Journal of Building Performance ISSN: 2180-2106 Volume 10 Issue 1 2019
http://spaj.ukm.my/jsb/index.php/jbp/index

A NUMERICAL ANALYSIS ON THE BEHAVIOR OF STEEL PLATE SHEAR WALLS WITH DIFFERENT NUMBER AND THICKNESS OF TRANSVERSE STIFFENERS

Rahim Abdi
Department of Civil Engineering, Taft Branch, Islamic Azad University, Taft, Yazd, Iran
Email: rahimabdi2365@gmail.com

Abstract
According to recent studies, steel plate shear walls (SPSWs) have been identified as a reliable system for lateral load resistance in high seismic regions. Considering the importance of stiffeners' geometry in SPSWs, in this study we attempted to numerically analyze the behavior of a steel frame under lateral loading equipped with a stiffened single-storey single-bay SPSW system. Three SPSW models with 1, 2 and 3 transverse stiffeners having a thickness of 10 mm, and one SPSW model with one transverse stiffener having different 5, 10, 20, and 30 mm thicknesses were designed and analyzed using eigenvalue linear buckling analysis in ABASQUS software to evaluate the effect of number and thickness factors of transverse stiffeners on the behavior of study frame. According to the results of the research, it was observed that with increasing number of transverse stiffeners, the maximum buckling capacity of the frame with SPSW increases which is technically remarkable. Also, with the increase in the number of transverse stiffeners, the contribution of each stiffener to increasing the ultimate capacity of the frame became more evident, which is economically considerable. Increasing the thickness of transverse stiffeners did not have a considerable effect on the buckling capacity of the SPSW.

Keywords: Number; numerical analysis; steel plate shear walls; transverse stiffeners; thickness.

Article history:
Submitted: 22/06/2018; Revised: 30/07/2018; Accepted: 20/08/2018; Online: 01/02/2019

INTRODUCTION

Although steel plate shear wall (SPSW) was known for many years, but no serious attention was paid to it, but in the last three decades this method is quite acceptable and has become popular especially in Japan and North America. This system is about 50% cheaper compared to the moment frame. It is easy to be installed and built and do not require any new technology. Engineers, technicians, and technical workers can implement it without the need for new skills. The speed of its installation is high and reduces the related costs. Also, its performance is better than bracing systems such as concentrically (CBF) and eccentrically braced frames (EBF) (Kulak et al., 1994). Another advantage of the SPSWs is the easy addition of an opening in the infill plate which is sometimes required for the passage of the facility, architectural goals, or structural reasons. However, if the opening is not properly designed, the seismic performance of the structure may be reduced (Alavi and Nateghi, 2013).The most important task of the steel shear wall is to withstand the horizontal lateral loads and overturning of the moment caused by the lateral loads. The steel shear walls are formed from a steel plate surrounded by beams and columns which are called boundary members. Also, the infill plate and the two boundary columns act as a vertical cantilevering plate (steel girder) where the columns are as the flange; the floor beams are as stiffeners, and steel plates are as the web (Sabouri-Ghomi et al., 2005; Gholhaki, 2009). In order to provide an economical design, the thickness of the steel plate is usually reduced. To improve the low buckling of thin steel plates, generally, longitudinal and transverse stiffeners are used to stiffen the steel plate (Deylami and Daftari, 2000). According to Yue and Hao (2016), the stiffeners on SPSWs not only effectively reduce the forces taken by beams and columns but also improve the overall cyclic performance of structural systems. They also increase the initial stiffness and buckling load capacity of SPSWs. Based on their results, the influence of connection stiffness on the load carrying capacity depends on the stiffness of columns and thickness of infill plates. In accelerated construction of high-rise buildings, gravity loads will inevitably be transferred to the wall panel and causing elastic buckling. In order to avoid buckling of slender wall panels under gravity or in serviceability limit states, channel stiffeners are attached to the wall (Zhao and Qiu, 2018). Some studies such as Tsai and Li (2010) and Alavi and Nateghi (2013), investigated SPSWs with various types of stiffener, including longitudinal stiffener, transverse stiffener, cross stiffener, diagonal stiffener, vertical and horizontal ribbed stiffener, etc. Installation of stiffeners can improve the behaviour of the SPSWs. It can cause 26% increase in energy dissipation capacity and 51.1% increase in the shear stiffness of steel plate (Sabouri-Ghomi and Sajjadi, 2012).

There are some numerical studies that have been conducted on SPSW models (stiffened and unstiffened) and their behaviour by local and foreign researchers. Among recent works, Deylami and Daftari (2000) analyzed non-linear behavior of SPSWs by investigating the effect of some important geometrical parameters such as plate thickness, opening aspect ratio and opening percentage. Their results showed that optimum aspect ratio for opening depends mostly on the plate thickness rather than the percentage of the opening. Rezai et al. (2004) presented detailed finite element model of a 4-storey SPSW in LS-DYNA software, and then studied the behavior of the model. The numerical models overpredicted the elastic stiffness of model, while the yield and ultimate strength as well as post-buckling behavior of the specimen were reasonably well predicted. Cyclic behaviour, deformability and rigidity of stiffened SPSWs were numerically studied by Alinia and Dastfan (2007). They found out that unstiffened SPSWs can provide a more ductile response while heavily stiffened SPSWs had a wider yield area, which cause higher energy dissipation. Habashi and Alinia (2010) investigated the nonlinear response of SPSW systems under lateral loading with respect to the interaction between the infill plates and frame members. According to them, the infill plates are very effective in the initial stages of loading and can absorb substantial part of storey shear. But they begin to lose their effectiveness when diagonal yield zones are developed in the infill plates. Ghodrati Amiri and Mirmiran (2011) compared the SPSW modelling in ABAQUS and SAP applications. The results obtained from the developed models indicated that the SPSWs, in addition to proper ductility, can withstand many loads. Therefore, they can be a good option for the lateral load bearing system of buildings. They found out that the use of shell element in ABAQUS is time consuming and difficult, but their results are accurate; although their application is more research-intensive and not practical. The modelling of SPSWs had acceptable results by using strip elements in SAP, but the modelling of SPSWs by membrane elements in SAP software did not provide good results. The reason for this was the high rigidity of these elements in the developed model. Hence, the model of the structure becomes too rigid which is different from reality. As a result, the answers will be unreliable. Esmaeili Niari et al. (2012) investigated the shear resistance of cold formed SPSWs with steel sheathing under monotonic loading by finite element analysis in ABAQUS software. The numerical results showed the good seismic performance of these walls with steel sheathing. Bhowmick et al. (2014) numerically examined behaviour of unstiffened SPSWs with circular perforations in the infill plates. For this purpose, they analyzed eight perforation patterns in a single storey SPSW of two different aspect ratios by using a geometric and material non-linear finite element model in order to assess the proposed shear strength model. Their comparison results showed the accuracy of the proposed model in predicting the design forces in the columns. Barkhordari et al. (2014) numerically studied the behavior of single and multi-story SPSWs of various aspect ratios with and without full-height rectangular openings. They found out that the relative reduction in the infill plate strength as well as the relative reduction in the initial stiffness and ductility due to the introduction of the openings can be reasonably assessed based on the relative reduction in the infill plate area. Mohammdi and Habibi (2016) Using the finite element software ANSYS, tried to introduce an optimal pattern for placing stiffeners in the shear wall in terms of strength and cost-effectiveness. In this regard, 21 different arrangements were investigated each of which had various plate thicknesses (5, 7, and 9 mm). The comparison of load-displacement curves of stiffened specimens with unstiffened ones showed that the use of stiffener in SPSWs significantly increase the strength of the system. By increasing the thickness of stiffeners in most of the studied patterns, it was observed that the ratio of increased strength to the weight of stiffeners decreased which indicates a reduction in the cost-effectiveness. Rahmzadeh et al. (2016) used finite element analysis to study the effect of the rigidity and arrangement of stiffeners on the buckling behaviour of SPSWs. They used transverse and/or longitudinal stiffeners in various practical configurations. They concluded that the use of stiffeners in SPSW systems not only improves the structural behaviour, such as stiffness, overall strength and energy absorption, but also leads to a reduction of the forces that are exerted on the boundary elements. Nonlinear behaviour of concrete stiffened SPSW with an opening was investigated by Shafaei et al (2017). They calculated the degradations of seismic factors (the initial stiffness, the ultimate shear strength, the ductility ratio, and the energy absorption) in terms of opening ratio. They observed that the behaviour of concrete stiffened SPSWs with an opening is completely different from corresponding SPSWs. Initial elastic stiffness of concrete stiffened SPSWs with an opening is independent of the opening location and ultimate shear strength is slightly affected by location. Also, a linear degradation in the initial elastic stiffness and the ultimate shear strength of the infill composite wall is observed due to increasing the opening ratio.

History of seismicity in Iran and the importance of resistant design of steel structures against lateral forces are vital to the future and development of Iran. In recent years, due to the development of cities and the progress of construction in every corner of the country, the need to pay attention to the issue of earthquakes, and wind power in high-rise buildings, has made it a serious problem for designers. On the other hand, while the experimental results unanimously support the rationale of using the post-buckling strength of the SPSWs in resisting lateral loading, the numerical modelling of the SPSW have resulted in mixed responses (Rezai et al., 2004). Considering this complication and importance of stiffeners' geometry in SPSWs, in this study we attempted to numerically analyze the behaviour of a steel frame under lateral loading equipped with stiffened SPSW system. The SPSW system has different number and thickness of transverse stiffeners. Our purpose is to examine the effects of number and thickness of transverse stiffeners in SPSW on the buckling behaviour of steel frame. This study is performed in ABAQUS software. First we introduce the study model and specimens. The results of the numerical modelling are given in next section, and finally the conclusions are presented.

STUDY METHOD

The analyzed model in this study, is a single-storey single-bay SPSW model with the span length of 6 m and storey height of 3 m designed by Habashi and Alinia (2010) according to the AISC Design Guide 20 and the AISC 341-05 rules and provisions. Figure 1(a) shows the 3D model of analyzed SPSW model and its boundary conditions. It includes rigid beam-to-column connection design. The bottom nodes of both columns flanges and webs were restrained from displacement in all directions. Plastic hinges were only allowed to form at the ends of horizontal and lower ends of vertical boundary elements. Designed section for beam is W14×176 and for column is W14×257. The model were meshed and modelled in ABAQUS software using 8-node reduced integrated shell element (S8R) (Fig.1b). The minimum size of structured mesh (in infill plate) is 10×10 cm, and the maximum size is 20×30 cm (in the perimeter frame).The used steel was ST37 model with Young's modulus (E)= 200 MPa and Poisson's ratio= 0.3. The elastic stress-strain curves were used to study the nonlinear behavior of the materials. Compressive loads were applied axially to the upper end of the beam which gradually increased from zero to the ultimate capacity of the system.

To evaluate the effect of number and thickness of transverse stiffeners on the behaviour of study frame, specimens were designed as following where the span length, storey height and plate thickness are fixed and have not changed:

- Three equipped with 1, 2 and 3 transverse stiffeners having a thickness of 10 mm and a width of 20 cm. They were named as SPSW-N1, SPSW-N2 and SPSW-N3, respectively. In SPSW-N2, the 6-meter span has turned into three 2-meter spans, while in SPSW-N3, the 6-meter span has been divided into four 1.5-meter spans (Fig. 2);
- One SPSW stiffened with one transverse stiffener having different 5, 10, 20, and 30 mm thicknesses and a width of 20 cm. They were named as SPSW-T5, SPSW-T10, SPSW-T20, and SPSW-T30, respectively.

To estimate buckling strength of the models, eigenvalue linear buckling analysis in ABAQUS software was conducted. Buckling is possible when compressive stresses or shear stresses are applied to a structure. To calculate the axial stress that causes buckling, we can use following formula, where F= the applied force or buckling load, and A= the cross-sectional area of the material with area perpendicular to the applied force:

$$\tau = \frac{F}{A} \qquad (1)$$

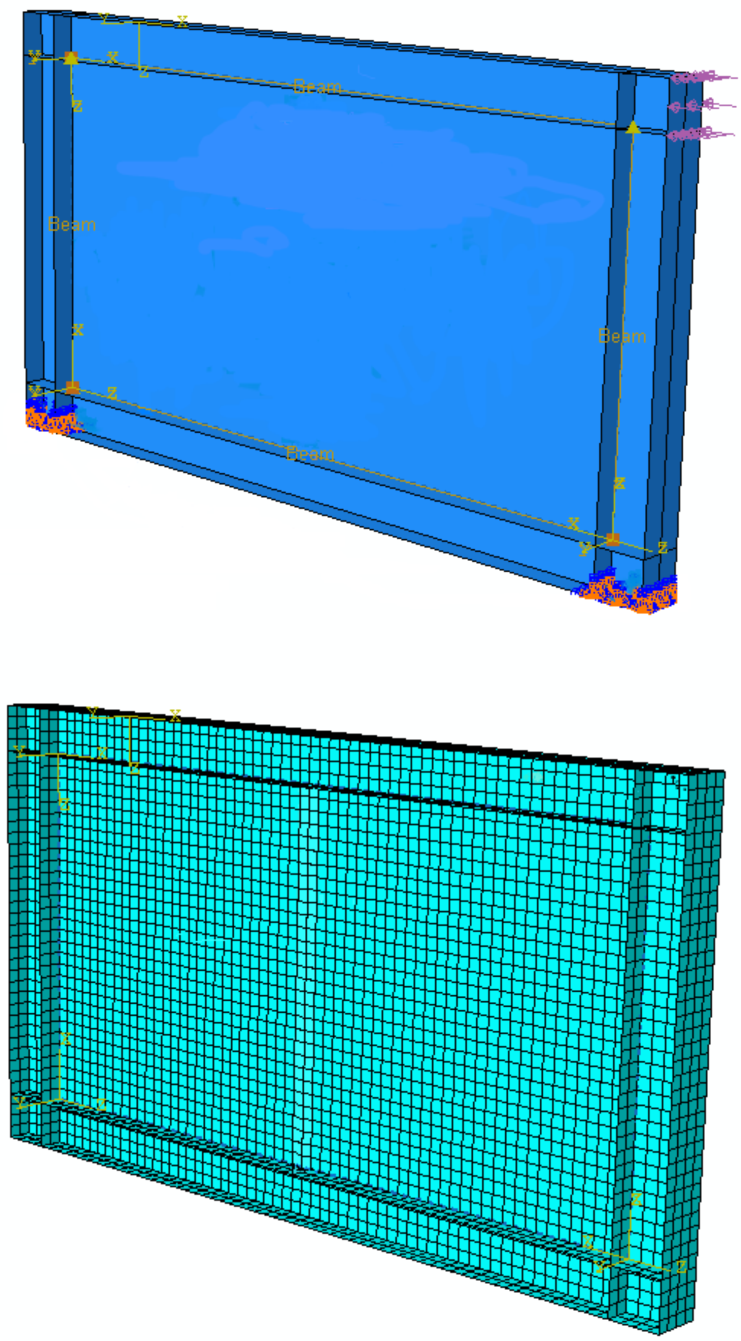


Figure 1: The 3D model and mesh of analyzed SPSW system

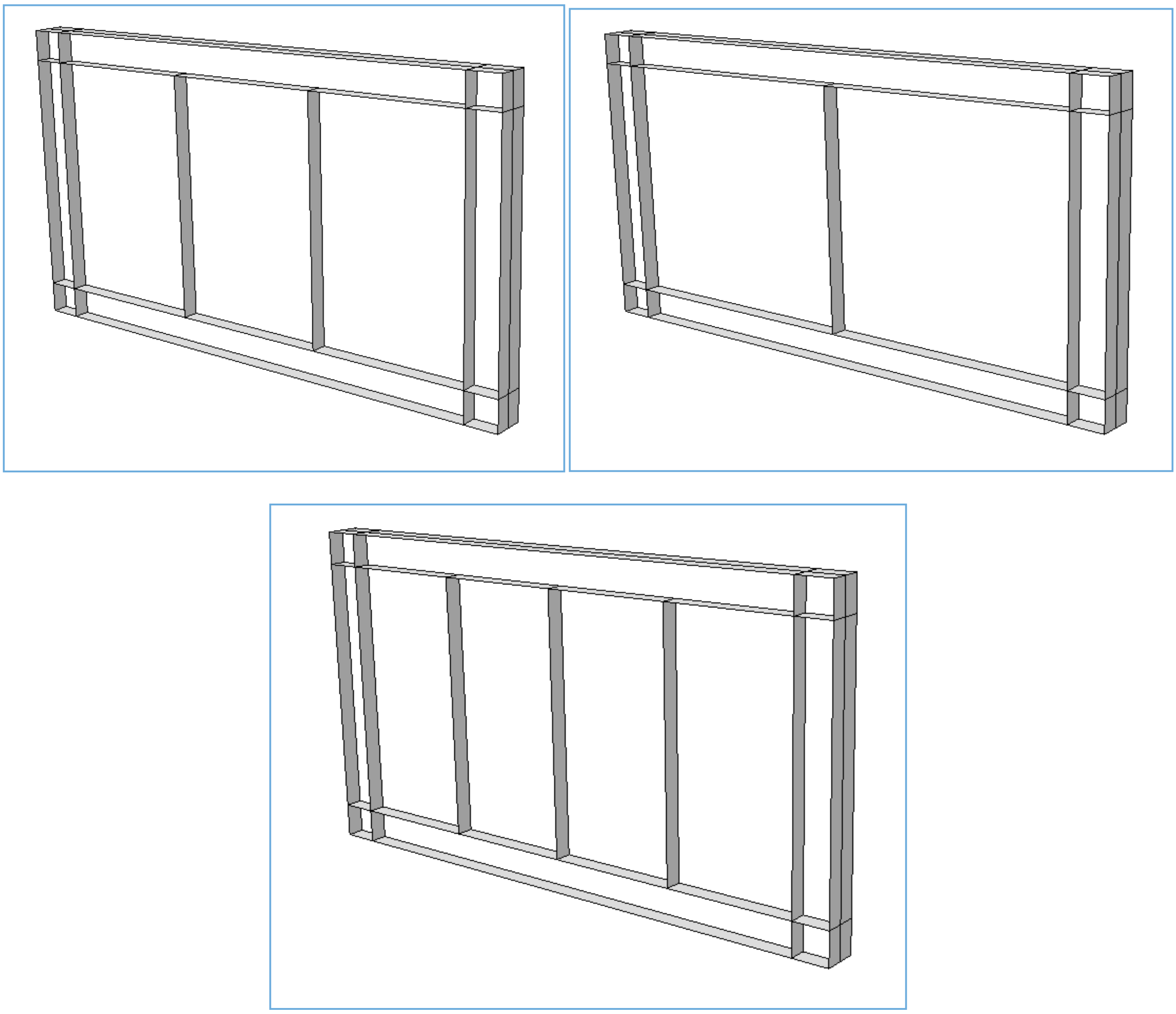


Figure 2: Specimens with one (SPSW-N1), two (SPSW-N2) and three transverse stiffeners (SPSW-N3)

Test verification
In order to verify the results and to ensure the accuracy of the numerical models, the results of this study were compared with the results of Habashi and Alinia (2010). They investigated nonlinear response of a single-storey single-bay unstiffened SPSW system with span length-to-story height ratio (L/h) = 1, h = 3000 mm, and infill plate thickness (t_w) = 3 mm under lateral loading using finite element analysis. Their model is shown in Figure 3. The beam-column connection included reduced beam section (RBS) where a= 200 mm, b= 300 mm and c= 95 mm. In their study, the behaviour of SPSW system with various infill plate thicknesses (3, 5, and 7 mm) and beam lengths (3-9 m) was evaluated.

Figure 4 shows the load-displacement curves of the current study and those presented by Habashi and Alinia. By comparing them, it can indicate the good agreement between them where the error rate was 14%. The major difference between the results was observed in 7-cm displacement where base shear was reported as 3038 kN in the current study, but in the results of Habashi and Alinia, it was reported as about 2600 kN.

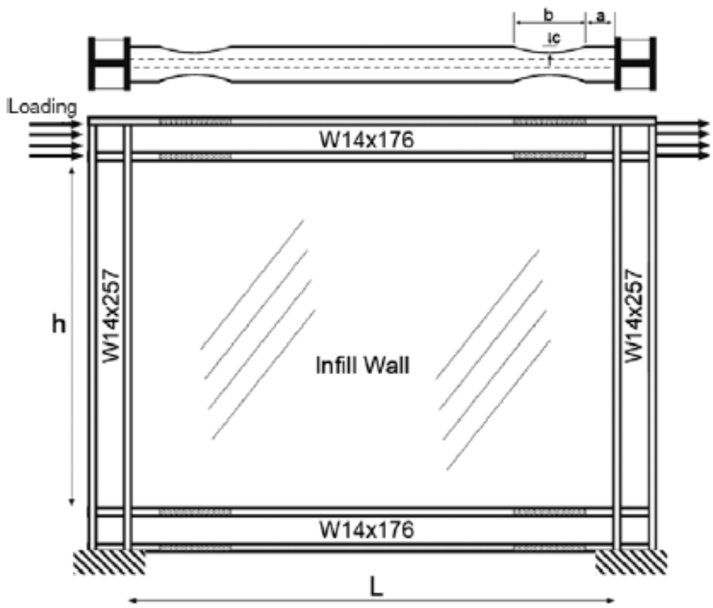
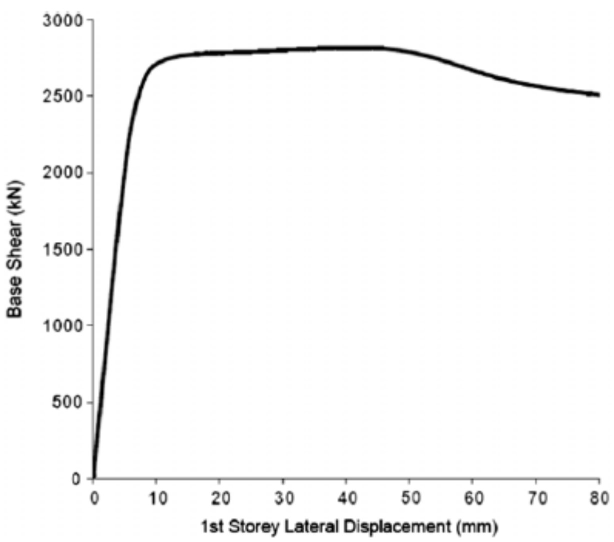
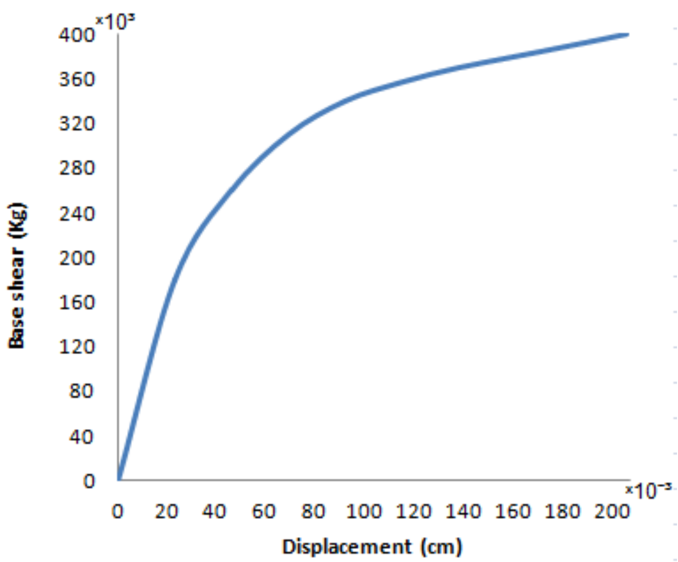


Figure 3:The SPSW system modeled by Habashi and Alinia (2010)



(a)



(b)

Figure 4: Load-displacement curves of SPSW system presented by Habashi and Alinia (a) vs. those in current study (b)

NUMERICAL RESULTS

In this section, we only presented the results of first or critical buckling mode of specimens to investigate the effect of number and thickness of transverse stiffeners on the behaviour of perimeter frame, because maximum buckling capacity was observed in the first mode when axial compressive force was applied; in other modes, the buckling capacity was decreased and the frame was deformed.

Effect of the number of transverse stiffeners

Figure 5 illustrates the first buckling mode of SPSW system for three models with transverse stiffeners. It can be seen that in SPSW-N1, the maximum displacement perpendicular to the plate in which buckling occurs, was observed from the load-applied area to the middle of the inner plate. Distortion and displacement occurred from the middle to the end of the plate. Deformation in stiffener was also observed. In SPSW-N2, local buckling was occurred between the two stiffeners and it can be seen that both stiffeners in both sides have been displaced and deformed. In SPSW-N3, maximum displacement was observed in the second area of the four created areas, and all three stiffeners have been deformed. It can also be seen that increasing number of transverse stiffeners leads to increased buckling and better control of the inner plate for greater lateral loading. In this model, the system can bear load more than other models.

Based on the results presented in Figure 5, maximum buckling capacity of the SPSW-N1 was 66.715 kg/cm^2 or 104.7 ton (Fig.5a). For the SPSW-N2, it was reported as 102.84 kg/cm^2 or 161.3 ton (Fig.5b), and for SPSW-N3, maximum buckling capacity was 155.10 kg/cm^2 or 243.3 ton (Fig.5c). Results showed that by adding one transverse stiffener to the SPSW, buckling capacity of the frame increased by 33%. This increase rate was 105% when two stiffeners were added, and then became 209% by adding three ones. This indicates that with the increase of the number of transverse stiffeners, the ultimate buckling strength of SPSW system increases which is technically considerable. If the increase in buckling capacity be divided into the number of stiffeners, it can be observed that in SPSW-N1, the incremental effect of each transverse stiffener on the increase of buckling capacity was 33%; in SPSW-N2, the role of each stiffener in increasing the buckling strength was 52% and for SPSW-N3, it was 69%. This suggests that with increasing the number of transverse stiffener, the contribution of each stiffener to increasing the ultimate buckling capacity of the frame becomes more evident which is economically remarkable. Figure 6 compare buckling capacities of specimens based on the distance between stiffeners. It can be seen that by gradually reducing the distance between transverse stiffeners, buckling capacity increases rapidly. By reducing the distance from 600 to 300 cm, the slope of the curve was 0.086, while by reducing the distance from 200 to 150 cm, the curve slope was 1.64; this is about 19 times the slope curve in previous distance reduction. This growth rate is considerable.

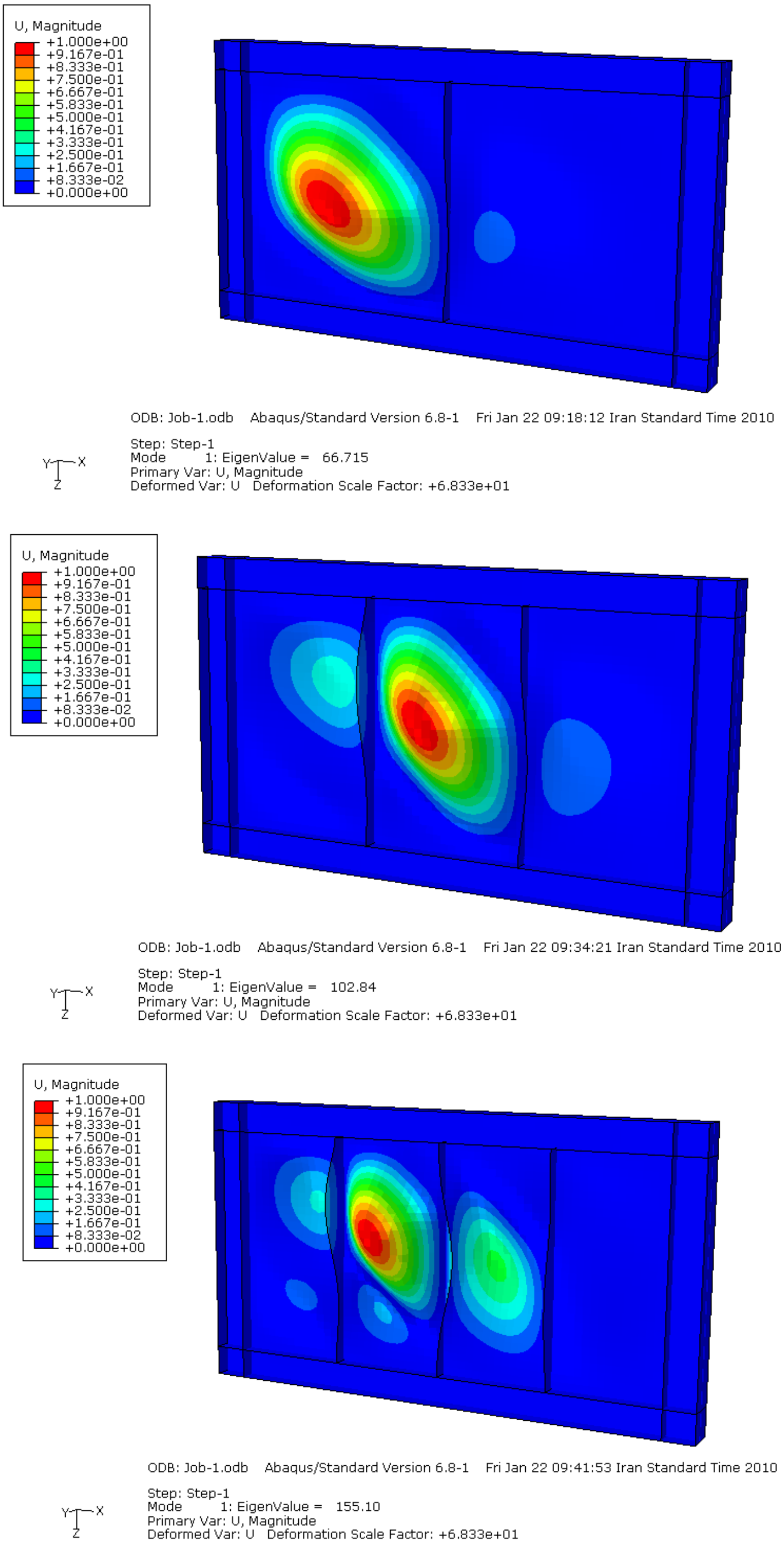


Figure 5: The first buckling mode of specimens with different number of transverse stiffeners

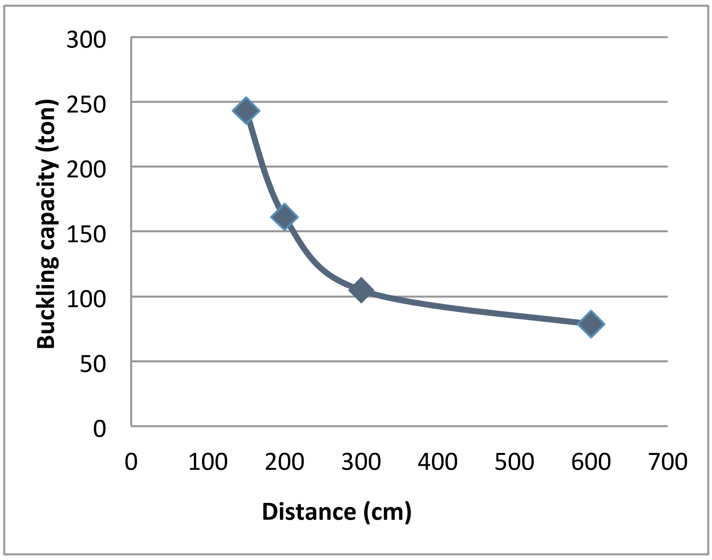


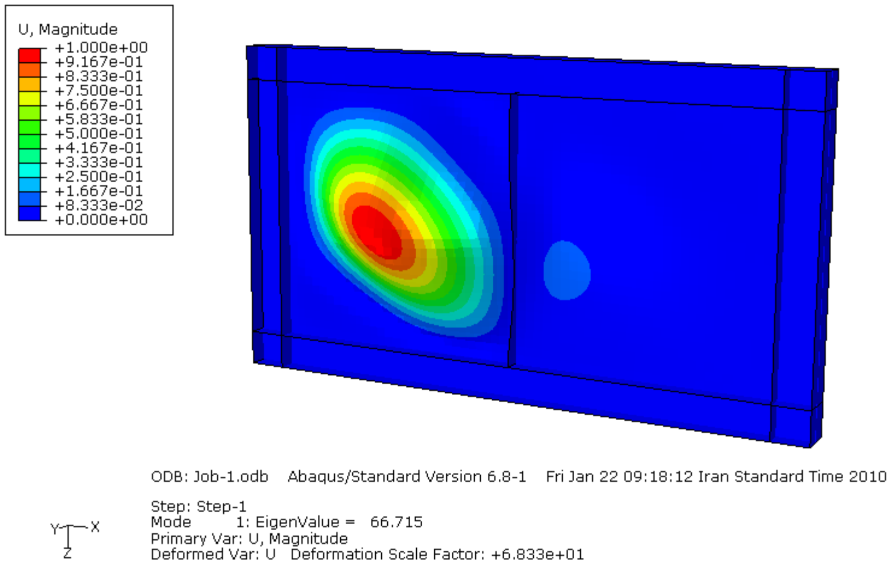
Figure 6: Comparing the buckling capacity of stiffened SPSW models based on the distance between stiffeners

Effect of the thickness of transverse stiffeners

The first buckling mode of specimens having stiffeners with various thicknesses (5, 10, 20, and 30 mm) is shown in Figure 7. In SPSW-T5, maximum displacement is observed in the loaded area and the stiffener has been deformed. In SPSW-T10, the buckling occurrence is similar to the previous model and the stiffener has also been deformed, but the increasing thickness has played a considerable role in controlling deformation in the front and increasing the overall capacity of the system. In SPSW-T20 the maximum displacement is observed near stiffener and loading area, no deformation in stiffener occurs, so better buckling capacity is received from the system. Finally, in SPSW-T30 the area far away from the loading zone is not distorted, and the stiffener remains unchanged without distortion and deformation. In this model, the system has a better response and more capacity than the previous three models.

Buckling capacity of specimen SPSW-T5 was reported as 66.715 kg/cm^2 or 104.7 ton (Fig. 7a). For SPSW-T10 it was 69.099 kg/cm^2 or 108.4 ton (Fig. 7b). Also for SPSW-T20 and SPSW-T30, buckling capacities were obtained as 70.823 kg/cm^2(111.1 ton) and 71.306 kg/cm^2 (111.8 ton), respectively (Fig. 7c and d).

Figure 8 illustrates the buckling capacities of SPSW models based on the thickness of stiffeners. By comparing the results, it can be found out that by increasing the thickness, buckling capacity of SPSWs increases; however, the slope of the curve gradually decreases. By increasing the thickness from 5 to 10 mm, the highest growth in buckling capacity is obtained which is 3.5%. With the increase from 20 to 30 mm, the capacity reached from 111.1 to 111.8 ton. The change is less than 0.6% which is negligible. Therefore, it is observed that the increase in thickness of transverse stiffeners has little effect on the buckling capacity of SPSWs.



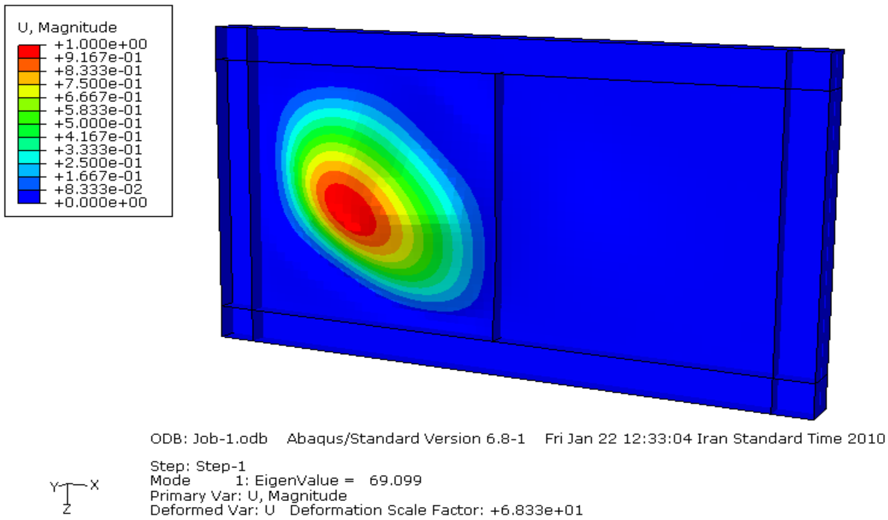
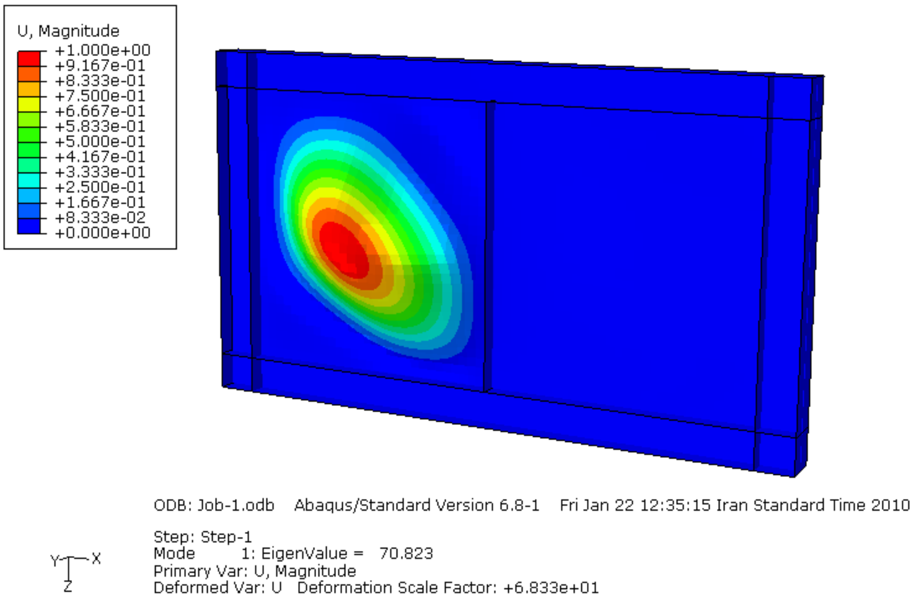


Figure 7:The first buckling mode of specimens with one transverse stiffener having different thicknesses



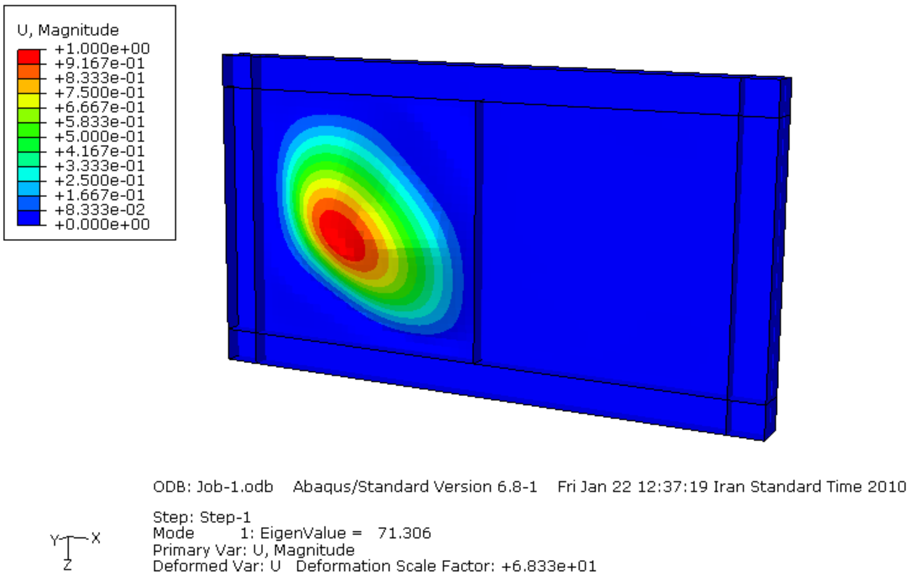


Figure 7: (Continued)

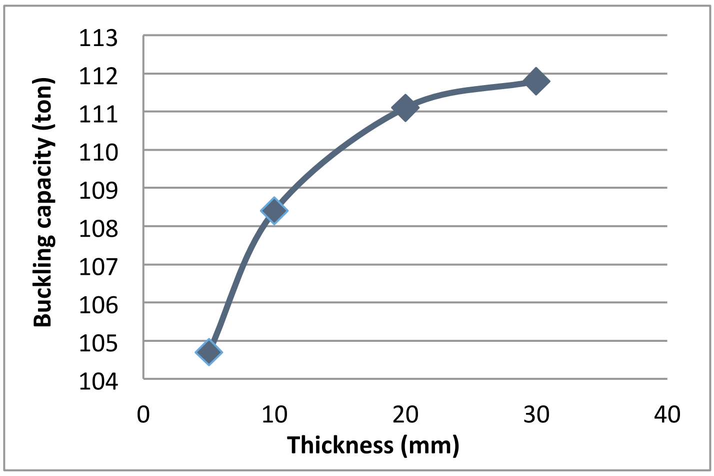


Figure 8: Comparing the buckling capacity of stiffened SPSW models based on the thickness of transverse stiffener

CONCLUSIONS

In this paper, the performance of single-storey single-bay stiffened SPSW models under lateral loads was numerically investigated. They were equipped with transverse stiffeners with different numbers (1-3) and thicknesses (5, 10, 20, and 30 mm) in order to examine their effect on the behaviour of study frame. Results showed that with the gradual reduction of the distance between stiffeners, buckling capacity increased rapidly; by reducing the distance from 600 to 300 cm, the increase was 86%, while by reducing the distance from 200 to 150 cm, the increase was reported as 164%. With the increase in the number of transverse stiffeners, the ultimate buckling capacity of the frame increased; by adding one stiffener to SPSW, the buckling capacity of the frame increased as 33%, while by using two and three stiffeners, the increase was reported as 105 and 209%, respectively. In the model with transverse stiffeners, the incremental effect of each stiffener in the growth of buckling capacity was 52%, while for the model with three transverse stiffeners it was reported as 69%. This indicates that by increasing the number of transverse stiffeners, the contribution of each of them to increasing the ultimate buckling capacity of the frame becomes greater which is economically considerable. According to the numerical results, it was also found that the increase of the thickness of transverse stiffeners had little effect on the behaviour of SPSWs by increasing their buckling capacity; by increasing the thickness from 5 to 10 mm, the highest growth in buckling capacity was 3.5%. With the increase from 20 to 30 mm, buckling capacity of SPSW reached from 111.1 to 111.8 ton. Further studies are recommended using SPSW system with pinned beam-to-column connection design. Also, examining the effects of different numbers and thicknesses of longitudinal stiffeners are recommended. Furthermore, more studies on different arrangements of stiffeners in SPSW system are suggested.

References

Alavi, E. and Nateghi, . (2013). Experimental Study on Diagonally Stiffened Steel Plate Shear Walls with Central Perforation. *Journal of Constructional Steel Research*, 89: 9-20.

Alinia, M.M. and Dastfan, M. (2007). Cyclic Behaviour, Deformability and Rigidity of Stiffened Steel Shear Panels. *Journal of Constructional Steel Research*, 63:554–563.

Barkhordari, M.A., Asghar Hosseinzadeh, S.A. and Seddighi, M. (2014). Behavior of steel plate shear walls with stiffened full-height rectangular openings. *Asian Journal of Civil Engineering*, 15(5): 741-759.

Bhowmick, A.K., Grondin, G.Y. and Driver, R.G. (2014). Nonlinear seismic analysis of perforated steel plate shear walls. *Journal of Constructional Steel Research,* 94: 103-113.

Deylami, A. and Daftari, H. (2000). Non-Linear. Behavior Of Steel Plate Shear Wall With Large Rectangular Opening. *Proceedings of the 12th World Conference on Earthquake Engineering*; Auckland, New Zeland, pp. 1-7.

Esmaeili Niari, S., Rafezy, B., and Abedi, K. (2012). Numerical Modeling and Finite Element Analysis of Steel Sheathed Cold-Formed Steel Shear Walls. *Proceedings of the 15th World Conference on Earthquake Engineering (15WCEE)*. Lisbon, Portugal.

Ghodrati Amiri, Gh. and Mirmiran, B. (2011). Optimal modeling techniques for steel plate shear walls. *Sazeh & Foolad*, 27-2(1):133-138. In Persian

Gholhaki, M. (2009). Effect of ductility coefficient on the behavior factor of thin steel plate shear walls. *Sazeh & Foolad*, 5(5):52-63. In Persian

Habashi, H.R. and Alinia, M.M. (2010). Characteristics of the wall-frame interaction in steel plate shear walls. *Journal of Constructional Steel Research*, 66:150-158.

Kulak, G.L., Kennedy, D.J.L., and Driver, R.G. (1994). Discussion of Experimental study of thin steel-plate shear walls under cyclic load by Caccese. V.. Elgaaly, M., and Chen, R. *ASCE Journal of Structurai Engineering*, 120(10):3072-3073.

Mohammdi, R. and Habibi, M.R. (2016). "Investigating the effect of different arrangement patterns of stiffeners on the resistance of steel plate shear walls. *Proceedings of the International Conference on Civil, Architecture and Urban Planning Elites*, Tehran, Iran. In Persian

Rahmzadeh, A., Ghassemieh, M., Park, Y. and Abolmaali, A. (2016). Effect of stiffeners on steel plate shear wall systems. *Steel and Composite Structures*, 20 (3): 545-569.

Rezai, M., Ventura, C.E., and Prion, H. (2004). Simplified and detailed finite element models of steel plate shear walls. *Proceedings of the 13th World Conference on Earthquake Engineering*. Vancouver, Canada.

Saburi-Ghomi,S. ,Venture. ,kharrazi, M. (2005). Shear analysis and design of ductile steel shear walls. *Journal of structural Engineering*, 131(6):878-889.

Sabouri-Ghomi, S. and Asad Sajjadi, R. (2012). Experimental and theoretical studies of steel shear walls with and without stiffeners. *Journal of Constructional Steel Research*, 75:152-159.

Shafaei, S., Farahbod, F. and Ayazi, A. (2017). Concrete stiffened steel plate shear walls with an unstiffened opening. *Structures*, 12: 40–53.

Tsai, K.C. and Li, C.H. (2010). Cyclic Tests of Four Two-storey Narrow Steel Plate Shear Walls-Part 1 Analytical Studies and Specimen Design. *Earthquake Engineering & Structural Dynamics*, 39 (7):775-799.

Yu, J.G. and Hao, J.P. (2016). Behaviour of semi-rigid steel frames with steel plate shear walls. *Advanced Steel Construction*, 12(2):154-173.

Zhao, Q. and Qiu, J. (2018). Experimental studies on channel-stiffened steel plate shear walls. *Structures Congress (April 19–21)*, Fort Worth, Texas, US.