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Hysteretic performance of SPSWs with trapezoidally horizontal corrugated web-plates

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Abstract. Previous research has shown that steel plate shear walls (SPSWs) are efficient lateral force-resisting systems against both wind and seismic loads. A properly designed SPSW can have high initial stiffness, strength, and energy absorption capacity as well as superior ductility. SPSWs have been commonly designed with unstiffened and stiffened infill plates based on economical and performance considerations. Recent introduction and application of corrugated plates with advantageous structural features has motivated the researchers to consider the employment of such elements in stiffened SPSWs with the aim of lowering the high construction cost of such high-performing systems. On this basis, this paper presents results from a numerical investigation of the hysteretic performance of SPSWs with trapezoidally corrugated infill plates. Finite element cyclic analyses are conducted on a series of flat- and corrugated-web SPSWs to examine the effects of web-plate thickness, corrugation angle, and number of corrugation half-waves on the hysteretic performance of such structural systems. Results of the parametric studies are indicative of effectiveness of increasing of the three aforementioned web-plate geometrical and corrugation parameters in improving the cyclic response and energy absorption capacity of SPSWs with trapezoidally corrugated infill plates. Increasing of the web-plate thickness and number of corrugation half-waves are found to be the most and the least effective in adjusting the hysteretic performance of such promising lateral force-resisting systems, respectively. Findings of this study also show that optimal selection of the web-plate thickness, corrugation angle, and number of corrugation half-waves along with proper design of the boundary frame members can result in high stiffness, strength, and cyclic performances of such corrugated-web SPSWs.

Keywords: steel plate shear wall; trapezoidally corrugated web-plate; numerical simulation; cyclic behavior; energy dissipation capacity

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1. Introduction

Steel plate shear walls (SPSWs) have been increasingly used as the primary or part of the primary lateral force-resisting system in design of buildings. Their application has been based on two different design philosophies as well as detailing strategies. Stiffened and/or stocky-web SPSWs with improved buckling stability and high seismic performance have been mostly used in Japan. Unstiffened and slender-web SPSWs, on the other hand, have been deemed as a rather economical alternative and accordingly widely used in the United States and Canada (Zirakian 2013). Nonconventional wall configurations, such as walls with corrugated panels, have been also considered and studied by some researchers as an effective alternative to improve the structural as well as seismic performances of unstiffened and slender-web SPSWs.

Mo and Perng (2000) reported an experimental study on framed shearwalls made of corrugated steel and demonstrated the improved seismic performance of such structural systems. Berman and Bruneau (2005), also, performed experimental study on light-gauge and single-story SPSW specimens with flat and corrugated infill plates using quasi-static loading. It was shown that the specimen utilizing corrugated infill plate can achieve significant ductility and energy dissipation while minimizing the demands placed on the surrounding framing. Another experimental study was conducted by Stojadinovic and Tipping (2008) to develop an alternative lateral bracing system comprising corrugated sheet steel shear walls for use with light-framed cold-formed steel buildings, which was considered to be stronger, more flexible and cost-effective relative to the traditional bracing systems. The results of a numerical study conducted by Gholizadeh and Yadollahi (2012), also, showed that the behavior of a corrugated plate is superior to that of a flat plate due to its higher loading capacity, ductility, and energy absorption capability. Additionally, the results of a recent experimental investigation, reported by Emami *et al*. (2013), on half-scale, one-story and single-bay steel shear walls with unstiffened and trapezoidally corrugated panels demonstrated the improved energy dissipation capacity, ductility, and initial stiffness of the corrugated-web SPSWs compared to the unstiffened SPSWs. Most recently, the behavior of trapezoidally corrugated SPSWs under monotonic and cyclic loadings was further investigated by Emami and Mofid (2014) through detailed numerical simulations. In another study reported by Edalati *et al*. (2014), the nonlinear behavior of SPSWs with sinusoidal and trapezoidal corrugated web-plates under lateral pushover load was investigated and the high performance of SPSWs with trapezoidal corrugated infill plates in terms of energy dissipation, ductility, and ultimate bearing was demonstrated.

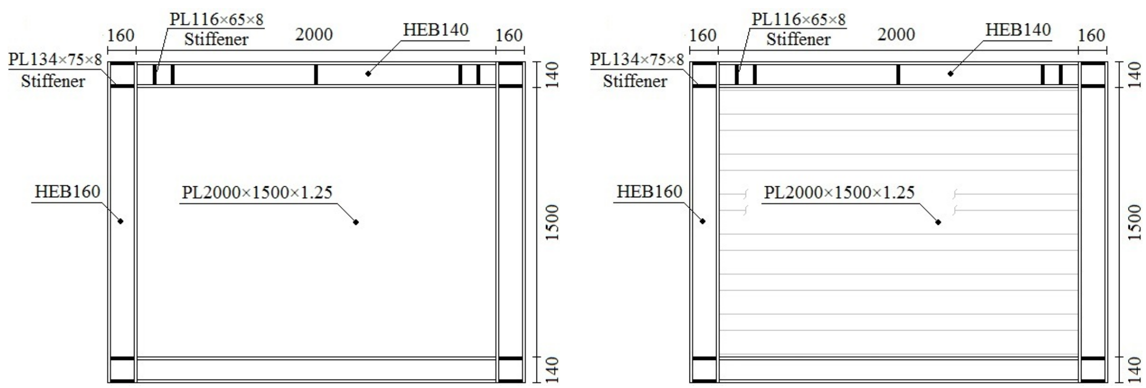
In this paper, the cyclic performances and energy dissipation characteristics of SPSWs with flat and corrugated web-plates of trapezoidal form are investigated comparatively by performing numerical parametric studies on the experimental specimens tested and reported by Emami *et al*. (2013) and Emami and Mofid (2014). To this end, various finite element models of the considered flat- and corrugated-web test specimens are developed by changing the geometrical and corrugation parameters including the web thickness, and number of corrugation half-waves and angle. Results and findings of this study can provide significant insight into the design of cost-effective and high-performing corrugated-web SPSWs with trapezoidal pattern.

2. Specifications of the considered SPSW models

In this research, the SPSW specimens with flat and trapezoidally corrugated infill plates, tested by Emami *et al*. (2013), are adopted and parametric studies are performed by changing the infill plate thickness, number of corrugation half-waves, and corrugation angle in the finite element models of these test specimens. Details of the modeled SPSW specimens with flat and corrugated web-plates are shown in Fig. 1. The tested specimens are modeled with minor modifications in this study. According to Emami *et al*. (2013), the SPSW specimens were designed based on the plate-frame interaction (PFI) method developed by Sabouri-Ghomi *et al*. (2005).

Geometrical properties of a typical corrugated web-plate with trapezoidal pattern are illustrated in Fig. 2, in which w = fold width, d = corrugation depth, θ = corrugation angle, t_w = web thickness, and N = number of corrugation half-waves. t_w, θ, and N are considered as the effective geometrical and corrugation parameters in evaluation of cyclic performance and energy dissipation characteristics of the flat- and corrugated-web SPSWs, and on this basis, 22 SPSW models with various t_w, θ, and N values are considered in this study.

The specifications of the considered SPSW models with flat and corrugated infill plates are summarized in Table 1. As it is seen in the table, the SPSWs are labeled such that the infill plate



(a) Flat-web SPSW specimen (b) Corrugated-web SPSW specimen

Fig. 1 Details of the modeled experimental specimens tested by Emami *et al*. (2013)

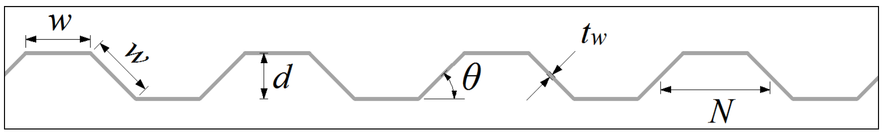


Fig. 2 Geometrical properties of the corrugated plate (N = 8)

Table 1 Specifications of the considered flat- and corrugated-web SPSW models

Web-plate form	Label	θ (deg.)	N	t_w (mm)	No. of models	
					Category	Total
Flat	F- t_w	-	-	1.25, 2, 3, 4, 5, 6	6	6
Trapezoidal	T-θ-N-t_w	30	8	1.25, 2, 3, 4, 5, 6	6	16
		45	6, 8, 10	3, 6	6	
		60	8	3, 6	2	
		90	8	3,6	2	

form and geometrical as well as corrugation properties of each model can be identified from the label. For instance, the label "*F-4*" indicates that the model has an unstiffened and flat infill plate with a thickness of 4 mm, also the label "*T-60-8-6*" indicates that the model has a corrugated web-plate of trapezoidal form with a corrugation angle of 60°, 8 corrugation half-waves, and a thickness of 6 mm.

3. Finite element modeling and verification

The steel shear walls are modeled and analyzed using ANSYS 11.0 (2007) finite element software. The eight-node SHELL93 element is used to model the steel shear walls, which has six degrees of freedom at each node including translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z axes. Moreover, this element has plasticity, stress stiffening, large deflection, and large strain capabilities, and is well-suited for modeling shells.

The multilinear representation of the stress-strain relationships for the considered steel material is shown in Fig. 3, which was obtained from tensile tests (Emami and Mofid 2014). It is noted that in the finite element modeling, in this study, the material properties are introduced by the *true* and not the *engineering* stress-strain relationships. The true stress and strain values are computed by using the relations reported by Roylance (2001). The yield stresses of the plate, beam, and column components are 207 MPa, 288 MPa, and 300 MPa, respectively. The von Mises yield criterion is adopted for steel material yielding, and kinematic hardening rule is incorporated in the nonlinear cyclic analysis of the SPSW models which also accounts for Bauschinger effect.

The boundary condition at the bottom of the shear wall model is set to fixed support. As well, in-plane lateral load is applied at the top of the model in a displacement-controlled and incremental manner. Fig. 4 illustrates two typical finite element models as well as the corresponding column-plate connection details for SPSWs with flat and corrugated infill plates. According to Emami *et al*. (2013), the infill panels of the test specimens were connected to the boundary frame by means of fish plates. Also, a combination of weld and bolt was used to connect the infill plate to the fish plate. Considering the plate-frame connection strength and fixity in the test specimens, the infill plate is directly connected to the boundary frame members in the finite element models, and the connection is indeed modeled as fixed.

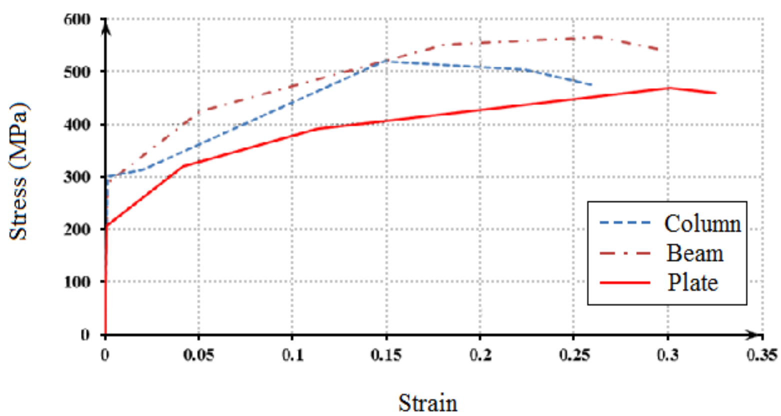
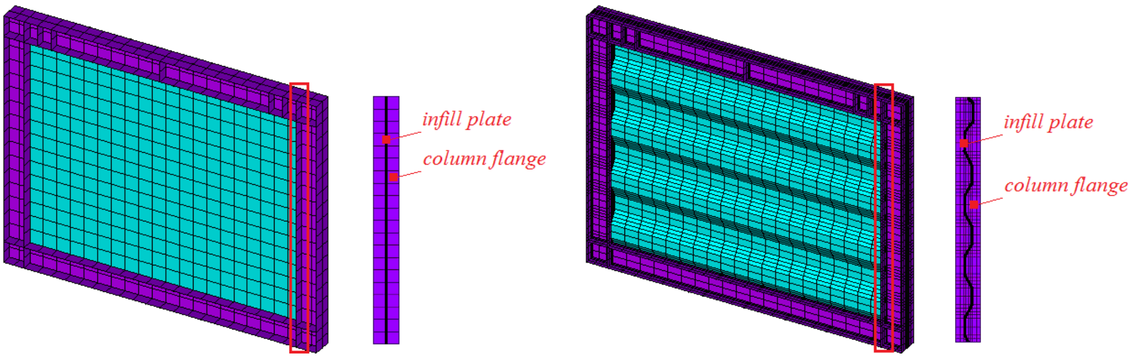
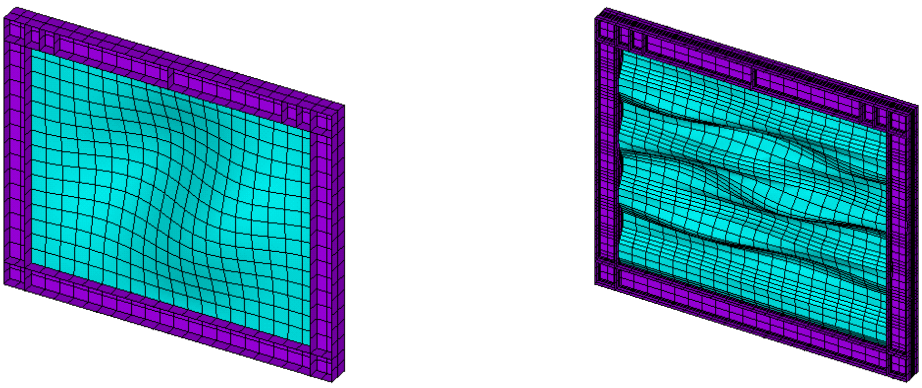


Fig. 3 Stress-strain relationships of the steel material (Emami and Mofid 2014)



(a) Flat-web SPSW model (b) Corrugated-web SPSW model

Fig. 4 Typical finite element models and column-plate connection details



(a) SPSW model with flat web-plate (b) SPSW model with corrugated web-plate

Fig. 5 First buckling mode shapes of typical flat- and corrugated-web wall models

In order to initiate buckling and also account for the effects of initial imperfections in the nonlinear analyses, very small out-of-plane deformations proportional to the lowest eigen-mode shape of elastic buckling are introduced to the SPSW models. Eurocode (2003) suggests that the out-of-plane imperfection of plates (U) shall be taken as the minimum value of $w_p/200$ and $h_p/200$, where w_p and h_p are the respective width and height of the infill plate. Accordingly, initial imperfections consistent with the first buckling mode shapes of the walls are applied by considering a scale factor (SF), determined by

$$SF = \frac{\min(w_p/200,\ h_p/200)}{D}, \tag{1}$$

in which D is the maximum out-of-plane deformation of the plate resulted from eigen buckling analysis. To achieve this, an eigen buckling analysis is performed to determine the first buckling mode prior to the nonlinear analysis of each SPSW model. The first buckling mode shapes of two typical wall models with flat and corrugated web-plates are shown in Fig. 5.

Both geometrical and material nonlinearities of steel shear walls are included in the analyses, and the wall models are loaded cyclically according to the history shown in Fig. 6.

The accuracy of the numerical simulation is verified through comparison of the finite element and test results by considering the two experimental specimens no. 1 and 3 tested by Emami *et al.* (2013), which herein are labeled as *F-1.25* and *T-30-8-1.25*, respectively. The considered test specimens and the corresponding finite element models were shown in Figs. 1 and 4, respectively.

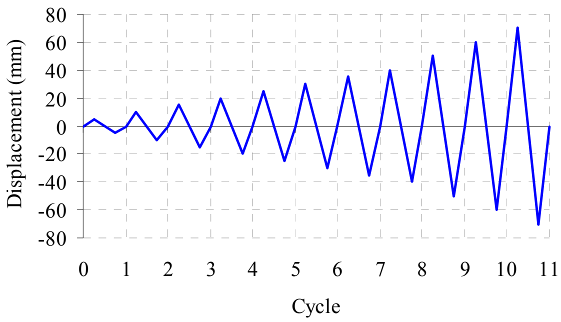
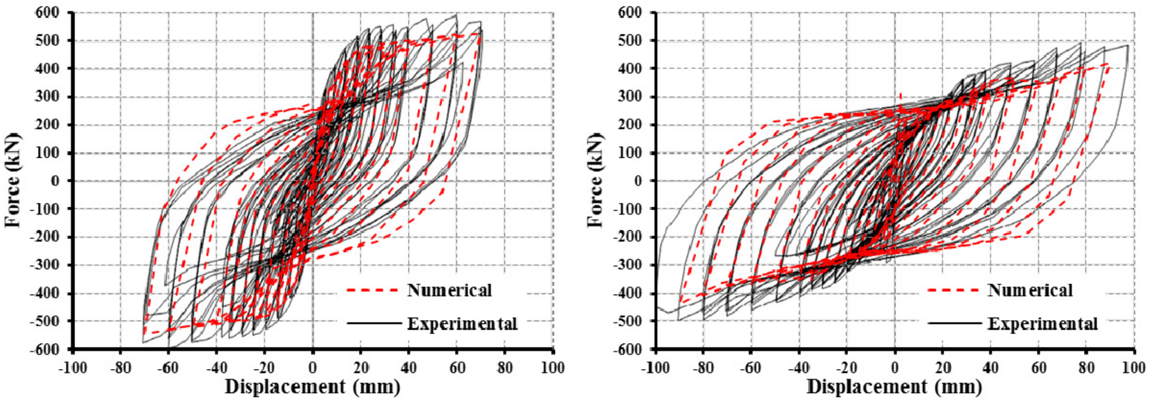


Fig. 6 Cyclic loading protocol



(a) Flat-web SPSW (F-1.25) (b) Corrugated-web SPSW (T-30-8-1.25)

Fig. 7 Comparison of experimental and numerical results

Table 2 Comparison of experimental results and numerical predictions for the ultimate strength and the corresponding displacement

Web-plate form	Ultimate strength (kN)		*Num./Exp.*	Displacement at ultimate strength (mm)		*Num./Exp.*
	Experimental	Numerical		Experimental	Numerical	
Flat (F-1.25)	580	544.2	*0.94*	70	69	*0.98*
Corrugated (T-30-8-1.25)	500	420	*0.84*	78	90	*1.14*

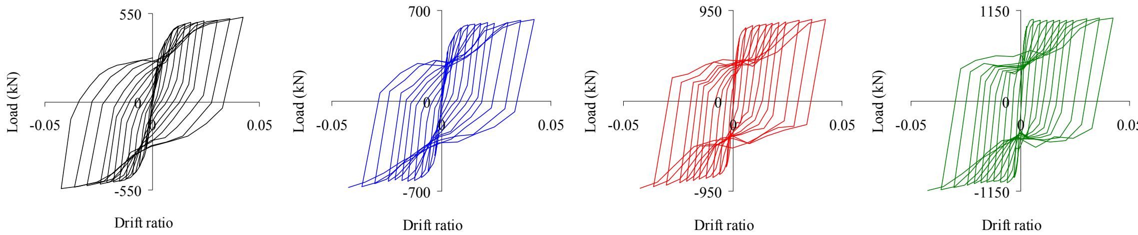
Fig. 7 shows the experimental and numerical cyclic results for the two considered SPSWs with flat and corrugated infill plates. Provided in Table 2 are also the experimental results and numerical predictions for the ultimate strength and the corresponding displacement for the flat- and corrugated-web steel shear walls.

As it is seen in Fig. 7 and Table 2, the agreement between the experimental and numerical results is good, and hence the validity of the finite element modeling and analysis is verified.

4. Hysteretic performance of SPSWs with flat infill plates

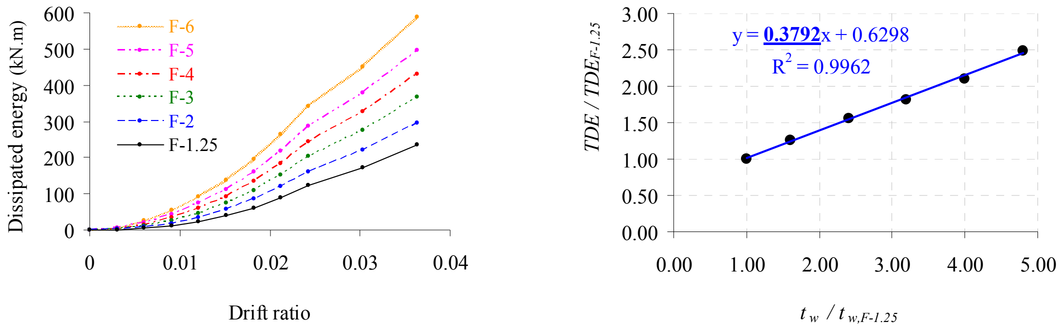
Thickness of the infill plate as the primary lateral force-resisting and energy dissipating component in a SPSW, is considered as an important parameter in design of this structural system. Smaller width-to-thickness (slenderness) ratio of the panel, i.e., larger web-plate thickness, can enhance the stiffness, strength, and deformation capacity of the steel panel. The width-to-thickness ratio of the panel can also be effectively reduced by using intermediate stiffeners; however, adding stiffeners can increase the cost of the construction (Chen and Jhang 2011). On the other hand, variation of the web-plate thickness can have a significant impact on the required stiffness and strength of the vertical (column) and horizontal (beam) boundary elements, such that reduction in web-plate thickness can reduce the strength and stiffness requirements on the boundary elements (Sabelli and Bruneau 2006). By considering the effectiveness of variation of web-plate thickness in adjusting the structural and seismic performances of SPSWs, the effect of web-plate thickness on the hysteretic performance of SPSWs with flat (unstiffened) infill plates is evaluated in this section.

The hysteresis curves of the *F-1.25*, *F-2*, *F-4*, and *F-6* models are shown in Fig. 8. The *F-1.25* model with the smallest web-plate thickness exhibits stable cyclic behavior with some pinching of the hysteresis loops due to the low buckling strength of its infill plate. On the other hand, it is found that cyclic behaviors of the *F-2*, *F-4*, and *F-6* models are also accompanied by accentuated pinching of the hysteresis loops due to increasing of the web-plate thickness. This is indeed attributed to the fact that thicker web plates exert larger forces on the boundary elements, especially on the columns, which may adversely affect the cyclic behavior of the SPSW system. This problem can be addressed by employing larger beam and column sections, which of course may not be always economical. Alternatively, employment of relatively thicker infill plates made of low yield point (LYP) steel material has been demonstrated (Zirakian and Zhang 2012, Zhang and Zirakian 2014) to be quite effective in improving the structural behavior and seismic



(a) F-1.25 (b) F-2 (c) F-4 (d) F-6

Fig. 8 Hysteresis curves of SPSW models with flat infill plates



(a) Dissipated energy vs. drift ratio

(b) Relationship between increase in web thickness and total dissipated energy

Fig. 9 Energy dissipation characteristics of SPSW models with flat infill plates

performance of SPSW systems. At any rate, selection of optimal web-plate thickness as well as proper design of the boundary frame elements, e.g., by applying the AISC 341-10 (2010) seismic provisions, can result in economically viable and structurally sound SPSW systems.

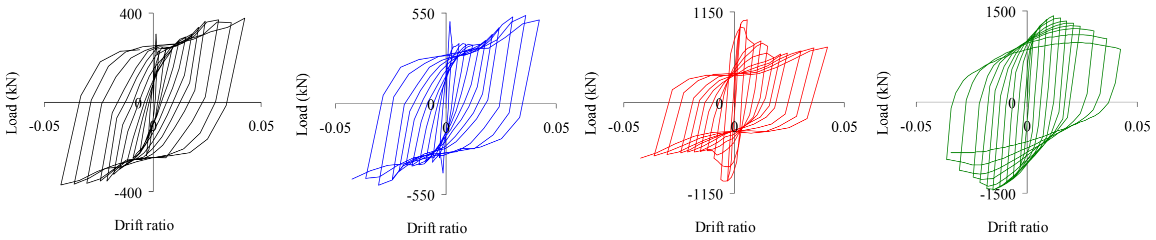
The energy dissipation characteristics of the flat-web SPSW models are also illustrated in Fig. 9. As it is seen in Fig. 9(a), increasing of the web-plate thickness augments the energy absorption capacity of the system. However, a closer look at the results reveals that the rate of increase of the dissipated energy amount is accompanied by a slight drop at about 0.024 drift ratio, which is attributed to the occurrence of yielding in vertical boundary elements. In fact by considering the importance of behavior of vertical boundary elements, yielding of these frame components due to higher level of stresses can have a direct effect on the overall performance of the SPSW system.

The relationship between the amounts of increase in the total dissipated energy (TDE) and web-plate thickness quantities is evaluated in Fig. 9(b), where the TDE and web-plate thickness values of different models are normalized by those of the *F-1.25* model with the smallest web-plate thickness. From the regression analysis results depicted in Fig. 9(b), it is evident that the $TDE / TDE_{F\text{-}1.25}$ values are linearly related with the $t_w / t_{w,F\text{-}1.25}$ values, and the ratio of increase of the dissipated energy to that of the web-plate thickness is 1.0:2.6 approximately. Based on the findings of the study performed by Zirakian and Zhang (2012), application of LYP steel infill plates in unstiffened SPSW systems can significantly improve the stiffening and damping capabilities of these structural systems and the aforementioned ratio can also be improved to 1.0:0.8 approximately.

5. Hysteretic performance of SPSWs with corrugated infill plates of trapezoidal pattern

5.1 Effects of variation of web-plate thickness

The effect of web-plate thickness on the hysteretic performance of SPSWs with trapezoidally corrugated infill plates is evaluated in this section. The hysteresis curves of the *T-30-8-1.25*, *T-30-8-2*, *T-30-8-4*, and *T-30-8-6* models with various web-plate thicknesses are shown in Fig. 10. The *T-30-8-1.25* model (Fig. 10(a)) with the smallest web-plate thickness undergoes a slight

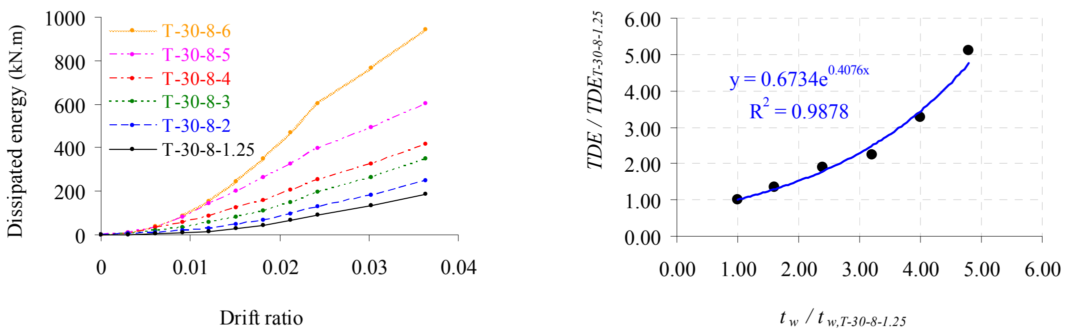


(a) T-30-8-1.25 (b) T-30-8-2 (c) T-30-8-4 (d) T-30-8-6

Fig. 10 Hysteresis curves of SPSW models with corrugated infill plates of various thicknesses

strength loss at a very low drift ratio and dissipates the energy through hysteresis loops with no significant pinching effect. The cyclic behavior of the *T-30-8-2* model (Fig. 10(b)) with relatively larger web-plate thickness, on the other hand, is accompanied by a considerable and abrupt strength drop at a low drift ratio, while the strength loss in the *T-30-8-4* model (Fig. 10(c)) is found to occur at a relatively higher drift ratio and in a rather gradual manner. Lastly, the *T-30-8-6* model (Fig. 10(d)) with the largest web-plate thickness is found to dissipate the energy through thicker hysteresis loops with no pinching, accompanied by gradual strength decay at a comparatively higher drift ratio. Overall, in addition to the effectiveness of the web-plate thickness increase on the stiffness and strength performances of the system, it is found that increasing of the web-plate thickness improves the cyclic behavior of SPSWs with trapezoidally corrugated infill plates by changing the shape of the hysteresis loops from "S" shape to "spindle" shape and also decreasing the severity of pinching effect. It is noted that increasing of the web-plate thickness in this case also increases the overall system demand on the boundary frame members, and this in turn results in the strength degradation.

Evaluation of the energy dissipation characteristics of the corrugated-web SPSW models, shown in Fig. 11(a), reveals that increasing of the web-plate thickness augments the energy absorption capacity of such structural systems. However, similar to the flat-web SPSWs case, the rate of increase of the dissipated energy undergoes a fairly substantial drop at about 0.024 drift ratio due to the performance of the boundary frame members. In addition, the regression analysis



(a) Dissipated energy vs. drift ratio (b) Relationship between increase in web thickness and total dissipated energy

Fig. 11 Energy dissipation characteristics of SPSW models with corrugated infill plates of various thicknesses results illustrated in Fig. 11(b) demonstrate that the $TDE / TDE_{T\text{-}30\text{-}8\text{-}1.25}$ and $t_w / t_{w,T\text{-}30\text{-}8\text{-}1.25}$ values are not linearly related in this case and the relationship is rather represented best by an exponential function as given in the figure.

5.2 Effects of variation of corrugation angle

The hysteretic performances of steel shear walls with trapezoidal web-plates of various corrugation angles are investigated in this section. Two series of SPSWs, viz. *T-30-8-3*, *T-45-8-3*, *T-60-8-3*, *T-90-8-3* and *T-30-8-6*, *T-45-8-6*, *T-60-8-6*, *T-90-8-6* models, with 30°, 45°, 60°, and 90° corrugation angles as well as 3 mm and 6 mm web-plate thicknesses are considered for the purpose of this case study. It is noted that the effects of variation of the corrugation angle are studied in two groups of SPSWs with different web-plate thicknesses, and the number of corrugation half-waves in all cases is kept constant at 8.

Evaluation of the hysteresis curves of the SPSW models with 3 mm infill plates, shown in Figs. 12(a) through 12(d), indicates that increasing of the web-plate corrugation angle from 30° to 90° results in the dissipation of the energy through spindle-shaped hysteresis loops with no pinching and also gradual strength decay. In contrast, the cyclic behavior of the SPSW models with 6 mm infill plates, shown in Figs. 12(e) through 12(h), does not seem to be affected noticeably by increasing of the corrugation angle.

Consistent with the abovementioned findings and as shown in Fig. 13, increasing of the corrugation angle augments the energy dissipation capacity of the SPSW models with 3 mm web-plates, while the depicted results show a decreasing and then increasing trend for the dissipated energy amount in case of the steel shear wall models with 6 mm infill plates. In fact, increasing of the corrugation angle from 30° to 90° in the SPSW models with smaller infill plates, i.e., *T-30-8-3* vs. *T-90-8-3*, results in about 30% increase in the total energy dissipation capacity.

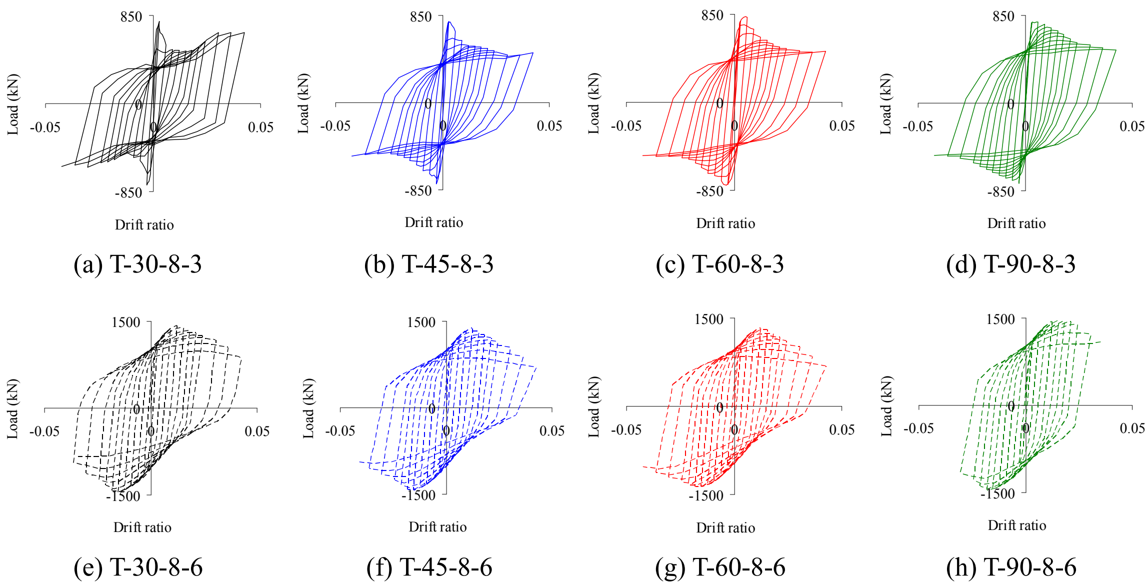


Fig. 12 Hysteresis curves of SPSW models with 3 mm and 6 mm infill plates of various corrugation angles

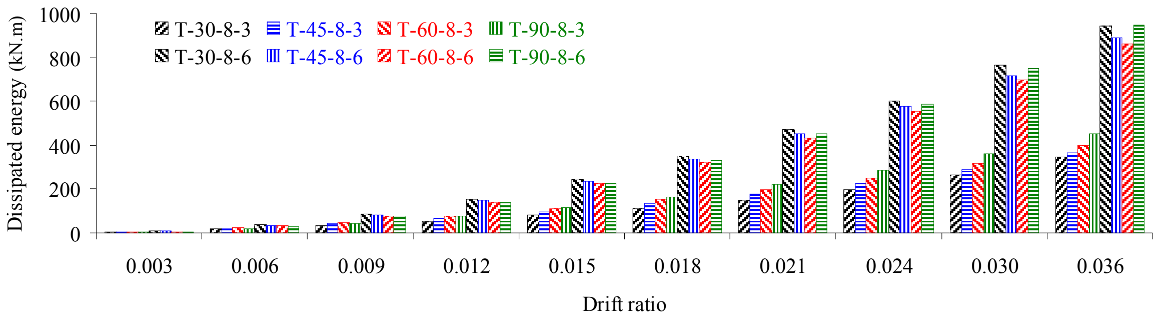


Fig. 13 Energy dissipation of SPSW models with 3 mm and 6 mm infill plates of various corrugation angles

Overall, results of this study indicate that increasing of the corrugation angle is fairly effective in increasing the energy absorption capacity of SPSW systems with thin infill plates.

5.3 Effects of variation of number of corrugation half-waves

In this section, the effects of variation of number of corrugation half-waves on the hysteretic performance of steel shear walls with trapezoidal web-plates are evaluated. Two series of SPSWs including the *T-45-6-3*, *T-45-8-3*, *T-45-10-3* and *T-45-6-6*, *T-45-8-6*, *T-45-10-6* models with 3 mm and 6 mm web-plate thicknesses are considered in this case study. SPSW models of each group possess 6, 8, and 10 corrugation half-waves, and the corrugation angle is kept constant at 45°.

Increasing of the number of corrugation half-waves from 6 to 10 in the six considered SPSW models, as shown in Figs. 14(a) through 14(f), does not seem to have a noticeable effect on the

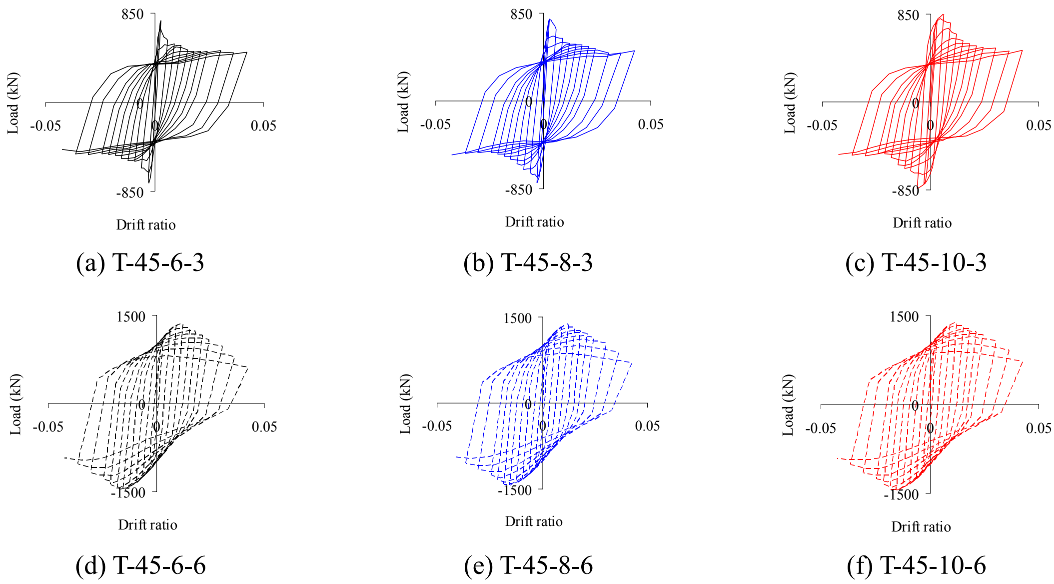


Fig. 14 Hysteresis curves of SPSW models with 3 mm and 6 mm infill plates of various numbers of corrugation half-waves

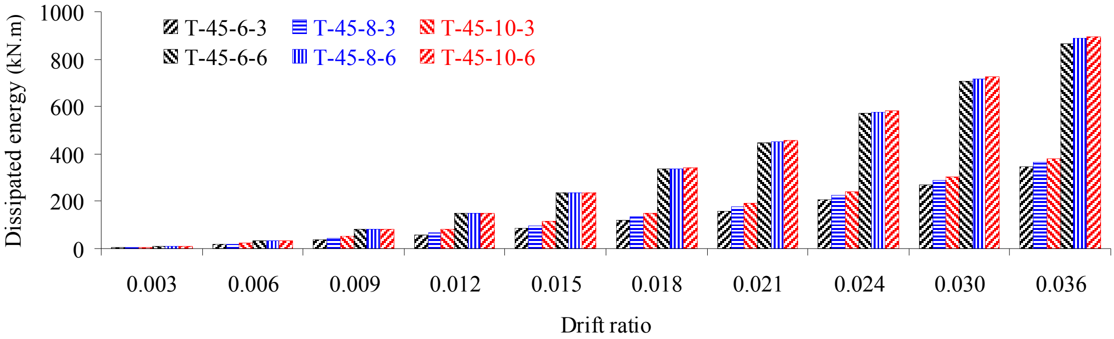


Fig. 15 Energy dissipation of SPSW models with 3 mm and 6 mm infill plates of various numbers of corrugation half-waves

cyclic performance, except that it results in gradual strength degradation in the *T-45-6-3*, *T-45-8-3*, and *T-45-10-3* models with smaller web-plate thickness. However, evaluation of the results shown in Fig. 15 reveals that increasing of the number of corrugation half-waves results in slight augmentation of the dissipated energy amount in both considered series of SPSW models. Accordingly, it is found that increasing of the number of corrugation half-waves from 6 to 10 results in augmentation of the total dissipated energy by 10% and 3% in cases of the SPSWs with 3 mm and 6 mm web-plate thicknesses, respectively.

Overall, despite the slight effectiveness of increasing of the number of corrugation half-waves in improving the energy-absorption capacity of SPSWs with relatively smaller web-plate thickness, e.g., 3 mm vs. 6 mm web-plate thickness, it may be concluded that variation of the number of corrugation half-waves in SPSWs with infill plates of trapezoidal pattern does not seem to have a considerable effect on the hysteretic performance of such systems.

6. Discussion

As mentioned before, the SPSW models in this study were developed by varying the geometrical properties of the infill plates in the specimens tested by Emami *et al*. (2013). It is noted that the boundary frame elements, i.e., beams and columns, were not changed or designed for various web-plate specifications. In fact, this consideration was made to evaluate the effects of web-plates with various properties on the performances of the boundary frame members and the overall SPSW system. On the other hand, it is quite important to note that changes in web-plate thickness can have a significant impact on the required stiffness and strength of the boundary frame members in a SPSW system. In addition, the ultimate strength of a steel panel is fully developed only when the corresponding frame members are sufficiently stiff and strong to anchor the tension diagonals (Sabelli and Bruneau 2006). On this basis, findings of this study, discussed in previous sections, demonstrated that if the boundary frame members are not designed properly, the structural performances of both flat- and corrugated-web SPSWs can be adversely affected in the form of increased pinching of the hysteresis loops (e.g., Fig. 8), reduced energy dissipation capacity (e.g., Figs. 9(a) and 11(a)), and strength degradation (e.g., Fig. 10).

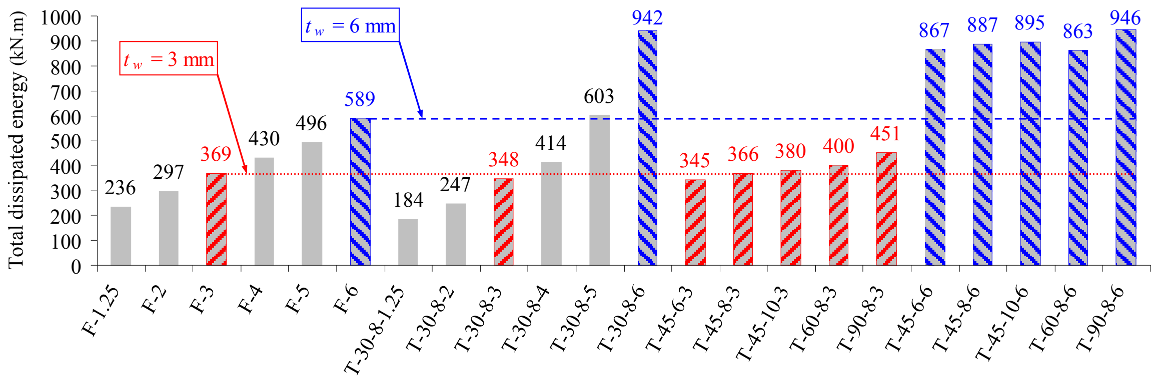
It was shown that increasing of web-plate thickness in both flat- and corrugated-web SPSWs is the most effective in improving the hysteretic performance of such systems. Furthermore, comparison of the results shown in Figs. 9(b) and 11(b) indicates that increasing of web-plate thickness is more effective in corrugated-web SPSWs with $\theta = 30°$ and $N = 8$ relative to SPSWs with flat webs. However, as discussed before, increasing of the web-plate thickness can increase the forces imposed on frame members. Based on the studies performed by Zirakian and Zhang (2012), Zirakian (2013), and Zhang and Zirakian (2014), application of LYP steel infill plates in SPSWs can facilitate the design and significantly improve the structural behavior and seismic performance of such systems. Accordingly, use of LYP steel material with extremely low yield stress as well as high ductility and elongation properties can provide the possibility of employing relatively thicker infill plates with reduced forces imposed on the boundary frame members.

In addition to the effectiveness of the web-plate thickness, increasing of the corrugation angle as well as number of corrugation half-waves in SPSWs with trapezoidally corrugated infill plates is also found to be fairly effective in increasing the energy absorption capacity of such structural systems especially with thin infill plates. Increasing of the corrugation angle from 30° to 90°, however, was found to be more effective compared to increasing of the number of corrugation half-waves from 6 to 10 in SPSW models with 3 mm (relatively thin) infill plates. Overall, it is believed that the hysteretic performance of SPSWs with corrugated web-plates of trapezoidal pattern can be effectively improved through proper selection of the infill plate geometrical parameters including t_w, θ, and N. This is further illustrated in Fig. 16(a), where the total energy absorption capacities of all considered flat- and corrugated-web SPSW models are shown.

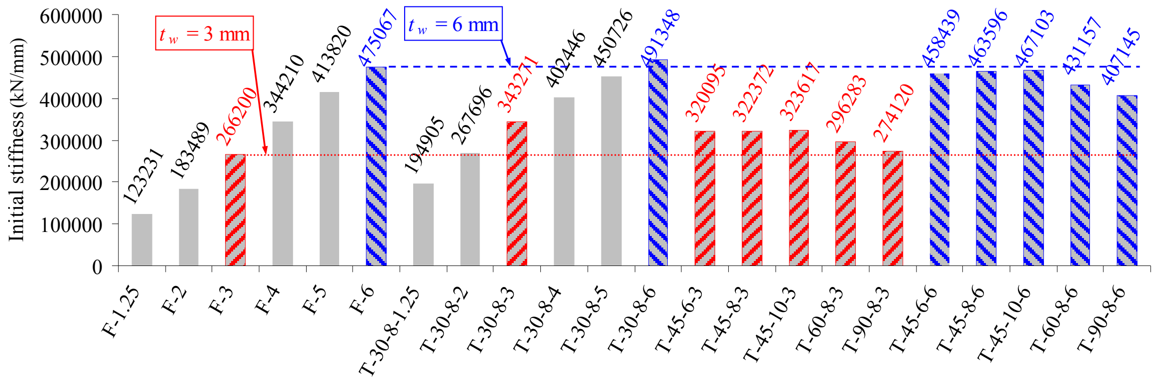
The results shown in Fig. 16(a) demonstrate that increasing of θ and N in corrugated-web SPSW models with 3 mm infill plates, for instance, results in higher energy absorption capacities compared to that of the *F-3* model. The *T-90-8-3* model exhibits even a higher capacity compared to the *F-4* model with larger infill plate thickness. In case of the SPSW models with 6 mm infill plates, as another example, it is found that all corrugated-web SPSWs possess remarkably higher capacities compared to that of the *F-6* model. The *T-30-8-5* model with relatively smaller infill plate thickness exhibits a similar performance with even slightly higher capacity compared to the *F-6* model.

Considering the importance of stiffness, strength, and energy dissipation capacity as three important properties of every lateral force-resisting system (Zirakian and Zhang 2012), the initial stiffnesses as well as maximum strengths of the SPSW models obtained from pushover analyses are also considered and shown in Figs. 16(b) and 16(c), respectively. Similar to the case of the total energy absorption capacity, increasing of web-plate thickness is found to be quite effective in improving the initial stiffness and maximum strength in cases of both flat- and corrugated-web SPSW models. In case of SPSW models with 3 mm infill plates, it is found that corrugated-web SPSW models possess higher performance in terms of initial stiffness and maximum strength compared to *F-3* model with flat infill plate. Similarly, higher initial stiffness and maximum strength are also achieved through application of corrugated infill plates in case of SPSWs with 6 mm infill plates. From Fig. 16(b), for instance, the *T-30-8-2* model with 2 mm web-plate thickness is found to provide slightly higher initial stiffness compared to the *F-3* model with 3 mm web-plate thickness. As another example, the *T-30-8-5* model in Fig. 16(c) exhibits a relatively higher maximum strength in comparison with the *F-6* model with thicker infill plate. All in all, these results are indicative of achieving high stiffness, strength, and energy dissipation capacity through employment of trapezoidally horizontal corrugated web-plates in SPSW systems.

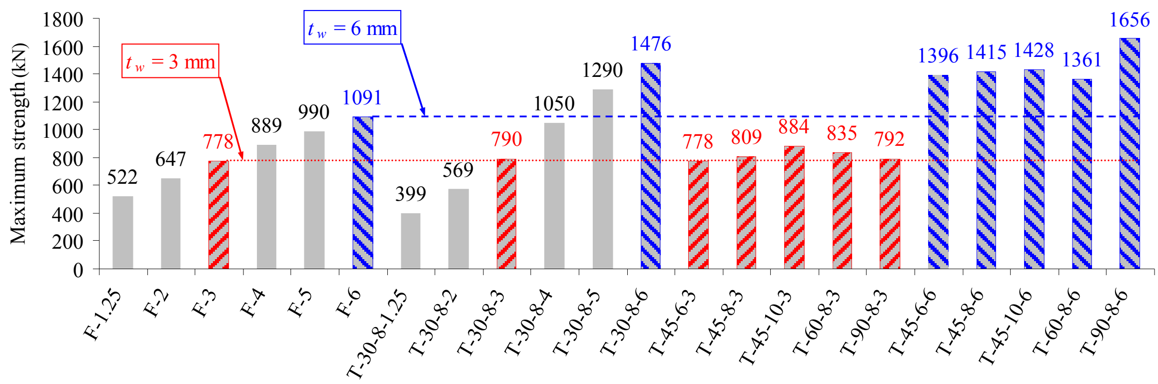
Based on the results and findings of this and other reported studies, it is concluded that optimal selection of web-plate thickness, corrugation angle, and number of corrugation half-waves and also proper design of the boundary frame members in steel shear walls with trapezoidally corrugated infill plates will result in high-performing and cost-effective SPSW systems as an efficient alternative to the stiffened SPSWs with relatively higher construction cost.



(a) Total energy absorption capacity



(b) Initial stiffness



(c) Maximum strength

Fig. 16 Performances of the SPSW models

7. Conclusions

In this paper, the cyclic performances and energy dissipation characteristics of SPSWs with flat and trapezoidally corrugated infill plates were primarily evaluated through detailed numerical simulations. Parametric studies were performed in order to evaluate the effectiveness of web-plate thickness, corrugation angle, and number of corrugation half-waves on the hysteretic performances of flat- and corrugated-web SPSWs.

Results of this study showed that hysteretic performance of SPSWs can be affected greatly as a result of variation of the web-plate thickness. Increasing of web-plate thickness in both flat- and corrugated-web SPSWs can significantly improve the hysteretic performance of such lateral force-resisting systems; however, this may result in larger forces imposed on the boundary frame members, which may in turn lead to increased pinching effect, reduced energy absorption capacity, and strength degradation, if the boundary frame members are not properly designed to resist the demands resulting from the effect of diagonal tension-field action within the web-plate. In addition, increasing of corrugation angle as well as number of corrugation half-waves were also found effective in improving the hysteretic performance of corrugated-web SPSWs especially with thin plates. Variation of the corrugation angle, however, was found to be more effective in adjusting the energy absorption capacity of such systems.

In addition, evaluation of initial stiffnesses and maximum strengths of the flat- and corrugated-web SPSW models, as two other important structural characteristics of such lateral force-resisting systems, demonstrated the capability of SPSWs with trapezoidally horizontal corrugated web-plates in providing high stiffness and strength performances.

Comparison and assessment of stiffness, strength, and hysteretic performances of SPSWs with unstiffened/flat and trapezoidally horizontal corrugated infill plates revealed that optimal selection of web-plate thickness, corrugation angle, and number of corrugation half-waves along with proper design of the horizontal and vertical boundary frame elements can result in efficient corrugated-web steel shear wall systems with high structural and seismic performances. Such systems can also be considered as an economical alternative to stiffened SPSWs with high construction cost.

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