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Structural performance assessment of trapezoidally-corrugated and centrally-perforated steel plate shear walls

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ABSTRACT

In recent years, there has been a growing interest towards the use of corrugated infill plates as an alternative to flat infill plates in steel plate shear wall (SPSW) systems. Corrugated plates offer various advantages over flat plates including higher energy dissipation capacity, ductility, out-of-plane stiffness, and improved buckling stability. On the other hand, perforation of the web-plate can allow the utility passage through SPSW and also can alleviate the problem of large panel force over-strength due to larger web-plate thickness. Considering the structural and architectural features of corrugated- and perforated-web SPSWs further research is required in order to obtain a better understanding of the structural and seismic performances of such efficient lateral force-resisting systems. On this basis, this paper investigates the cyclic behavior and energy absorption capabilities of SPSWs with trapezoidally-corrugated and centrally-perforated infill plates. To this end, numerous finite element models with various geometrical properties are developed and analyzed under cyclic loading. Results and findings of this study are indicative of effectiveness of the web-plate thickness, corrugation angle, and opening size on the hysteretic performance of corrugated- and perforated-web steel shear wall systems. Optimal and proper selection of the aforementioned geometrical parameters can result in SPSW systems with desirable structural behavior and seismic performance.

1. Introduction

Steel plate shear walls (SPSWs) are efficient lateral force-resisting systems which are commonly used in design and retrofit of buildings. Structural and economical considerations may result in the design of SPSWs with unstiffened or stiffened as well as slender or stocky infill plates. Structural behavior and seismic performance of such systems are directly influenced by the geometrical and material characteristics of the web plates as the primary lateral force-resisting components. Among various considered configurations, SPSWs with corrugated and/or perforated infill plates have lately gained some attention and accordingly several studies have been reported in this regard.

Mo and Perng [12] reported an experimental study on framed shear walls with corrugated steel plates and demonstrated improved seismic performance of such structural systems. Stojadinovic and Tipping [16] performed an experimental study in order to develop an alternative lateral bracing system comprising corrugated sheet steel shear walls for use with light-framed cold-formed steel buildings. Moreover, a numerical study conducted by Gholizadeh and Yadollahi [9] showed that the structural behavior of a corrugated plate can be superior to that of a flat plate due to its higher loading capacity, ductility, and energy absorption capability. Emami et al. [6], also, reported an experimental research on the cyclic behavior of trapezoidally-corrugated and unstiffened steel shear walls and compared the stiffness, strength, ductility ratio, and energy dissipation capacities of steel shear walls with unstiffened, trapezoidally vertical corrugated, and trapezoidally horizontal corrugated infill plates. Recently, Tong and Guo [17] investigated the elastic buckling behavior of steel trapezoidally-corrugated shear walls with vertical stiffeners theoretically and numerically and proposed formulas for predicting the elastic buckling loads of stiffened steel trapezoidal corrugated shear walls.

Roberts and Sabouri-Ghomi [14] performed a series of cyclic loading tests on unstiffened steel shear walls with centrally-placed circular openings of varying diameters. As reported, all the tested panels exhibited stable hysteresis loops and adequate ductility for the first four loading cycles without significant loss in their load-carrying capacity. Vian and Bruneau [19] conducted an experiment to investigate the efficiency of steel infill panels with circular openings. The test specimen displayed stable S-shaped hysteresis loops with little or no pinching. Furthermore, Moghimi and Driver [13] studied the effect of regular perforation patterns on SPSW column demands. This study showed that although the perforations reduce the shear capacity of the infill plate considerably, they may not reduce the force demands on the columns. Valizadeh

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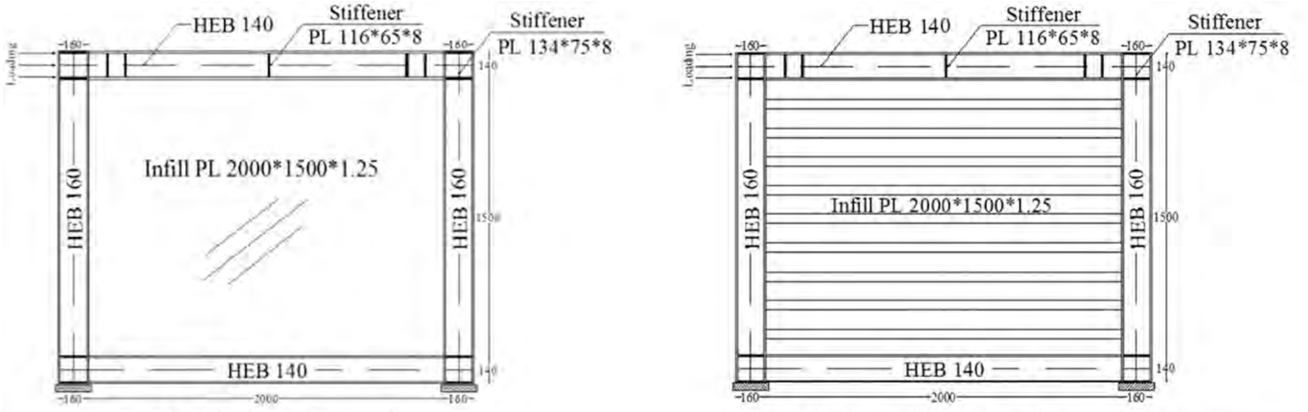


(a) Flat-web specimen
(web thickness = 1.25 mm)

(b) Corrugated-web specimen
(corrugation angle = 30°, web thickness = 1.25 mm, and number of corrugation half-waves = 8)

Fig. 1. Details of the modeled experimental specimens tested by Emami et al. [6].

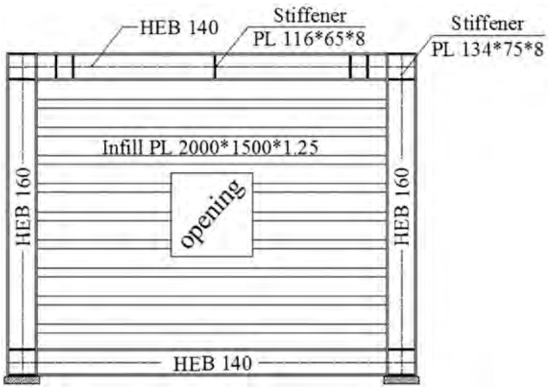


Fig. 2. Details of a typical trapezoidally-corrugated and centrally-perforated SPSW model.

et al. [18], also, conducted an experimental investigation on cyclic behavior of steel shear walls with centrally-placed circular opening. The effects of existence of the central perforation and the opening size on some structural parameters, i.e. initial stiffness, strength, and energy absorption, were evaluated in this study. Lately, Barkhordari et al. [3] reported a numerical study on the behavior of SPSWs with stiffened full-height rectangular openings and evaluated the stiffness, strength, and ductility performances of such perforated steel shear walls. In addition, Sabouri-Ghomi and Mamazizi [15] investigated the structural behavior of stiffened SPSWs with two rectangular openings experimentally. It was shown that the interval between the two openings had no effect on the ultimate shear strength, stiffness, and energy absorption, while the existence of openings led to reduction in values of the aforementioned parameters.

The stiffness, strength, and energy absorption performances of corrugated and perforated SPSWs were investigated numerically by Farzampour et al. [8]. Some of the advantages and disadvantages of employment of corrugated and perforated infill plates in terms of structural performance of SPSW systems were demonstrated. This research intends to focus on the cyclic performance and energy dissipation capability of corrugated and perforated SPSWs in order to gain a better understanding of seismic performance of such lateral force-resisting systems. To this end, non-perforated SPSW specimens tested and documented by Emami et al. [6] and Emami and Mofid [5] were selected and numerical parametric studies were performed by varying some geometrical and corrugation parameters including the web-plate thickness, corrugation angle, and opening size.

Table 1
Characteristics of the SPSW models.

Web-plate form	Label	θ (deg.)	t_w (mm)	O (%)	No. of models
Trapezoidal	$T\text{-}\theta\text{-}t_w\text{-}O$	30	1.25, 2, 3, 4	0, 5, 15, 30	16
		45	1.25, 2, 3, 4	0, 5, 15, 30	16
		60	1.25, 2, 3, 4	0, 5, 15, 30	16
		90	1.25, 2, 3, 4	0, 5, 15, 30	16

2. Characteristics of SPSW models

In order to investigate the performance of SPSWs with corrugated and perforated infill plates, parametric studies are performed on two SPSW specimens tested by Emami et al. [6] whose details are illustrated in Fig. 1. Infill plate thickness (t_w) and corrugation angle (θ) as well as centrally-placed square opening size (O) are considered as the varying parameters in this study. Details of a typical corrugated and perforated steel shear wall model are shown in Fig. 2.

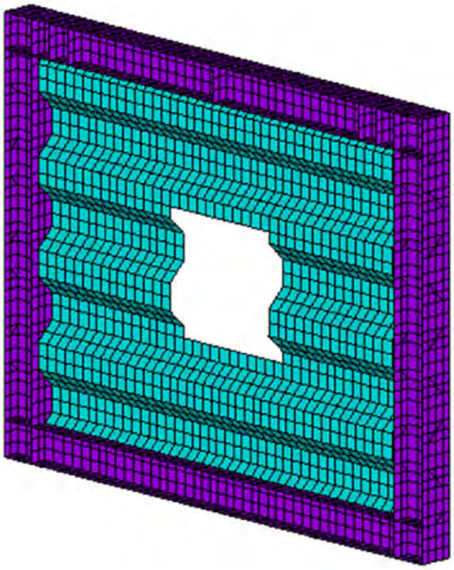


Fig. 3. A typical finite element model.

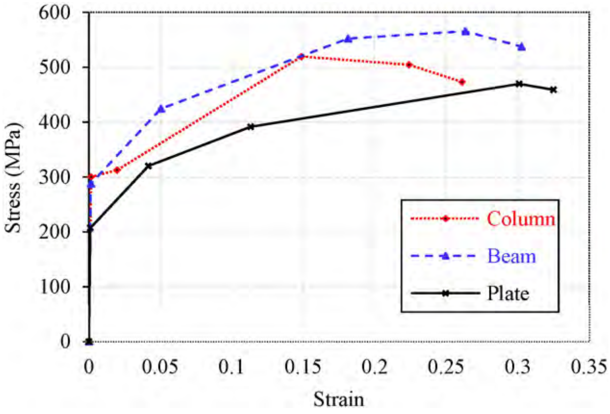


Fig. 4. Stress-strain relationships of the steel material [5].

The characteristics of the SPSW models are summarized in Table 1. As shown in the table, the SPSW models are labeled such that the geometrical properties of the infill plates can be identified from the label. For example, the label *T-30-1.25-10* indicates that the model has a trapezoidally-corrugated infill plate with a corrugation angle of 30°, thickness of 1.25 mm, and an opening with an area equal to 10% of the infill plate area. In addition, all corrugated web-plates have eight corrugation half-waves.

3. Finite element modeling and verification

SPSWs are modeled and analyzed using the finite element program ANSYS 16.1 [2]. The eight-node SHELL93 element with three translational and three rotational degrees of freedom at each node is used to model the steel shear walls. This element has plasticity, stress stiffening, large deflection, and large strain capabilities.

In order to ensure high accuracy in modeling and analysis, convergence and mesh refinement studies are performed. A typical finite element model is shown in Fig. 3. The boundary condition at the bottom of the shear wall model is a fixed support. In-plane lateral load is applied at the top of the model in a displacement-controlled and incremental manner. All SPSW models are restrained against out-of-plane displacement at their beam-to-column joints as per the test setup.

The multilinear representation of the stress-strain relationships for the steel material is shown in Fig. 4, which is obtained from tensile tests [5]. The yield stresses of the plate, beam, and column components were 207 MPa, 288 MPa, and 300 MPa, respectively. The Young's modulus of elasticity and Poisson's ratio were assumed to be 210 GPa and 0.3, respectively. The von Mises yield criterion is adopted for failure criterion.

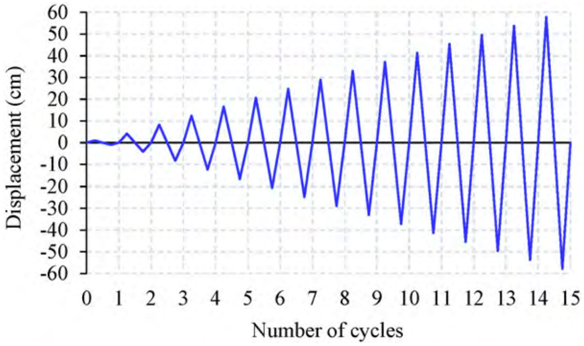


Fig. 6. Cyclic loading protocol.

Initial imperfections are incorporated in the finite element models in order to initiate buckling. Eurocode [7] suggests that out-of-plane imperfection of plates (U) shall be taken as the smaller of $w/200$ and $h_w/200$, where w and h_w are the fold width and web height, respectively. Initial imperfections consistent with the first buckling mode shape of the SPSWs are incorporated by using a scale factor determined from dividing the minimum of $w/200$ and $h_w/200$ by the maximum out-of-plane deformation of the web-plate obtained from Eigen buckling analysis. The first buckling mode shapes of the SPSW models with flat and corrugated web-plates used for the validation are shown in Fig. 5.

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

The accuracy of the finite element modeling is verified by comparing the numerical predictions with the results obtained from the experiments conducted by Emami et al. [6]. The numerical and experimental results are shown in Fig. 7 and tabulated in Table 2. From Fig. 7 and Table 2, the agreement between the numerical predictions and test results is good, which is indicative of validity and accuracy of the numerical simulations.

4. Effects of web-plate perforation

The hysteretic performance and energy absorption capacity of steel shear walls make such structural systems suitable to be used as seismic resistant elements in low- to high-rise buildings. However, introduction of openings in these lateral force-resisting and energy dissipating systems can reduce the shear and energy absorption capacity of the infill plate [4], and consequently adversely affect the overall performance of

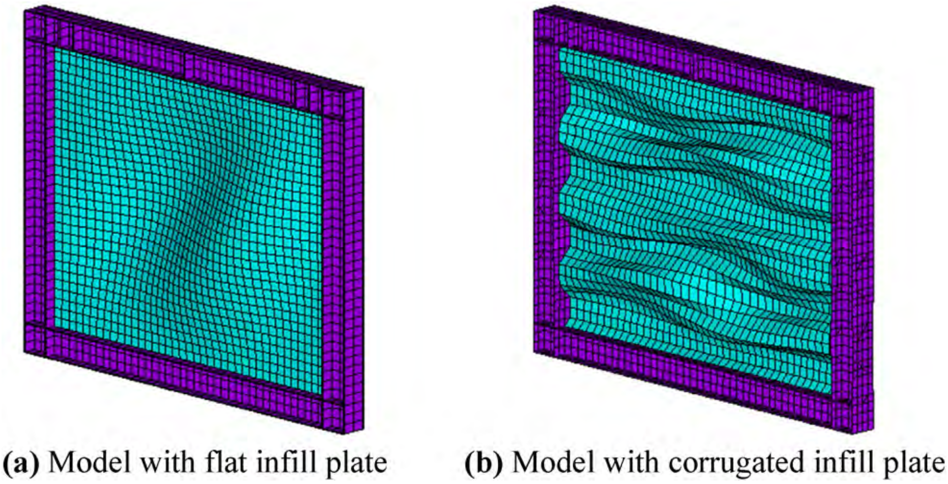
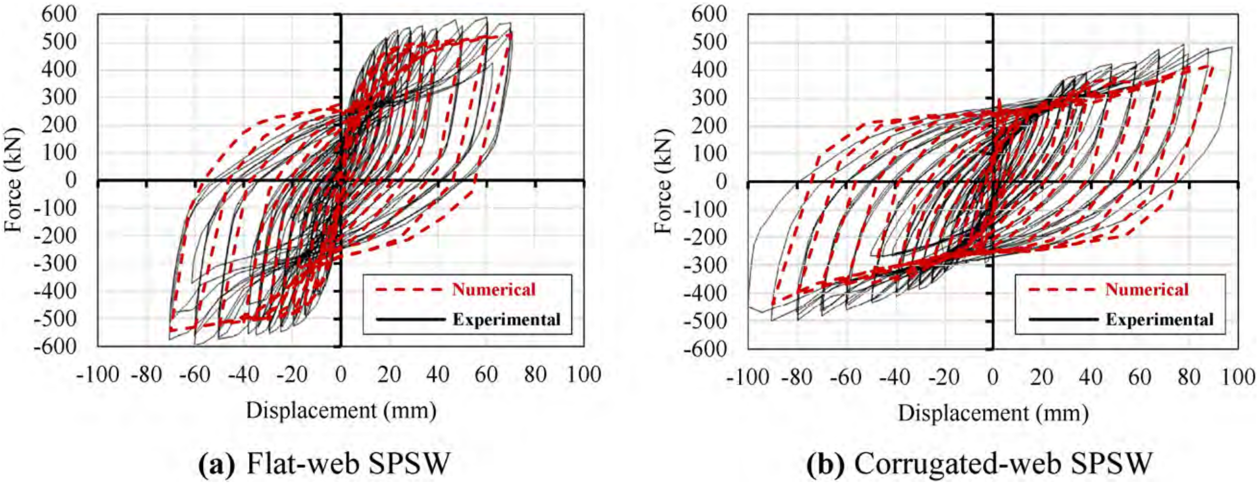

(a) Model with flat infill plate **(b)** Model with corrugated infill plate

Fig. 5. First buckling mode shapes of the SPSW models.



(a) Flat-web SPSW

(b) Corrugated-web SPSW

Fig. 7. Validation of numerical simulation.

the system. Hence, AISC 341-10 [1] requires the openings in web-plates to be bounded on all sides by intermediate boundary elements, unless otherwise justified or permitted. In this section, the effects of web opening on the cyclic performance and energy dissipation capacity of trapezoidally-corrugated and centrally-perforated steel shear walls are investigated.

The principal stress contour plots at 60 mm displacement (≈0.037 drift ratio) for two typical SPSWs with $\theta = 60°$, $t_w = 1.25$ mm, and $O = 0\%$, 5%, 15%, and 30% are shown in Figs. 8(a) through (h). From the figures it is evident that introduction of web opening and increasing of the opening size lower the level of stresses developed in the infill plate. This is indicative of lower contribution of the infill plate tension field action to the overall behavior of the SPSW system, and also increased overall system demand on the boundary frame members. In addition, the typical load-displacement curves in Fig. 8(i) demonstrate that introduction of web opening reduces the initial stiffness and strength of the corrugated-web SPSW system.

The hysteresis curves of corrugated-web SPSW models with $\theta = 30°$, 45°, 60°, and 90°, $t_w = 1.25$ mm, and $O = 0\%$, 5%, 15%, and 30% are shown in Fig. 9. The objective is to study the effects of web opening size on the cyclic performance of corrugated-web SPSWs with different corrugation angles.

From Fig. 9, it is found that SPSW models with no web opening, i.e. $O = 0\%$, have by and large stable cyclic behavior accompanied by some pinching of the hysteresis loops due to buckling of the infill plates. Increasing of infill plate corrugation angle from 30° to 90° seems to be effective in improving the hysteretic behavior of the non-perforated SPSW system. In fact, increasing of the corrugation angle decreases the severity of pinching effect in the hysteresis loops and accordingly the shape of the hysteresis loops is changed from *S* shape to *spindle* shape. Moreover, it is observed that as a result of perforation of the web plate and increasing of the opening size, pinching of the hysteresis loops is reduced and cyclic behavior of the SPSW system is dominated by the performance of the boundary frame. This is attributed to the fact that increasing of the web opening size lowers the contribution of the web-plate to the lateral resistance of the SPSW system. Increasing of the web opening size, in addition, decreases the energy absorption capacity of the corrugated-web SPSW system as illustrated in Fig. 10.

Fig. 11 shows the variation of the total dissipated energy (TDE) versus web opening size in trapezoidally-corrugated steel plate shear panels with centrally-placed square opening. In this figure, the web opening and TDE values of the corrugated-web SPSW models are normalized by those of the non-perforated models with identical corrugation-angle and web-thickness values. From Figs. 10 and 11, it is evident that introduction of 5% web opening results in a considerable drop in energy absorption capacity of the SPSW system, while increasing of the opening size from 5% to 15% and from 15% to 30% decreases the energy absorption capacity with a relatively lower rate. Considering the important role of the infill plate as the primary lateral force-resisting and energy dissipating component in steel shear walls, the effects of introduction and size of the web-plate central square opening should be carefully considered in seismic design of the SPSW systems.

5. Effects of variation of corrugation angle

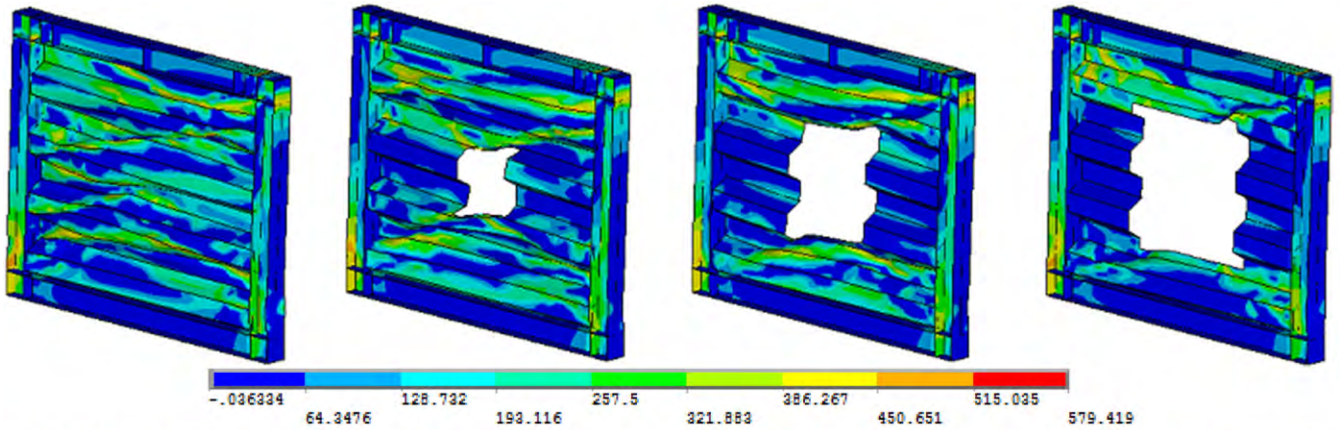
In this Section, the effects of variation of web-plate corrugation angle on cyclic performance and energy dissipation capacity of corrugated- and perforated-web SPSWs are investigated. The hysteresis curves as well as the dissipated energy-drift ratio plots of the SPSW models with $\theta = 30°$, 45°, 60°, and 90°, $t_w = 2$ and 3 mm, and $O = 5\%$ and 15% are shown in Figs. 12 and 13, respectively.

In case of SPSWs with $t_w = 2$ mm and $O = 15\%$, increasing of the corrugation angle from 30° to 90° seems to be quite effective in improving the cyclic behavior and energy absorption capability of the system. A fairly similar trend is observed in case of the steel shear walls with 3 mm web thickness and 15% web opening. Increasing of the corrugation angle alleviates the pinching of the hysteresis loops and improves the cyclic behavior of the models with $t_w = 2$ mm and $O = 5\%$; moreover, despite the scatter in the results shown in the corresponding dissipated energy-drift ratio plot, increasing of the corrugation angle is found to be by and large effective in increasing the energy dissipation capacity of the system. In addition, the cyclic performance of the SPSWs with 3 mm web thickness and 5% web opening is in general improved due to increasing of the corrugation angle; however, the corresponding dissipated energy-drift ratio plot shows that the energy dissipation capacity of the system is slightly reduced in case of 90° corrugation angle.

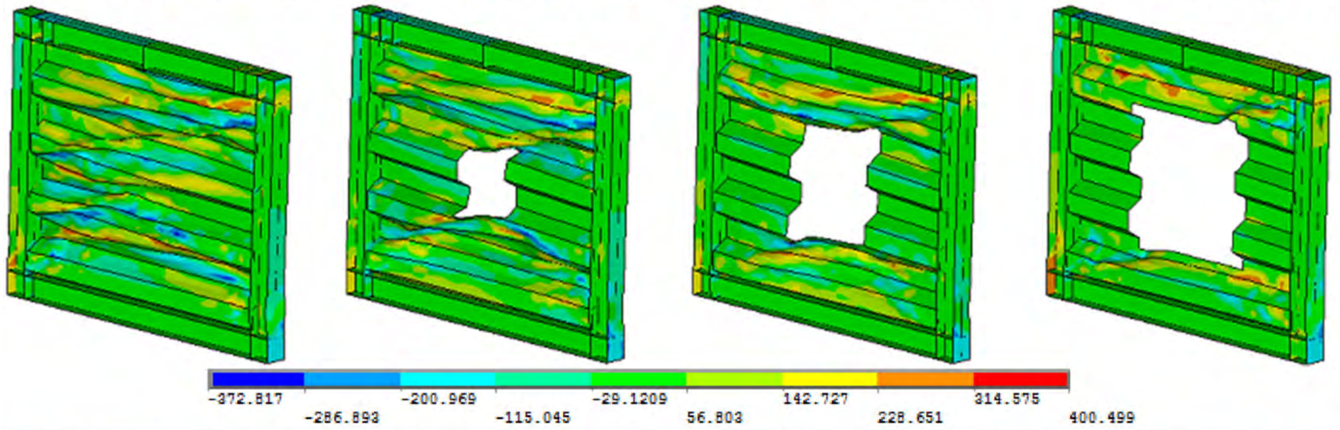
Overall, increasing of the corrugation angle from 30° to 90° is found to be more or less effective in improving the cyclic performance and energy dissipation capacity of corrugated- and perforated-web steel shear walls.

Table 2
Comparison of numerical predictions and experimental results.

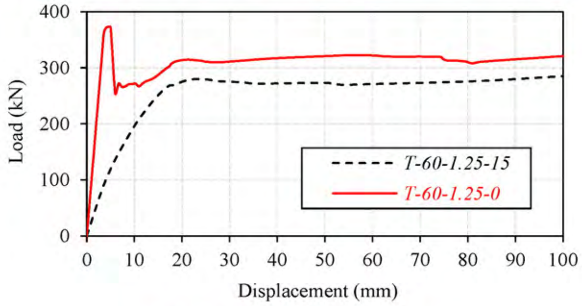
Criterion	Flat web		Num./exp.	Corrugated web		Num./exp.
	Exp.	Num.		Exp.	Num.	
Ultimate strength (KN)	580	544.2	0.94	500	420	0.84
Displacement (mm)	70	69	0.99	78	90	1.15



(a) *T-60-1.25-0* (1st principal stress) **(b)** *T-60-1.25-5* (1st principal stress) **(c)** *T-60-1.25-15* (1st principal stress) **(d)** *T-60-1.25-30* (1st principal stress)



(e) *T-60-1.25-0* (2nd principal stress) **(f)** *T-60-1.25-5* (2nd principal stress) **(g)** *T-60-1.25-15* (2nd principal stress) **(h)** *T-60-1.25-30* (2nd principal stress)



(i) Typical load-displacement curves

Fig. 8. Principal stress contour plots at 60 mm displacement (≈0.037 drift ratio) and load-displacement curves for SPSWs with and without web opening.

6. Effects of variation of infill plate thickness

Since infill plates in SPSWs are considered as the primary lateral force-resisting and energy dissipating elements, their thickness can play a major role in adjusting the stiffness, strength, and energy absorption capacity of such systems. Increasing of the web-plate thickness can significantly improve the structural performance of the system; however, it will also increase the stiffness and strength requirements on the boundary elements and result in an overall less economical system. It should be noted that increasing of web-plate thickness can result in larger design demands particularly on the surrounding vertical frame members, i.e. columns, and the failure mode of the system can be governed by column instability so that further increases in the web-plate thickness can have only a negligible effect on the strength of the system. On the other hand, perforation of the web-plate not only can allow the utility passage through SPSW but also can alleviate the problem of large panel force over-strength due to larger web-plate thickness.

The effects of variation of infill plate thickness on the hysteretic performance of corrugated- and perforated-web steel shear walls are investigated in this section. To this end, the performances of the steel shear wall models with $\theta = 30°$, $45°$, $60°$, and $90°$, $t_w = 1.25$, 2, 3, and 4 mm, and $O = 30\%$ are evaluated. The cyclic performances and dissipated energy-drift ratio plots of the considered models are illustrated in Figs. 14 and 15, respectively.

From Fig. 14, it is found that increasing of the infill plate thickness from 1.25 mm to 4 mm at 30°, 45°, 60°, and 90° corrugation angles and 30% web opening does not result in a noticeable change in the shapes of the hysteresis loops; however, it is certainly effective in improving the stability of the perforated web plate. It is important to note that performance of the SPSW system in this case study with 30% web opening is dominated by the performance of the surrounding

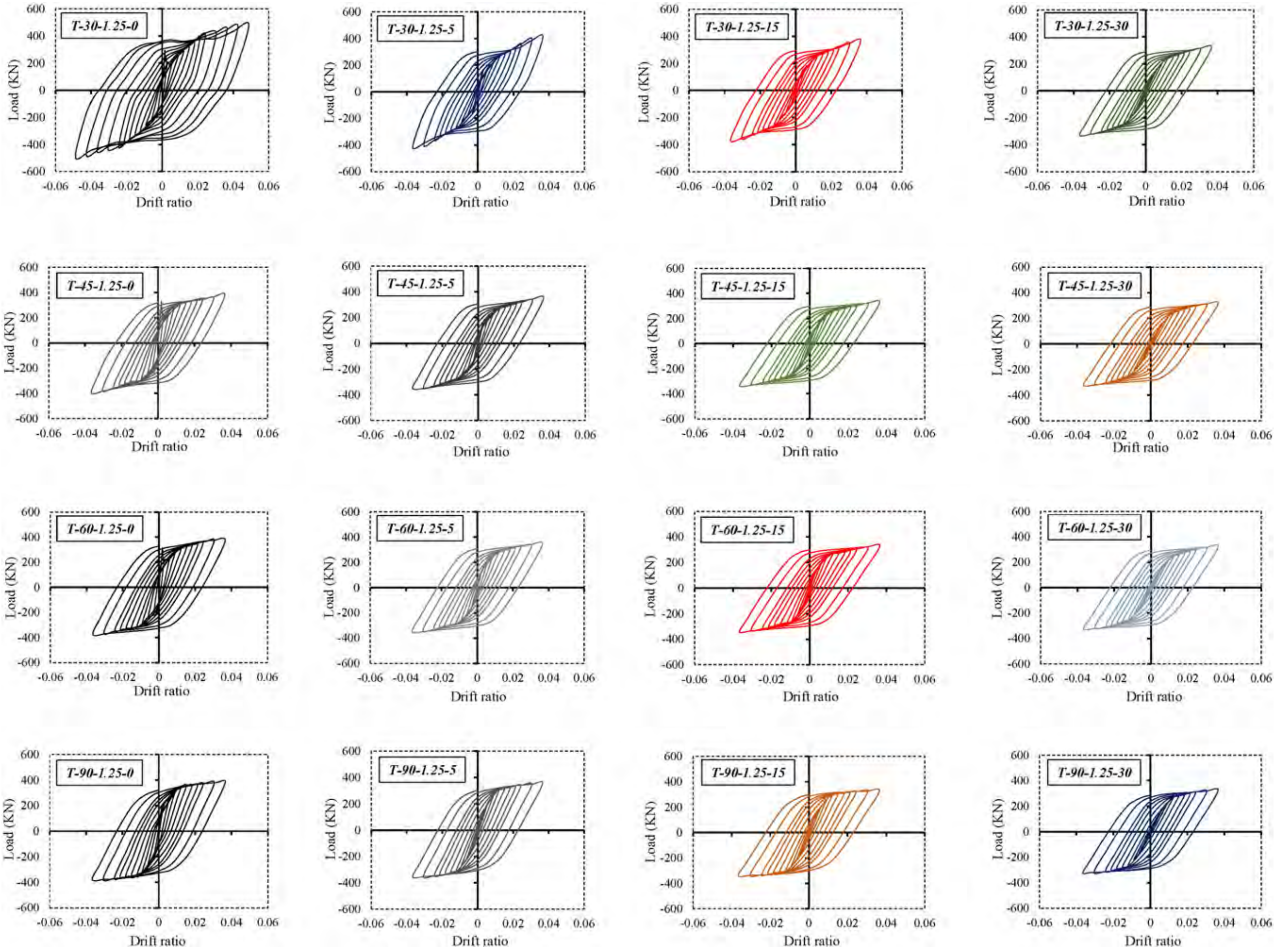


Fig. 9. Hysteresis curves of SPSW models with corrugated infill plates of various opening sizes.

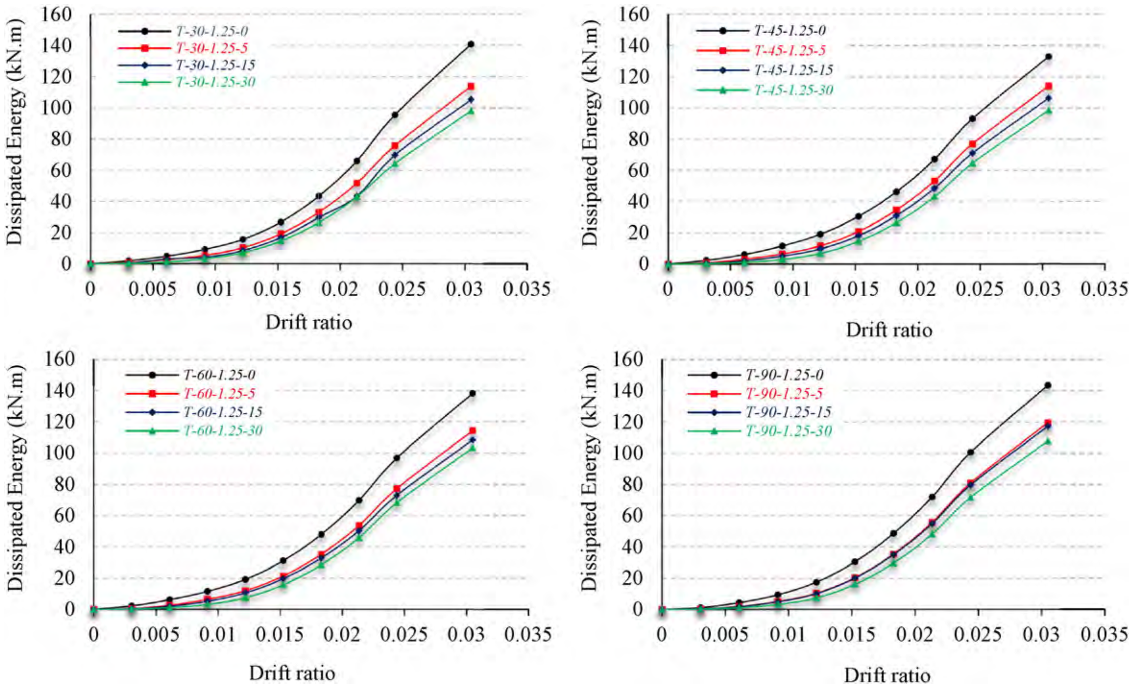


Fig. 10. Dissipated energy vs. drift ratio (variation of web opening size).

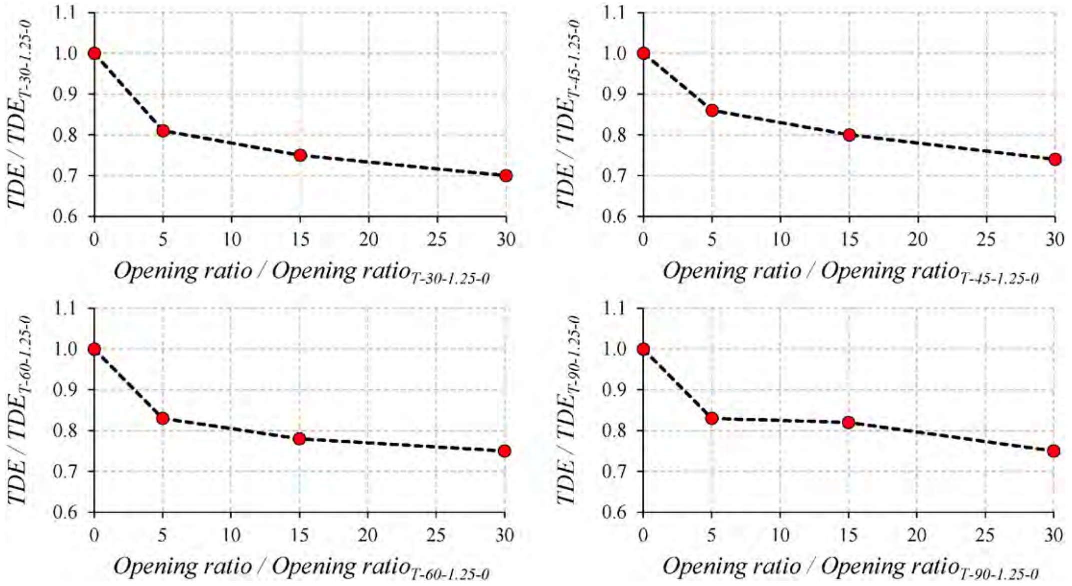


Fig. 11. Variation of total dissipated energy versus web opening size.

frame rather than that of the infill plat, and hence the cyclic performance of the system is not significantly influenced by the increase in web-plate thickness. In contrast, assessment of the dissipated energy-drift ratio plots in Fig. 15 clearly indicates that increasing of the web-plate thickness is quite effective in increasing the energy dissipation capacity of the system with different web-plate corrugation angles.

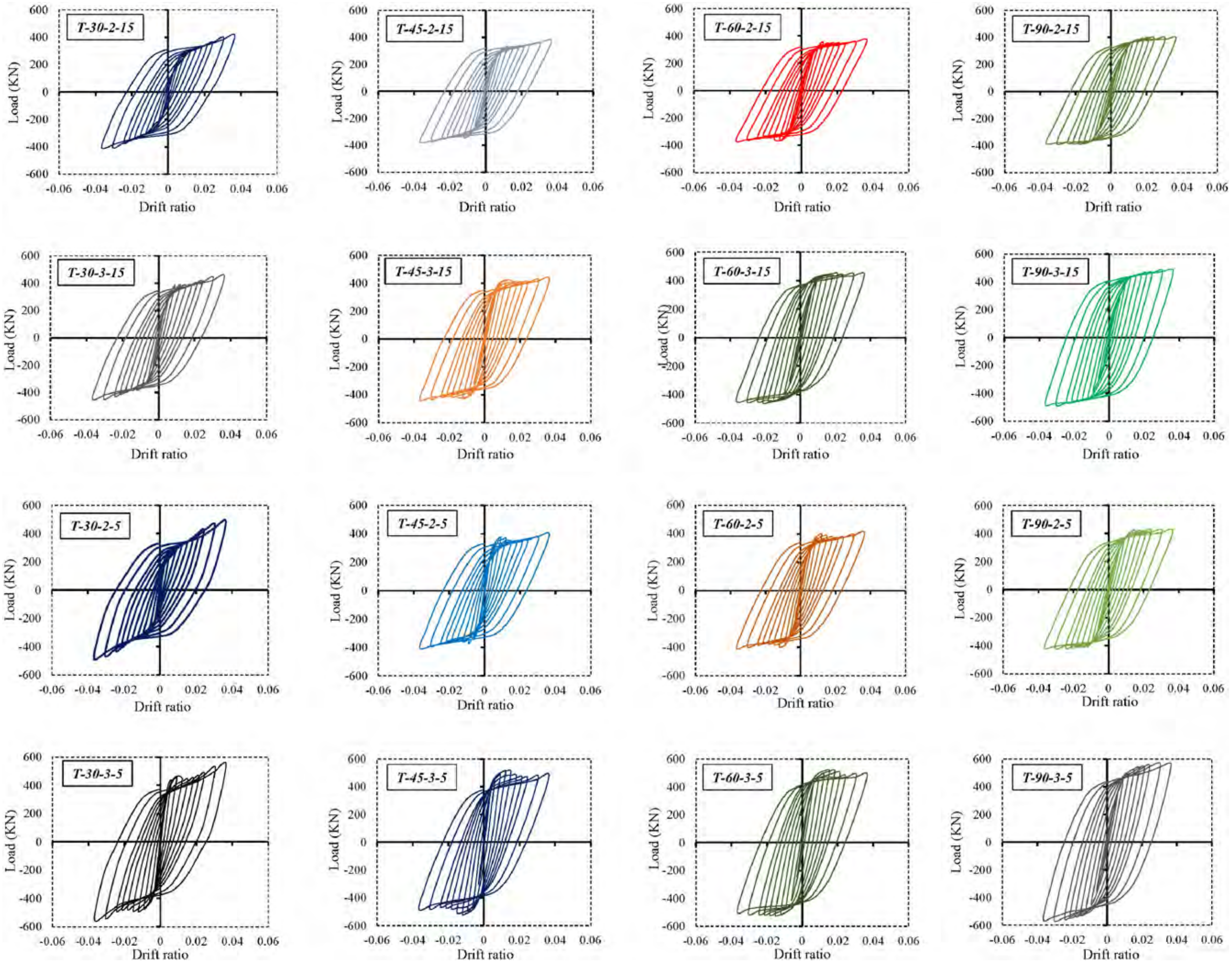


Fig. 12. Hysteresis curves of SPSW models with corrugated infill plates of various corrugation angles.

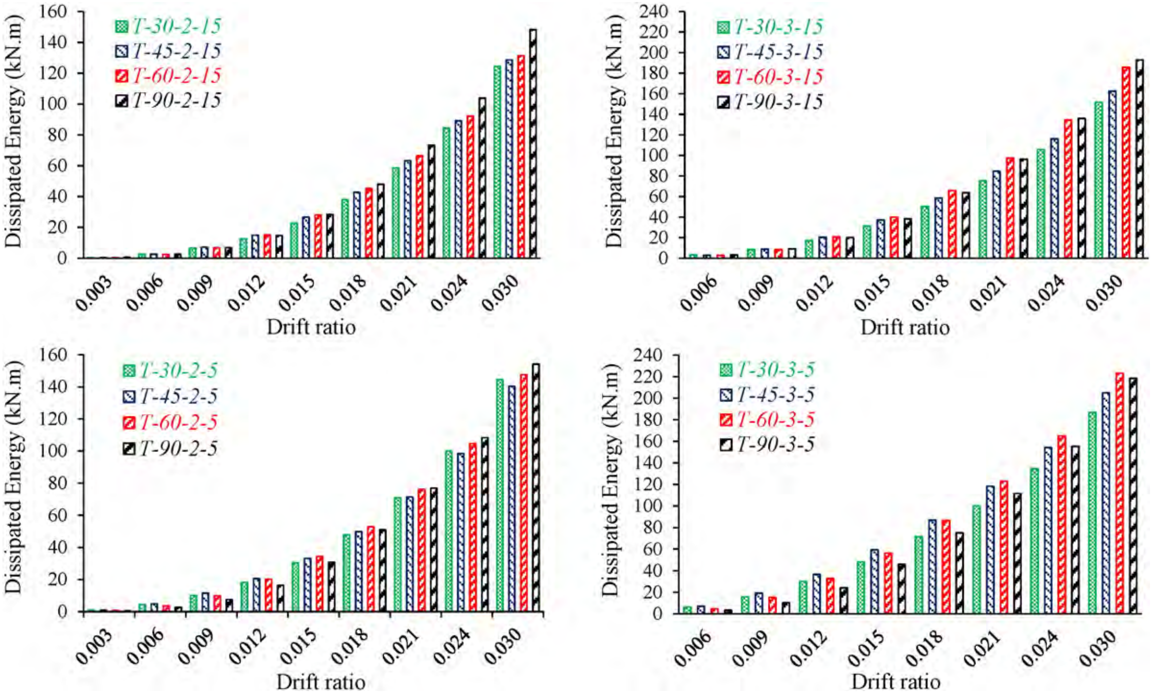


Fig. 13. Dissipated energy vs. drift ratio (variation of corrugation angle).

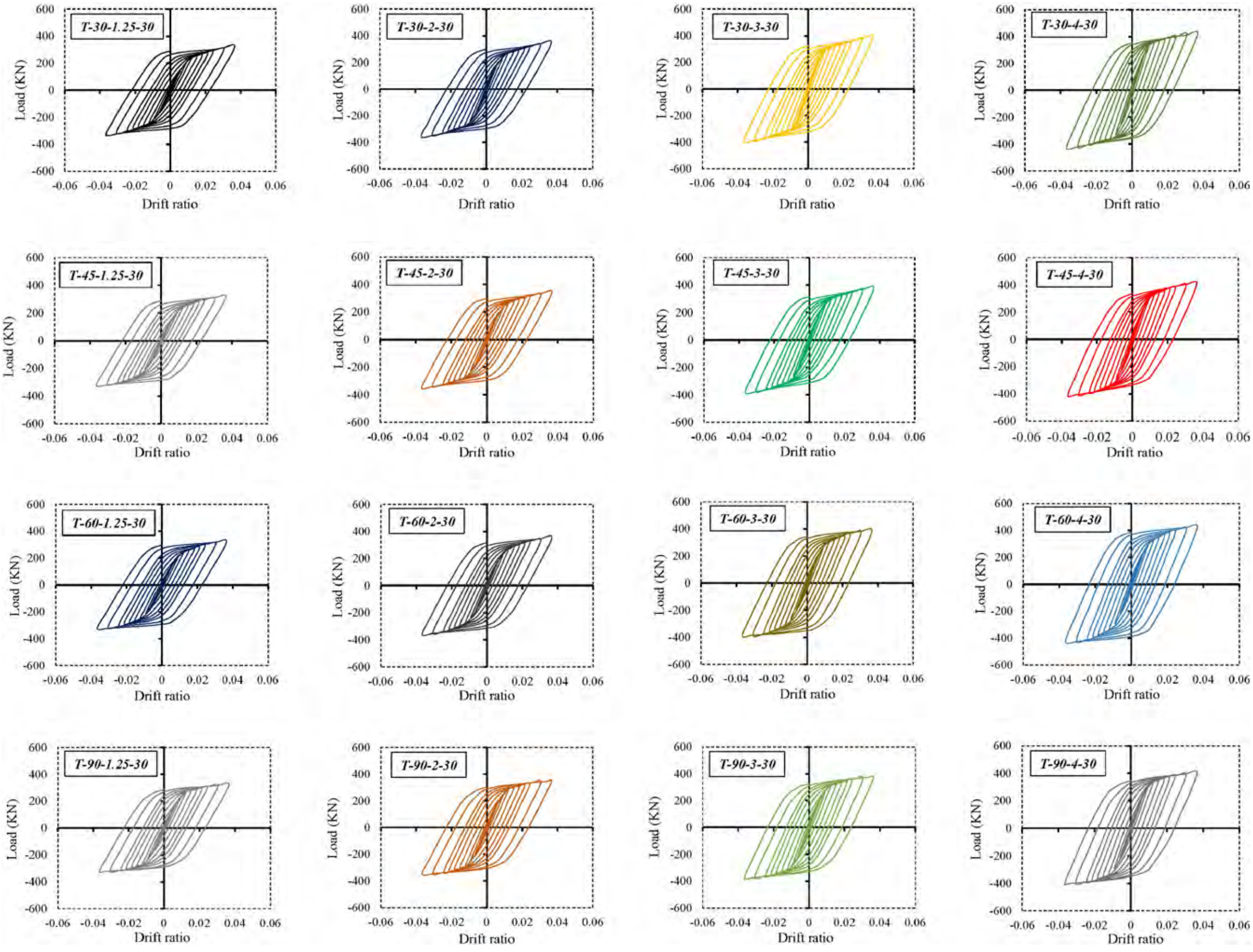


Fig. 14. Hysteresis curves of SPSW models with corrugated infill plates of various thicknesses.

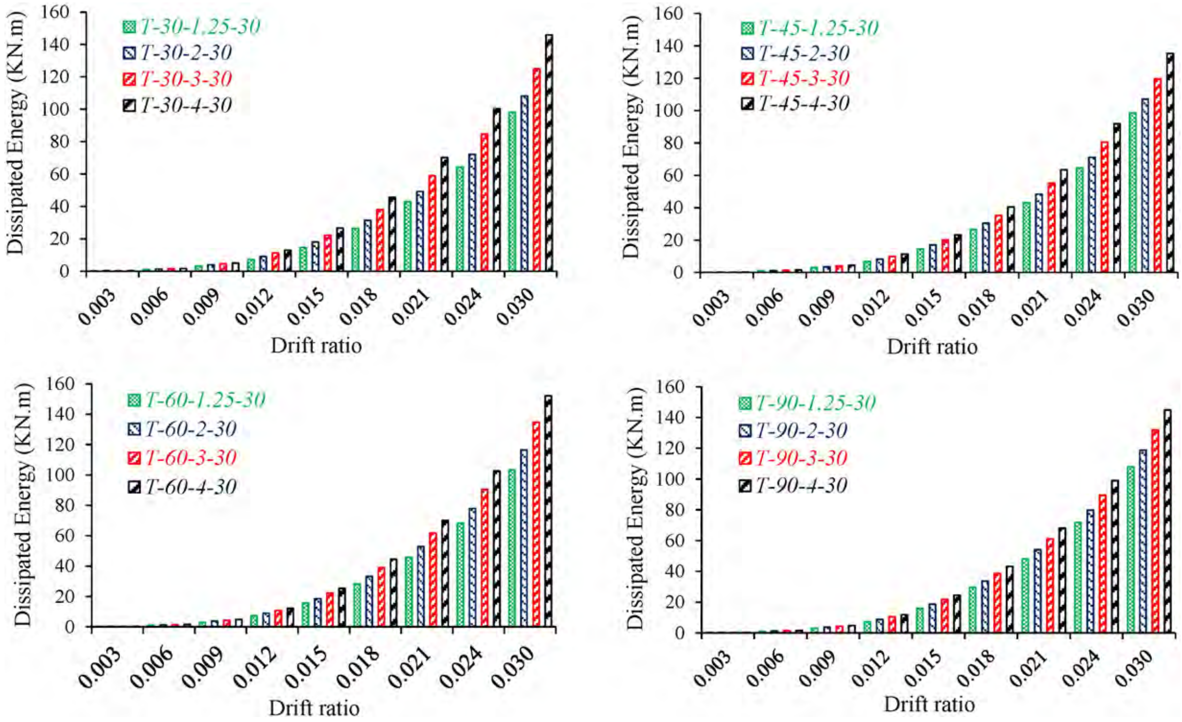


Fig. 15. Dissipated energy vs. drift ratio (variation of web thickness).

Findings of this case study show that increasing of the infill plate thickness from 1.25 mm to 4 mm results in 30% increase in the energy absorption capacity of the system, on average.

Fig. 16 shows the relationship between the normalized web thickness and total dissipated energy for SPSWs with different corrugation angles and 30% web opening. The depicted regression analysis results are indicative of a linear relationship between the increase in web thickness and energy dissipation capacity of the system in all cases. These findings substantiate the effectiveness of increasing of web-plate thickness in improving the energy dissipation capabilities of SPSW systems and can be applied for efficient seismic design and retrofit of such corrugated- and perforated-web lateral force-resisting systems.

7. Toughness

The *toughness* of structure refers to a potential capacity to prevent failure by absorbing energy under the action of external factors [10]. On this basis, toughness can be considered as an important seismic performance parameter indicative of the capability of a structure in absorbing the seismic energy imparted to it from earthquake ground motions.

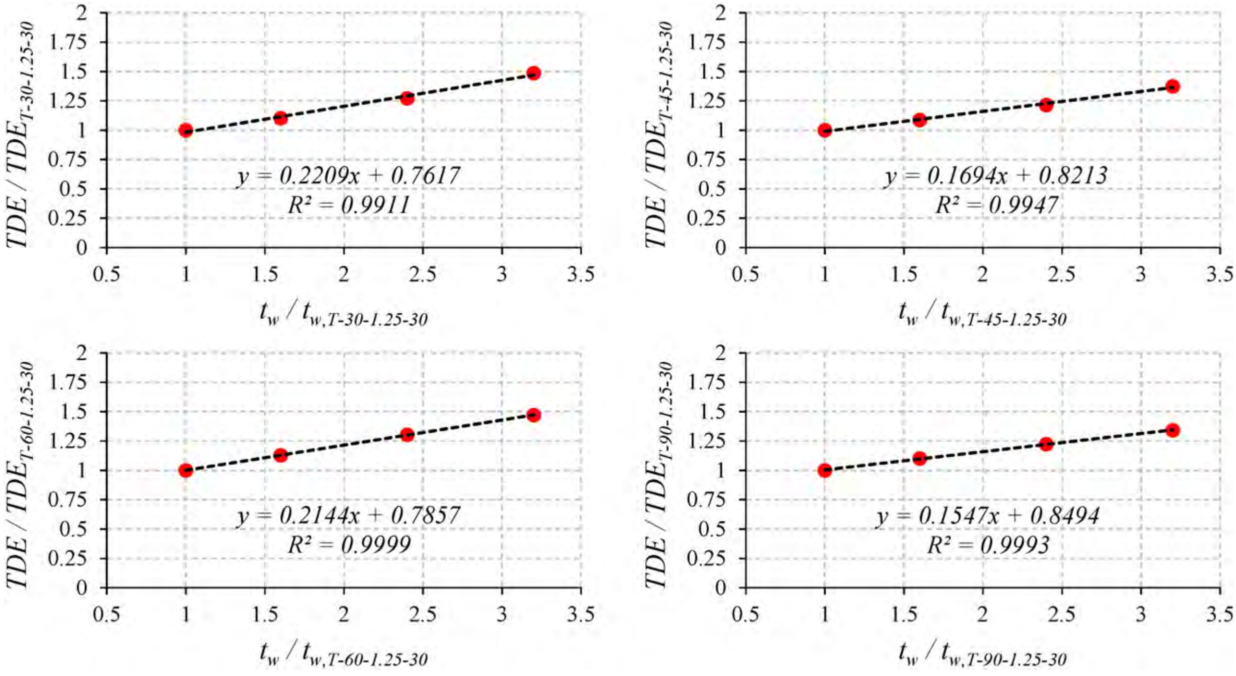
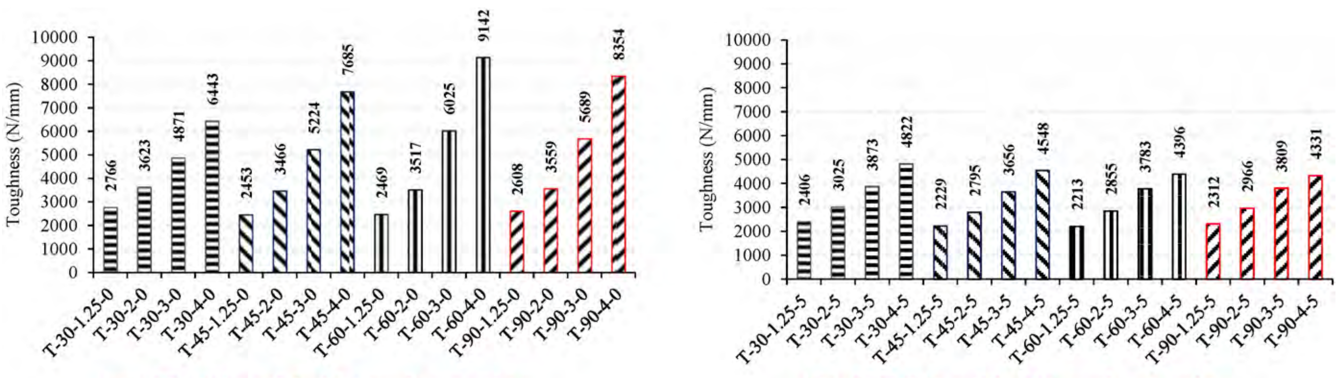
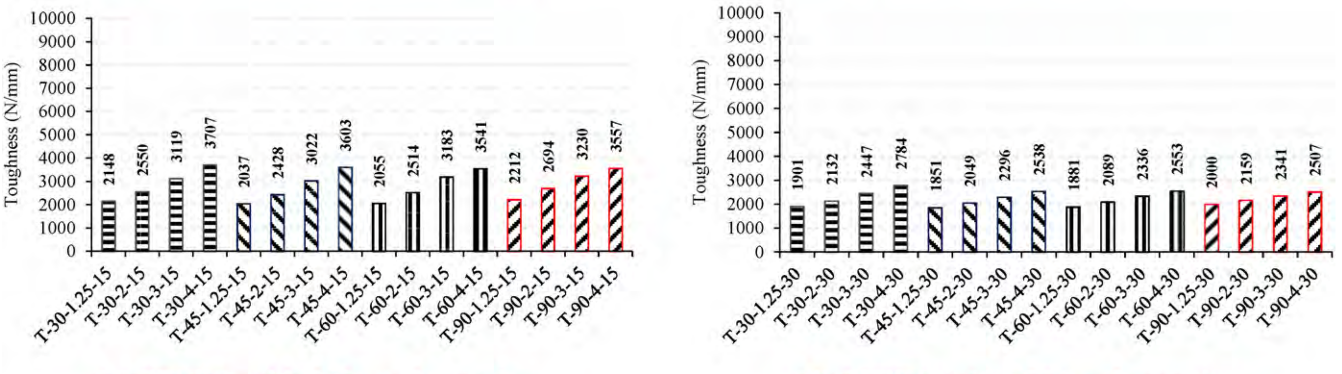


Fig. 16. Relationship between web thickness and total dissipated energy.



(a) SPSWs with 0% web opening **(b)** SPSWs with 5% web opening



(c) SPSWs with 15% web opening **(d)** SPSWs with 30% web opening

Fig. 17. Toughness of SPSW models with various geometrical properties.

In other words, toughness is a measure of the energy absorption capacity of a structure that is defined as the area under the force-deflection response curve [11]. The toughness of a structure indeed enables large deformations to occur during a seismic loading without collapse of the structure or endangering life safety.

In SPSWs, toughness can be achieved by designing and detailing the structural system so that significant inelastic deformation capacity can be provided primarily through web plate yielding in order to protect the rest of the structure from damage. Considering the importance of toughness as an effective parameter in seismic design and retrofit of steel shear wall systems, this section focuses on the toughness (energy absorption capacity) assessment of the corrugated- and non-perforated/perforated-web steel shear wall systems. The toughness of the SPSW models with various geometrical properties is determined by integrating the area under the load-displacement curve up to 82 mm displacement (0.05 drift ratio) and illustrated in Fig. 17.

From Fig. 17, it is evident that perforation of the web-plate decreases the toughness of the system, and the drop in toughness due to web opening is further accentuated by increasing of the infill plate thickness. In other words, increasing of the web opening size is found effective in lowering the toughness of the system especially at larger web thicknesses. On the other hand, increasing of web thickness from 1.25 mm to 4 mm is found to be quite effective in increasing the toughness of the system. In case of variation of the corrugation angle, despite some scatter in results, it is observed that increasing of θ from 30° to 45° in general results in a little decrease in toughness while further increasing of θ from 45° to 90° by and large increases the toughness of the system. This trend is slightly varied at larger web thicknesses where increasing of the corrugation angle from 30° to 90° tends to lower the toughness marginally.

As a result, among the considered geometrical parameters increasing of web thickness is found to be quite effective in increasing the toughness. Also, introduction of web opening and increasing of the web perforation size are found to have certain effect in reducing the toughness of the corrugated-web steel shear walls.

8. Conclusion

This paper focuses on the cyclic performance and energy absorption capacity assessment of trapezoidally-corrugated and centrally-perforated steel shear walls. Corrugated- and perforated-web SPSWs offer various structural and architectural features which can be effective in widespread application and efficient design of such lateral force-resisting systems.

Numerous finite element models with various geometrical properties were developed and analyzed under cyclic loading. Web-plate thickness, corrugation angle, and opening size were considered as the key parameters for performance assessment of the SPSWs in this study.

It was found that introduction of web opening can lower the load-bearing capacity of the infill plate as the primary lateral force-resisting and energy dissipating element, which can in turn adversely affect the cyclic performance and energy absorption capability of the system, if not detailed properly. It was also demonstrated that increasing of web opening size is directly coupled with the decreasing of energy dissipation capacity of the system and a linear relationship was obtained between these two quantities. Introduction and increasing of size of the web opening was also shown to reduce the contribution of the infill plate to the overall performance of the system and to increase the overall system demand on the boundary frame members.

In addition, the results of this study also indicated that increasing of the web-plate corrugation angle from 30° to 90° can be more or less effective in improving the cyclic performance and energy dissipation capability of the system. The major effectiveness of increasing of the web-plate thickness in improving the hysteretic performance of corrugated- and perforated-web SPSWs was shown as well. Furthermore, a linear relationship was obtained between the increase in web thickness and energy dissipation capacity of the system. Lastly, increasing of web thickness and introduction of web opening as well as increasing of its size were shown to be the most effective parameters in, respectively, increasing and lowering the toughness of the SPSW system.

It is important to note that the structural performance of SPSWs may be adversely affected by the failure of the connection between the infill plate and the boundary frame members. This issue may be of more concern in steel shear walls with perforations having sharp corners where plate cracking may develop due to stress concentration and propagate into the plate-frame connection zone. Hence, the proper design of the plate-frame connection by using a hybrid configuration, i.e. combination of weld and bolt, fish plates as well as accurately-sized, two-sided fillet welds at the perimeter of web plates, and also the proper bounding of the web openings on all sides by means of intermediate boundary elements will ensure the occurrence of the web-plate tension yielding prior to the connection failure, particularly at local areas of higher stress. In fact, the plate-frame connection should be designed for the expected yield strength of the web plate, which can be accomplished through application of proper bolts accompanied by high-quality fillet welds in order to provide the required strength of the connection.

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