capacity, and serviceability problems, and use of heavily-stiffened and/or thick infill plates in SPSW systems with relatively higher structural, seismic, and serviceability performance, on the other hand, may undesirably impose high fabrication and construction costs. Hence, employment of unstiffened LYP steel infill plates in SPSW systems may enable to balance both structural and economical considerations and consequently to apply relatively cost-effective SPSW systems with improved buckling stability, serviceability and damping capability. On this basis, structural behaviour and damping characteristics of SPSWs with unstiffened LYP steel infill plates were investigated in this paper via nonlinear finite element analysis.

Slenderness ratios of the infill plates were selected on the basis of slender, moderate, and stocky classification of steel plates in the light of using LYP steel material. In order to achieve this, the limiting thicknesses corresponding to concurrent geometrical-material bifurcation of the moderate infill plates with various aspect ratios were initially predicted theoretically and verified by nonlinear finite element analyses.

Results of the nonlinear finite element analyses showed that SPSW systems with properly-designed boundary frame members as well as unstiffened LYP steel infill plates generally possess desirable strength, stiffness, and hysteresis performance. Particularly, use of LYP steel infill plates results in a favorable plate-frame yielding sequence and in fact facilitates the design of the SPSW systems. It is notable that use of LYP steel enables the employment of moderate and/or stocky infill plates with relatively low yielding and high buckling capacities, that this, in turn, considerably increases the damping capability of the SPSW system.

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