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Behavior prediction of corrugated steel plate shear walls with openings

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ABSTRACT

Corrugated steel plate and simple steel plate shear wall construction is a widely accepted and efficient lateral force resisting construction. The widespread use is motivated by the large initial stiffness, high level of energy absorption, and ability to accommodate openings. There is a dearth of information regarding the detailed nonlinear, inelastic behavior of corrugated steel plate shear walls, particularly walls with openings. Presented here are the results of a detailed, numerical parametric study comparing corrugated steel plate and simple steel plate shear walls, with and without openings. Parameters studied are plate thickness, angle of corrugation, opening size, and opening placement. Behaviors of interest for comparison are initial stiffness, ultimate strength, energy absorption, force–displacement relationship. The present study results indicate that the use of trapezoidal corrugated steel shear walls increases initial lateral stiffness, increases energy absorption and increases ductility while it reduces ultimate strength. In addition, the corrugated steel plate shear wall postpones the ultimate strength and degradation point relative to a corresponding unstiffened simple steel plate shear wall, which is a desirable characteristic for seismic resistance. An ultimate strength prediction procedure for corrugated steel plate shear walls with optimized rectangular opening position is developed and proposed.

1. Introduction

Steel plate shear walls are an efficient and widely constructed lateral force resisting system, particularly in areas of high seismic hazard. Significant strength, ductility and initial stiffness at relatively low cost and short construction time are the primary motivations for the construction type [1–9]. Steel plate shear walls, as evaluated in the present study, consist of a rigidly connected girder and two columns to form a moment resisting frame with a steel plate infill. The moment resisting frame coupled with the steel plate shear wall increases both redundancy and ductile behavior of the system [10].

Numerous studies have been conducted to investigate the lateral resistance, stiffness, and buckling behavior of shear wall systems and to propose prediction models [11–19]. Typically, stiffeners around openings are introduced into the shear wall design to limit the shear buckling and preserve the shear capacity of plate. However, stiffener fabrication and installation significantly increases material and labor costs in addition to added inspection requirements [8]. Therefore, a corrugated shear panel is proposed as a viable alternative to simple, stiffened steel plate shear walls as the need for stiffeners is eliminated, particularly around openings. Due to out-of-plane stiffness, trapezoidal corrugated infill plate's present significant initial stiffness, as each corrugation supports adjacent corrugations in the out-of-plane direction. Additionally, the plastic strain around openings is limited as a consequence of the corrugated infill plate geometry.

CSSW is a relatively new, untested, and innovative steel shear wall construction that mitigates the early buckling behavior of steel shear walls. Due to the lack of available knowledge regarding the response, elastic and inelastic behavior, and design requirements for corrugated steel shear walls, including the effect of openings, the present study has been devised. The present study extensively analyzes corrugated steel plate shear walls with and without openings and compares results to simple SSWs. The formulation of the theoretical ultimate strength of CSSW is required, including the effect of openings, opening position, and aspect ratio.

Objectives for the present study are to develop efficient analysis procedures to predict the ultimate shear strength of corrugated steel plate shear walls with rectangular openings. Prediction of force–displacement, initial stiffness, ultimate shear strength, ductility, plastic strain contours and energy absorption as a function of shear wall geometry are sought.

A detailed finite element analysis has been conducted on 135 simple (unstiffened) steel plate shear walls and 405 corrugated steel plate shear walls with and without openings in the execution of a parametric study that includes variables of opening size, steel plate thickness, shear wall aspect ratio, corrugation angle and opening positions. The results are processed to establish an efficient design and analysis methodology.

Abbreviations: CSSW, Corrugated Steel Plate Shear Wall; SSW, Simple (unstiffened) Steel Plate Shear Wall.

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0143-974X/

Table 1
Model dimensions.

Name	Type	Opening geometry and position			
		Plate thickness (mm) [A]	Length (L′) × height (h′) (mm × mm) [B]	Opening position [C]	Angle of corrugation [D]
S-t[A]-W[B]([C])	SSW	1.5, 2, 2.5, 3.25, 4	1000 × 700 [1] 1500 × 1000 [2] 2250 × 1500 [3]	1, 2, 3, 4, 5, 6, 7, 8, 9	NA
C[D]-t[A]-W[B]([C])	CSSW	1.5, 2, 2.5, 3.25, 4	1000 × 700 [1] 1500 × 1000 [2] 2250 × 1500 [3]	1, 2, 3, 4, 5, 6, 7, 8, 9	90°, 45°, 0°

2. Parametric study design

An extensive, numerical, parametric study of steel shear walls was conceived to include the variables most commonly considered over the most common range of each variable. A total of 540 single story CSSWs and SSWs with different opening positions, opening sizes, plate thicknesses and angles of corrugation have been investigated as indicated in Table 1, failure modes and force–displacement curves have been evaluated as well (Fig. 1). The five different plate thicknesses and the three corrugation angles are considered based on common values mentioned in the published literature [7,9,10,18,19].

3. Numerical model details

Fig. 2 presents the loading and member sizes and orientation. The height and length of the story panel are 3.2 m and 4.8 m, centerline to centerline, respectively, simulating the conventional residential building [10]. The moment frame is modeled as rigid frame construction with regard to girder-to-column connections. The SSW and CSSW without openings are designed based on the PFI method in which the plate–frame interaction is precisely considered [15]; thus, the effect of vertical load was ignored.

The girder is modeled as laterally braced against the out-of-plane movement, simulating commonly observed construction conditions.

The simulations were undertaken using the commercially available finite element package of ABAQUS. Each model (see Fig. 3) was constructed using the general purpose four node shell element that is capable of large displacements and nonlinear behavior. This shell element was used for all components of the structure, including the standard rolled columns and girder. Material yield limits of the steel plate and rolled sections are taken as 340 MPa and 390 MPa, respectively, following the work of Habashi and Alinia [21]. The beam-to-column connections are moment-resisting, therefore all intersecting shell elements are directly connected. The steel shear wall is connected directly and continuously to the columns and girder as suggested by Emami and Mofid [8]. The bottom edge support girder and column bases are fixed, similar to the boundary conditions of Emami et al. and Driver et al. models [9,10].

The simulations were performed under displacement-controlled loading with the aid of a dynamic explicit numerical procedure. The loading is applied by subjecting the model at the upper girder to monotonically increased lateral displacement up to the ASCE7–10 [20] suggested 2.5% ultimate drift ratio of the story.

4. Validation of numerical results

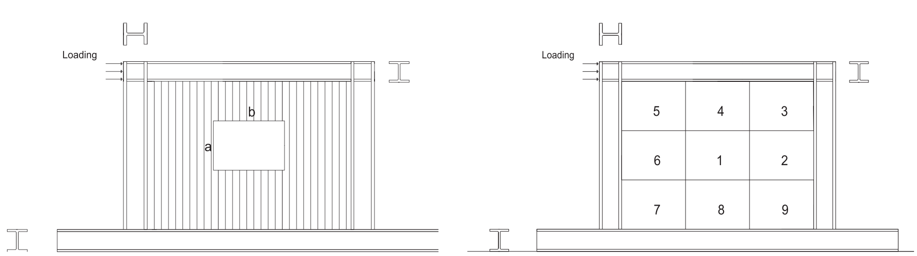
To establish the accuracy of the numerical modeling methodology, two sets of well established laboratory tests have been compared to the simulation results. Failure modes, load–displacement curves, and model overall behavior under monotonic loading protocol have been compared with those of the experimental studies. A four-story steel plate shear wall tested by Driver et al. [10], and a one story corrugated steel plate shear wall tested by Emami et al. [9] are considered. The results, as depicted in Fig. 4, indicate close agreement between these established laboratory test results and the numerical models of the present study. Based on comparison of published pushover response to FEM model in software, Driver et al. is within 98%, and Emami's model is within 85% of accuracy in prediction of models pushover behavior.

5. Presentation and discussion of results

5.1. General behavior

Generally, each of the 540 simulations exhibited inelastic buckling and different degrees of in-plane stiffness. The in-plane stiffness of the CSSW decreases abruptly in the direction of corrugation. Therefore, the tension field in CSSW generates incompletely and to some extent, in a complicated mechanism similar to previous literatures [12]. Hence, the interaction of the tension field action with openings of several sizes and locations has been throughly investigated.

Figs. 5 and 6 present the general behavior of the typical CSSW and SSW model, with and without an opening, under monotonic loading. The lateral load–displacement results have been processed and categorized into three stages: Initially the general behavior of all models with and without an opening is elastic. As load is increased, the CSSW begins to experience local buckling. However, the SSW experiences no significant local buckling, but global buckling modes are observed. The CSSW early local buckling behavior results in a delay of the ultimate strength peak and degradation trend. Through a



a) CSSW with opening   b) Opening location

Fig. 1. Configuration of opening geometry.

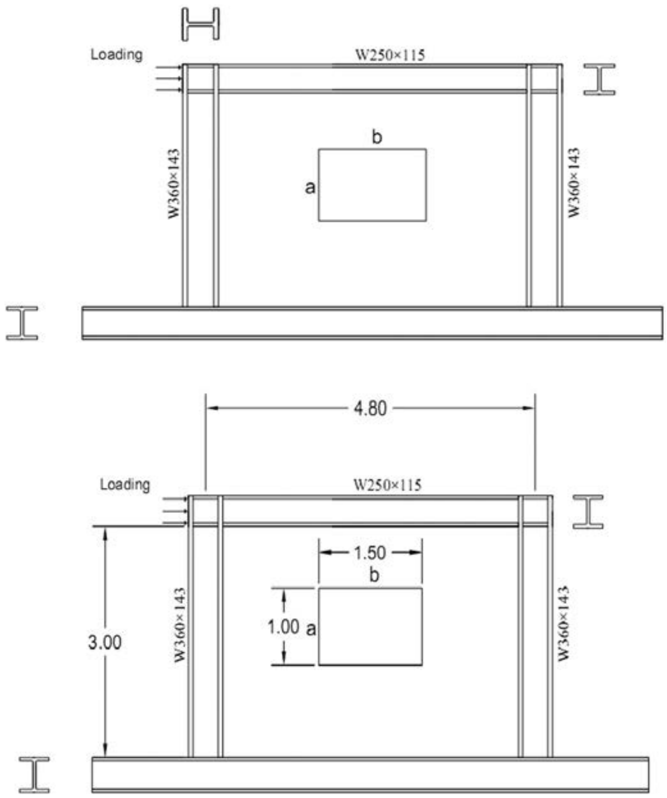


Fig. 2. Steel shear wall member sizes and orientation, loading, and opening.

propagation of buckling, a tension field begins to resist the lateral shear load; thus, the post buckling deformation continues with increasing load until first yielding. At this post buckling region of the force–displacement response, the difference between CSSW and SSW pushover behaviors is negligible.

Following elastic behavior, the response of CSSW and SSW are nonlinear, yielding zones begun to distribute themselves within the plate. The yielding behavior of the SSW with an opening begins from the corner of the opening. Inclusion of an opening in SSW results in a more than 50% stiffness degradation; however, corresponding CSSW with opening has negligible stiffness degradation. The degradation point—the displacement, at which shear force begins to decrease, is postponed in CSSW as compared with a corresponding unstiffened SSW. The CSSW geometry prevents yielding adjacent to the opening, leading to smaller plastic strains at a given displacement. Fig. 5 presents the plastic strain at a 2.5% drift ratio for CSSW and SSW with opening.

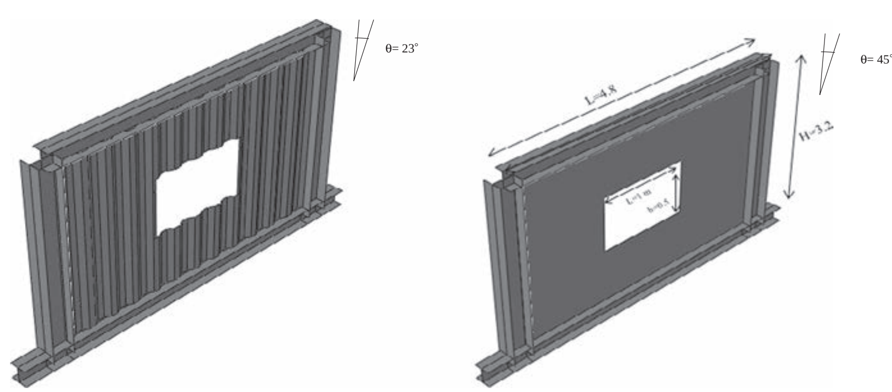
In the final loading stage, all CSSW and SSW systems behave nonlinearly, both in geometric and material. The corner regions of the opening yield during this stage. The stiffness of the SSW system without an opening is as much as 50% higher than that of a system with an opening; however, in certain cases, the stiffness becomes zero as the load is increased. The CSSW ultimate shear strength is generally achieved at displacements five times higher than that of SSW which may be a desirable characteristic where seismic performance of the structural system is a consideration.

5.2. Detailed results discussion on CSSW and SSW with opening

The ultimate strength behavior of CSSW and SSW is presented in Fig. 7. It can be observed that thicker infill plates increases the ultimate strength for both CSSW and SSW; however, SSW has slightly better performance for a given thickness. The overall performance of the shear wall depends on the thickness of the plate and opening size. Each thickness exhibits different performance; therefore, the comparison between CSSW and SSW is precise if the panel thickness and opening size are considered. Moreover, initial stiffness of CSSW is generally 20% higher than a corresponding SSW, leading to a lower level of non-structural damage. This difference is most pronounced for thinner infill as observed from Fig. 8. Additionally, the ductility of a CSSW as determined from procedures proposed by Habashi and Alinia [21] and Hosseinzadeh and Tehranizadeh [18] is 80% higher than that of the simple SSW, particularly in a system with a smaller opening as presented in Fig. 9. It is also observed that the opening size has considerable influence on the CSSW ductility.

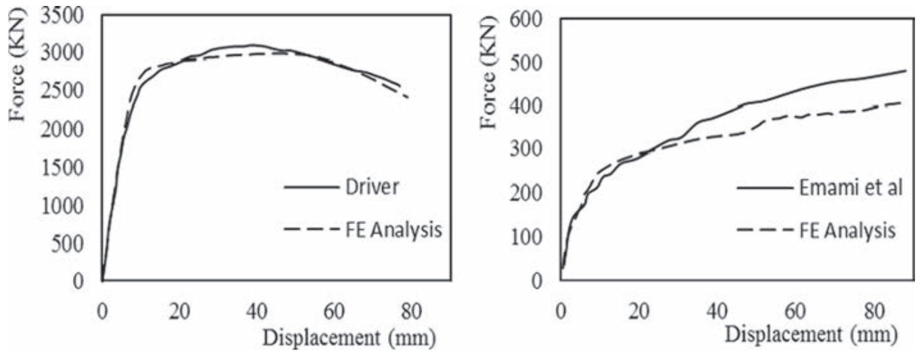
5.3. Corrugation angle in CSSW and SSW without an opening

The response of CSSW and SSW without an opening as a function of wall thickness is presented in Fig. 10a) through c). It can be observed from these figures that corrugation has no substantial effect on the ultimate strength of the shear wall system. However, when CSSW is compared to SSW, CSSW exhibits 30% to 50% greater initial stiffness and ductility, especially for thinner plates. The effect of corrugation angle does not significantly affect the ultimate strength or stiffness under the simulated, monotonic loading.



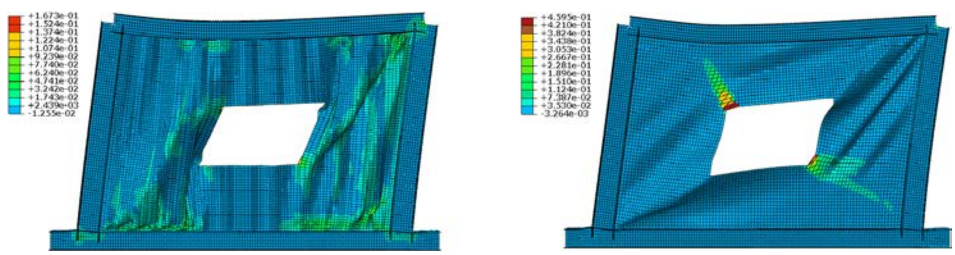
a) CSSW with opening (α =90) b) SSW with opening

Fig. 3. Numerical model with tension inclination angle, Θ and corrugation angle, α.



a) Driver et al (1997) b) Emami et al (2013)

Fig. 4. Comparison of the load–displacement curves.



a) CSSW with Opening b) SSW with Opening

Fig. 5. CSSW (a) and SSW (b) plastic strain with opening position [1], 2.5% drift.

5.4. Corrugation angle in CSSW with opening

CSSW behavior as affected by opening size is investigated in this section. It can be observed from Fig. 11 that corrugation angle has no significant effect on the ultimate strength of CSSW with an opening. However, a corrugation of 45° has slightly better performance, due to having corrugation's direction paralleled with the tension field, after shear walls post-buckling point under monotonic loading. Additionally, by increasing the opening dimensions, the behavior of the model would approximately converge to the behavior of the frame. Thus, this would indicate that the angle of corrugation would have less influence on larger opening sizes.

It is observed from Fig. 12 that the stiffness of CSSW increases as the wall thickness increases and stiffness decreases as the opening size increases. All CSSW responses follow this trend. The CSSW stiffness with a corrugation angle of 90° is higher than that of the other angles due to higher out-of-plane shear buckling stiffness.

The ductility of CSSW is primarily influenced by opening size as observed particularly for walls with smaller openings. This difference is clearly observable in Fig. 13 where a significant difference between response behavior is presented affected by opening sizes.

5.5. CSSW with opening regarding different aspect ratios

CSSW with different aspect ratios with different thicknesses and opening sizes have been investigated. It has been observed that initial stiffness and ultimate shear strength is improved by higher

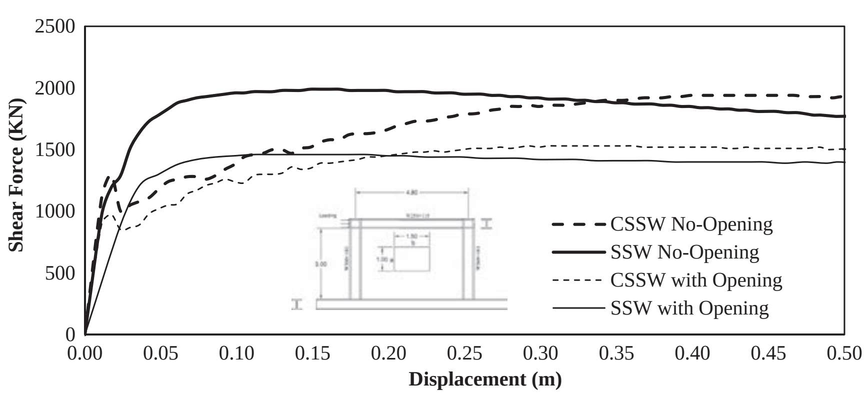


Fig. 6. Load–displacement curves of CSSW and SSW with and without openings angle of corrugation = 90°.

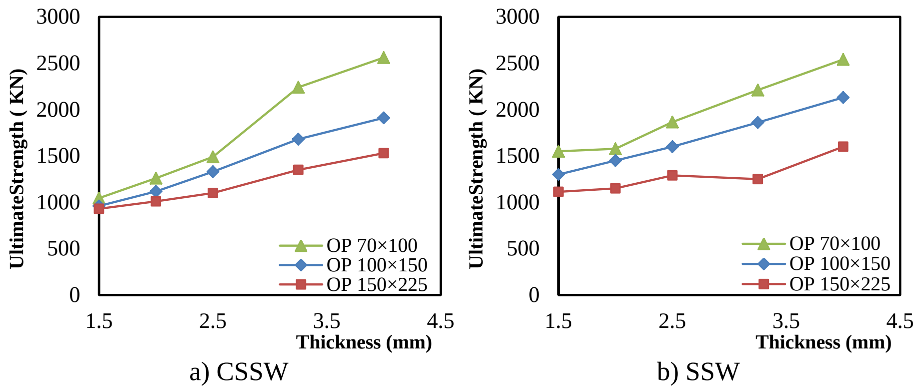


Fig. 7. Ultimate strength as a function of thickness (angle of corrugation = 90°).

aspect ratios. Results for all considered wall aspect ratios have been normalized to the corresponding CSSW with an aspect ratio of 1.5.

As the openings size increases, the effect of aspect ratio is more pronounced. This behavior is due to an increase in the steel plate dimensions which results in a greater tension field effect—the increase in steel plate dimensions allows the CSSW to produce tension field more efficiently, which is the mechanism responsible for the increase in ultimate shear strength and stiffness of SSW. Higher aspect ratios for shear walls with large openings have more significant effect on the behavior of CSSWs with openings compared to CSSWs with no openings. It has been observed that increasing the thickness of the infill results in higher ultimate shear strength and stiffness (see Figs. 14 and 15).

5.6. Lateral stiffness and strength as a function of opening

To better understand the effect of openings, the ratio of ultimate shear strength and initial stiffness of each configuration to that of a wall with no opening has been evaluated. The stiffness ratio of $K_{(Opening)}/K$ (initial stiffness of single opening to no opening) and ultimate strength $F_{U(Opening)}/F_U$ (ultimate shear strength of single opening to no opening) are plotted as functions of d/D in Figs. 16 and 17, where d is the diameter of a rectangular opening and D is the diameter of the shear wall. The diameter of panel could be calculated considering the length and height of the panel as follows:

$$D^2 = L^2 + H^2 \quad (1)$$

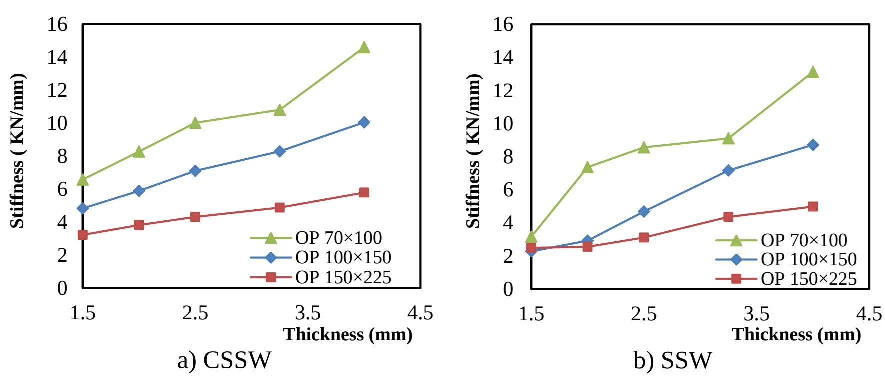


Fig. 8. Initial stiffness as a function of thickness (angle of corrugation = 90°).

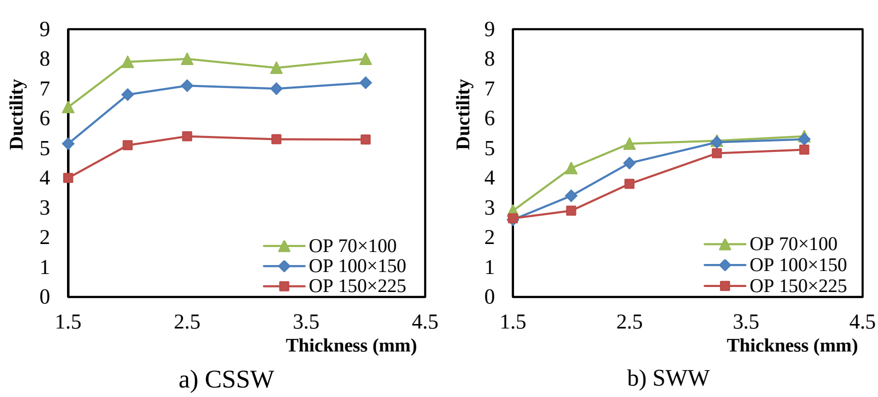


Fig. 9. Ductility as a function of thickness (angle of corrugation = 90°).

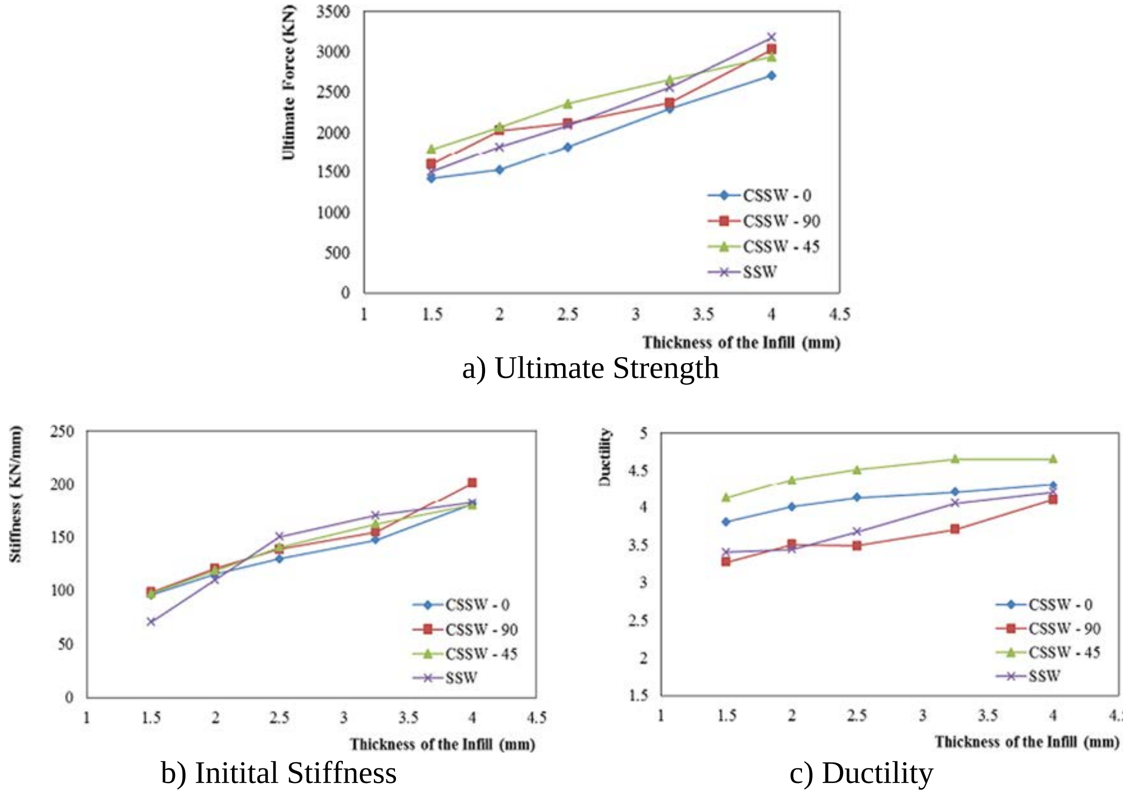


Fig. 10. Ultimate shear, stiffness, and ductility as a function of thickness for CSSW and SSW without openings.

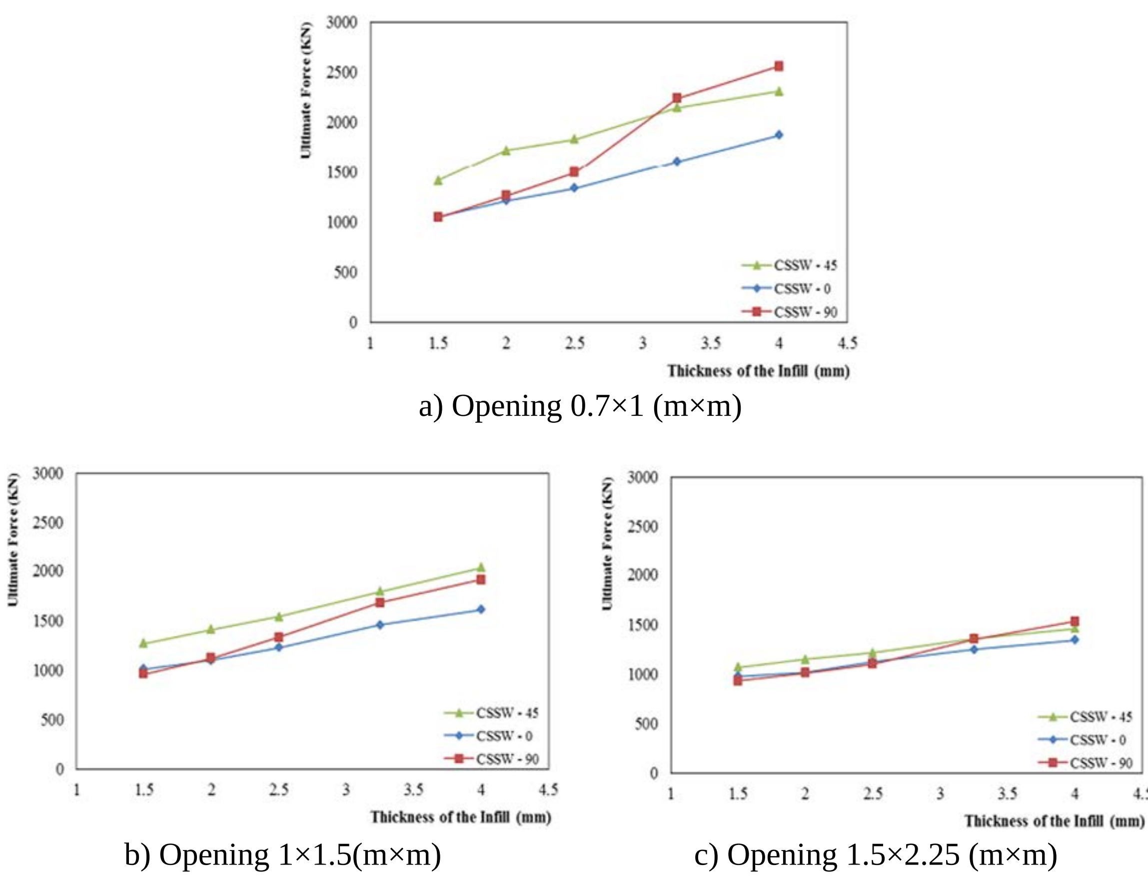
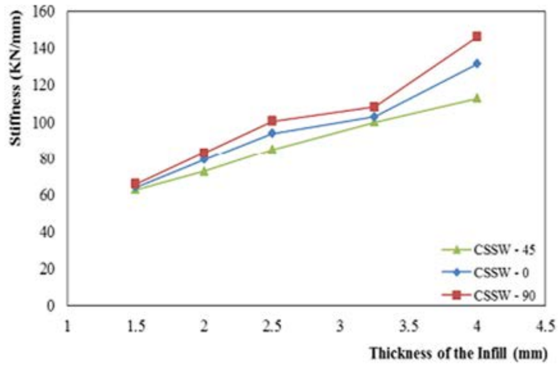
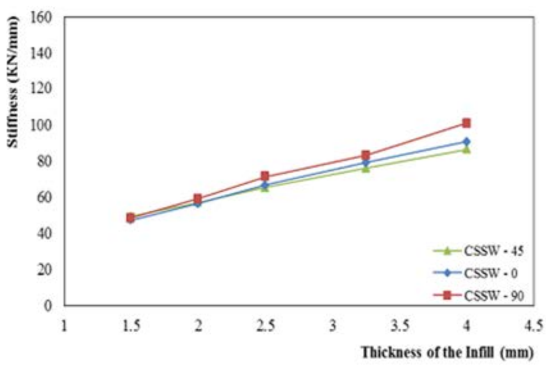


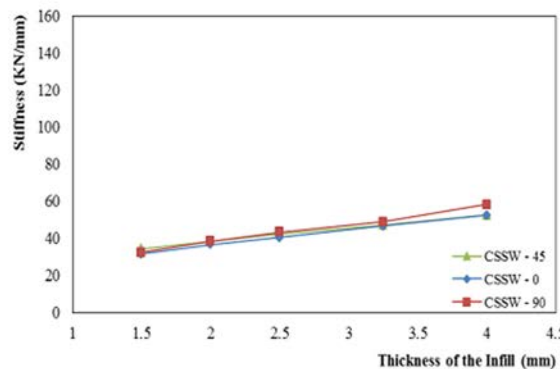
Fig. 11. CSSW ultimate shear for different center opening sizes as a function of thickness and corrugation angles.



a) Opening 0.7×1 (m×m)

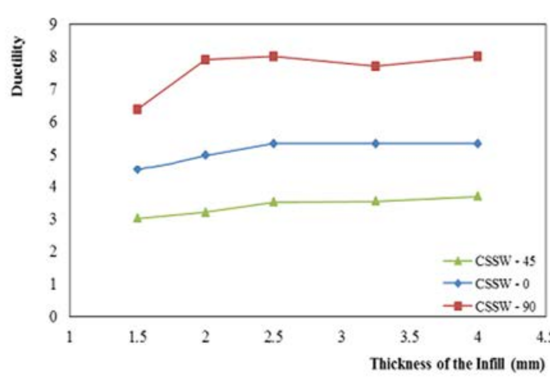


b) Opening 1×1.5(m×m)

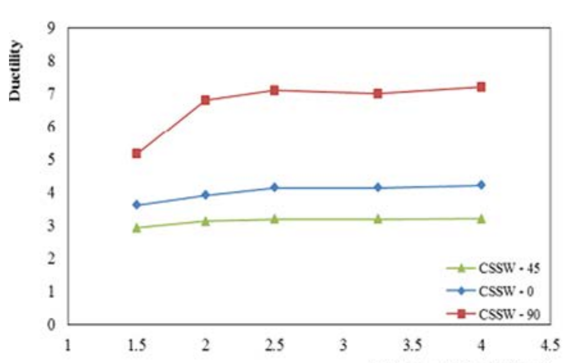


c) Opening 1.5×2.25 (m×m)

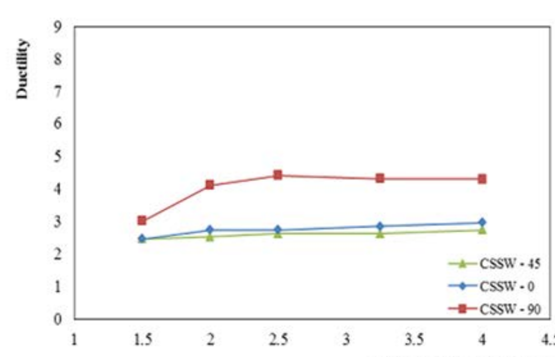
Fig. 12. Initial stiffness curves for middle-opening CSSW regarding different corrugation angles.



a) Opening 0.7×1 (m×m)



b) Opening 1×1.5(m×m)



c) Opening 1.5×2.25 (m×m)

Fig. 13. CSSW ductility with middle-opening for different corrugation angles.

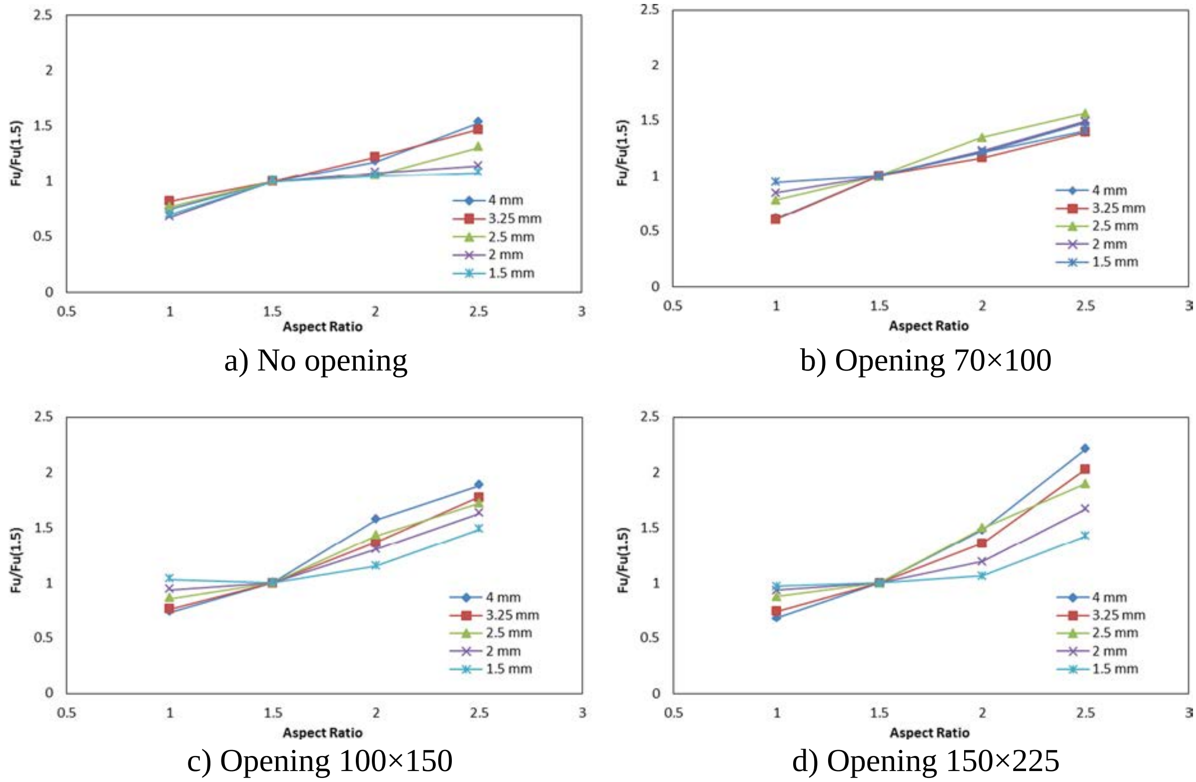


Fig. 14. CSSW ultimate strength as a function of aspect ratios on CSSW with 90° angle of corrugation for 1.5 mm, 2 mm, 2.5 mm, 3.25 mm, and 4 mm.

The same procedure could be assumed for calculation of opening diameter as well. It can be observed that the ultimate shear strength and stiffness ratios linearly decay with an increase in opening size (Figs. 16 and 17).

A linear regression analysis was completed to develop a prediction model for the ultimate shear strength of a steel shear wall. This included consideration of Eqs. (2)–(5) and the data presented in Figs. 16 and 17. The prediction model for CSSW ultimate shear

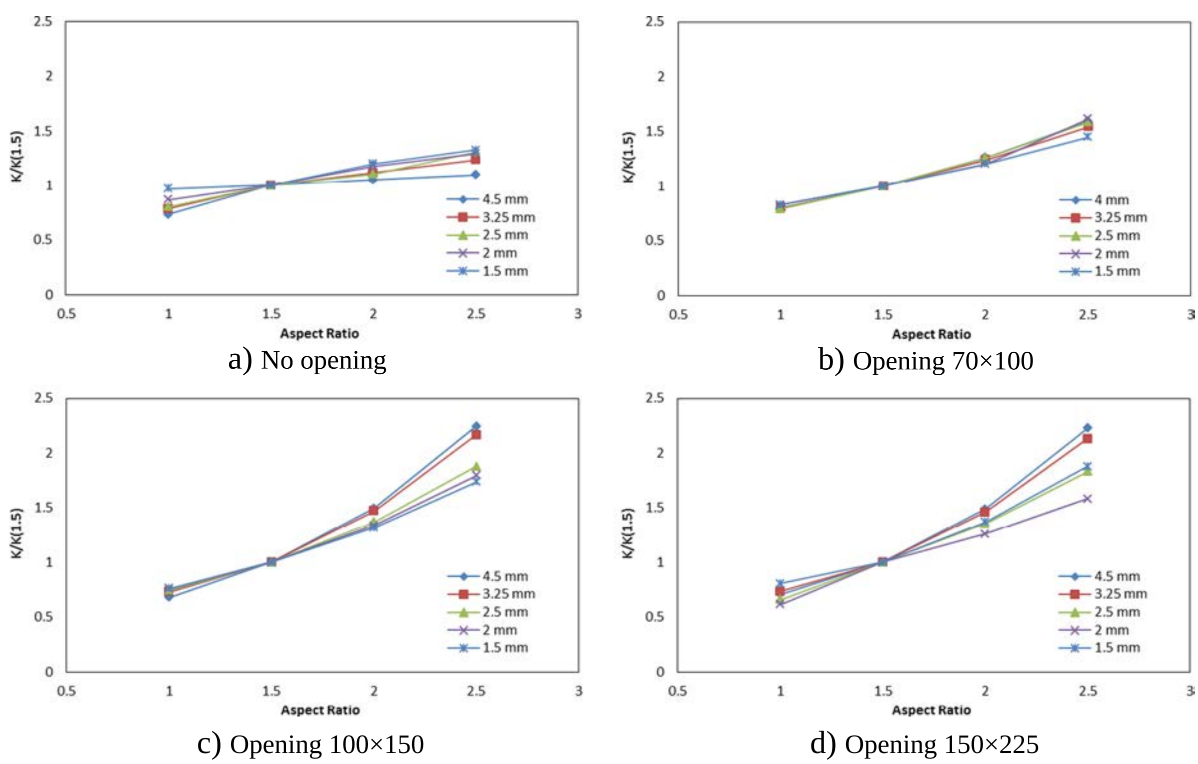


Fig. 15. CSSW stiffness as a function of aspect ratio with 90° angle of corrugation for thicknesses of 1.5 mm, 2 mm, 2.5 mm, 3.25 mm, and 4 mm.

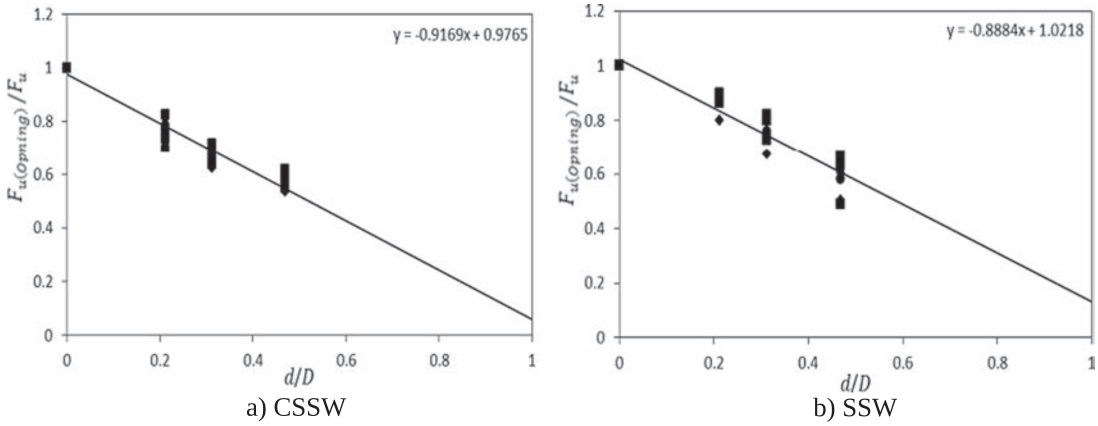


Fig. 16. Effect of diameter ratio on ultimate strength ratio.

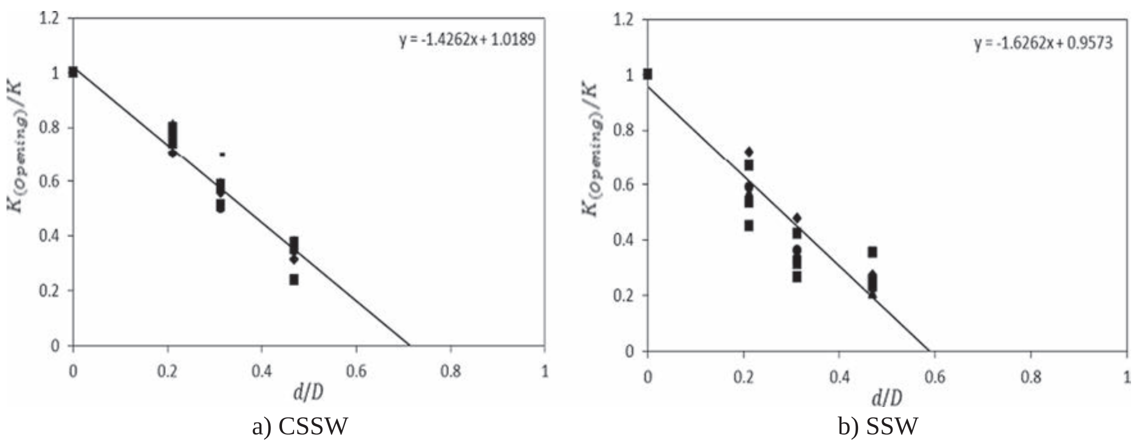


Fig. 17. Effect of diameter ratio on stiffness ratio.

strength with a rectangular opening is presented in Eq. (6) by considering Eqs. (2) through (5):

$$F_{su(op)} = F_{su}(1-d/D) \tag{2}$$

in which $F_{su(op)}$ is the ultimate strength capacity of CSSW with opening, F_{su} is the ultimate strength of a CSSW without opening:

$$F_{su} = \left[F_{pt} + F_{fu}\right] \tag{3}$$

where F_{pt} is strength capacity of plate, and F_{fu} is the strength capacity of the frame. F_{pt} is given by Eq. (4):

$$F_{pt} = Lt\left(\tau^{e}_{cr,\ in} + 0.5\sigma_{ty}\sin 2\theta\right) \tag{4}$$

where L and t are the length and thickness of the panel, $\tau^{e}_{cr,\ in}$ is the interactive elastic shear buckling capacity of plate and σ_{ty} is the Von-Mises tension field yield stress. F_{fu} is given by Eq. (5):

$$F_{fu} = 4M_{fp}/h \tag{5}$$

where M_{fp} and h are the column plastic moment capacity, and height of the plate, respectively. Therefore, the $F_{su(op)}$ is formulated as:

$$F_{su(op)} = \left[Lt\left(\tau^{e}_{cr,\ in} + 0.5\sigma_{ty}\sin 2\theta\right) + 4M_{fp}/h\right](1-d/D) \tag{6}$$

where $\tau^{e}_{cr,\ in}$ is the interactive shear buckling stress, obtained as follows [16]:

$$\frac{1}{\left(\tau^{e}_{cr,\ in}\right)} = \frac{1}{\left(\tau^{e}_{cr,\ G}\right)} + \frac{1}{\left(\tau^{e}_{cr,\ L}\right)} \tag{7}$$

$$\tau^{e}_{cr,\ L} = \frac{K\pi^2 E}{12(1-\upsilon^2)}\left(\frac{t}{L}\right)^2 \tag{8}$$

$$\tau^{e}_{cr,\ G} = \frac{36\beta E}{\left[12(1-\upsilon^2)\right]^{.25}}\left[\frac{\left(\frac{d}{t}\right)^2 + 1}{6\gamma}\right]^{0.75}\left(\frac{t}{h}\right)^2 \tag{9}$$

where $\tau^{e}_{cr,\ G}$ and $\tau^{e}_{cr,\ L}$ are global and local shear buckling stresses; respectively, E and v are Young's modulus of elasticity and Poisson's ratio; a is flat panel width; β is boundary condition factor; and γ is corrugation geometric factor [16].

5.7. Opening position

CSSW is presented as an alternative to stiffened shear walls [9]. It is observed that opening location has a tangible effect on initial stiffness and ultimate strength of simple SSW. However, opening location does not have a significant effect on the response of stiffened walls [13].

In the present study, behavior of CSSW with nine opening locations has been comprehensively investigated. The wall with a centrally located opening is established as the benchmark—ultimate strength, stiffness and ductility for each variation were evaluated and compared to the benchmark (Table 2). The results presented in Table 2 have also been

Table 2
Characteristic ratio of different opening locations.

Zones/opening size	1	2	3	4	5	6	7	8	9
a) Ultimate strength ratio									
Opening 70 × 100	1	1.03	1.07	0.98	1.10	0.94	1.01	1.00	0.92
Opening 100 × 150	1	1.14	1.14	1.09	1.14	1.03	1.04	1.00	1.00
Opening 150 × 225	1	1.09	1.14	1.15	1.14	1.13	1.02	1.01	1.00
b) Stiffness ratio									
Opening 70 × 100	1	1.05	1.16	1.12	1.09	1.09	1.14	1.12	1.01
Opening 100 × 150	1	1.04	1.17	1.12	1.09	1.09	1.12	1.13	1.08
Opening 150 × 225	1	0.77	1.21	1.16	1.12	1.12	1.20	1.25	1.00
c) Ductility ratio									
Opening 70 × 100	1	0.98	1.03	1.14	1.02	0.98	1.06	1.28	1.11
Opening 100 × 150	1	1.01	1.17	1.14	1.01	0.99	1.16	1.39	1.03
Opening 150 × 225	1	0.76	1.07	1.02	0.98	0.77	1.20	1.35	1.09

normalized to the benchmark. The opening positions 3, 4, 7, and 8 (see Fig. 18) generally respond with higher strength, stiffness and ductility. The stiffness, strength and ductility degradation in CSSW with an opening is largely due to a significant opening interference with the tension field. Therefore, installation of an opening off the diagonal tension field will result in improved structural performance (Fig. 18)

5.8. Energy absorption

The load–displacement region between onset of inelastic and a half cycle load with 30% drift ratio can be approximated as the energy absorption capacity of the system. Utilizing this definition, Fig. 19 presents the energy absorption capacity of CSSW and SSW, with an opening, under lateral shear loading. The solid and dashed lines of Fig. 19 represent the average shear wall energy absorption of walls with a centrally located opening as a function of opening size. It is observed that the absorption energy decays with increasing opening size for both CSSW and SSW. The SSW energy absorption capacity is consistently less than that of CSSW. Moreover, the CSSW energy absorption capacity for all plate thicknesses is larger than SSW.

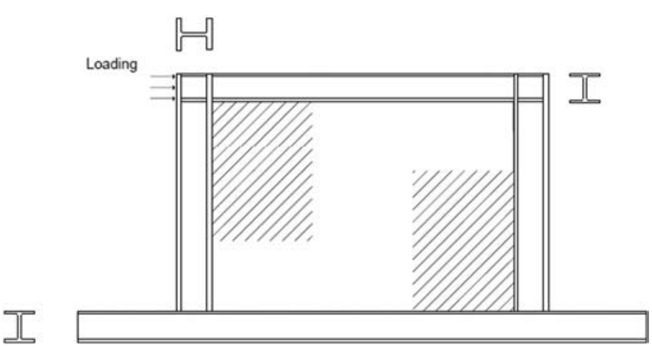


Fig. 18. Suggested location for opening installation (hatched).

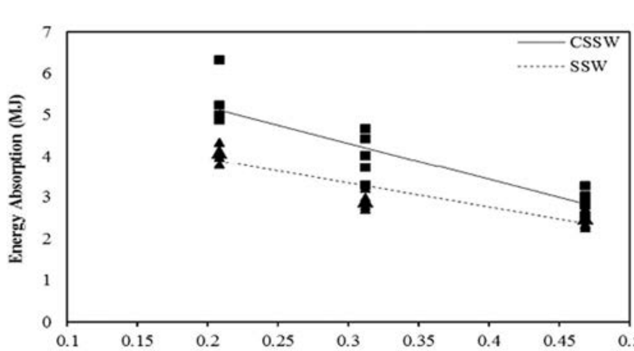


Fig. 19. Energy absorption capacity of SSW and CSSW with 90° corrugation.

Table 3
Comparison of dissipated energy.

Thickness	OP 70 × 100		AER*	OP 100 × 150		AER*	OP 150 × 225		AER*
	CSSW	SSW		CSSW	SSW		CSSW	SSW	
1.5 mm	5.0	4.1	22.3%	3.3	2.9	14.5%	2.5	2.3	10.2%
2 mm	5.0	4.3	15.1%	3.7	2.7	37.0%	2.9	2.2	28.4%
2.5 mm	4.9	3.8	30.2%	4.0	2.8	44.2%	2.8	2.3	19.1%
3.25 mm	4.9	4.0	22.9%	4.4	3.0	48.8%	3.0	2.9	3.8%
4 mm	6.3	4.3	46.2%	4.7	3.2	45.8%	3.3	3.0	9.6%

* AER: Absorbed Energy Ratio difference.

Table 3 presents the increase of absorbed energy by CSSW as compared to a corresponding SSW for different thicknesses and opening size. Significantly, the CSSW with central opening configuration exhibits considerable absorbed energy for each thickness compared with corresponding SSW.

6. Summary and conclusions

The behavior of the unstiffened and corrugated steel plate shear walls with and without an opening have been investigated. Corrugated panels postpone the ultimate strength and degradation point leading to better performance under seismic loads. The following observations and conclusions are drawn from the present study:

- In the case of shear walls with openings, initial stiffness and ductility of CSSW range from 30% to 50% higher than corresponding SSW.
- In most cases, ultimate shear strength of SSW is higher than that of CSSW with a negligible margin.
- CSSW plastic strains of the regions immediately surrounding an opening are less than those of SSW due to the geometry of corrugated panels.
- The initial stiffness and ductility of corrugated shear walls without an opening are generally higher than those of unstiffened shear walls, especially in lower thicknesses.
- Larger aspect ratio shear walls exhibit an increased performance of up to 250% in ultimate shear strength and initial stiffness, particularly for walls with larger openings.
- The ultimate shear strength analysis of CSSW and SSW with an opening can be simplified by multiplying 'without-an-opening' results with the factor of $(1 - d/D)$ regardless of opening location.
- Installation of openings off the diagonal tension field leads to improved performance increase of approximately 10% under monotonic loads.
- The energy absorption capacity is approximately 25% higher for CSSW than the corresponding SSW. This indicates the suitability of CSSW with an opening under cyclic loadings in regard to different size of the openings.

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