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Numerical study on the structural performance of corrugated low yield point steel plate shear walls with circular openings

Mahdi Shariati [1,2a], Shervin Safaei Faegh [3b], Peyman Mehrabi [3c],
Seyedmasoud Bahavarnia [4d], Yousef Zandi [5e], Davood Rezaee Masoom [6f],
Ali Toghroli[*7], Nguyen-Thoi Trung [1,2g] and Musab N A Salih [8h]

[1] *Division of Computational Mathematics and Engineering, Institute for Computational Science, Ton Duc Thang University, Ho Chi Minh City, Vietnam*
[2] *Faculty of Civil Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam*
[3] *Department of Civil Engineering, K.N. Toosi University of Technology, Tehran, Iran*
[4] *Department of Civil Engineering, Qeshm International Branch, Islamic Azad University, Qeshm, Iran*
[5] *Department of Civil Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran*
[6] *Department of Civil Engineering, Islamic Azad University, Central Tehran Branch, Tehran, Iran*
[7] *Institute of Research and Development, Duy Tan University, Da Nang 550000, Vietnam*
[8] *School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia*

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Abstract. Corrugated steel plate shear wall (CSPSW) as an innovative lateral load resisting system provides various advantages in comparison with the flat steel plate shear wall, including remarkable in-plane and out-of-plane stiffnesses and stability, greater elastic shear buckling stress, increasing the amount of cumulative dissipated energy and maintaining efficiency even in large story drifts. Employment of low yield point (LYP) steel web plate in steel shear walls can dramatically improve their structural performance and prevent early stage instability of the panels. This paper presents a comprehensive structural performance assessment of corrugated low yield point steel plate shear walls having circular openings located in different positions. Accordingly, following experimental verification of CSPSW finite element models, several trapezoidally horizontal CSPSW (H-CSPSW) models having LYP steel web plates as well as circular openings (for ducts) perforated in various locations have been developed to explore their hysteresis behavior, cumulative dissipated energy, lateral stiffness, and ultimate strength under cyclic loading. Obtained results reveal that the rehabilitation of damaged steel shear walls using corrugated LYP steel web plate can enhance their structural performance. Furthermore, choosing a suitable location for the circular opening regarding the design purpose paves the way for the achievement of the shear wall's optimal performance.

Keywords: steel plate shear wall; corrugated web plate; low yield point steel; circular opening; cyclic loading

1. Introduction

Over the last few decades, steel shear wall structural systems have been widely used as lateral load resisting systems in mid and high rise buildings in various countries. Despite the merits of these systems, including significant lateral stiffness, reducing inter-story drift, acceptable ductility and energy dissipation, adequate lateral strength, etc., several disadvantages in their seismic behavior during the earthquake simulation in laboratory tests or a real earthquake in the building site have been observed. The small amount of buckling stress, especially in slender web plates as well as in-plane and out-of-plane instabilities in the post-buckling stage, can be pointed out as demerits of flat steel plate shear walls. Stiffening the flat web plate using stiffener plates to improve strength, stiffness, energy dissipation, and stability of the system may have some drawbacks such as time-consuming construction process, increase in construction costs, and producing inevitable residual stresses in steel shear walls. Further, several innovative techniques such as using composite steel plate shear walls to eliminate shear buckling of the flat web plate, as well as adding energy absorbent element made of a more ductile material to the infill plate for modifying deficiencies and emerging conspicuous seismic performance improvements in the flat steel plate shear wall system have been proposed (Arabzade *et al*. 2011, Emami and Mofid 2017), but some of them are not practical or easy to use.

Considering these facts, utilizing corrugated web plates as a replacement for the flat ones in the design of steel plate shear walls or for rehabilitation purposes have been

*Corresponding author, Ph.D.,
E-mail: alitoghroli@duytan.edu.vn
[a] Ph.D., E-mail: shariati@tdtu.edu.vn
[b] MS.c., E-mail: safaei.faegh.s@gmail.com
[c] MS.c., E-mail: peyman804m@gmail.com
[d] Ph.D. Candidate, E-mail: bahavarnia@yahoo.com
[e] Ph.D., E-mail: zandi@iaut.ac.ir
[f] MS.c., E-mail: davood.rezaee83@gmail.com
[g] Ph.D., E-mail: nguyenthoitrung@tdtu.edu.vn
[h] Ph.D. Candidate, E-mail: nasmusab2@live.utm.my

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suggested. Generally, the CSPSW is considered as a promising alternative to the flat steel plate shear wall owing to further initial stiffness, higher out-of-plane stiffness, and stability, having the accordion behavior of corrugations and lower construction cost (Emami *et al*. 2013). The existence of ribs in the corrugated web plate brings about a marked increase in axial and out-of-plane stiffnesses along the direction parallel to the ribs; however, the stiffness in the direction perpendicular to the ribs becomes low, which is known as "Accordion Effects" (Zhao *et al*. 2017). Therefore, if the horizontal corrugated web plate is used in a CSPSW, the web plate will not have resistance against the gravity forces, so that it will be in the pure shear state due to lateral loads. On the other hand, the extra potential of deformation stored in corrugated steel plates compared with the flat ones can mitigate the pressure upon boundary elements. In the light of this deformation potential along with the significant stiffness and out-of-plane stability resulting from distinctive geometry of the corrugated web plates, considerable energy dissipation, more stable hysteresis cycles even if the number of loops goes beyond the normal limit as well as complete formation of the tension field after buckling of the corrugated web plates can be achieved in steel shear walls regarding lower construction costs and without using stiffener plates.

A research by Emami *et al*. 2013) carried out a couple of experiments on two CSPSW specimens with trapezoidally horizontal and vertical corrugated steel web plates (H-CSPSW and V-CSPSW) and one shear wall specimen with a unstiffened flat steel web plate to compare and distinguish their hysteresis behavior, lateral stiffness, cumulative dissipated energy, and ductility. Their study also investigated applying two methods adopted for calculating the lateral strength of flat steel plate shear walls, namely Strip (Thorburn *et al*. 1983) and PFI (Sabouri-Ghomi *et al*. 2005) methods to the CSPSWs.

In addition (Bahrebar *et al*. 2016) developed numerous CSPSW finite element models to perform a parametric study upon the web plate thickness, angle of waves, and square opening size located in the center of the infill plate so as to evaluate their impacts on the performance of the shear walls. By means of parametric comparison among numerical models of steel plate shear walls with flat and corrugated web plates subjected to monotonic loading, (Farzampour *et al*. 2015) have shown that the initial lateral stiffness, dissipation energy and ductility of the shear walls with corrugated web plates are greater than those of shear walls with flat infill plates, whether in the case of having an opening or not. As reported, the corrugated web plates are more suitable alternatives than flat ones in the seismic design since they postpone the ultimate strength and degradation point of steel shear walls. To scrutinize the seismic performance of cold-formed steel shear walls sheathed with corrugated steel sheets under combined gravity and lateral loading (in both monotonic and cyclic states), (Zhang *et al*. 2016) conducted a test program including many full-scale wall assemblies alongside numerical investigation and concluded that gravity load at the service load level results in the enhancement of shear strength and initial stiffness of the specimens. Recently, Zhao *et al*. (2017) conducted a series of cyclic and pushover analyses on the finite element models of steel plate shear walls with trapezoidally and sinusoidally corrugated web plates (in both horizontal and vertical wave directions) and flat web plate, in such a way that gravity loads were taken into account as well. This research demonstrated that the performance of CSPSWs is less influenced by gravity loads and the weakness of the boundary elements compared with the flat steel plate shear walls.

Employment of low-yield-point steel in structural fuses has attracted many researchers' attention because of having a yield stress in the range of 100 MPa as well as its outstanding capacity of deformation (Xu *et al*. 2016, Al Kajbaf *et al*. 2018, He *et al*. 2018). The advantages of using this kind of steel instead of conventional steel in the flat web plate of steel shear walls have been also examined through laboratory tests and numerical modeling (Suzuki 1998, Chen and Jhang 2006, Chen and Jhang 2011, Zirakian and Zhang 2015). The LYP steel web plate can also be utilized to retrofit earthquake-damaged steel shear walls with the aim of improving their structural function. Due to the lower yield point of the LYP steel infill plate, its thickness has to be increased in order to keep the panel's lateral strength constant during the retrofit process, so that several benefits will appear in the system.

The use of LYP steel was suggested to reduce irregular yielding behaviour and enhance the structural performance of construction components. Hence, different studies have been carried out on the quality of LYP steel in recent years. Moreover, applying the LYP steel in steel-concrete composites such as shear connectors could be an appropriate opportunity to conduct further studies. Besides, scholars might need to form the LYP steel as a cold-formed channel or angle shear connector and examine the structural behaviour of proposed components that are subjected to monotonic loading tests (Shariati *et al*. 2010, 2011a, c, 2012a, b, c, d, e, 2013, 2014a, b, 2015, 2016, 2017, Khorramian *et al*. 2015, 2016, 2017, Shahabi *et al*. 2016a, b, Tahmasbi *et al*. 2016, Hosseinpour *et al*. 2018, Nasrollahi *et al*. 2018, Wei *et al*. 2018, Davoodnabi *et al*. 2019).

Since the well-known intelligence algorithms such as the artificial neural network (ANN), genetic programming (GP), artificial neuro-fuzzy inference system (ANFIS), bee colony, firefly, and particle swarm optimization (PSO) have been successfully carried out on various studies, structural engineers have been encouraged to employ these approaches in the prediction and optimization of experimental data related to LYP steel elements in the future. The use of analytical methods not only develops the prior algorithms but also decreases the need for further investigations on different engineering topics (Sinaei *et al*. 2012, Toghroli 2015, Toghroli *et al*. 2014, 2016, Hamdia *et al*. 2015, Mohammadhassani *et al*. 2015, Mansouri *et al*. 2016, Safa *et al*. 2016, Thang *et al*. 2016, Khorami *et al*. 2017, Tai *et al*. 2017, Sadeghipour Chahnasir *et al*. 2018, Sari *et al*. 2018, Sedghi *et al*. 2018, Toghroli *et al*. 2018a, Armaghani *et al*. 2019, Katebi *et al*. 2019, Mansouri *et al*. 2019, Shariati *et al*. 2018, 2019d, Trung *et al*. 2019a, Xu *et al*. 2019).

LYP steel has a variety of advantages that can persuade researchers to utilize it in other building components. Therefore, using the LYP rebar as reinforcement in concrete could be a different challenge for scholars to evaluate the performance of new reinforced concrete structures (Arabnejad Khanouki *et al*. 2011, 2016, Sinaei *et al*. 2011, Mohammadhassani *et al*. 2014a, b, Shah *et al*. 2016, Heydari and Shariati 2018, Luo *et al*. 2019, Xie *et al*. 2019).

Recycled materials and reproduced aggregates have been employed along with different concrete design mixtures as pervious concrete. Besides, using the reinforced pervious concrete or fibrous porous concrete is a reliable choice for pavement constructions. Consequently, the LYP steel fibres or recycled LYP steel fibres and chips as replacement aggregates could be applied in perviousconcrete and evaluated by researchers (Toghroli *et al*. 2017, Bazzaz 2018, Bazzaz *et al*. 2018, Nosrati *et al*. 2018, Toghroli *et al*. 2018b, Li *et al*. 2019, Shariati *et al*. 2019a, c, Suhatril *et al*. 2019, Trung *et al*. 2019b).

Concerning the properties of LYP materials, the LYP steel bars or fibers could be a sustainable replacement for the typical industrial and synthetic fibers. Furthermore, the use of hybrid fibers and aggregates which incorporate together and act as complement elements can cover and address the property requirements of high-performance concrete (Abedini *et al*. 2017, Ziaei-Nia *et al*. 2018, Sajedi and Shariati 2019). In addition, the application of different structural health monitoring techniques has been investigated through previous studies. These techniques can be helpful to evaluate the shear-wall behaviour in different situations (Hamidian *et al*. 2012).

Since the seismic events have always been a concern to researchers (Moghaddam *et al*. 2009), the dynamic

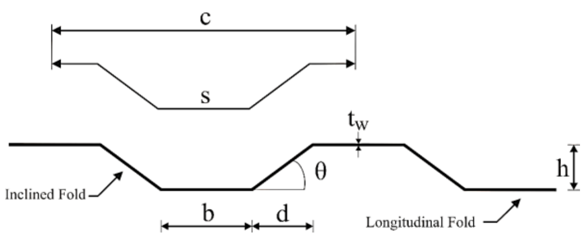
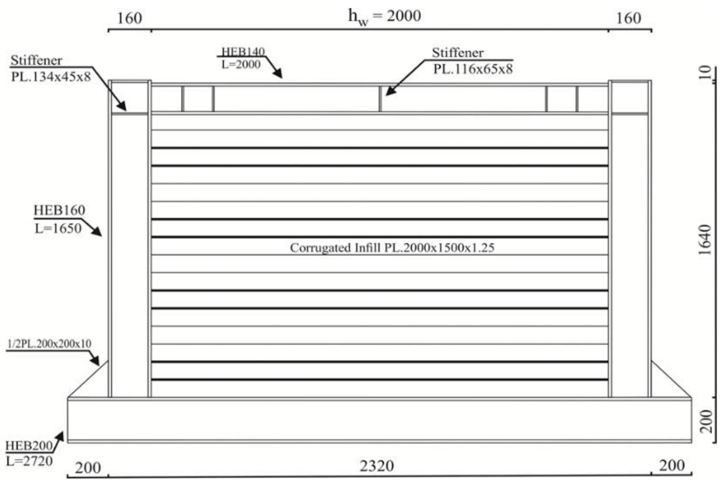
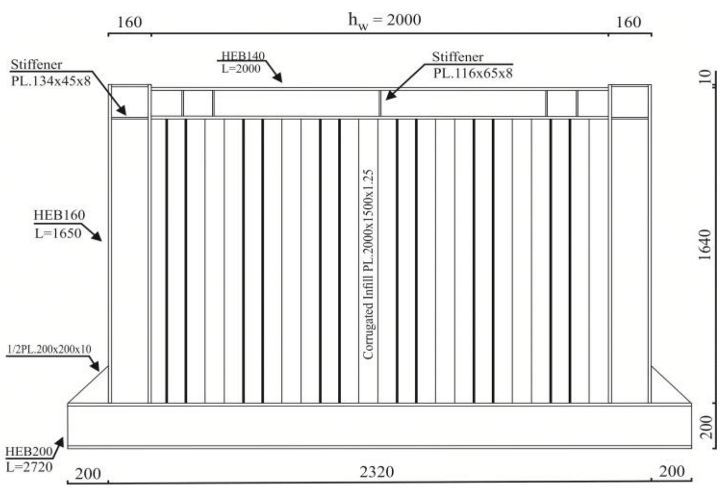


Fig. 1 Geometric notations of trapezoidally corrugated web plates



(a)



(b)

Fig. 2 Geometric details of corrugated steel plate shear wall specimens tested by (Emami *et al*. 2013): (a) Tested horizontal corrugated-web shear wall; and (b) Tested vertical corrugated-web shear wall performance of the structural elements has been assessed through different studies and experimental investigations (Shariati *et al*. 2011b, Fanaie *et al*. 2012, 2016). Therefore, the seismic behaviour can be observed by performing a series of cyclic and monotonic tests on structural components not only to evaluate the performance of a specific component but also to find key design parameters. Moreover, the dynamic response of the structural dampers has been studied extensively in recent years. Hence, using the LYP steel in engineered dampers and seismic bracings could be an appealing topic for researchers (Arabnejad Khanouki *et al*. 2010, Daie *et al*. 2011, Jalali *et al*. 2012, Kazerani *et al*. 2014, Ghassemieh and Bahadori 2015, Shah *et al*. 2015, Bahadori and Ghassemieh 2016, Khorami *et al*. 2017a, Najarkolaie *et al*. 2017, Ismail *et al*. 2018, Shariati *et al*. 2018, Zandi *et al*. 2018, Abedini *et al*. 2019, Milovancevic *et al*. 2019).

In the current study, following finite element modeling verification of two half-scale trapezoidally horizontal and vertical corrugated steel plate shear walls by Emami *et al*. (2013) laboratory tests results, the advantages of using LYP steel web plate as a substitute for the damaged ordinary steel web plate in the H-CSPSW model is investigated, provided that the panel's lateral strength is kept constant during this replacement. Then, through comparison with unperforated H-CSPSW as a benchmark, different circular opening locations, and their impacts on each of the structural performance factors of the perforated H-CSPSW with LYP steel web plate are presented, and the most suitable opening locations are suggested.

Table 1 Geometric parameters of the trapezoidal corrugated web plates

b (mm)	d (mm)	c (mm)	s (mm)	$\boldsymbol{\theta}$ (°)	h (mm)	$\boldsymbol{h_w}$ (mm)	$\boldsymbol{t_w}$ (mm)
100	86.6	373.2	400	30	50	2000	1.25

2. Characteristics of CSPSW specimens

Two one-story single-bay steel plate shear walls with trapezoidally horizontal and vertical corrugated infill plates, tested by (Emami *et al*. 2013), are selected to verify finite element modeling, but only the simulated H-CSPSW will be employed to examine its structural behavior under different conditions in the remainder of this study. The geometric properties of the trapezoidally corrugated infill plates and details of tested CSPSW specimens are shown in Figs. 1 and 2, respectively.

The tested specimens have rigid beam-to-column connections by utilizing complete joint penetration groove welds in the beams flanges and fillet welds in the beams webs. Some of the previously published studies have recommended using frame rigid connections as the preferable option in both ordinary and LYP steel plate shear walls since they provide the frame with better responses in energy absorption and dissipation (Chen and Jhang 2011, Emami *et al*. 2013). The bottom beams of the laboratory models are fully restrained to the floor. Moreover, two transverse girders are connected to each of the top beams as lateral bracings to avoid out of plane displacements. Geometric parameters of the trapezoidal corrugated web plates and mechanical properties of steels utilized in the members (measured values by Emami *et al*. (2013) and Zirakian and Zhang (2015)) are summarized in Tables 1 and 2, respectively.

Table 2 Mechanical properties of steels used in the members

Element	Type	Modulus of elasticity E (GPa)	Poisson's ratio υ	Steel type	Yield stress F_y (MPa)	Ultimate stress F_u (MPa)
Beam	HE-B140	210	0.3	St 44	288	456
Column	HE-B160	210	0.3	St 44	300	443
Web plate	Corrugated	210	0.3	St 12	207	290
		200	0.3	LYP 100	100	-

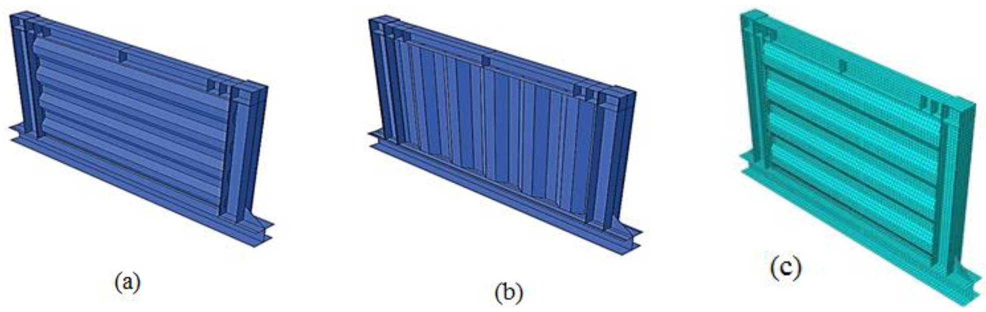


Fig. 3 Numerically modeled horizontal and vertical corrugated steel plate shear walls: (a) H-CSPSW model; (b) V-CSPSW model; (c) A meshed model

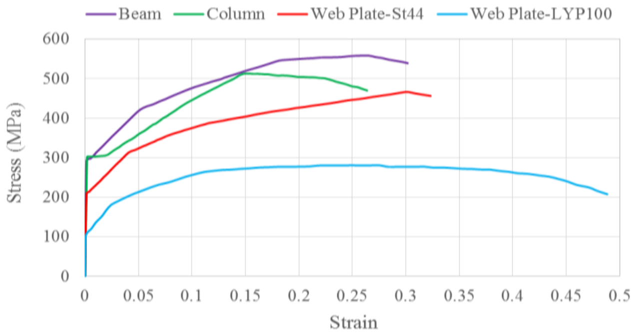
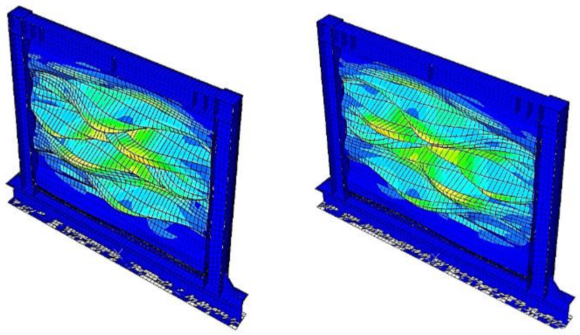


Fig. 4 Stress-strain relationships of steels used in the members



(a) (b)

Fig. 5 Buckling mode shapes of the simulated H-CSPSW obtained from Eigen analyses: (a) First buckling mode; and (b) Second buckling mode

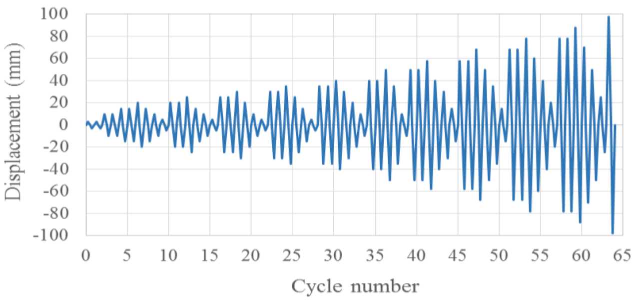


Fig. 6 Displacement control loading protocol

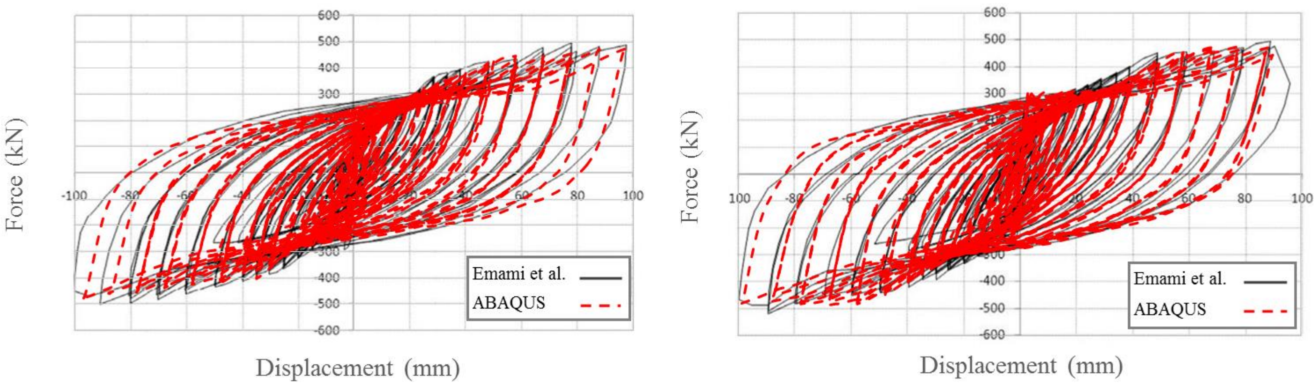
3. Finite element modeling and verification

The general-purpose nonlinear finite element analysis software of ABAQUS (Version 2014), is used for numerical modeling and analysis of the CSPSW specimens under cyclic loading. The four-node S4R shell elements are utilized to construct the CSPSW finite element models. These elements possess 6 degrees of freedom per node and with the help of reduced integration, can accurately predict the behavior of slender members in nonlinear time-saving analyses. Only structured quad elements are used in the meshing process to achieve desirable convergence in analyses. In order to improve the accuracy of the analyses, the mesh size was limited to 30 mm throughout the models. Furthermore, mesh refinement and partitioning techniques are implemented to ensure the high precision of finite element modeling (a meshed model is shown in Fig. 3(c)). According to the tested specimens, joints are rigidly modeled by means of merge technique. The bottom part of each panel is completely fixed, and lateral bracings are also provided for the upper beams' flanges against out of plane displacements.

Materials stress-strain relationships used in numerical modeling, as depicted in Fig. 4, were obtained from the coupon tests performed by (Emami and Mofid 2014), also (Zirakian and Zhang 2015). Both material and geometrical nonlinearities are considered in the finite element models.

The initial imperfection is one of the most important and influential parameters in the buckling strength of corrugated or flat steel plate shear walls, especially with slender web plate. In order to provide conditions close to reality considering the geometrical imperfections and residual stresses resulting from shop working are actually inevitable, the initial imperfection should be allocated with appropriate mode shape and proper magnitude to the finite element models.

Eurocode 3 EN 1993-1-5 (2006) has proposed that the initial imperfection value for subpanel plates can be adopted as 1/200 of the smallest panel dimension and corresponding to its critical buckling mode shape. According to the numerous analyses conducted in this study, it turned out that the CSPSW models' buckling strength is mainly dependent on their first and second buckling modes. Hence, an initial imperfection equal to 1/200 of the smallest panel dimension



(a) H-CSPSW (b) V-CSPSW

Fig. 7 Finite element modeling verification of the corrugated steel plate shear walls

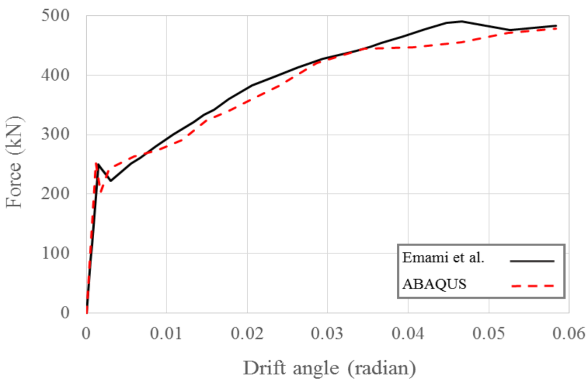


Fig. 8 Envelope curve of hysteresis diagrams of the H-CSPSW

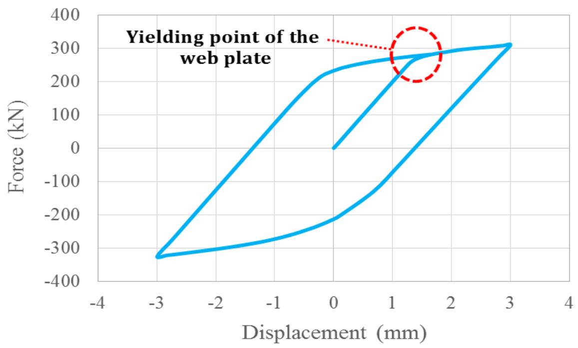


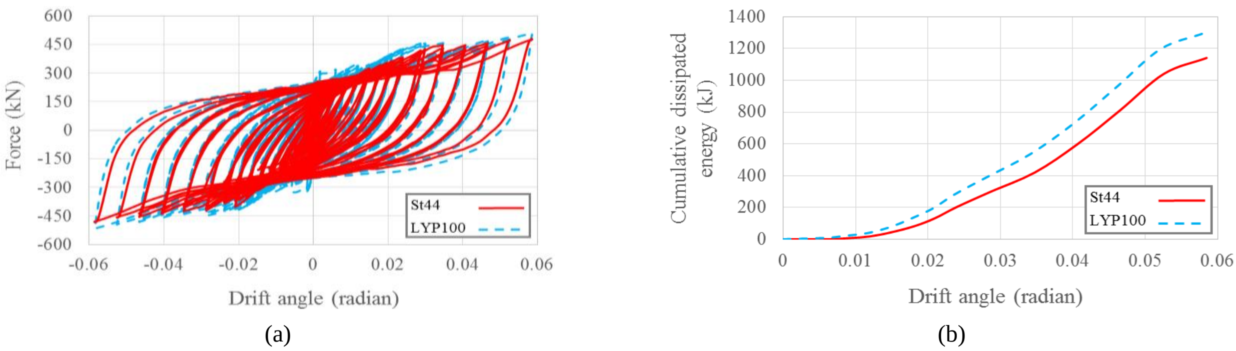
Fig. 9 First loading cycle of the simulated H-CSPSW with the LYP steel infill plate

is divided by the maximum displacement obtained from Eigen buckling analysis in each mode (as can be observed in Fig. 5), and then these values in each intended mode shape are coded into the finite element software.

The AC154 quasi-static cyclic loading protocol employed during the experiment is implemented to simulate earthquake load on the numerical models (Fig. 6). The negligible effects of inertia in the quasi-static loading make the static-general analysis method a suitable option for the finite element analyses. The inability to choose the most appropriate analysis method alongside the emergence of many errors during the finite element analysis usually leads to using a simplified version of the loading protocol. However, in this paper, the complete cyclic loading protocol is used to verify the CSPSW finite element models.

Since a large number of cycles are required in the numerical analyses, combined half-cycle hardening based on the plastic properties of used materials is adopted to define the realistic behavior of the panels in the plastic phase. The reliability and accuracy of the finite element modeling are evaluated by comparing hysteresis responses obtained from the numerical models with Emami et al. test results (Emami *et al.* 2013). The Presented results in Fig. 7 indicate a high level of convergence and agreement.

Although the shear buckling capacity of corrugated steel plates is significantly more than that of unstiffened flat steel plates, they are also prone to buckling prior to shear yielding. Subsequent to the elastic or elastoplastic buckling, both flat and corrugated steel web plates may continue post-buckling resistance against lateral loads through a phenomenon called "tension field action" until they reach tensile yielding along the inclined direction of the tension field. If the boundary members were designed to withstand the forces of the tension field, CSPSW would have great post-buckling strength in the light of considerable in and out of plane stiffnesses as well as the stability of the



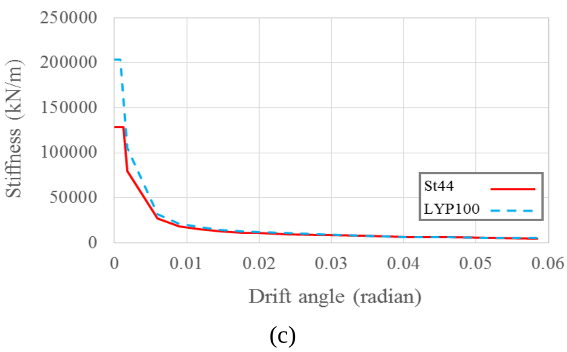


Fig. 10 Performance comparison between ordinary steel (St44) web plate and LYP100 steel web plate used in the simulated H-CSPSW: (a) Hysteresis diagram, (b) Cumulative dissipated energy, and (c) Secant stiffness

corrugated web plate. As depicted in Fig. 8, both numerical and experimental specimens of the H-CSPSW have experienced shear buckling in the first cycle of displacement.

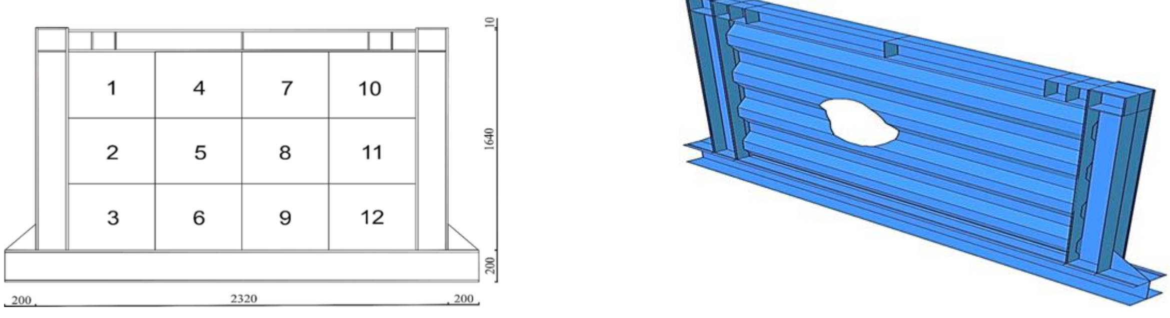
4. Advantages of replacing ordinary steel web plate with LYP steel web plate in damaged CSPSWs

Application of steel web plates with the low yield point enhances the probability of occurring desirable shear yielding mode than shear buckling mode in steel shear wall systems. Also, the lower yield strength of the web plate (in comparison with boundary members) provides preferable distribution of strength and ensures that the boundary members would not fail before reaching the ultimate strength capacity of the frame (Emami *et al*. 2013). These features of LYP steel web plates besides their noticeable deformation capacity allow the shear wall to have an early uniform shear yielding throughout the infill plate in a lower inter-story drift, thereby starting the premature energy absorption and dissipation, and then smaller forces and deformations would be imposed on surrounding members during upcoming cycles. The replacement of ordinary steel web plate by the web plate made of LYP steel in a damaged steel plate shear wall can obviate some weaknesses and flaws in the system related to damping and stiffening characteristics. The objective of this section is to scrutinize the structural performance improvements resulting from replacing corrugated LYP steel web plates in damaged CSPSWs. Hence, it is assumed that the conventional steel web plate of the simulated H-CSPSW was damaged during an earthquake and is replaced by a corrugated LYP steel infill plate with a specified thickness to keep the lateral strength of the frame constant after this change.

After conducting a series of numerical analyses to find the most appropriate LYP steel web plate thickness by which the lateral strength of simulated H-CSPSW remains approximately unchanged, the amount the LYP web plate thickness was found with the value of 2.25 mm. Despite yield stress value of the ordinary steel is more than twice that of LYP steel, buckling of the ordinary steel web plate makes the required thickness of the LYP steel web plate for having constant lateral strength in the H-CSPSW, has not been doubled. The shear yielding of the corrugated LYP steel web plate with 2.25 mm thickness in the first loading cycle of the simulated H-CSPSW can be seen in Fig. 9.

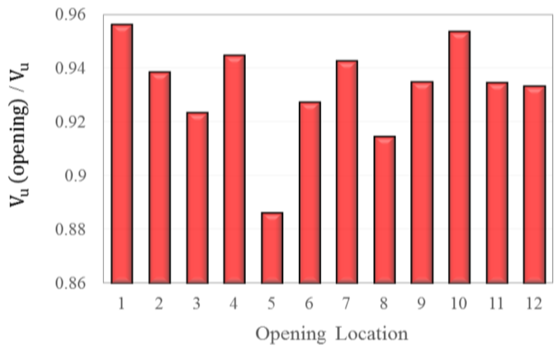
The remainder of this section seeks to comprehensively explore replacing 1.25 mm corrugated conventional steel (St44) web plate with 2.25 mm corrugated LYP100 steel web plate in the simulated H-CSPSW. Since it is only focused on the variations in the behavior of infill plates in the numerical analyses, the boundary members experience no change during this replacement. As depicted in Fig. 10(a), the hysteresis diagram of the H-CSPSW with LYP steel web plate has almost equal ultimate strength with the case of using the ordinary steel infill plate. From Fig. 10(b) it is clear that both panels have continued to absorb and dissipate energy up to about 6% story drift angle, whereas the cumulative dissipated energy of the H-CSPSW with LYP steel infill plate is roughly 13.8% higher than that of H-CSPSW with ordinary steel infill plate. Fig. 10(c) indicates that the initial secant stiffness of H-CSPSW with LYP steel web plate is considerably larger than before the replacement. The 58% initial stiffness enhancement affected by replacing the LYP steel web plate in the frame, leads to the significant reduction of displacement in the elastic stage prior to the shear yielding of the infill plate. The stiffness of the H-CSPSW with LYP steel infill plate is continuously larger than that of H-CSPSW with ordinary steel infill plate throughout cyclic loading until both stiffnesses converge to a very small amount.

The results show that due to the perceptible increase in the lateral stiffness and cumulative dissipated energy, and changing undesirable failure mode of the H-CSPSW (buckling) into the shear yielding, the corrugated LYP steel web plate has the capability to be a suitable replacement for the corrugated ordinary steel web plate in an earthquake-damaged steel shear wall. Moreover, this replacement is also associated with the reduction in inter-story drift, decrease in P-Δ effects, prevention or delay in buckling instability of the web plate, and stabilizing hysteresis loops during an earthquake. All in all, it can be said that this change improves the structural performance of the steel shear wall system in both service and ultimate states.



(a) (b)

Fig. 11 Introducing circular openings in the LYP steel web plate of simulated H-CSPSW: (a) Locations of the circular opening in the H-CSPSW; and (b) A finite element example of the H-CSPSW with the circular opening



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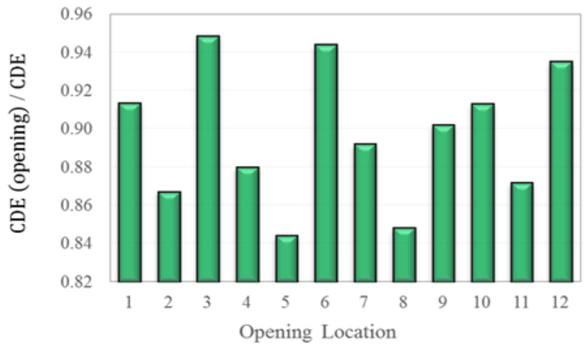

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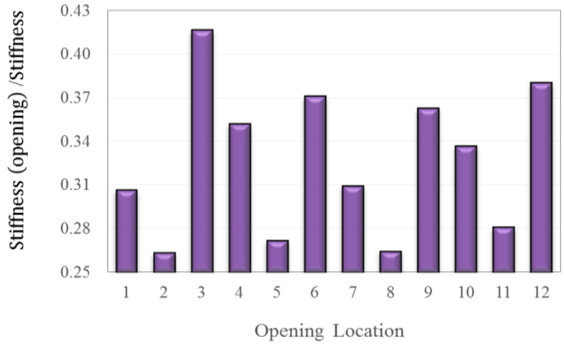
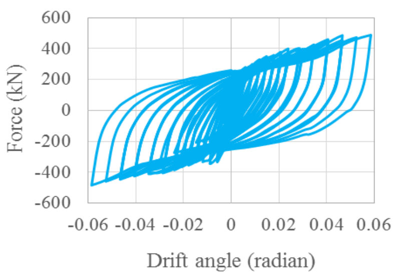


(c)

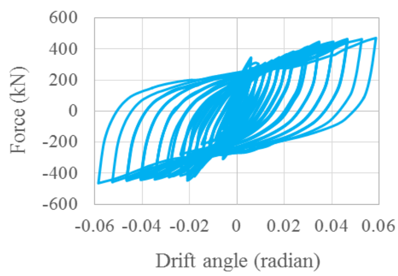
Fig. 12 Performance comparison of the horizontal corrugated LYP steel web plate shear wall in 12 different circular opening locations: (a) Ultimate strength; (b) Cumulative dissipated energy; and (c) Initial stiffness

5. Effects of opening location on the performance of H-CSPSW with LYP steel infill plate

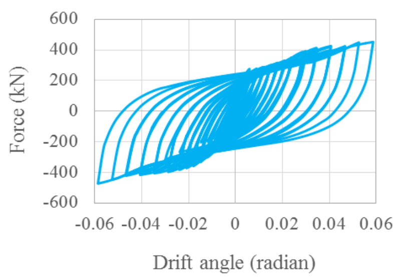
Given the formation of inclined tension field in steel plate shear walls, the presence of opening (mechanical duct) in different places while the shear wall is subjected to cyclic loading has inconsistent and occasionally dramatic effects on the stability, strength, and cumulative dissipated energy of the panel. Using stiffener plates to strengthen surrounding areas of the opening in flat steel plate shear



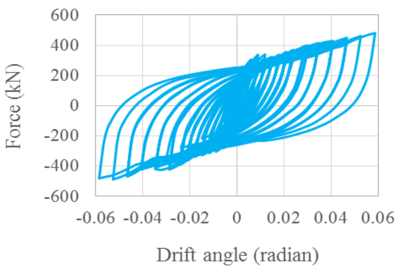
(a)



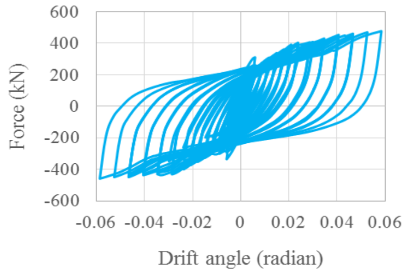
(b)



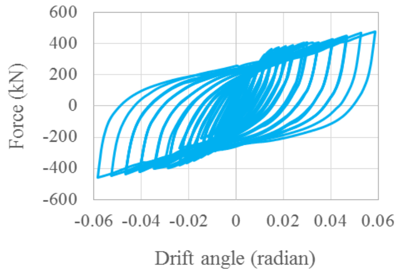
(c)



(d)



(e)



(f)

Fig. 13 Hysteresis diagrams of the H-CSPSW FE models with LYP steel web plates including circular openings: (a) Opening location 1; (b) Opening location 3; (c) Opening location 5; (d) Opening location 7; (e) Opening location 9; and (f) Opening location 11 walls is an alternative that may bring about deleterious consequences stated before. The substantial in-plane and out-of-plane stiffnesses and stability in CSPSWs than those of flat steel plate shear walls as well as inefficiency in fastening stiffener plates to the corrugated web plate indicates the need to examine the influence of opening on the cyclic performance of CSPSWs. In this section, 12 circular openings whose areas are equal to 5% of the web plate area (in diameter of 437 mm), are introduced in 12 different sections (each one is 500×500 square mm) of 2.25 mm corrugated LYP steel infill plate embedded in the simulated H-CSPSW (as shown in Fig. 11). Then, the performance of perforated H-CSPSW in each location under cyclic loading is exhaustively investigated and compared to the unperforated one as a benchmark.

The initial imperfection values are considered to be constant in whole 12 finite element models in the light of unchanged dimensions of the simulated H-CSPSWs. The analysis results are presented in Figs. 12 and 13.

As illustrated in Fig. 12(a), almost all horizontal corrugated LYP steel plate shear walls with circular openings have maintained higher than 90% of the ultimate strength corresponding to the unperforated state (except location 5). The results reveal that the angle of tension field inclination in the H-CSPSW mainly disturb the symmetry of graphs, but all in all upper positions and far from the center of web plate such as numbers 1 and 10 compared with the opposite lower positions such as numbers 3 and 12, have come up with better results for the H-CSPSW's ultimate strength. As shown in Fig. 12(b), unlike the ultimate strength, the placement of the circular opening in lower positions and far from the center of the infill plate results in better cumulative dissipated energy responses than upper positions. Almost in all locations (except location 5), the panel has maintained higher than 85% of the cumulative dissipated energy capacity related to the unperforated state.

As observed in Fig. 12(c), getting closer to the center of the web plate reduces stiffness. In addition, the presence of the circular opening in lower positions of the panel provides better initial stiffness responses than higher positions. Contrary to what has just been noted for the ultimate strength and cumulative dissipated energy, the circular opening causes a drastic reduction of initial stiffness in the H-CSPSWs compared with unperforated one. The reduced initial stiffness is about 26%-42% of the unperforated panel's initial stiffness, regarding the circular opening location.

According to the Fig. 13, despite the presence of circular openings in the horizontal corrugated LYP steel plate shear walls, none of these specimens have experienced pinching phenomenon in their hysteresis diagrams up to the last cycle of loading. These findings confirm that the perforated H-CSPSWs have the capability of yielding acceptable ultimate strength and energy dissipation responses under cyclic loading, but adverse effects concerned with the reduction of stiffness should be considered in the design of them.

6. Conclusions

In this paper, the structural performance of a half-scale one-story single-span horizontal corrugated steel plate shear wall retrofitted by the LYP-steel web plate was investigated under cyclic loading, and then the impacts induced by different circular opening locations upon the shear wall behavior have been fully detected. The following results and observations are drawn from the current study:

(1) The replacement of corrugated LYP-steel web plates in damaged CSPSWs, especially in the case of utilizing slender ordinary-steel infill plates, results in improvement of the hysteresis behavior, change of improper buckling mode of the infill plate (if it would be probable) into shear yielding mode, increase in the cumulative dissipated energy and dramatic enhancement of the panel's initial stiffness. Therefore, the structural and non-structural damages during an earthquake can be severely reduced in such a novel lateral force resisting system.

(2) According to the numerical modeling results, the presence of circular opening (mechanical duct) with 5% area of the horizontal corrugated LYP steel web plate in 12 various locations did not lead to the emergence of pinching behavior in any of perforated H-CSPSWs' hysteresis diagrams. These openings in the worst-case scenario can only reduce the ultimate strength by 12% and the cumulative dissipated energy by 16% compared with the unperforated state. However, they have a considerable impact on the initial stiffness of the panel, as it lies between 58% and 74% reduction compared with the unperforated state. Eventually, the best location for a mechanical duct in H-CSPSWs, firstly, is recommended away from the center of web plate as far as possible, and secondly, if the ultimate strength of H-CSPSW is regarded as the dominant design parameter, using upper parts of the infill plate will ensure better responses. However, if the cumulative dissipated energy or initial stiffness of H-CSPSW is regarded as the dominant design parameter, choosing lower parts of the infill plate will provide better responses.

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