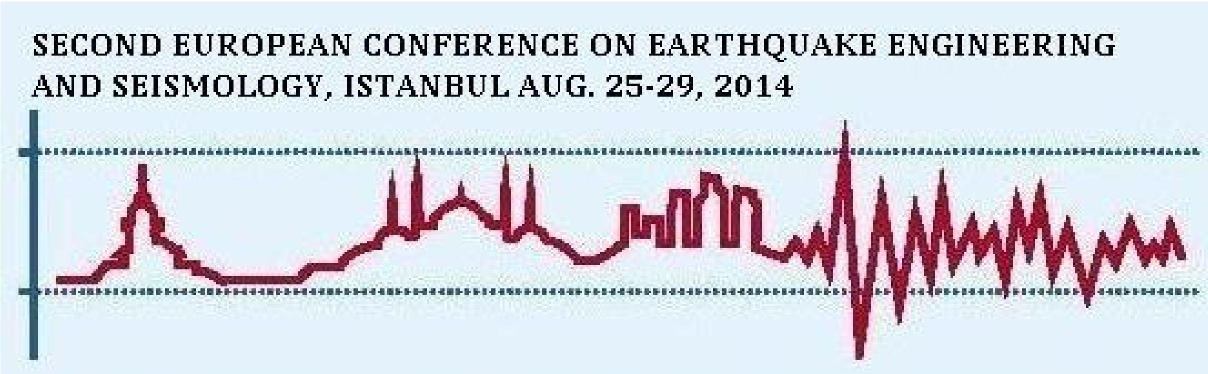


ON THE BEHAVIOROF CORRUGATED STEEL SHEAR WALLS WITH AND WTHOUT OPENINGS

Alireza Farzampour[1] and Mohammad Yekrangnia[2]

ABSTRACT

The nonlinear behavior of trapezoidal corrugated steel shear walls with rectangular openings has been studied in this paper. A series of corrugated and simple shear walls with and without openings regarding different angles of corrugation and different infill plate's thickness have been investigated. This analytical study was conducted to compare the force-displacement curves, initial stiffness and ultimate strength of corrugated steel shear walls. The results show that utilizing trapezoidal corrugated panels increase initial stiffness of shear wall system, while decrease the ultimate strength. In addition, corrugated steel shear wall postpones the ultimate strength and degradation compared with corresponding unstiffened steel shear wall, which is highly beneficent seismic characteristic of these structural elements. Furthermore, the maximum plastic strain of the near-edge opening elements is significantly higher for unstiffened shear wall compared to corrugated one.

INTRODUCTION

Steel shear walls are widely utilized as an efficient lateral resistance system in areas with high hazard seismicity. This structural system with significant strength and ductility has been implemented in a number of high-rise buildings as an economical way of providing more space, considerable strength, faster speed of construction, better quality control and lighter structures (Ghosh and B.kharmale, 2010). These lateral resistance systems could be used in new buildings as well as old ones for the purpose of retrofitting (Emami et al., 2013). A steel shear wall consists of a beam and columns connected to each other to make a moment-resisting or simple frame. An appropriate steel shear wall has relatively high ultimate strength, ductility, and a significant initial stiffness which is highly essential for limiting the lateral drifts in structures. Steel shear walls equipped with the moment-resisting beam-to-column connection frame would increase the redundancy, and ductile behavior of the system.

Numerous researches and a number of experiments have been conducted to investigate the lateral resistance and stiffness of the system. The experimental tests have been performed to indicate the principal behavior of this structure. In addition, analytical formulation has been suggested for calculation of distinctive parameters of steel shear walls (Berman et al., 2003). Among the considerable matters of concern attributed to steel shear walls is the shear buckling behavior as one the most important factor in seismic design of steel shear walls and stress distribution in slender plates (Sabouri-Ghomi et al., 2005). The interactive shear buckling stress has been investigated and analytical formulation has been introduced to formulate local and global shear buckling stresses (Yi et al., 2008). In this regard, stiffeners have been introduced for shear walls with openings to limit the

[1] M.Sc. Student, Sharif University of Technology, Tehran, alireza_farzampour@mehr.sharif.ir
[2] Ph.D. Candidate, Sharif University of Technology, Tehran, yekrangnia@mehr.sharif.ir

shear buckling to local buckling (Hosseinzadeh and Tehranizadeh, 2012) and increase the interactive shear buckling of plate. However, construction of stiffeners would impose a significant time and financial expenses, and might be particularly vulnerable to welding imperfections (Emami et al., 2013). Therefore, corrugated shear panel is proposed as a special and innovative substitution for stiffened steel shear walls to reduce attributed costs especially in shear walls with openings.

Utilizing corrugated steel shear walls could be beneficent from two different viewpoints: first, due to out-of-plane stiffness, trapezoidal corrugated plates would have a noticeable initial stiffness and as each sub- panels could support adjacent sub-panels in out-of-plate direction. Second in the case of steel shear walls with openings; the plastic strain would be limited because of the shape and geometry of corrugated infill plate.

In sum, openings in steel shear walls are commonly provided due to necessary access requirements. Corrugated steel panels with openings could be implemented as a suitable substitution for unstiffened and stiffened steel shear wall regarding various design aspects for different purposes such as higher interactive buckling, effective stress distribution, out-of-plane stiffness, and lower cost of construction to name but a few. Thus, in the present study, a number of unstiffened steel shear walls (SSW) and corrugated steel shear walls (CSSW) with and without openings are numerically analyzed. Opening size, corrugation angle and thickness of the infill plates are discussed. The changes in system's displacement -force curves, initial stiffness, ultimate strength and plastic strain contours are investigated and depicted.

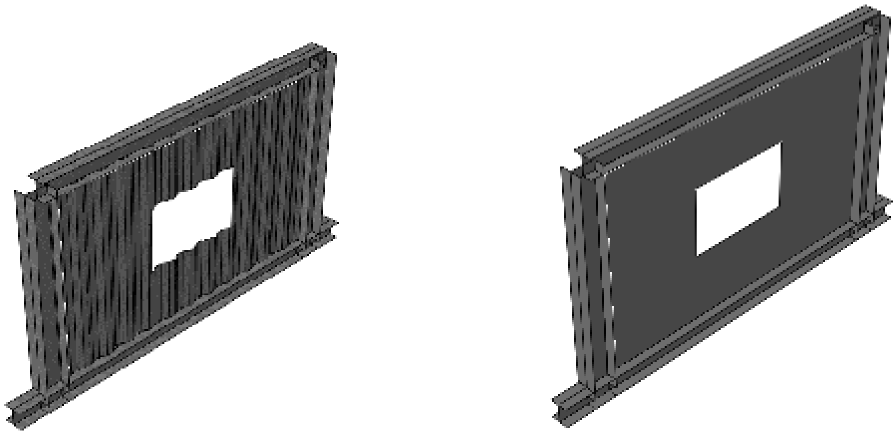
NUMERICAL MODELING:

In this part, the modeling procedure and description of models are presented. In each case, failure modes and force-displacement curves have been evaluated. A variety of single-story CSSW and SSW with different opening size, plate thickness, and angles of corrugation have been investigated. Fig.1 shows schematically representation of typical modeled configuration. The height and length of the story panel are 3.2m and 4.8m, respectively. The surrounding frame is assumed to be completely welded with shear infill plate. The unstiffened shear wall without opening is designed based on established design criteria, the PFI method in which the plate frame interaction is precisely considered (Sabouri-Ghomi et al., 2005), the designed boundary elements is indicated in Table.1.

Table 1. Boundary elements dimensions in models.

Design of Specimens	Profile	Web height (mm)	Web thickness (mm)	Flange width (mm)	Flange thickness (mm)
Beams	W 360×347	407	27.2	404	43.7
Columns	W 360×551	465	42	418	67.6

The upper beam of the frame is restrained against out-of-plane movement due to real behavior of the diaphragm conditions in structures. Finite element modeling of distinctive configurations is performed under displacement-controlled loading with the aid of dynamic explicit numerical procedure in the commercial software ABAQUS. The general-purpose-four-node shell element (S4R) has been utilized for numerical simulation of all parts of the models. This reduced integrated element not only decreases the running time but also prevent from the undesirable occurrence of shear locking effects. The stated element is appropriate for large displacements and nonlinear behavior of steel models.



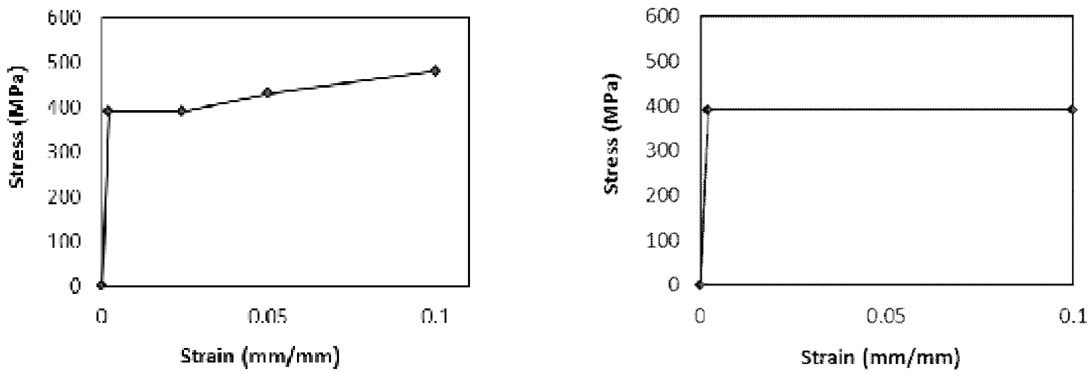
a) CSSW with opening b) SSW with opening

Figure 1. Schematic representation of the models

In addition, mesh sensitivity analysis is performed to reach the appropriate element size. The loading is applied by subjecting the model to monotonically increasing lateral displacement until the suggested drift ratio of the story 2.5% according to UBC (1985). The geometrical characteristics of the studied models are given in Table.2. Moreover, the mechanical properties of the steel infill plates and steel profiles are chosen according to Habashi and Alinia (2010) according to Fig.2.

Table 2. Models' dimensions

Name	Type	Opening		Plate Thickness(mm)[A]	Ang. of Corrugation[D]	No. Runs
		Opening Dimensions (m×m) [B]	Opening Position ([C])			
S-t[A]-W[B]([C])	SSW	{1}: 0.7×1,{2}:1×1.5,{3}:1.5×2.25	1-2-3-4-5-6-7-8-9	1.5,2,2.5,3.25,4	-	150
C[D]-t[A]-W[B]([C])	CSSW	{1}: 0.7×1,{2}:1×1.5,{3}:1.5×2.26	1-2-3-4-5-6-7-8-9	1.5,2,2.5,3.25,4	135-90-45-0	500



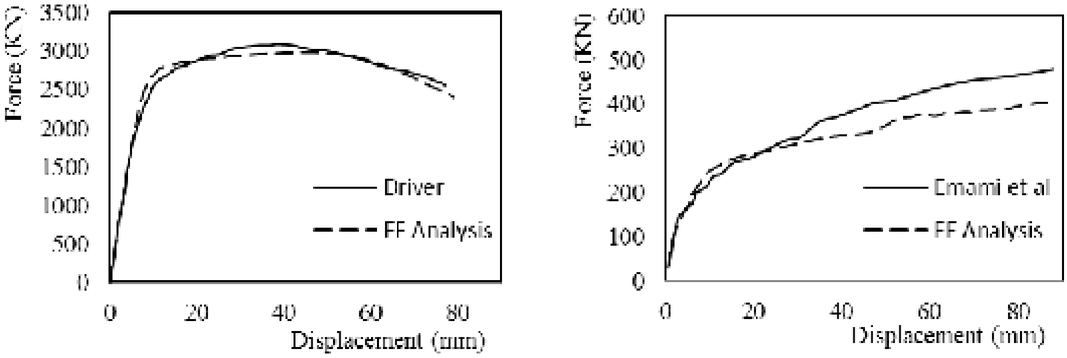
a) Beam and Column b) Plate

Figure 2. Materials stress-strain curves

VALIDATION OF NUMERICAL RESULTS:

For verification purpose, modeling procedure of two well-known tests has been investigated. Failure modes, load-displacement curves and models' behavior under monotonic and cyclic loading protocol have been validated by comparing the experimental and numerical results. A Four-story steel shear wall tested by Driver et al., (1998), and one story corrugated steel shear wall tested by Emami et al.,

(2011) are considered. The results, as depicted in Fig.3 show close agreement between tests and numerical models.



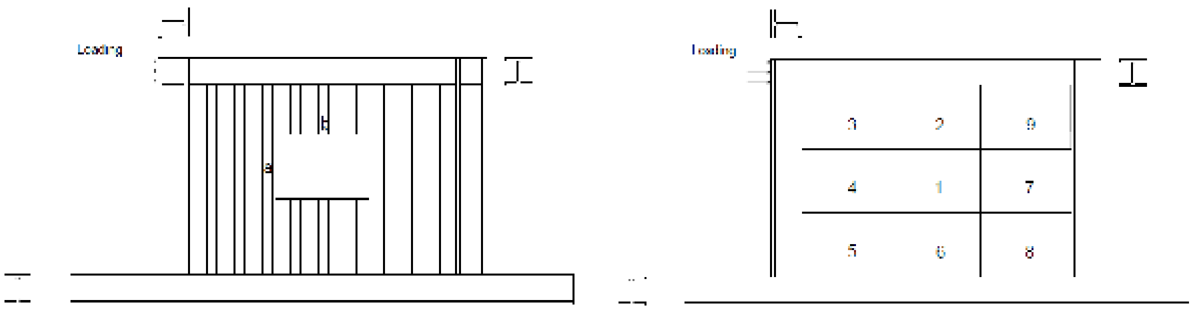
a) Driver et al b) Emami et al

Figure 3. Comparison the load-displacement curves)

DISCUSSION OF THE RESULTS:

General Description:

Both CSWW and SSW with and without opening is considered regarding varied size and position of the openings over the infill plate. Pushover analysis is carried out for each model with loading at the story level as indicated in Fig.4(a); it is expected that the tension field is propagated along the diagonal line of the plate. As for inelastic buckling, in-plane stiffness of the corrugated panels decreases abruptly in direction of corrugation; therefore, tension field in corrugated plate forms incompletely and to some extent, in a complicated mechanism (Emami and Mofid, 2012); Therefore, the interaction of the tension field with opening in varied size and locations have been evaluated. In this study, each of three opening size is considered in nine different position regarding different plate's thickness as shown in Fig. 4(b). A total number of 700 models are implemented in this numerical study.



a) CSSW with openings b) Openings' location

Figure 4. Configuration of models

General behavior:

Fig.5 shows the general behavior of the typical CSSW and SSW with and without openings regarding different plate thickness under monotonic loading. The lateral load-displacement curves have been investigated and categorized to three different stages:

At first stage, the general behavior of all models with and without openings behaves elastically. By increasing the load, the corrugated panels begin to experience local buckling; however, the unstiffened ones experience no significant local buckling and their buckling modes are limited to global. This fact leads to delay in occurrence of ultimate strength peak and degradation trend in corrugated walls. As a result, the system with openings experiences a significant loss of stiffness. By propagation of local buckling in the plate, the tensile field begins to resist the lateral shear load; thus, the post buckling deformations continue until the first yielding point occurs. Regarding this part of the force-displacement curve, the difference between pushover behaviors is negligible among the models; however, the initial stiffness is higher for the steel shear walls without openings.

In the second stage, the general behavior of steel shear wall is nonlinear. Yielding zones would distribute within plate. The nonlinear behavior of the steel shear walls with opening begins from the corner edge of the opening. Opening results in substantial stiffness degradation in steel shear walls compared with steel shear walls without any. The push over curves start to diverge in this part, and the divergence rate is considerably higher in SSW with openings. in this regard, the geometry of CSSW prevent the yielding of openings adjacent elements leading to smaller values for plastic strain in a specific displacement. Fige.6 shows the stresses at the first yielding point for CSWW and SSW with opening.

In this stage all the CSSW and SSW systems behaves nonlinearly both in geometry and material and the corner regions of the opening are yielded. Stiffness of the system without opening is higher than that of a system with opening; however, in all the curves the stiffness is tending to become zero, As it is depicted in Fig.5 the ultimate strength has happened in larger displacements in corrugated steel shear walls compared with simple shear walls, this behavior could have highly beneficent effects in seismic performance of the structural elements.

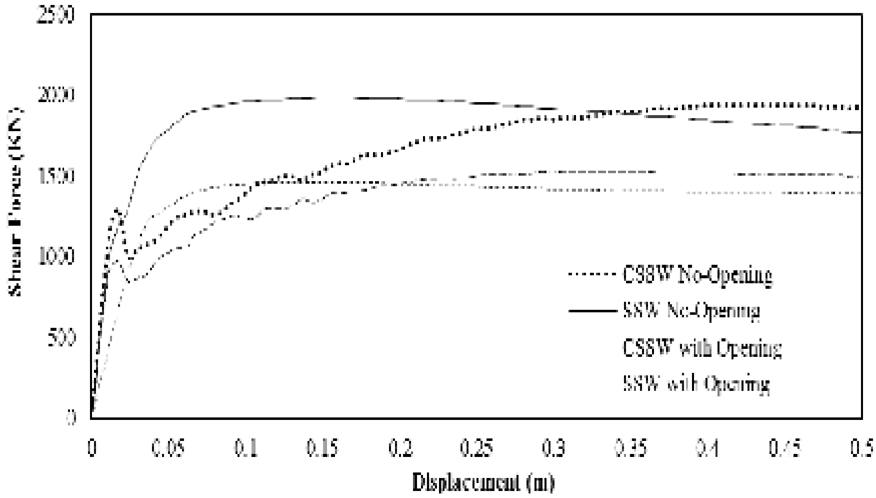


Figure 5. Load-displacement curves of CSSW and SSW with and without openings

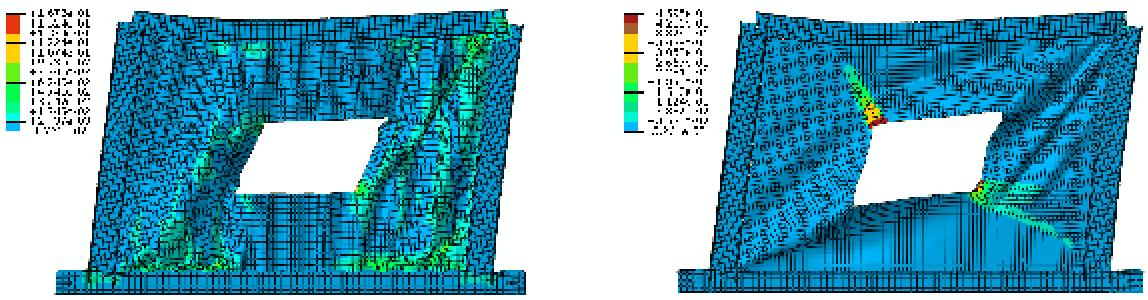
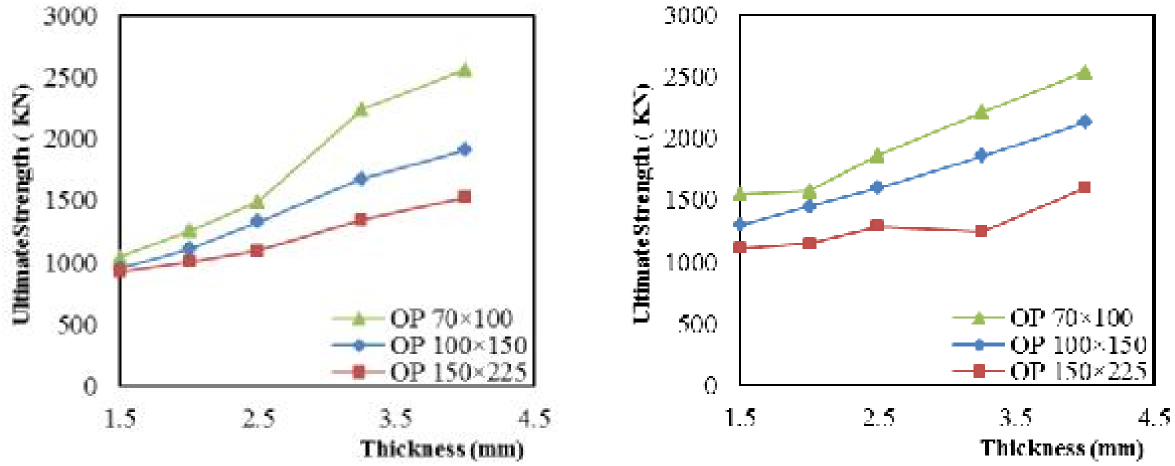


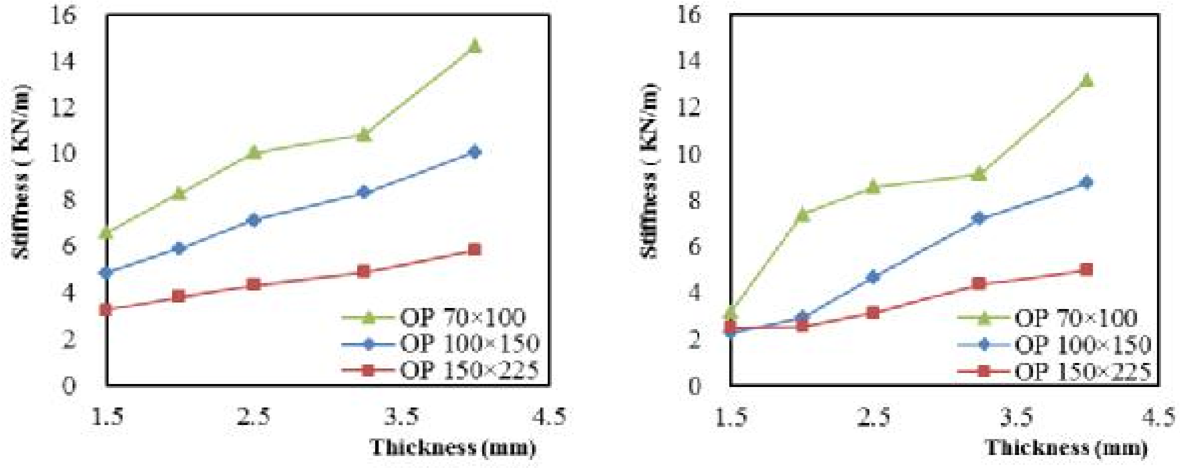
Figure 6., Plastic strain in CSWW and SSW with middle opening in 2.5% drift ratio

The general behavior of ultimate strength-thickness curves is indicated in Fig.7. It is concluded that by increasing the thickness of the infill plate, the ultimate strength would increase in both CSWW and SSW; however, SSW has slightly better performance in each thickness. Moreover, initial stiffness of CSWW is tangibly better than corresponding SSW, leading to less non-structural damages for building equipped with corrugated steel shear wall. This difference could be seen in lower thickness of the infill much clearly (Fig.8). In addition, the ductility of vertically corrugated steel shear wall is significantly higher than that of the simple steel shear wall especially in systems with lower sized opening as indicaed in Fig.9. Moreover; the opening size has cosiderable effects on the ductility of the shear wall in corrugated panels.



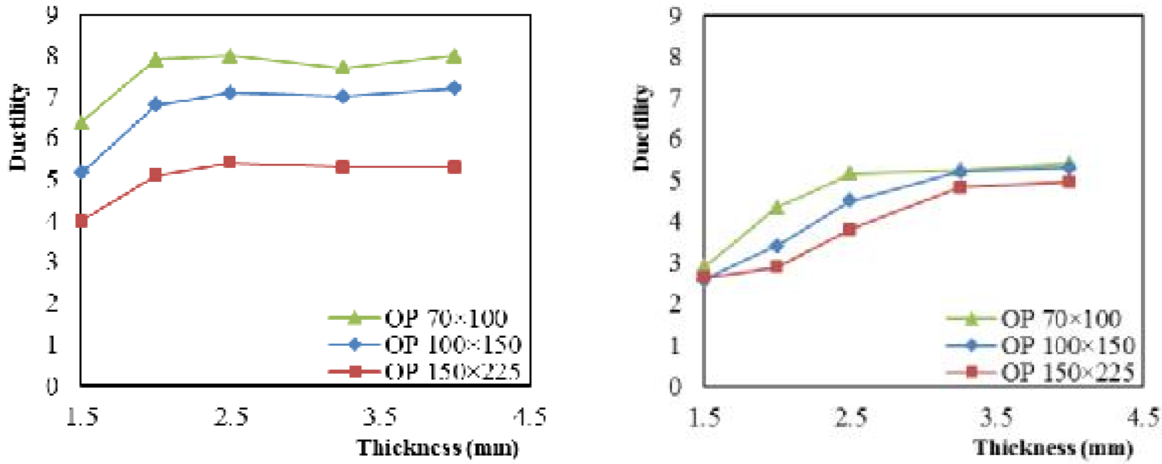
a) CSWW b) SSW

Figure 7. Variation of ultimate strength with thickness



a) CSWW b) SSW

Figure 8. Variation of initial stiffness with thickness

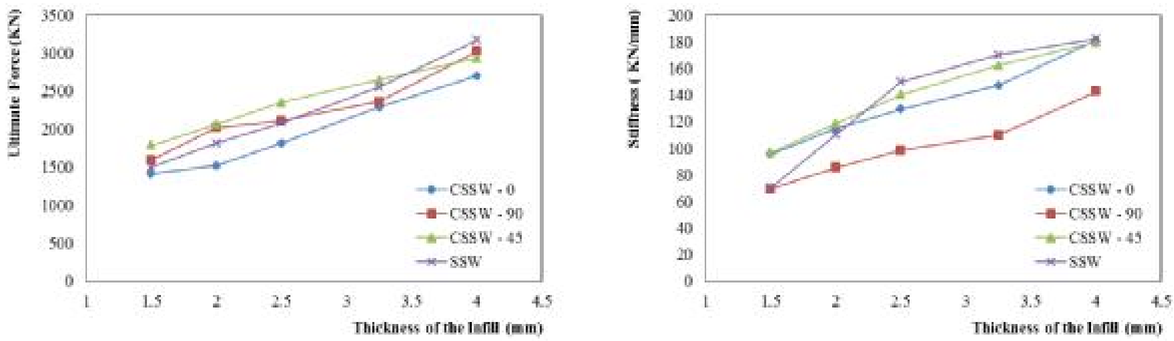


a) CSWW b) SSW

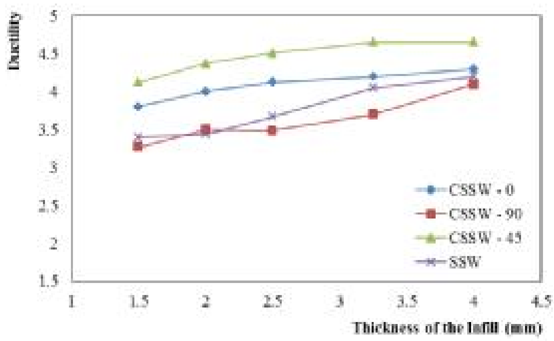
Figure 9. Variation of ductility with thickness

Discussion of the corrugation angle in CSWW and SSW without openings:

The behavior of CSSW and SSW without opening is depicted in Fig.7. It has been observed that utilizing corrugated steel shear wall would have no substantial effect on the ultimate strength of the system; however, it is concluded that CSSW would lead to higher initial stiffness and ductility especially in thinner infill plates. Moreover, variation in corrugation angle has no significant effects on ultimate strength and stiffness of the models.



a) Ultimate Strength b) Initial Stiffness



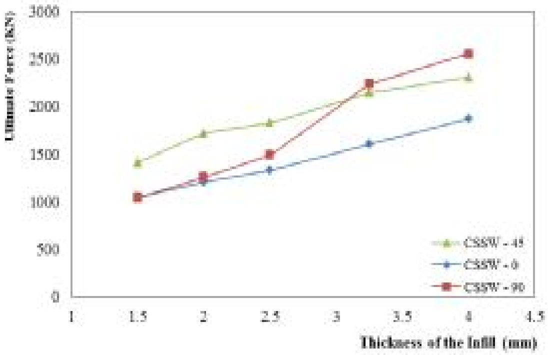
c) Ductility

Figure 10. Differences between CSSW and SSW without openings

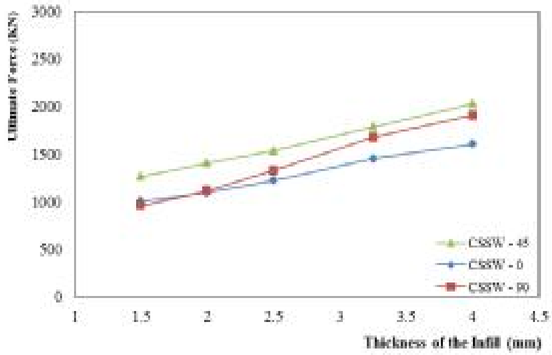
Discussion of corrugation angle in CSWW with openings:

In this part the behavior of the CSSW regarding different opening size is investigated. It has been observed that variation in the corrugation angle has no significant effects on the ultimate strength of CSSW with openings (Fig.11); however, corrugation of 45 degrees has slightly better performance due to having corrugation direction parallels tension field after shear wall's post-buckling point under monotonic loading.

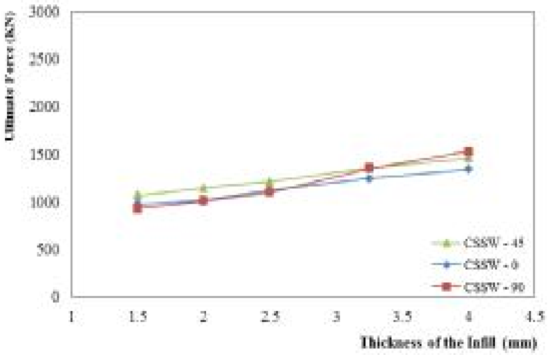
Additionally, by increasing the opening's dimensions, the behavior of the model would approximately converge to behavior of the frame; this would indicate that the angle of corrugation would have less influence in larger opening's size.



a) Opening 0.7×1 (m×m)



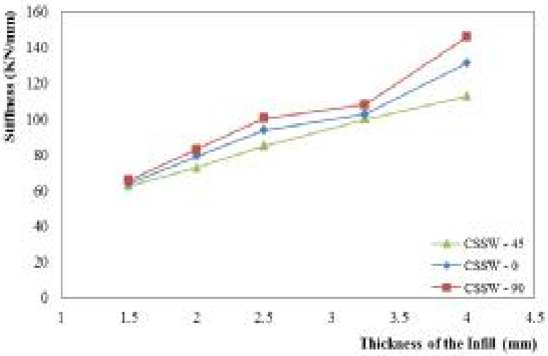
b) Opening 1×1.5(m×m)



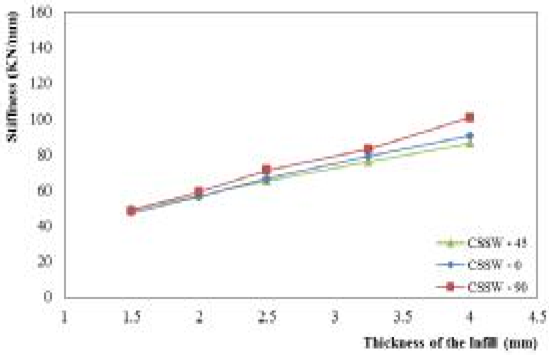
c) Opening 1.5×2.25 (m×m)

Figure 11. Angle of corrugation in CSSW with middle opening regarding ultimate strength

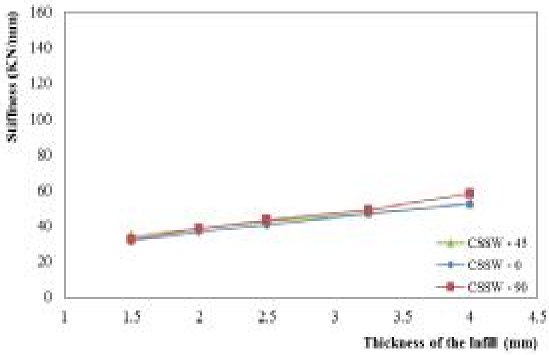
As indicated in Fig.12, the stiffness of the CSSW rises if the thickness of the model increases, and models with larger opening size have smaller in-plane stiffness. All the corrugated steel shear walls follow same trend regarding thickness of the infill plate. The stiffness of the model with corrugation angle of 90 degrees is higher than that of the other models due to having the least buckling length against the loading orientation, and subsequently higher buckling strength.



a) Opening 0.7×1 (m×m)



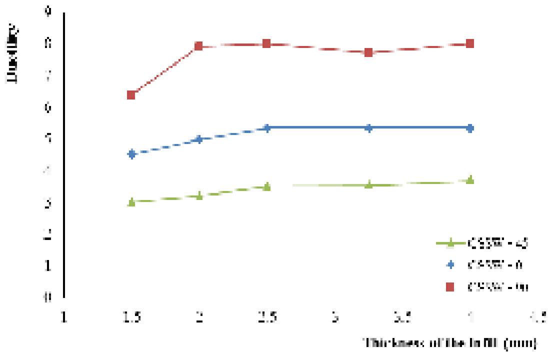
b) Opening 1×1.5(m×m)



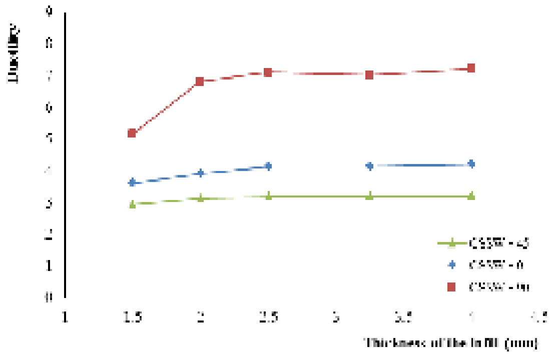
c) Opening 1.5×2.25 (m×m)

Figure 12. Angle of corrugation in CSSW with middle opening regarding initial stiffness

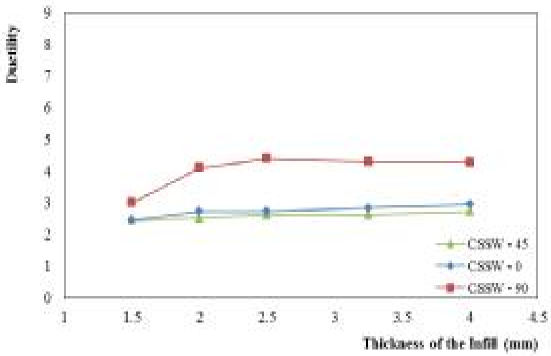
Furthermore, the ductility of CSSW is substantially affected by opening size; however, the thickness of the model and the angle of corrugation would have limited effect on the ductility of CSSW, especially in larger opening size. The difference between the models' ductile behavior is clearly inferred in lower size openings (Fig.13).



a) Opening 0.7×1 (m×m)



b) Opening 1×1.5(m×m)



c) Opening 1.5×2.25 (m×m)

Figure 13. Angle of corrugation in CSSW with middle opening regarding ductility

CONCLUSIONS

In this study, the behavior of the unstiffened and corrugated steel shear walls with and without opening have been investigated. Corrugated panels postpone the ultimate strength and degradation point leading to better performance under seismic loads. In the case of shear walls with openings, initial stiffness and ductility of CSSW are considerably higher than corresponding SSW; however, ultimate strength of SSW is rather higher than that of CSSW with a negligible margin. The plastic strains of openings' surrounding elements of CSSW is less than SSW due to geometry of corrugated infill plate. Furthermore, the initial stiffness and ductility of corrugated shear walls without openings are generally higher than those of unstiffened shear walls especially in lower thicknesses.

REFERENCES

Driver RG, Kulak GL, Kennedy DJL, Elwi AE (1998) "Cyclic test of four-story steel plate shear wall, " *J Struct Eng ASCE*, 124(2):112-20.

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

Emami E, Mofid M (2012) "On the hysteretic behavior of trapezoidally corrugated steel shear walls," *THE STRUCTURAL DESIGN OF TALL AND SPECIAL BUILDINGS*,

Hosseinzadeh S.A.A. and Tehranizadeh M (2012) "Introduction of stiffened large rectangular openings in steel plate shear walls," *Journal of Construction Steel Research*, 77 (2012) 180–192

Habashi HR, Alinia MM (2010)"Characteristics of the wall-frame interaction in steel plate shear walls," *Journal of Construction Steel Research*, 66(2)150–158

Jeffrey W. Berman and Michel Bruneau (2005) "Experimental Investigation of Light-Gauge Steel Plate Shear Walls," *Journal of Structural Engineering ASCE*, 130(1):259-267

Siddhartha Ghosh and Swapnil B.Kharmale (2010)"RESEARCH ON STEEL PLATE SHEAR WALL," *Structural Steel and Castings, 57-106*

Sabouri-Ghomi S., Ahouri E., Sajadi R., Alavi M., Roufegarinejad A., Bradford M.A. (2012) "Stiffness and strength degradation of steel shear walls having an arbitrarily-located opening," *Journal of Constructional Steel Research,* 79 (2012) 91–100

Sabouri-Ghomi S, Venturaand C, Kharraz M(2005)"Shear Analysis and Design of Ductile Steel Plate Walls," *Journal of Structural Engineering ASCE*, 131(2008):878-889

Yi J, Gil H, Youm K, Lee H (2008) "Interactive shear buckling corrugated steel webs," *Engineering Structures*, 30(6) 1659–1666