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Nonlinear buckling analysis of steel plate shear walls with trapezoidally-corrugated and perforated infill plates

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Abstract
Based on considerable out-of-plane stability of corrugated plates, such plates can be considered as viable alternatives to unstiffened and stiffened steel plates in structural systems such as steel plate shear walls (SPSWs). This study investigates the effects of variation of corrugation parameters and inclusion of infill plate opening on the structural performance of trapezoidally-corrugated SPSWs under monotonic loading through finite element simulation using ANSYS. Buckling stability, stiffness, strength, and ductility performances of numerous SPSW models developed based on web-plate thickness, corrugation angle, and opening size parameters are investigated. Square openings are implemented at the center of the infill plates with areas equal to 5, 10, 15, 20, 25, and 30 percent of the web-plate out-of-plane projected area. The accuracy of the finite element modeling is verified through comparison of numerical and experimental results. Findings of this study show that proper design of the boundary frame members and optimal selection of the web-plate thickness as well as corrugation parameters can result in desirable performance of steel shear walls with trapezoidally-corrugated and perforated infill plates, particularly despite the detrimental effects of web-plate opening, as partly shown in this paper.

1. Introduction
Steel plate shear wall (SPSW) is an efficient lateral force-resisting system. A properly-designed SPSW can have high initial stiffness, strength, energy absorption capacity, and ductility. SPSWs have been commonly designed with unstiffened and stiffened infill plates based on economical and performance considerations. Advantageous structural features of corrugated plates have led to the employment of such elements in stiffened SPSWs with the aim of lowering the high construction cost of such high-performing systems.

Research has been conducted on shear walls employing corrugated steel plates. Mo and Perng (2000) conducted an experimental study on framed shear walls with corrugated infill plates and

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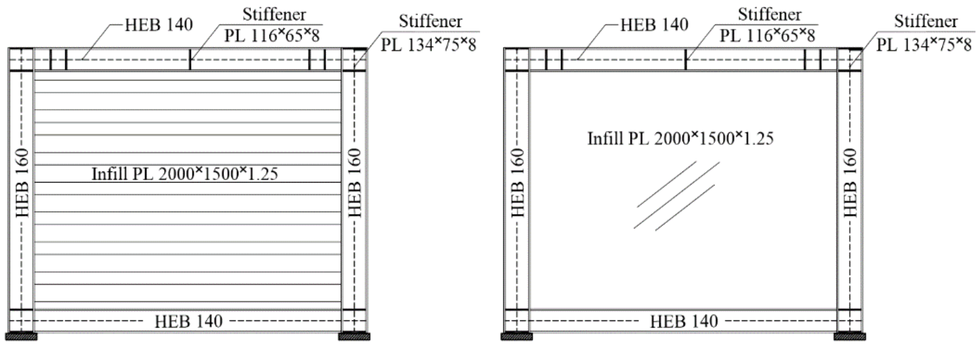
demonstrated the improved seismic performance of such structural systems. Berman and Bruneau (2005), also, performed experimental study on light-gauge and single-story SPSW specimens with flat and corrugated infill plates using quasi-static loading. It was shown that the specimen utilizing corrugated infill plate can achieve significant ductility and energy dissipation while minimizing the system demand on the surrounding framing. Recently, the behavior of trapezoidally-corrugated SPSWs under monotonic and cyclic loadings was further investigated by Emami et al. (2013) and Emami and Mofid (2014) through experimental and numerical approaches. In addition, Bayat (2014) performed a comparative study on SPSWs with trapezoidally- and sinusoidally-corrugated infill plates and demonstrated the relatively higher structural performance of trapezoidally-corrugated shear walls. Kalali et al. (2015), also, have reported a detailed numerical parametric study on the stiffness, strength, and hysteretic performances of SPSWs with flat and trapezoidally horizontal corrugated infill plates.

Research on SPSWs with openings has also gained researchers' attention. Roberts and Sabouri-Ghomi (1992) carried out an experimental and theoretical investigation on the hysteretic characteristics of unstiffened perforated steel plate shear panels with centrally placed circular openings under quasi-static cyclic loading. It was observed that the strength and stiffness of the panels decrease approximately linearly by increasing of the opening size. Vian and Bruneau (2005) conducted experimental tests to examine the efficiency of steel infill panels with circular openings where an effective reduction factor was proposed to take the reduced strength and stiffness of panels with circular holes into account. Recently, Barkhordari et al. (2014) reported a numerical study on the behavior of SPSWs with perforated flat infill plates. In this study, two types of opening, i.e. partial-height and full-height, were considered. It was demonstrated that the behavior of a SPSW with opening depends on the opening type and the stiffened full-height opening.

In this paper, the buckling stability and structural performances of SPSWs with trapezoidally-corrugated and perforated infill plates are investigated 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 varying the geometrical and corrugation parameters including the web-plate thickness, corrugation angle, and opening size.

2. Specifications of SPSW models

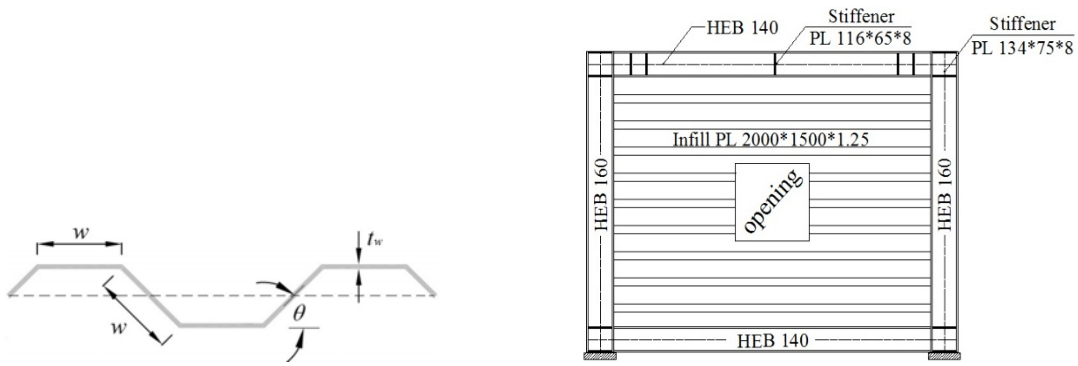
To investigate the performances of SPSWs under monotonic loading, two SPSWs tested by Emami et al. (2013) are adopted (Fig. 1) and parametric studies are performed by changing the geometrical properties of the infill plates including the web-plate thickness (t_w), corrugation angle (θ), and opening size (O). On this basis, 100 SPSW models are considered in this study. Properties of the considered SPSW models are illustrated in Fig. 2 and summarized in Table 1.



Specimen *T-30-8-1.25* Specimen *F-1.25*

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

(Note: All units are in millimeters.)



Corrugated plate properties Typical trapezoidally-corrugated and perforated SPSW model

Figure 2: Geometrical properties of considered SPSW models

(Note: All units are in millimeters.)

Table 1: Specifications of considered SPSW models

Web-plate form	Label	θ (deg.)	t_w (mm)	O (%)	No. of models
Flat	F-t_w	-	1.25, 2, 3, 4	-	4
Trapezoidal	T-θ-t_w-O	30	1.25, 2, 3, 4	0, 5, 10, 15, 20, 25, 30	24
		45	1.25, 2, 3, 4	0, 5, 10, 15, 20, 25, 30	24
		60	1.25, 2, 3, 4	0, 5, 10, 15, 20, 25, 30	24
		90	1.25, 2, 3, 4	0, 5, 10, 15, 20, 25, 30	24

As it is seen in Table 1, the SPSW models are labeled such that the infill plate 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, and also the label *T-60-6-5* indicates that the model has a corrugated web-plate of trapezoidal form with a corrugation angle of 60º, web-plate thickness of 6 mm, and an opening with an area equal to 5 percent of the infill plate area. It should be noted that all corrugated web-plates have eight corrugation half-waves.

3. Finite element modeling and verification

SPSWs are modeled and analyzed using ANSYS 11.0 (2007) finite element software. 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, and is well-suited for modeling shells.

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 set to 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 test setup.

The multilinear representation of the stress-strain relationships for the considered steel material is shown in Fig. 4, which was obtained from tensile coupon tests (Emami and Mofid, 2014). The yield stresses of the plate, beam, and column components are 207 MPa, 288 MPa, and 300 MPa, respectively. Young's modulus of elasticity and Poisson's ratio are considered to be 210 GPa and 0.3, respectively, for the steel material. Moreover, the von Mises yield criterion is adopted for the steel material yielding.

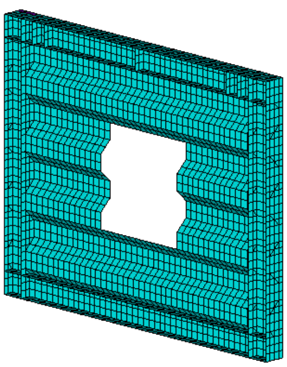


Figure 3: Typical finite element model

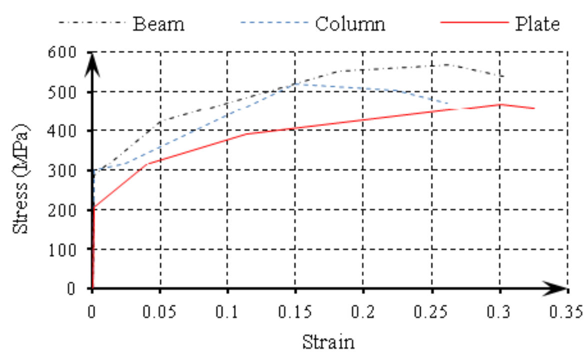
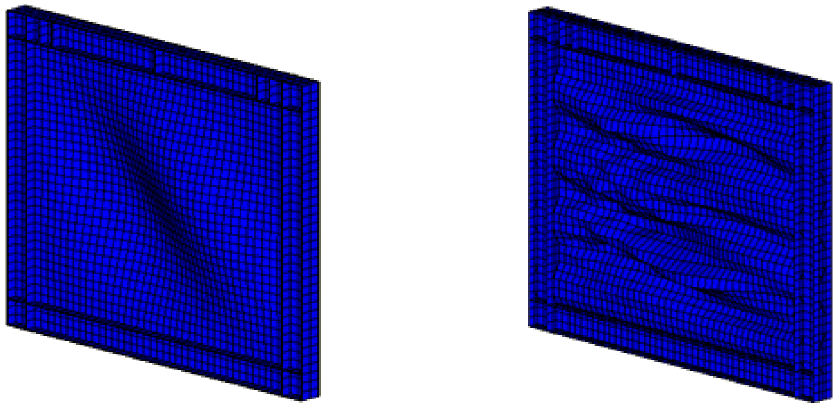


Figure 4: Stress-strain relationships of the steel material (Emami and Mofid, 2014)

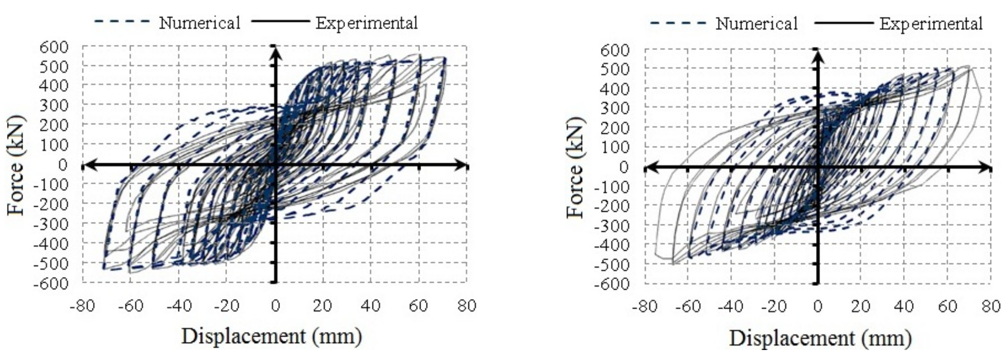
Initial imperfections are applied in the finite element models in order to initiate buckling in the nonlinear analyses. Eurocode (2003) suggests that out-of-plane imperfection of plates (U) shall be taken as the smaller of $w/200$ and $h_w/200$, where w and h_w are the fold width (Fig. 2) and web height, respectively. Accordingly, initial imperfections consistent with the first buckling mode shapes of the SPSWs are introduced to all models by considering 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 resulted from eigen buckling analysis. The first buckling mode shapes of two typical SPSW models with flat and corrugated web-plates are shown in Fig. 5.



Flat-web model Corrugated-web model

Figure 5: First buckling mode shapes of two typical SPSW models

Finally, the accuracy of the numerical simulation is verified by comparing the finite element analysis results with the experimental results of two specimens tested by Emami et al. (2013), as shown in Fig. 6. From the figure, the agreement between numerical and experimental results is pretty good in cases of both flat- and corrugated-web SPSWs. This is indicative of validity of the finite element modeling and analysis.



Flat-web SPSWs (*F-1.25*) Corrugated-web SPSWs (*T-30-1.25-0*)

Figure 6: Validation of numerical simulation

4. Discussion of results

The effects of stiffness of the boundary frame members and variation of web-plate thickness and corrugation angle on the buckling stability of SPSWs are investigated in this section. In addition, considering the significance of stiffness, strength, and energy dissipation characteristics of lateral force-resisting systems, the performances of the SPSW models in terms of initial stiffness, ultimate strength, and ductility are also evaluated through assessment of the numerical results from nonlinear buckling analyses.

4.1 Buckling strength

Two issues are investigated in case of buckling behavior and strength of SPSWs. These include the plate-frame interaction in buckling of SPSWs with flat infill plates (Fig. 7) and variation of buckling strength of SPSWs with non-perforated infill plates (Fig. 8). In general, results of this study confirm that (i) use of corrugated infill plates is quite effective in increasing the buckling strength of SPSWs, and (ii) introduction of web opening and increasing the opening size lower the buckling strength of SPSWs remarkably.

The Pcr-s.s. / Pcr-infill and Pcr-cl. / Pcr-infill ratios for flat-web SPSW models are shown in Fig. 7, where Pcr-s.s. and Pcr-cl. are the theoretical critical loads for plates under pure shear with respective simple and clamped support conditions and Pcr-infill is the buckling load of the *partially-restrained* infill plate in steel shear wall determined form eigen buckling analysis. As it is seen in Fig. 7, by increasing of the web-plate thickness from 1.25 mm to 4 mm the Pcr-s.s. / Pcr-infill ratios get closer to unity while Pcr-cl. / Pcr-infill ratios stray farther from unity. This indicates that increasing of infill plate thickness without proper design of the boundary frame members can result in large deformation of the boundary frame members and consequently weak performance of the system. On this basis and as demonstrated by Zirakian and Zhang (2015), the support conditions of infill plates in code-designed SPSW systems should be quite close to the clamped support condition in order to ensure high performance of the system.

From Fig. 8 it is evident that increasing of web-plate thickness is quite effective in increasing the buckling capacity of non-perforated and flat- as well as corrugated-web SPSWs. It is also found that the rate of increase of the buckling strength due to increase of the web-plate thickness gets higher as θ increases from 30° to 90°. On this basis, the highest rate of increase of the buckling strength is found in case of SPSWs with 90° corrugation angle.

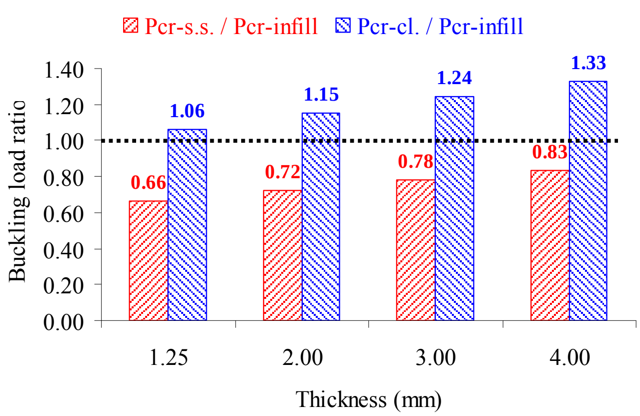


Figure 7: Plate-frame interaction in buckling of SPSWs with flat infill plates

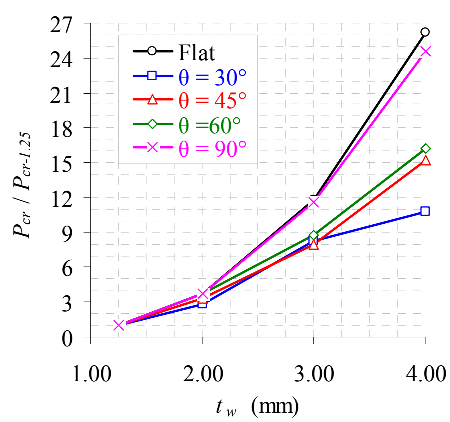


Figure 8: Variation of buckling strength of SPSWs with non-perforated infill plates

4.2 Initial stiffness

The stiffness performance of the corrugated-web SPSW models is investigated by considering the finite element analysis results illustrated in Fig. 9. It is observed that increasing of θ from 30° to 90° is in general somewhat effective in decreasing the initial stiffness. On the other hand, it is evident that increasing of t_w from 1.25 mm to 4 mm is effective in increasing the initial stiffness. Furthermore, it is found that introduction of 5% opening results in a considerable drop in initial stiffness, while increasing of opening size from 5% to 30% is comparatively less effective in reducing the initial stiffness.

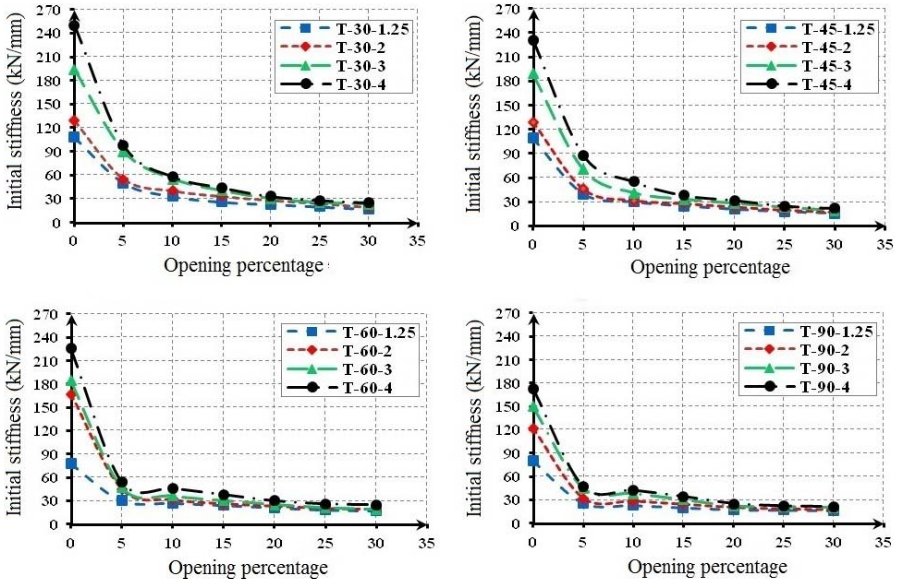


Figure 9: Initial stiffnesses of the SPSW models with 30º, 45º, 60º, and 90º corrugation angles

4.3 Ultimate strength

The strength performances of the SPSW models are investigated in here. To achieve this, the ultimate strengths of the trapezoidally-corrugated and perforated infill plates in the SPSW models are determined by subtracting the load-displacement curves of the surrounding frames from the curves of the SPSW panels. Consideration of ultimate strengths of the infill plates is due to the fact that SPSW panels did not undergo strength degradation. On the other hand, subtraction of the two curves is based on the inspiration taken from Sabouri-Ghomi et al.'s (2005) plate-frame interaction (PFI) model whose applicability and effectiveness has been demonstrated through numerous studies. The von Mises stress contour plots of *T-45-3-0* and *T-45-3-15* models at rotations corresponding to the ultimate strengths of the infill plates are shown in Fig. 10. The determined ultimate strengths are also presented in Fig. 11.

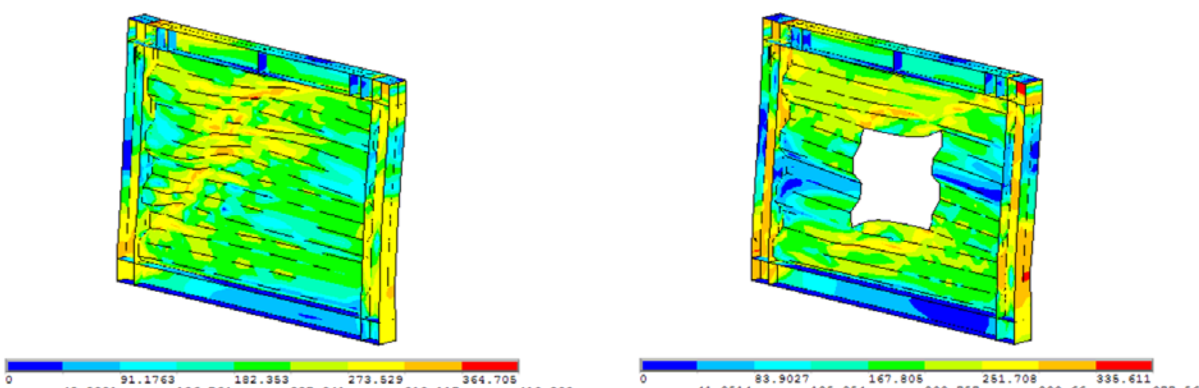


Figure 10: von Mises stress contour plots of *T-45-3-0* and *T-45-3-15* models

From Fig. 11, increasing of θ from 30° to 90° does not seem to have a remarkable effect on the ultimate strength, while increasing of t_w from 1.25 mm to 4 mm is found to be quite effective in increasing of the strength. In addition, inclusion of 5% perforation in the fill plate results in 58% strength reduction on average, while increasing of opening size from 5% to 30% decreases the strength with a lower rate.

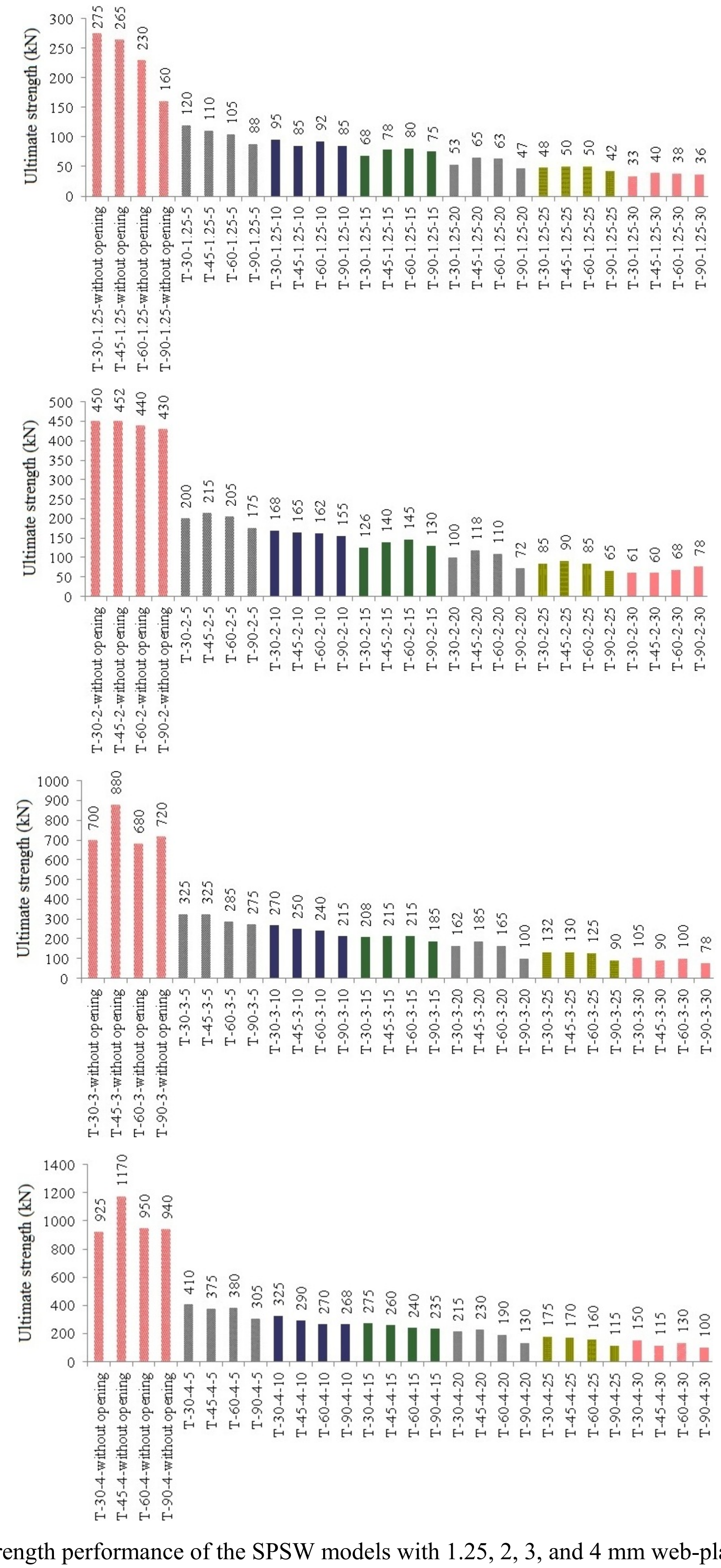


Figure 11: Strength performance of the SPSW models with 1.25, 2, 3, and 4 mm web-plate thicknesses

4.4 Ductility

Ductility is an important parameter in seismic performance assessment of lateral force-resisting systems. In SPSWs, web plates should effectively participate in providing the system ductility. On this basis, the ductility performance of the SPSW models is evaluated by considering a ductility factor defined as the ratio of displacement corresponding to the ultimate strength (Δ_{max}) to displacement corresponding to the yield strength (Δ_y), i.e. ductility ratio = Δ_{max} / Δ_y. The ductility factors of the SPSW models are provided in Fig. 12.

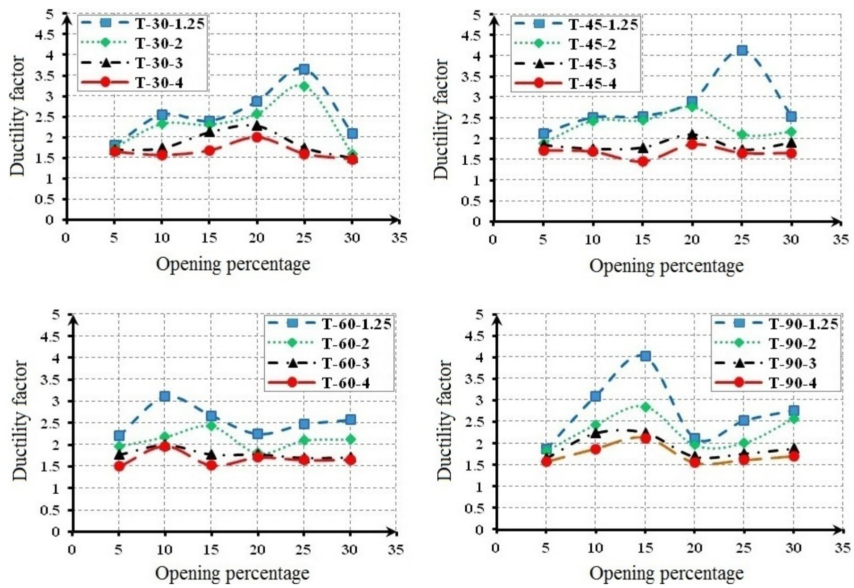


Figure 12: Ductility of the SPSW models with 30º, 45º, 60º, and 90º corrugation angles

Due to the scatter in results, it seems that ductility of the SPSW models is not affected remarkably by variation of the corrugation angle. In contrast, it is clearly observed that increasing of web-plate thickness lowers the ductility of the system to some extent. The minimum and maximum values of ductility factor for models with 4 mm and 1.25 mm web-plate thicknesses are about 1.5 and 4.0, respectively. In addition, as seen in Fig. 12, variation of the web-plate opening size does not have a clear and specific effect on the ductility of the system.

5. Conclusion

In this paper, the buckling stability, stiffness, strength, and ductility performances of steel shear walls with trapezoidally-corrugated and perforated infill plates were investigated via detailed numerical simulations. Numerous finite element models were considered based on web-plate thickness, corrugation angle, and opening size parameters for the purpose of this study. Increasing of web plate thickness was shown to be quite effective in improving the buckling stability, stiffness, and strength, reducing the ductility, and also increasing the overall system demand on the boundary frame members of SPSWs. Variation of the corrugation angle, on the other hand, was not found to have a specific effect on the strength and ductility of the system, while increasing of this corrugation parameter was found to be somewhat effective in decreasing the initial stiffness. In addition, introduction of web-plate perforation and increasing of the opening size were shown to have detrimental effects by reducing the buckling strength, initial stiffness, and strength of the system, while ductility of the system was not affected specifically by the variation of the opening size. Overall, it can be concluded that proper design and detailing of SPSWs with trapezoidally-corrugated and perforated infill plates can result in desirable performance of such systems. Further numerical and especially experimental studies can provide significant insight into the efficient design and application of steel shear wall systems with trapezoidally-corrugated web-plates.

References

ANSYS 11.0 (2007). ANSYS 11.0 Documentation. ANSYS Inc.

Barkhordari, M.A., Asghar Hosseinzadeh, S.A., Seddighi M. (2014). "Behavior of steel plate shear walls with stiffened full-height rectangular openings." *Asian Journal of Civil Engineering*, Technical Report, 15 (5) 741-760.

Bayat, M. (2014). "Evaluation and comparison behavior of corrugated steel plate shear walls." *Latin American Journal of Solids and Structures*, Vol. 11. (In Press)

Berman, J.W., Bruneau, M. (2005). "Experimental investigation of light-gauge steel plate shear walls." *Journal of Structural Engineering*, ASCE, 131 (2) 259-267.

Emami, F., Mofid, M. (2014). "On the hysteretic behavior of trapezoidally corrugated steel shear walls." *The Structural Design of Tall and Special Buildings*, 23 (2) 94-104.

Emami, F., Mofid, M., Vafai, A. (2013). "Experimental study on cyclic behavior of trapezoidally corrugated steel shear walls." *Engineering Structures*, 48 (March) 750-762.

Eurocode (2003). Design of Steel Structures. Part 1.5: Plated Structural elements. European Committee for Standardization, Brussels.

Kalali, H., Hajsadeghi, M., Zirakian, T., Alaee, F.J. (2015). "Hysteretic performance of SPSWs with trapezoidally horizontal corrugated web-plates." *Steel and Composite Structures, An International Journal*, 19 (2). (In Press)

Mo, Y., Perng, S. (2000) "Behavior of framed shearwalls made of corrugated steel under lateral load reversals." *Advances in Structural Engineering*, 3 (3) 255-262.

Roberts, T.M., Sabouri-Ghomi, S. (1992). "Hysteretic characteristics of unstiffened perforated steel plate shear panels." *Thin-Walled Structures*, 14 (2) 139-151.

Sabouri-Ghomi, S., Ventura, C.E., Kharrazi, M.H.K. (2005). "Shear analysis and design of ductile steel plate walls." *Journal of Structural Engineering*, ASCE, 131 (6) 878-889.

Vian, D., Bruneau, M. (2005). Steel Plate Shear Wall for Seismic Design and Retrofit of Building Structures. MCEER Technical Report 05-0010, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo.

Zirakian, T., Zhang, J. (2015). "Buckling and yielding behavior of unstiffened slender, moderate, and stocky low yield point steel plates." *Thin-Walled Structures*, 88 (March) 105-118.