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Effects of Aspect Ratio and Plate Thickness on the Behavior of Unstiffened Steel-Plate Shear Walls with Pinned and Rigid Connections

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Abstract

Unstiffened steel plate shear walls (SPSWs) have been in use mostly in recent years. In this numerical study, the buckling behavior of a single-storey single-bay unstiffened SPSW with two pinned and rigid beam-column connections under lateral loading is investigated. The SPSW had different wall aspect ratios (L/h=1, 1.5, 2, 2.5, and 3) and infill plate thicknesses (t_w= 3, 5, and 7 mm). Their effect on the buckling behavior of SPSW was examined using buckling analysis in ABAQUS software. Results indicated that with the increase of infill plate thickness, the lateral resistance of unstiffened SPSW system increases, but by increasing wall aspect ratio, its resistance decreases. In both connection designs, the model with L/h=1 (square-shaped model) showed better ductility and higher stiffness and strength in all three thicknesses. Maximum shear stress responses of SPSW models showed that in pinned design with L/h=1, the most change in shear stress values was 8% when infill plate thickness reached from 5 to 7 mm; while for rigid connection, it was reported as 7% when it increased from 3 to 5 mm. This indicates that in rigid connection, increasing the infill plate thickness has less effect on the increase of lateral resistance. By examining the performance of rigid and pinned beam-to-column connections with different wall aspect ratio and infill plate thickness, it was found out that maximum shear stress in rigid connection increased by 11% compared to pin connection. It was concluded that an optimum unstiffened SPSW model had a wall aspect ratio of 1 and infill plate thickness of 7 mm.

Keywords: Steel Plate Shear Wall; Unstiffened; Pinned Connection; Rigid Connection; Aspect Ratio; Plate Thickness.

1. Introduction

In the past two decades the steel plate shear wall (SPSW) has been used in a number of buildings in Japan and North America as part of innovative lateral force resisting system. It consists of steel infill plates bounded by horizontal (beams) and vertical boundary elements (columns). This system has many advantages including high initial stiffness, excellent ductility, robust resistance to cyclic degradation and significant energy dissipation [1]. Similar to plate girders, the SPW system optimizes component performance by taking advantage of the post-buckling behavior of the steel infill panels. The infill plates are meant to serve as the fuse elements. When damaged during an extreme loading event, they can be replaced at a reasonable cost and restore the full integrity of the building. The thickness of the infill plate in a SPSW is often governed by factors other than strength; this often results in much stronger shear walls than required for lateral load resistance. This creates a problem in capacity design, as it introduces excessive design forces to the boundary members, and thus increasing their required size [2]. To address this problem, the use of light-gauge, cold-formed, steel

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infill plates or low yield strength steel [3, 4], vertical slits [5, 6], or a regular pattern of circular perforations in the infill plate [4] have been proposed. A properly designed SPSW can have high initial stiffness, strength, and energy absorption capacity as well as superior ductility. SPSWs have been commonly designed with unstiffened and stiffened infill plates based on economical and performance considerations.

There are some experimental studies on single or multi-storey unstiffened SPSWs to assess their behavior. For example, Caccese et al. [7] in an experimental study on seismic behavior of unstiffened thin SPSW under cyclic loading, indicated that the specimens with thinner plates exhibit an inelastic behavior that was controlled primarily by yielding of the thin plate. The specimens with thicker plates showed an inelastic behavior that was primarily governed by the columns, and the capacity of the specimen with the thickest plate is limited by the instability of the column. Behbahanifard et al [8] tested a 3-storey unstiffened SPSW under both lateral and cyclic loading. They concluded that column flexibility parameters can significantly affect the behavior of SPSWs. Some studies such as Tsai and Li [9] and Alavi and Nateghi [10], further investigated SPSWs with various types of stiffeners including longitudinal stiffener, transverse stiffener, cross stiffener, diagonal stiffener, vertical and horizontal ribbed stiffener, etc. Sabouri-Ghomi and Mamazizi [11] tested two one-story SPSWs with and without stiffeners and one of their surrounding frames, and then studied their behavior. Installation of stiffeners improved the behavior of the steel plate shear walls. It caused 26% increase in energy dissipation capacity and 51.1% increase in the shear stiffness of steel plate while its effect on the steel plate shear strength was minor. In another study, Nie et al. [12] showed that the strength and stiffness characteristics of the walls were reduced in walls with openings. Sabouri-Ghomi and Mamazizi [13] experimentally studied the effects of two openings on the structural behavior of SPSWs. Their tests were performed on three one-third scaled single-story SPSW specimens with two rectangular openings under quasi-static cyclic loading. Their results showed that the ultimate shear strength, stiffness and energy absorption were the same in all three perforated specimens and the interval between the two openings had no effect on these values. Rajeev et al. [14] compared the behavior of geometrically different unstiffened and stiffened SPSWs with and without openings under quasi static cyclic and monotonic loading conditions. According to them, the use of stiffeners on both sides of the infill panels can significantly improve the strength and stiffness performance of stiffened SPSW system compared to Unstiffened SPSW.

There are also some numerical studies on stiffened or unstiffened SPSW systems. For example, Deylami and Daftari [15] 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. Also, for a determined opening percentage, the thinner plates attain their maximum shear capacity with smaller opening aspect ratio. Rezai et al. [16] showed the accuracy of the finite element models on predicting the behavior of SPSWs in terms of elastic stiffness, yield and ultimate strength as well as post-buckling behavior. Alinia and Dastfan [17] numerically studied cyclic behaviour, deformability and rigidity of stiffened SPSWs. According to them, unstiffened SPSWs provide a more ductile response while heavily stiffened SPSWs have a wider yield area, which in turn results in higher energy dissipation. Habashi and Alinia [18] studied the nonlinear response of SPSW systems under lateral loading with respect to the interaction between the infill plates and frame members. They showed that the infill plates are very effective in the initial stages of loading (up to the drift angle of 1%) and absorb substantial part of storey shear. But, once diagonal yield zones are developed in the infill plates, they begin to lose their effectiveness.

Nie et al. [12] used finite element model of a single-story wall panel with boundary columns to investigate the lateral force resistance behavior of stiffened SPSWs and found good agreement between the experimental and numerical results. Bhowmick et al. [2] numerically examined behaviour of unstiffened SPSWs with circular perforations in the infill plates. For this purpose, eight perforation patterns in a single storey SPSW of two different aspect ratios were analyzed using a geometric and material non-linear finite element model to assess the proposed shear strength model. Their comparison results demonstrated the accuracy of the proposed simple model to predict the design forces in the columns. Rahmzadeh et al. [1] used finite element analysis to study the effect of the rigidity and arrangement of stiffeners on the buckling behavior 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 behavior, such as stiffness, overall strength and energy absorption, but also leads to a reduction of the forces that are exerted on the boundary elements. Zirakian and Zhang [19] numerically evaluated the structural behavior and performance of SPSWs with unstiffened low yield point steel infill plates. Their numerical results revealed the efficient strength, stiffness, and cyclic performances of such systems.

Kalali et al. [20] presented a numerical investigation of the hysteretic performance of SPSWs with trapezoidally corrugated infill plates. Finite element cyclic analyses were conducted on a series of flat- and corrugated-web SPSWs to examine the effects of web-plate thickness, corrugation angle, and number of corrugation half-waves on the hysteretic performance of these systems. Their study showed that optimal selection of the web-plate thickness, corrugation angle, and number of corrugation half-waves along with proper design of the boundary frame members can result in high stiffness, strength, and cyclic performances of such corrugated-web SPSWs. Rajeev et al. [14] studied different configuration of stiffeners in SPSWs with and without openings in ANSYS software. Numerous finite element models were considered based on infill plate thickness, opening percentage and stiffener configuration. Excellent agreement was observed between numerical and experimental results. For the numerical model the peak load observed during the test was underestimated only by 4%. Formisano and Lombardi [21] conducted a parametric finite element analysis on different series of perforated SPSWs by changing the number and diameter of the holes, the plate thickness and the metal material. The influence of gravity loads on the overall performance of SPSW under the monotonic and cyclic loadings was investigated numerically by Lv and Li [22]. For this purpose, they analyzed specimens with the axial stresses of the boundary columns equal to 100, 200 and 300 MPa. They found very good predictions of the ultimate strengths, hysteresis properties and failure modes. In another numerical investigation by Verma and Ranjan Sahoo [23] on the seismic behaviour of SPSWs with staggered web configurations in OpenSees application, nonlinear static and dynamic analyses were performed to compare the drift response, hinge mechanisms, and steel tonnage."Staggered SPSWs showed uniform drift distribution and reduction in interstorey drift and axial force demand on the vertical boundary elements".

In the traditional analysis and design of steel frames, beam-column connections are often assumed to be rigid, semi-rigid or pinned. Most of experimental studies mentioned above have been focused on performance of SPSW test specimens with the moment resisting (rigid) connections between the boundary elements. There are also some studies examined seismic behaviors of steel frames with semi-rigid beam-column connections [24-27]. In SPSW systems, boundary elements with rigid beam-column connections require the use of larger structural sections to be capable of resisting the induced flexural demand. Smaller structural sections can be used if pinned beam-to-column connections are employed because of the reduced material requirements in the boundary elements [28]. There are only a few researches on SPSWs with pinned beam-to-column connections [28-30]. Considering this limitation and the importance of the influence of beam-column connection and wall characteristics on the behavior of SPSWs, in this paper we aimed to investigate the performance of unstiffened SPSW with rigid and pinned beam-column connections under lateral loading (compressive forces). An analytical study is carried out using finite element analysis in ABAQUS software to evaluate the strength of unstiffened SPSWs with different aspect ratios and infill plate thicknesses.

2. Methodology

In this study we analyzed a single-storey single-bay SPSW model developed by Habashi and Alinia [18] with the span length-to-story height ratio (L/h) = 1, h = 3000 mm, and infill plate thickness (t_w) = 3 mm, designed according to the AISC Design Guide 20 [31] and the AISC 341-05 [32] rules and provisions. Designed section for beam is W14×176 and for column is W14×257. Two primary design types were studied: rigid beam-to-column and pinned beam-to-column connections. They had different L/h ratio (1, 1.5, 2, 2.5, and 3) and infill plate thicknesses (t_w= 3, 5 and 7 mm). Figure 1 shows the 3D model of SPSW models. Horizontal and vertical boundary elements as well as infill plate were meshed and modeled in ABAQUS finite element software using 8-node reduced integrated shell element (S8R). The reduced integrated formulation was used in order to provide more accurate results and to reduce computation time. 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 ST37 steel was employed having Young's modulus (E) = 200 MPa and Poisson's ratio = 0.3. The yield stress of steel in frame members was 385 MPa and for infill wall it was 327 MPa. For material modeling, elastic stress-strain curves of materials were used (Figure 2).

Compressive forces (lateral loads) were applied to the upper end of the beam (from left to right) which gradually increased from zero to the ultimate capacity of the system to investigate its buckling behavior. 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 (Figure 1).

Linear buckling analysis was used to estimate buckling strength of the models where deformation scale factor was +1.000e+00. Buckling is possible when compressive stresses or shear stresses are applied to a structure. In this regard, the shear stress contours were illustrated for each model. The average shear stress (τ) is calculated using following equation, where F= the applied force, and A= the cross-sectional area of the material with area perpendicular to the applied force.

$$\tau = \frac{F}{A} \tag{1}$$

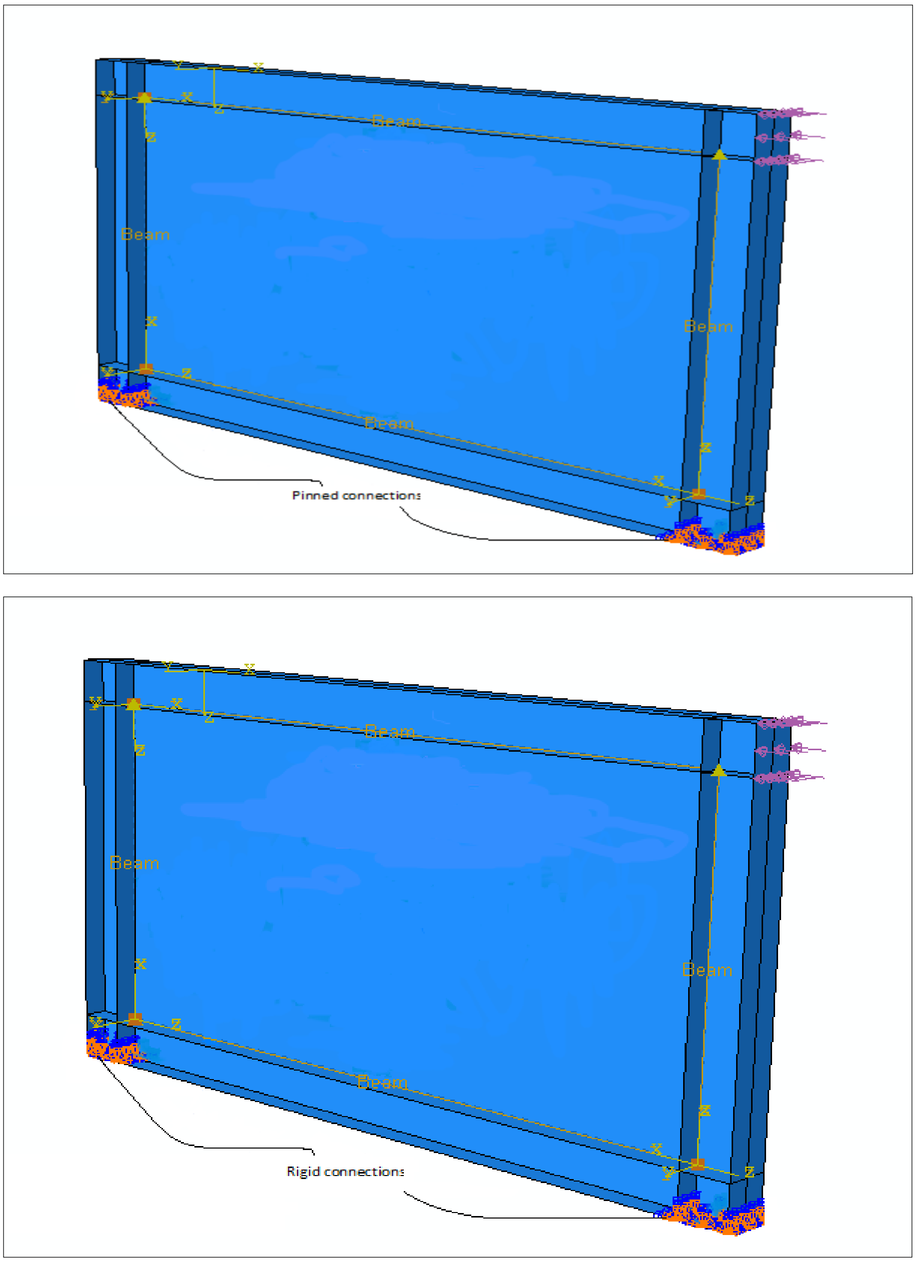
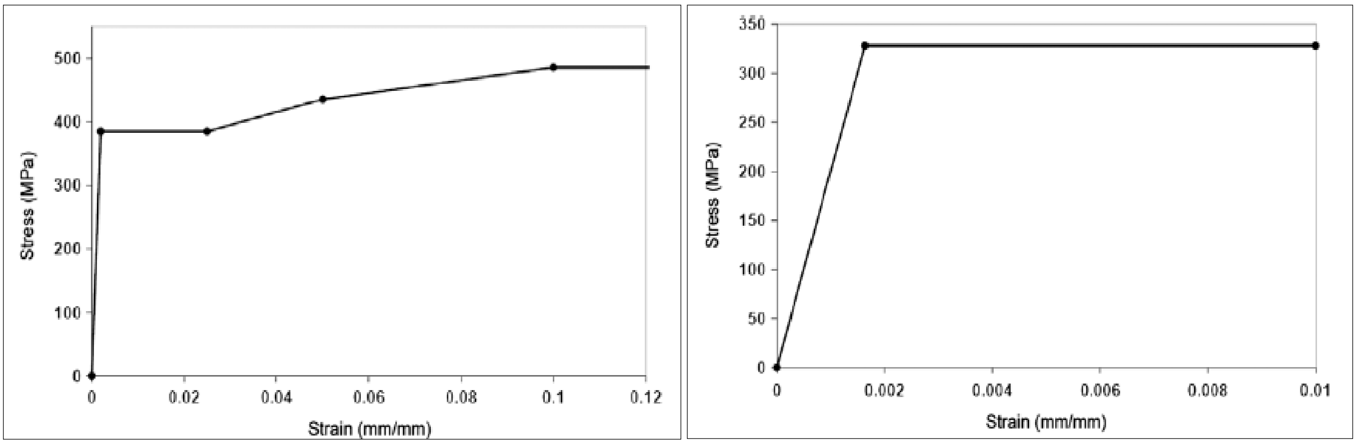


Figure 1. Abaqus model of SPSW system with rigid and pinned beam-to-column connections considering boundary conditions



(a) Frame members **(b) Infill walls**

Figure 2. Material stress-strain curves adapted from [18]

2.1. Test Verification

For validating the accuracy and applicability of non-linear finite element model of beam-column connections in SPSW system, the numerical models were calibrated with the model developed by Habashi and Alinia [18]. They investigated nonlinear response of SPSW systems under lateral loading. 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. By conducting finite element and pushover analyses, SPSW system was studied by varying the beam length from 3 m to 9 m (L/h= 1, 1.4, 1.8, 2.2, 2.6 and 3) and infill thicknesses (t_w=3, 5 and 7 mm). For more details see Reference [18].

Load-displacement curves of numerical results and those of verified results presented by Habashi and Alinia are shown in Figure 4 which indicates a good agreement between them (Error rate= 14%). The major difference between the results was observed in 7-cm displacement where base shear was reported as 3038 kN, while in the results of Habashi and Alinia, it was reported as about 2600 kN.

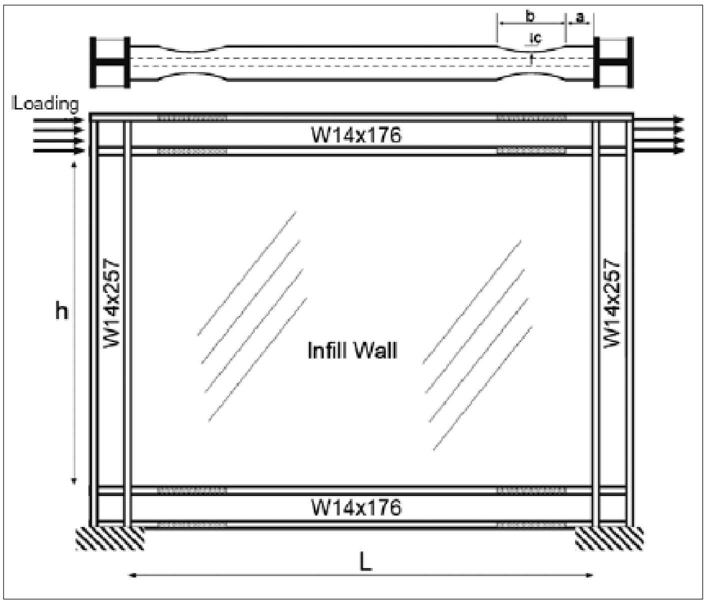
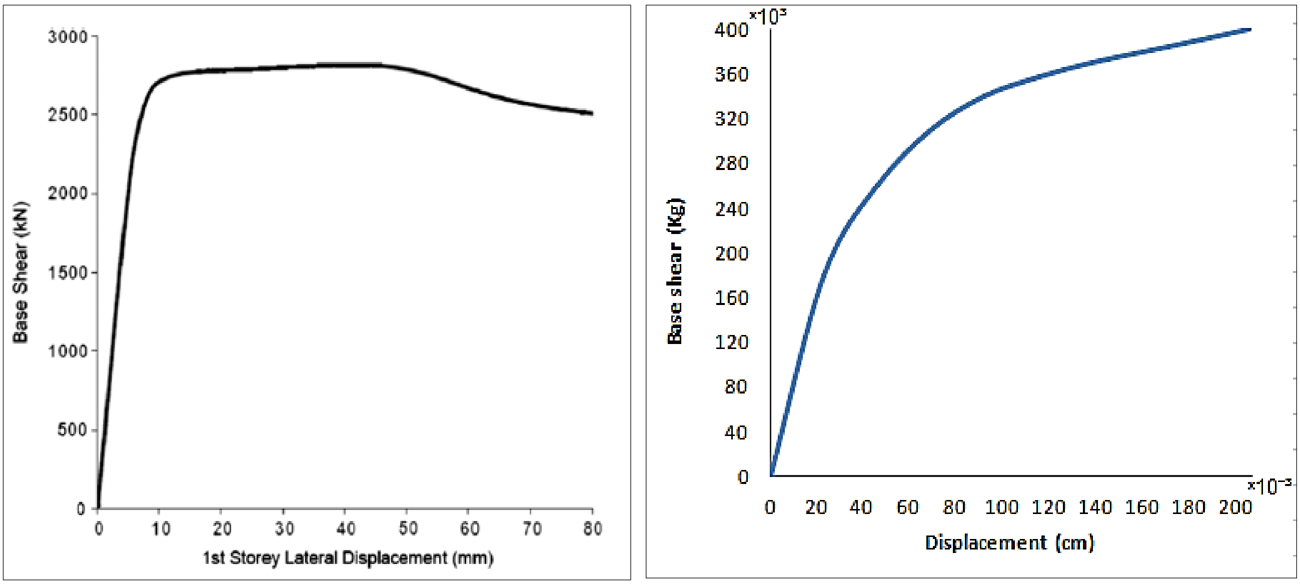


Figure 3. SPSW system modeled in [18]



(a) (b)

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

3. Numerical Results

In this section, shear stress responses of SPSW systems with two rigid and pinned connections with respect to their different wall aspect ratio and infill plate thicknesses are presented to find out their optimum aspect ratio and infill plate thickness.

3.1. SPSW with Pinned Beam-to-Column Connection

Figure 5 illustrates the shear stress contours of SPSW models with pinned beam-to-column connection. In SPSW with L/h=1 (square-shaped model) in all three thicknesses, the stress has distributed on the entire infill plate and the deformation inside the plate is almost uniform (red areas), while the blue areas have remained in the linear elastic range. The increase of shear stress from 3 to 5 mm was 7% and from 5 to 7 mm it was 8%. Therefore, it is observed that, despite the increase in thickness, its effect on aspect ratio of 1 is not considerable. This is because of the uniform distribution of stress in the infill plate.

In SPSW model with L/h=1.5, the distributed stress is almost elastic, and the local buckling occurrence was observed in less shear stress value compared to the model with L/h=1, and the thickness effect is greater such that in an increase from 3 to 5 mm, the values of maximum shear stress almost has tripled, while with the increase of t_w from 5 to 7 mm, the increase in maximum shear stress is 93%.

In the model with L/h=2, the distributed stress inside the infill plate was linear, and the local buckling which stopped analysis and presenting report by the software, was occurred in less shear stress than that of model with aspect ratio of 1. By increasing t_w to 5 mm, maximum shear stress was increased by 62%, while this increase was only 37% when t_w increased from 5 to 7 mm.

In the model with L/h=2.5, it was observed that local buckling was occurred in the corner of the pinned frame at lower shear stress than the SPSW model with square shape. Similar to the model with aspect ratio of 2, the highest increase in maximum shear stress was observed when t_w increased to 5 mm (69%). For the increase from 5 to 7 mm, the increase rate was 40%.

Finally in SPSW with L/h=3 where maximum shear stress is less than that of square-shaped model, results showed that before the buckling occurrence in infill plate, the perimeter frame was buckled at the connection area and also at the location where the force was applied. Similar to the models with aspect ratios of 2 and 2.5, the highest increase in maximum shear stress in this model was observed when t_w was increased to 5 mm (62%). When t_w increased from 5 to 7 mm, this increase was 37%.

Overall, it was found out that the model with aspect ratio of 1 had better ductility and higher stiffness and strength in all three 3, 5, and 7 mm infill plate thickness. Also, the increase of plate thickness had the highest effect on increasing maximum shear stress in the model with L/h=1.5.

The maximum shear stress results of SPSW models with pinned beam-to-column connection are presented in Table 1. Figure 6 plots the comparison of these results. By the increase of wall aspect ratio, It was observed that the performance of the system with lower thicknesses was better in model with L/h=1. With the increase of aspect ratio, the effect of the infill thickness on the performance of SPSW system was increased. Maximum shear stress values are the values at which buckling occurs; hence, by increasing the thickness of the infill plate, the buckling can occur in higher shear stresses. This indicates that optimum infill plate thickness in pinned beam-to-column connection is 7 mm.

Table1. Maximum shear stress in SPSW system with pinned beam-to-column connection

	Wall aspect ratio	Plate thickness (mm)		
		3	**5**	**7**
SPSW with pinned design	1	5924	6391	6931
	1.5	629.6	2072	4003
	2	902.4	1471	2025
	2.5	1198	2027	2857
	3	850.2	1379	1894

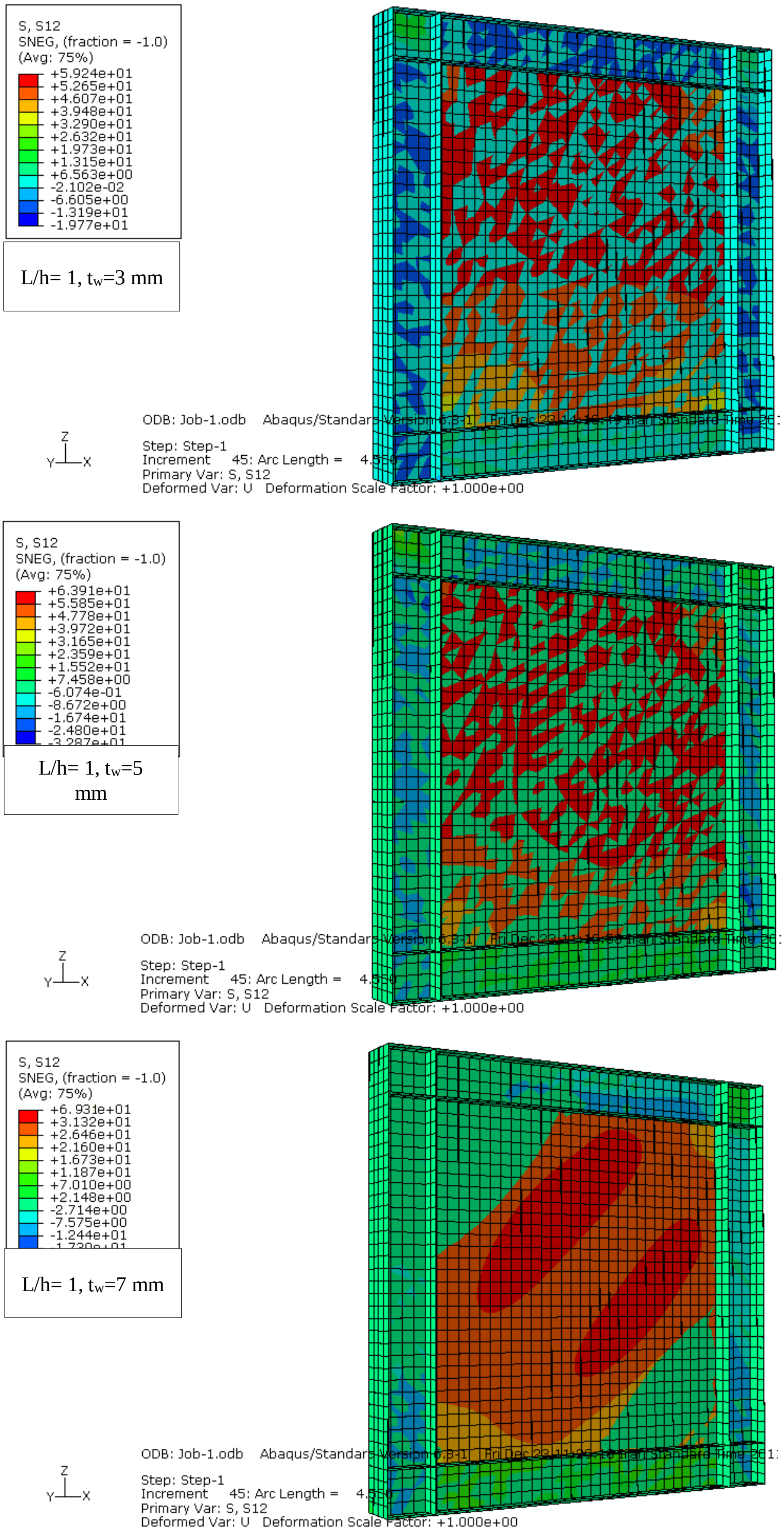
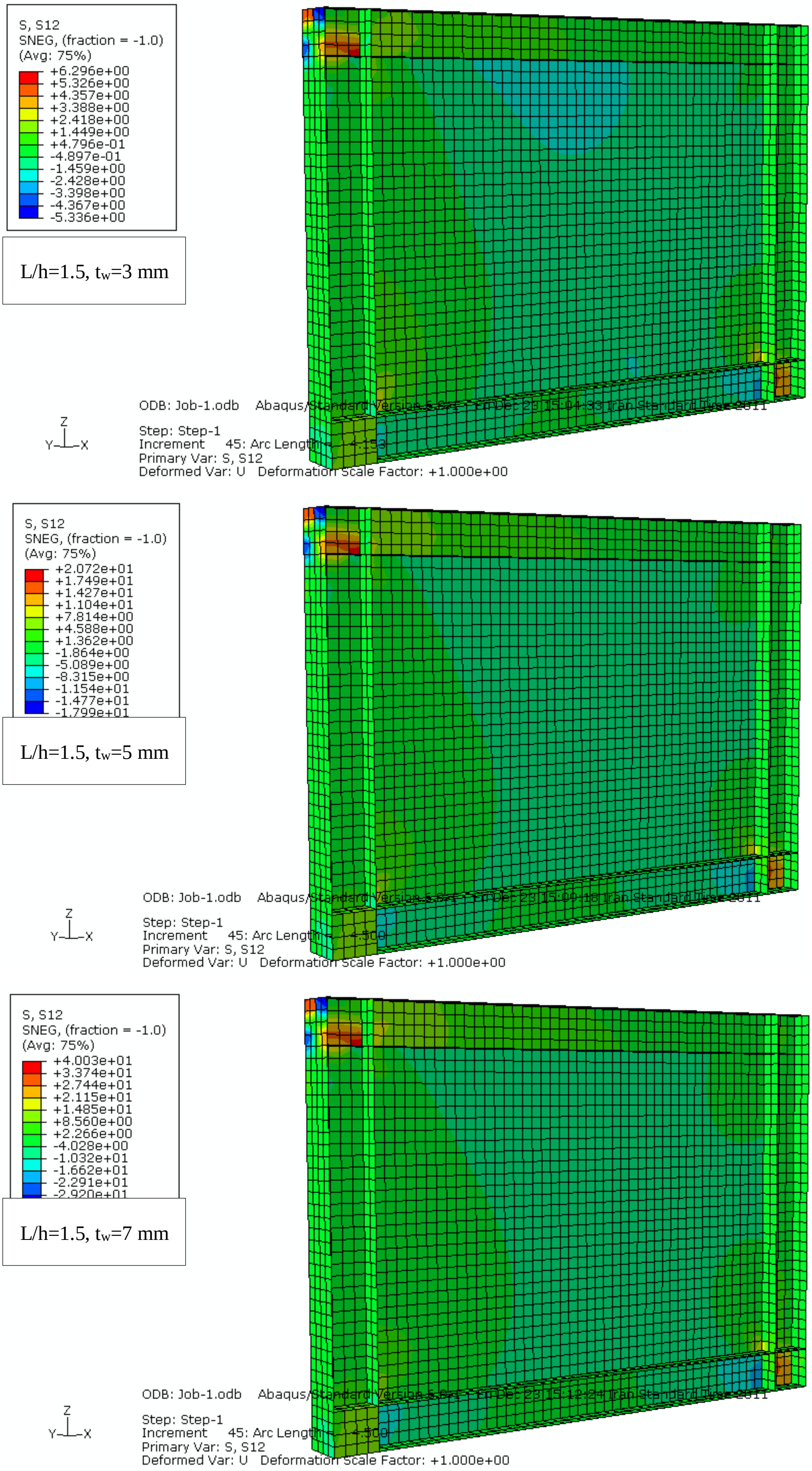


Figure 5. Shear stresses in SPSW with pinned design having various aspect ratios and thicknesses



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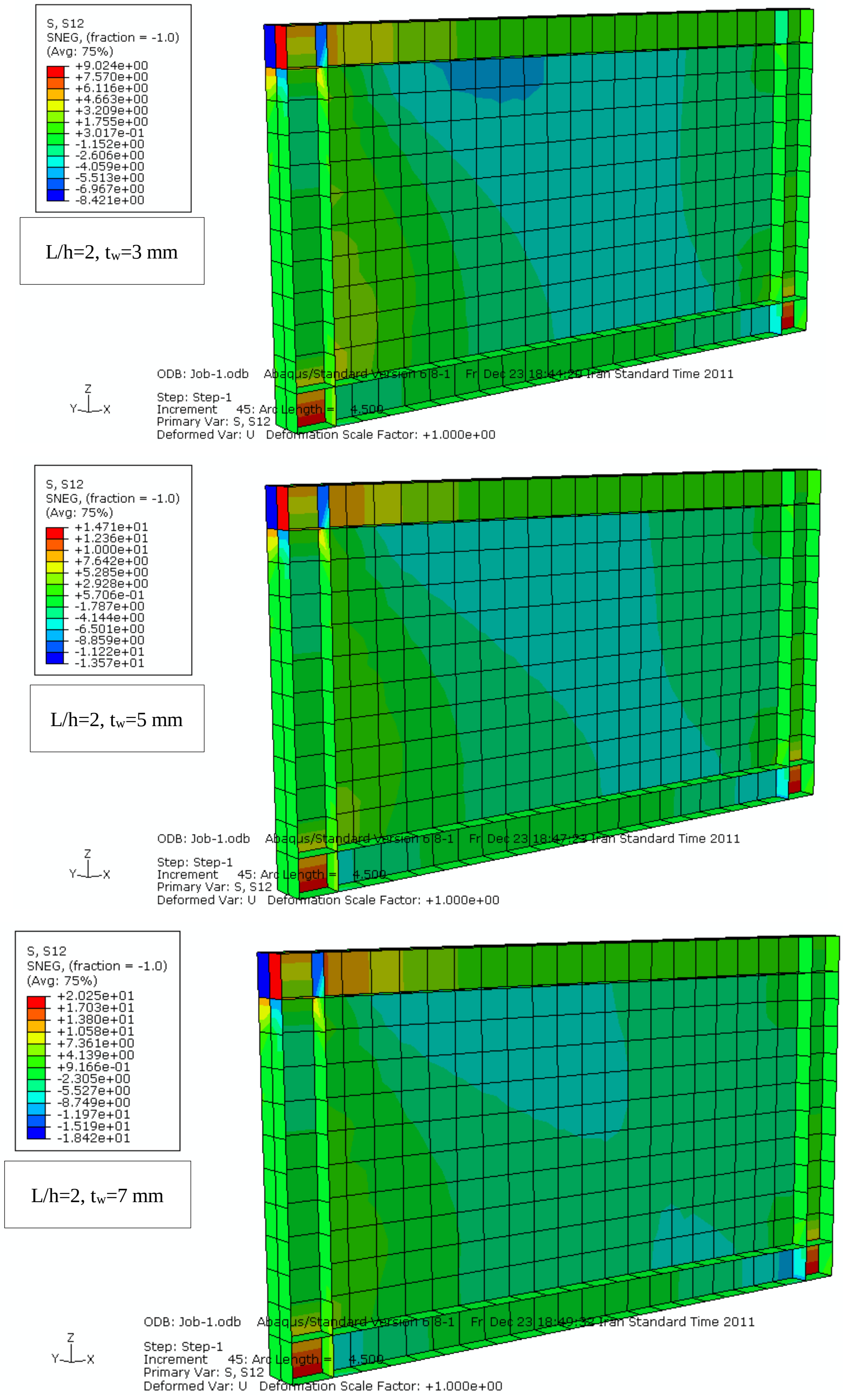

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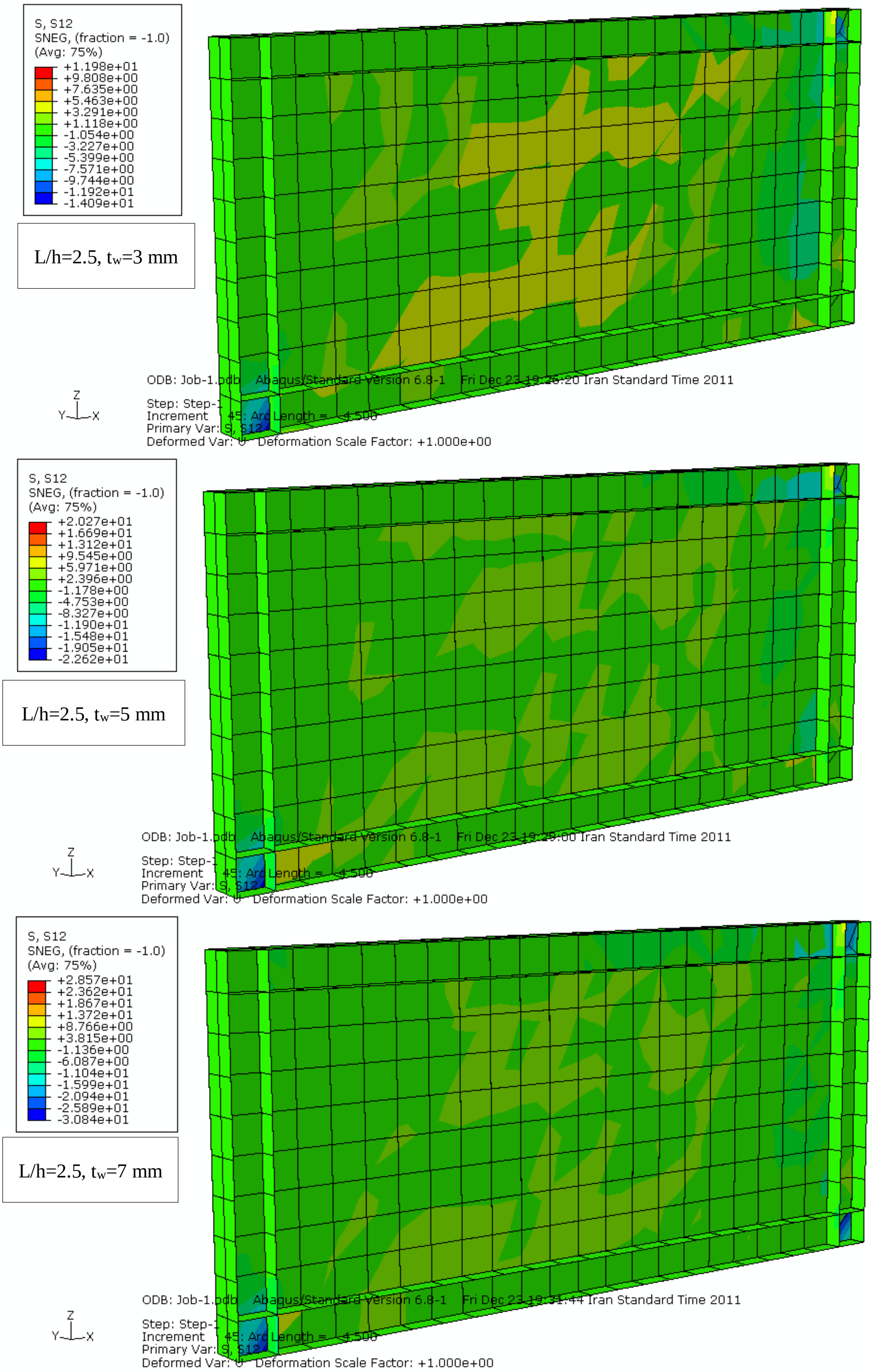

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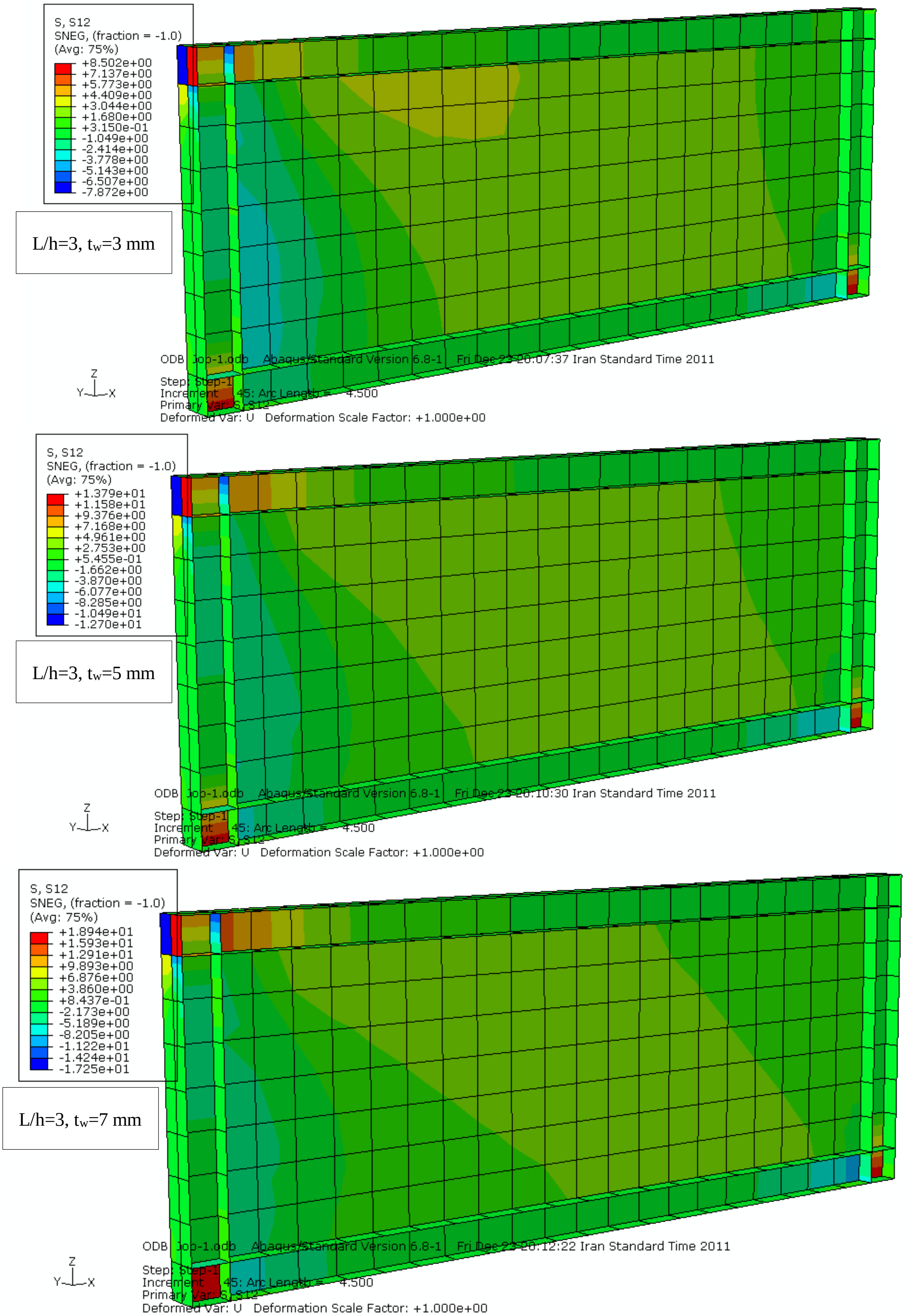

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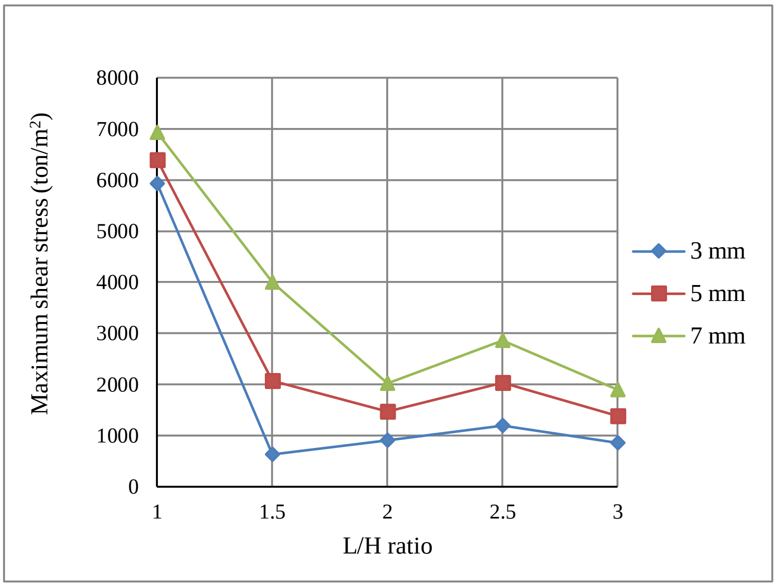


Figure 6. Comparison of maximum shear stress results in SPSW with pinned design

3.2. SPSW with Rigid Beam-to-Column Connection

Shear stress distributions of SPSW model with rigid beam-to-column connection are illustrated in Figure 7. The interpretation of shear stress contours in this design is similar to those of SPSW with pinned design. In SPSW model with L/h=1, maximum shear stress was increased by 7% when t_w increased to 5 mm, and by 4% when t_w reached 7 mm. This shows that the effect of increase in thickness is not high in this aspect ratio due to the uniform distribution of stress in the infill plate.

In the model with L/h=1.5, the effect of increase in thickness was higher compared to the model with L/h=1. When t_w was increased to 5 mm, maximum shear stress increased by three times, and when it reached to 7 mm, the increase in value of maximum shear stress was almost 100%. For the SPSW model with L/h=2, when t_w increased from 3 to 5 mm, maximum shear stress increased by 63%. When t_w reached 7 mm, the increase in maximum shear stress was reported as 37%. This indicates that this model can behave better with 5-mm infill plate thickness. In the model with L/h=2.5, by increasing t_w to 5 mm, maximum shear stress was increased by 69%, while this increase was only 40% when t_w increased from 5 to 7 mm. This indicates the similar behavior between the models with aspect ratio of 2 and 2.5; they had better behavior with 5-mm infill plate thickness. Finally, shear stress results of the model with L/h=3 showed that this, similar to the models with aspect ratios of 2 and 2.5, the highest increase in maximum shear stress was observed when t_w increased to 5 mm (62%). For the increase from 5 to 7 mm, the increase rate was 37%.

In overall, the model with aspect ratio of 1 had better ductility and with higher stiffness and strength in all infill plate thickness. Based on the results, the use of thicker inflate plates in SPSW with rigid connection can increase the lateral resistance of the system. Also, in the model with L/h=1.5, the increase of plate thickness had the highest effect on increasing maximum shear stress, and consequently on its behavior. Table 2 presents the maximum shear stress results for the SPSW model with rigid design and Figure 8 illustrates the comparison of these results. The effect of infill thickness is evident in all aspect ratios, and higher infill thickness has lead to increased resistance. By increasing the thickness of infill plate, the maximum shear stress significantly increased and buckling occurred in higher shear stress similar to the model with pinned connection. So, we can say that optimum infill plate thickness in this connection was 7 mm .With the increase of wall aspect ratio, maximum shear stress results of the models with all infill plate thicknesses were decreased; in this regard, it can be said that the SPSW system with rigid beam-to-column connection had best behavior with aspect ratio of 1 (square shape).

Table 2. Maximum shear stress in SPSW system with rigid beam-to-column connection

	Wall aspect ratio	Plate thickness (mm)		
		3	5	7
SPSW with rigid design	1	6582	7102	7424
	1.5	631.5	2099	4221
	2	1003	1635	2250
	2.5	1332	2252	3174
	3	944	1532	2104

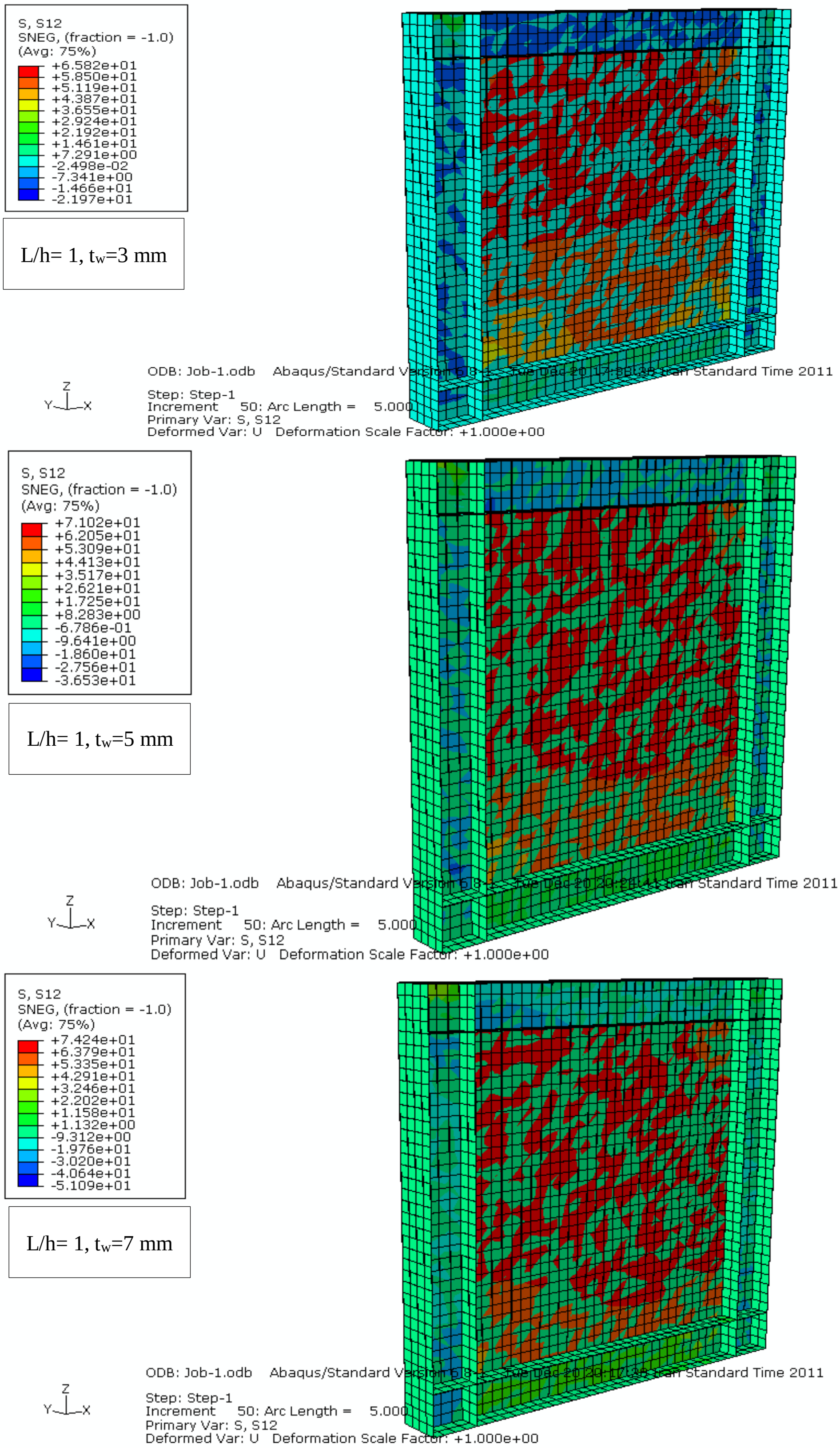
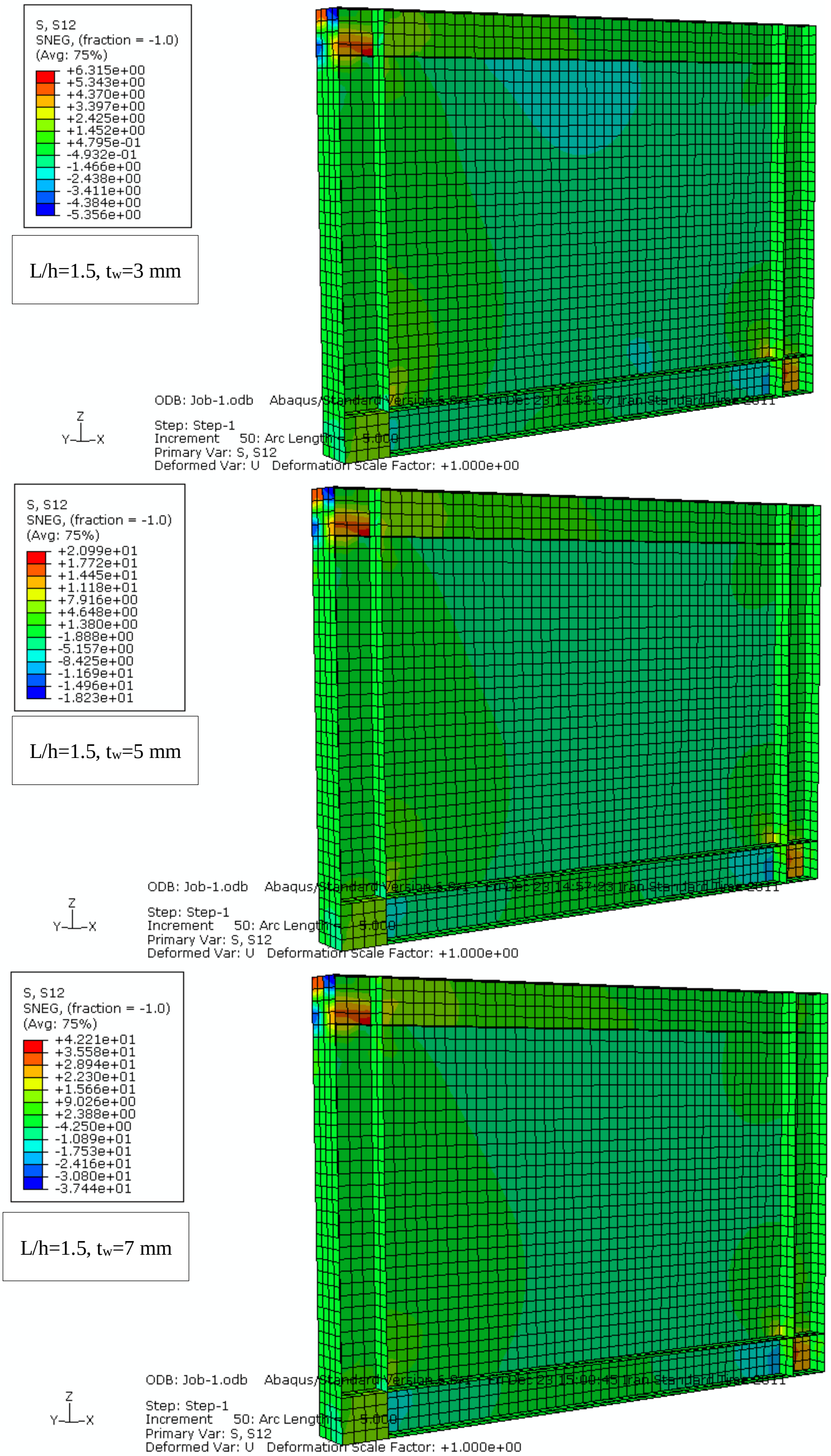


Figure 7. Shear stresses in SPSW with rigid design having various aspect ratios and thicknesses



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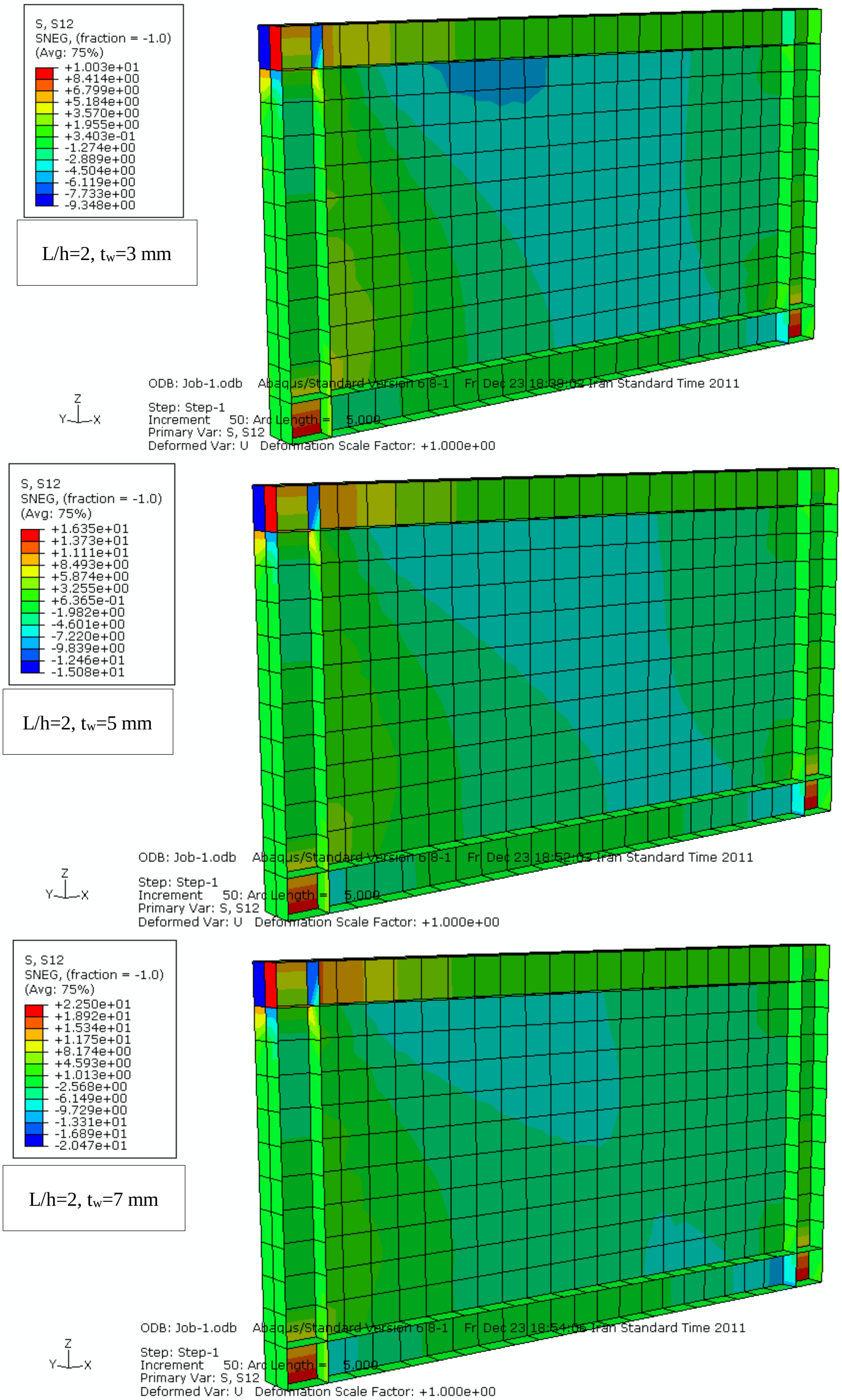

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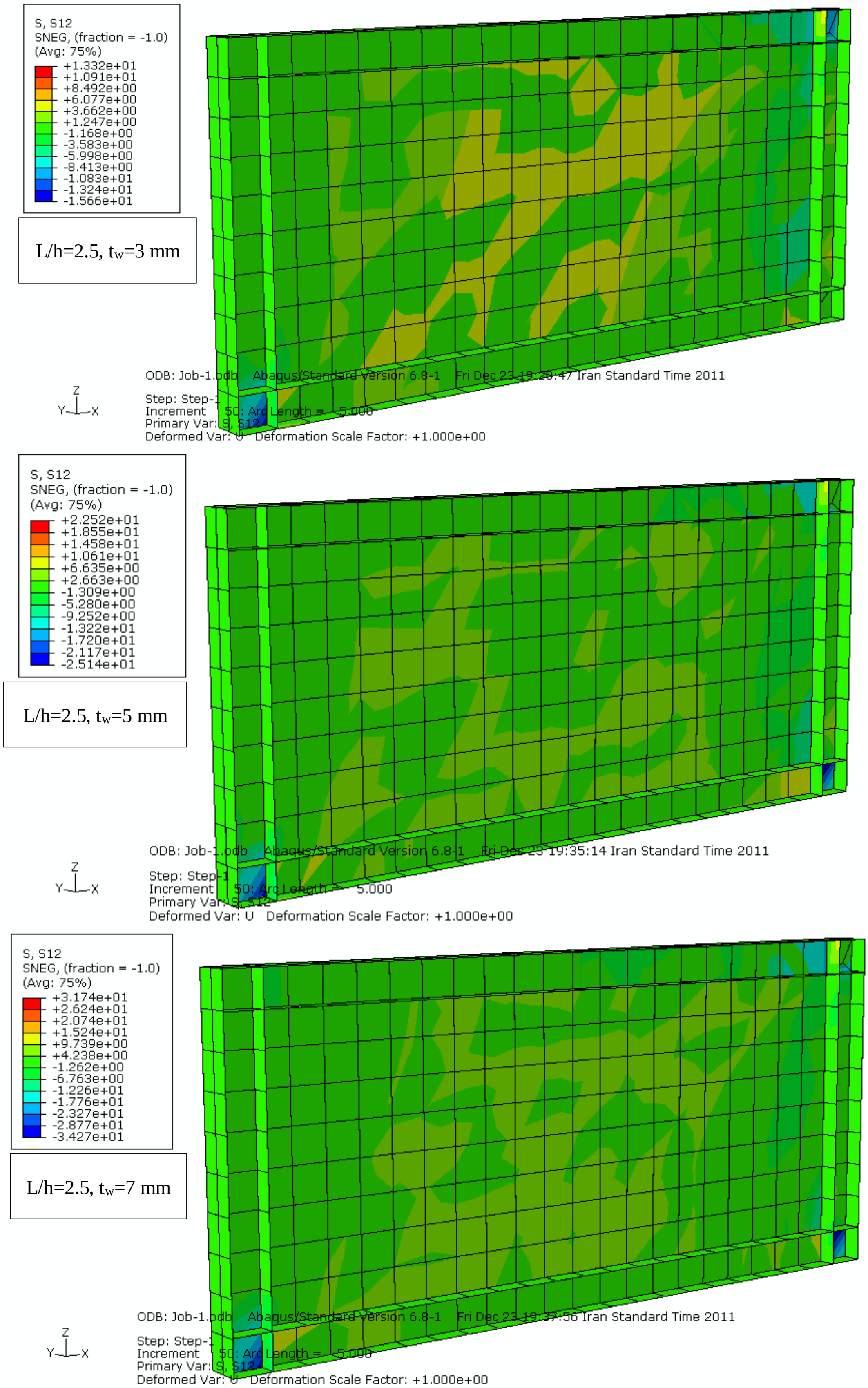

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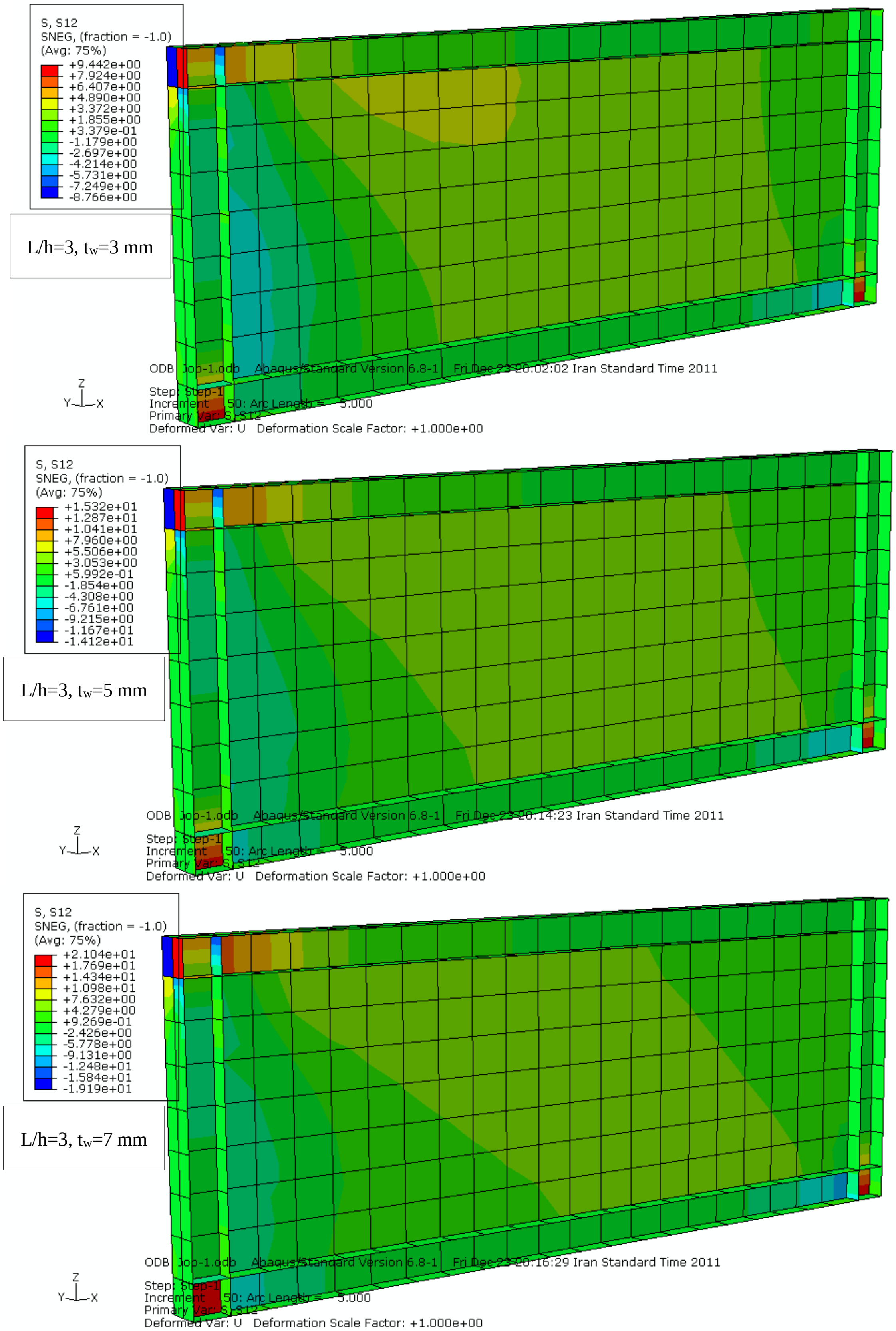

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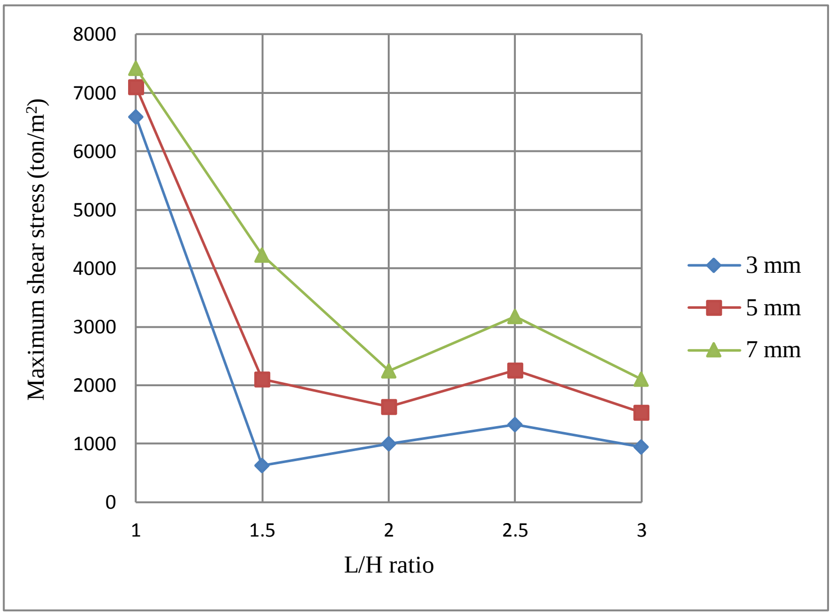

Figure 8. Comparison of maximum shear stress results in SPSW with rigid design

4. Conclusion

In this paper, it was attempted to numerically investigate the effect of wall aspect ratio and infill plate thickness on the buckling behavior of a single-storey single-bay unstiffened SPSW with two pinned and rigid beam-column connections under lateral loads. By applying linear buckling analysis in ABAQUS software, results revealed the effect of infill plate thickness in models with various aspect ratios in both designs where the high thickness led to increased buckling strength of SPSW model. The model with L/h=1 (square-shaped SPSW model) showed better ductility and higher stiffness and strength in all three thickness. In pinned design, the most change in shear stress in model with L/h=1 (square-shaped model) was 7% when the plate thickness increased from 3 to 5 mm. and when it reached to 7 mm, the increase in buckling strength was 8%. For the rigid design, it was reported as 7% by increasing thickness to 5 mm and almost 4% with an increase from 5 to 7 mm. This indicates that in rigid beam-column connection, increasing the infill plate thickness has less effect on the increase of lateral resistance. By comparing the type of beam-column connections in SPSW with the same infill thickness (3 mm) and aspect ratio (L/h=1), it was found out that the increase in lateral resistance is equivalent to 11% which is technically acceptable. In SPSW model with rigid connection having 7mm-infill thickness and aspect ratio of 1, lateral resistance increased by 75% compared to L/h=1.5 and compared to L/h=3, the increase was 252%. In SPSW with pinned connection, these increases were 75 and 265%, respectively. Overall, it was concluded that with the increase of infill plate thickness, the lateral resistance of unstiffened SPSW system increases, but by increasing wall aspect ratio, its resistance decreases. The optimum wall aspect ratio and infill plate thickness was 1 and 7 mm, respectively. We recommend further research on studying the behavior of stiffened SPSWs with both connection designs and wall aspect ratios by adding openings to the infill wall or adding reinforcing sheets inside the wall with a variety of thicknesses and arrangements.

5. Funding

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6. References

[1] Rahmzadeh, A., Ghassemieh, M., Park, Y. and Abolmaali, A. "Effect of stiffeners on steel plate shear wall systems." Steel and Composite Structures 20 (2016): 545-569. http://dx.doi.org/10.12989/scs.2016.20.3.545.

[2] Bhowmick, A.K., Grondin, G.Y. and Driver, R.G. "Nonlinear seismic analysis of perforated steel plate shear walls." Journal of Constructional Steel Research 94 (2014): 103-113. https://doi.org/10.1016/j.jcsr.2013.11.006.

[3] Berman J.W. and Bruneau, M. "Experimental investigation of light-gauge steel plate shear walls." Journal of Structural Engineering 131(February 2005):259-67. https://doi.org/10.1061/(asce)0733-9445(2005)131:2(259).

[4] Vian D. "Steel plate shear walls for seismic design and retrofit of building structures." PhD dissertation, State University of New York, N.Y, USA, (2005). http://mceer.buffalo.edu/pdf/report/05-0010.pdf.

[5] Hitaka, T. and Matsui, C. "Experimental study on steel shear walls with slits." Journal of Structural Engineering 129(2003):586-95. https://doi.org/10.1061/(ASCE)0733-9445(2003)129:5(586).

[6] Cortes, G. and Liu, J. "Experimental evaluation of steel slit panel–frames for seismic resistance." Journal of Constructional Steel

Research 67(February 2011):181–91. https://doi.org/10.1016/j.jcsr.2010.08.002.

[7] Caccese, V., Elgaaly, M. and Chen, R., “Experimental Study of Thin Steel-Plate Shear Walls under Cyclic Load”, Journal of Structural Engineering, 1993, Vol. 119, No. 2, pp.573-587.

[8] Behbahanifard, M.R., Grondin, G.Y. and Elwi, A.E. “Experimental and numerical investigation of steel plate shear wall.” Structural Engineering Report 254. Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada, (2003): 1-121. https://era.library.ualberta.ca/items/d3a1bbad-4280-43e9-af85-55e7b4d77a4a/view/70a025b9-731c-4020-9e00-b928f4a51b2f/SER254.pdf.

[9] Tsai, K.C. and Li, C.H. "Cyclic Tests of Four Two-storey Narrow Steel Plate Shear Walls-Part 1 Analytical Studies and Specimen Design." Earthquake Engineering & Structural Dynamics 39 (2010):775-799. https://doi.org/10.1002/eqe.977.

[10] Alavi, E. and Nateghi, F. "Experimental Study on Diagonally Stiffened Steel Plate Shear Walls with Central Perforation." Journal of Constructional Steel Research 89 (2013):9-20. https://doi.org/10.1016/j.jcsr.2013.06.005.

[11] Sabouri-Ghomi, S. and Asad Sajjadi, R. “Experimental and theoretical studies of steel shear walls with and without stiffeners”, Journal of Constructional Steel Research 75 (August 2012): 152-159. https://doi.org/10.1016/j.jcsr.2012.03.018.

[12] Nie, J.G., Zhu, L., Fan, J.S. and Mo, Y.L. "Lateral Resistance Capacity of Stiffened Steel Plate Shear Walls." Thin-Walled Structures 67(2013): 155-167. https://doi.org/10.1016/j.tws.2013.01.014.

[13] Sabouri-Ghomi, S. and Mamazizi, S. “Experimental investigation on stiffened steel plate shear walls with two rectangular openings.” Thin-Walled Structures 86 (January 2015): 56-66. https://doi.org/10.1016/j.tws.2014.10.005.

[14] Rajeev,A., Jacob, B. and Muhamed, S. “Behavioural Comparison of Geometrically Different Steel Plate Shear Walls.” International Journal for Research in Applied Science & Engineering Technology 4(2016):661-681. https://www.ijraset.com/fileserve.php?FID=5682.

[15] Deylami, A. and Daftari, H. “Non-Linear. Behavior of Steel Plate Shear Wall with Large Rectangular Opening”. Proceedings of the 12th World Conference on Earthquake Engineering; Auckland, New Zeland, (2000): 1-7. www.iitk.ac.in/nicee/wcee/article/0408.pdf.

[16] Rezai, M., Ventura, C.E. and Prion, H. "Simplified and detailed finite element models of steel plate shear walls." Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada, (2004). www.iitk.ac.in/nicee/wcee/article/13_2804.pdf.

[17] Alinia, M.M. and Dastfan, M. "Cyclic Behaviour, Deformability and Rigidity of Stiffened Steel Shear Panels." Journal of Constructional Steel Research 63(2007): 554–563. https://doi.org/10.1016/j.jcsr.2006.06.005.

[18] Habashi, H.R. and Alinia, M.M. “Characteristics of the wall-frame interaction in steel plate shear walls.” Journal of Constructional Steel Research 66(2010): 150-158. https://doi.org/10.1016/j.jcsr.2009.09.004.

[19] Zirakian,T. and Zhang, J. “Seismic design and behavior of low yield point steel plate shear walls.” International Journal of Steel Structures 15(March 2015): 135–151. https://doi.org/10.1007/s13296-015-3010-8.

[20] Kalali, H., Hajsadeghi, M., Zirakian, T. and Alaee, F.J. “Hysteretic performance of SPSWs with trapezoidally horizontal corrugated web-plates.” Steel and Composite Structures 19(2015):277-292. https://doi.org/10.12989/scs.2015.19.2.277.

[21] Formisano, A. and Lombardi, L. “Numerical prediction of the non-linear behaviour of perforated metal shear panels.” Cogent Engineering 3(March 2016): 1156279. https://doi.org/10.1080/23311916.2016.1156279.

[22] Lv, Y. and Li., Z-X. “Influences of the gravity loads on the cyclic performance of unstiffened steel plate shear wall.” Structural Design of Tall and Special Buildings 25(2016): 988-1008. https://doi.org/10.1002/tal.1294.

[23] Verma,A. and Ranjan Sahoo, D. “Seismic behaviour of steel plate shear wall systems with staggered web configurations.” Key Engineering Materials 47(2018): 660-677 https://doi.org/10.1002/eqe.2984.

[24] Yu, J.G. and Ha, J.P. “Behaviour of semi-rigid steel frames with steel plate shear walls.” Advanced Steel Construction 12(2016):154-173. https://doi.org/10.18057/ijasc.2016.12.2.5.

[25] Azizinamini, A. and Radziminski, J.B. "Static and Cyclic Performance of Semi-rigid Steel Beam-column Connections." Journal of Structural Engineering 115(1989): 2979-2999. https://doi.org/10.1061/(ASCE)0733-9445(1989)115:12(2979).

[26] Elnashai, A.S. and Elghazouli, A.Y. "Seismic Behavior of Semirigid Steel Frames." Journal of Constructional Steel Research 29(1994):149-174. https://doi.org/10.1016/0143-974X(94)90060-4.

[27] Kishi, N., Chen, W.F. and Goto, Y. "Effective Length Factor of Columns in Semi-rigid and Unbraced Frames." Journal of Structural Engineering 123(1997): 313-320. https://doi.org/10.1061/(ASCE)0733-9445(1997)123:3(313).

[28] Ranjan Sahoo, D., Singh Sidhu, B. and Kumar, A. “Behavior of Unstiffened Steel Plate Shear Wall with Simple Beam-to-column Connections and Flexible Boundary Elements.” International Journal of Steel Structures 15(2015): 75-87. https://doi.org/10.1007/s13296-015-3005-5.

[29] Xue, M. and Lu, L. “Interaction of infilled steel shear wall panels with surrounding frame members.” Proceedings of the 1994 Annual Task Group Technical Session, Structural Stability Research Council: reports on current research activities, Lehigh University, Bethlehem, PA., (1994).

[30] Sabelli, R. and Bruneau, M. “AISC Design Guide 20- Steel Plate Shear Walls.” American Institute of Steel Construction, Chicago, IL. (2007).

[31] AISC. "Steel design guide 20, steel plate shear walls." Chicago (IL): American Institute of Steel Construction, (2007).

[32] AISC, ANSI/AISC 341-05. "Seismic provisions for structural steel buildings." Chicago (IL): American Institute of Steel Construction, (2005).