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On the improvement of steel plate shear wall behavior using energy absorbent element

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KEYWORDS
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Abstract. Structural engineers have recognized unstiffened Steel Plate Shear Wall (SPSW) as an economical lateral resisting system due to the post-buckling capacity, energy dissipation, and deformability. This study investigates practical application of an added Energy Absorbent Element (EAE), subjoined to the SPSW in order to improve seismic behavior of the SPSW. The EAE is an aluminum shear panel with or without bracings and surrounding frame. Furthermore, a series of parametric studies are implemented to examine the effect of dimensions, position, and formation of the EAE. It is assumed that the lateral loading is applied as quasi-static loading. Further, nonlinearity of the material and the geometry are included in the models. The results reveal that by adding the EAE adjacent to the surrounding frame of the SPSW, not only dissipated energy, but also ultimate strength of the system can be efficiently increased.

1. Introduction

The efficiency of shear walls in resisting lateral forces induced by earthquake or wind in multi-story buildings has long been recognized by scientists and design engineers. Steel Plate Shear Wall (SPSW) is one of the possible options for lateral resistance of buildings. This system consists of steel plates, one story high and one bay wide connected to the adjacent beams and columns by weld, bolt or both. The plates are installed on one or more bays for the full height of the building [1,2]. In recent years, steel plate shear walls have been incorporated in the multi-story buildings. They consist of thin flat steel plates referred to as infill panels which are framed by beams and columns [3-6]. The experimental and analytical studies on the thin SPSWs have been performed under monotonic and cyclic loading [7-17]. The surrounding steel frame can be applied with either simple or moment-resisting beam-to-column connections. When moment-resisting beam-to-column connections are present in this system, they generate inherent redundancy and significant energy dissipation [11]. In the early applications of the SPSWs in the United States and Japan, the walls had numerous vertical and horizontal stiffeners. The main purpose of the stiffeners was to prevent elastic and global buckling and to increase the shear buckling strength of the wall. However, in the today's steel fabrication shops, welding stiffeners to shear panels can be costly and time-consuming. Therefore, the analytical and experimental research pieces of realistic specimens have described that the unstiffened steel plate, due to its post-buckling capacity, functions in a highly ductile and efficient manner. As a result, in most recent applications of the SPSWs in the United States and Canada, unstiffened steel plates have been used. Furthermore, a series of cyclic and shaking table tests on the SPSWs were implemented in the University of British Columbia [18,19].

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Although a properly designed and detailed SPSW has high lateral strength, initial stiffness, ductility, and energy dissipation, in this study, one extra element is further introduced as Energy Absorbent Element (EAE). This element can increase dissipated energy as well as strength of the new created system. Therefore, a series of parametric studies have been implemented to investigate the effect of position, dimension, and formation of the EAE in order to improve the SPSW behavior.

2. Method of study

2.1. Modeling and material property

To study the behavior of the SPSW systems, it is required that a three-dimensional analysis be implemented in order to capture the out-of-plane deformations, buckling shear strength, the ultimate shear strength, as well as energy absorption capacity. In the SPSWs with the EAE, a three-dimensional modeling is more significant because of the special geometry of the EAE. However, three-dimensional solid finite elements with translational degrees of freedom per node will not probably involve the out-of-plane deformation of the shear wall components and can result in a stiff model. Therefore, in this study, the shear wall components have been modeled utilizing a 4-node doubly curved general purpose shell element with finite membrane strain and second-order accuracy. This element allows transverse shear deformation. In addition, this element is not sensitive to element distortion and avoids parasitic locking. The stress distribution over the element is defined at four Gauss points located at the mid-surface of the element. The flexural behavior of this shell element at each Gauss point is integrated over nine integration points.

Nonlinearity of the material and the geometry were included in the models. Material properties of the shear panel, the surrounding frame, and the EAE are considered to be isotropic bilinear hardening rule. The assumed stress-strain relationship of the material is indicated in Figure 1. The material of the shear panel of the EAE is merely aluminum and the remaining materials are steel. Young's modulus and other material properties are as follows:

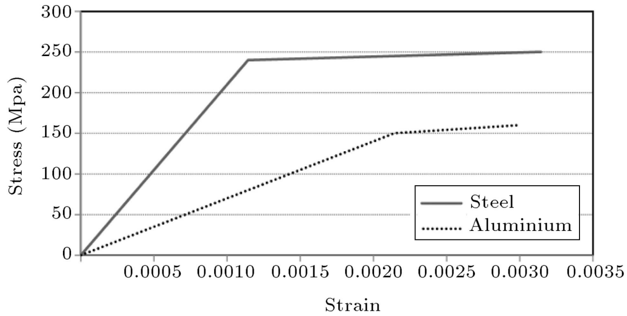


Figure 1. Stress-strain relationship.

$$\text{Steel}: \quad E_{\text{elastic}} = 210 \text{ GPa}, \quad E_{\text{plastic}} = 8 \text{ GPa},$$

$$v = 0.3, \quad \sigma_y = 240 \text{ MPa}$$

$$\text{Aluminum}: \quad E_{\text{elastic}} = 70 \text{ GPa}, \quad E_{\text{plastic}} = 5 \text{ GPa},$$

$$v = 0.35, \quad \sigma_y = 150 \text{ MPa}.$$

The Von-Mises yield criterion, known to be the most convenient for metals, is used in this study [20,21].

2.2. Geometry and boundary condition

Two ordinary width-height ratios of the SPSWs are modeled; the first one as 4/3 and the second one as 3/4. Exact geometry and dimension of the both models are illustrated in Tables 1 and 2. In each model, top beam section and section of columns are HE-B200. Further, thickness of the steel and aluminum shear panel is similar and equal to 3.0 millimeters in all models. For each model, the translation and rotation at the bottom nodes of the columns and the shear panel are prevented. Further, the beam-column connections as well as panel-frame connections are fixed. The models which contain

Table 1. Models with width-height ratio 4/3 (unit: m).

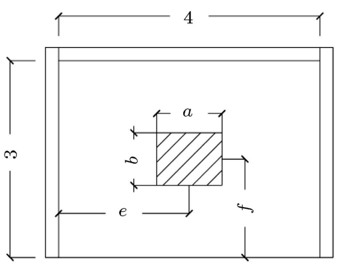
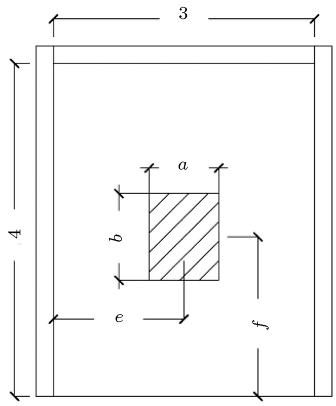
Model	Name	*a*	*b*	*e*	*f*
	S_1	–	–	–	–
	S_2	1.0	0.75	2.0	1.5
	S_3	2.0	1.5	2.0	1.5
	S_4	1.0	0.75	2.5	1.5
	S_5	2.0	1.5	3.0	1.5
	S_6	1.0	0.75	2.0	1.875
	S_7	2.0	1.5	2.0	2.25
	S_8	1.0	0.75	2.5	1.875
	S_9	2.0	1.5	3.0	2.25
	S_{10}	4.0	1.5	2.0	2.25

Table 2. Models with width-height ratio 3/4 (unit: m).

Model	Name	a	b	e	f
	S_{11}	–	–	–	–
	S_{22}	0.75	1.0	1.5	2.0
	S_{33}	1.5	2.0	1.5	2.0
	S_{44}	0.75	1.0	1.875	2.0
	S_{55}	1.5	2.0	1.875	2.0
	S_{66}	0.75	1.0	1.5	2.5
	S_{77}	1.5	2.0	1.5	3.0
	S_{88}	0.75	1.0	1.875	2.5
	S_{99}	1.5	2.0	1.875	3.0
	S_{100}	3.0	2.0	1.5	3.0

energy absorbent element, connection of bracing to the surrounding frame of the energy absorbent system is hinged. To prevent the surrounding frame from out-of-plane translation, the nodes at the center of beam are restrained from translation in the global z-direction.

2.3. Loading and analysis

In order to investigate the effect of the EAE upon the ultimate strength, stiffness, as well as capacity of the energy dissipation of the shear panels, a series of simulations are conducted on the SPSWs containing the EAE under monotonic and cyclic shear loading. It is assumed that the shear loading is applied as quasi-static loading. All of the analyzed models are described in Figures 2 and 3. The nonlinear nature of the problem dictates that an iteration scheme should be utilized to achieve successive solutions along the equilibrium path. Due to the quasi-static shear loading, static stress analysis, or modified Riks analysis [22], is suitable because the inertia effects are negligible and nonlinearity can be considered. In fact, where the load-displacement response exhibits a negative stiffness, and if the structure releases strain energy to maintain equilibrium, modified Riks analysis should be employed.

2.4. Verification of the finite element models

In order to verify the results of the finite element analyses, one model was simulated according to the flat SPSW specimen tested by authors [23,24]. The dimensions and specifications of the tested specimen are indicated in Figure 4(a). The test setup and relevant finite element model are shown in Figure 4(b). The analysis resulted in acceptable predictions of the ultimate strength, stiffness, and capacity of dissipation energy. The comparison between the experimental and the finite element hysteretic loops is indicated in Figure 5.

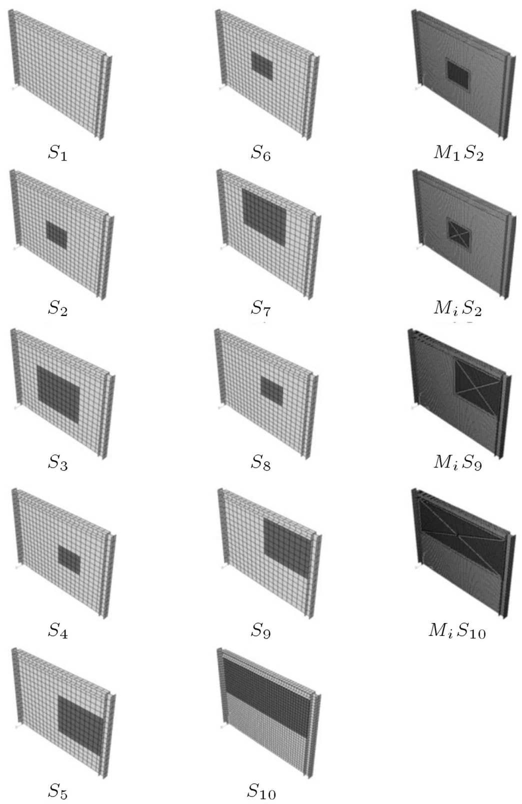


Figure 2. Finite element models with width-height ratio 4/3.

3. Parametric study

3.1. Effect of width-height ratio of the SPSW

At first, two ordinary width-height ratios of the SPSWs were modeled: the first one as 4/3 and the second one as 3/4. All of the models and their dimensions are illustrated in Tables 1 and 2 along with Figures 2 and 3. Shear force-displacement diagrams of the analyzed models are described in Figure 6. As it is indicated in Figure 6, the buckling strength and the ultimate strength of the models with width-height

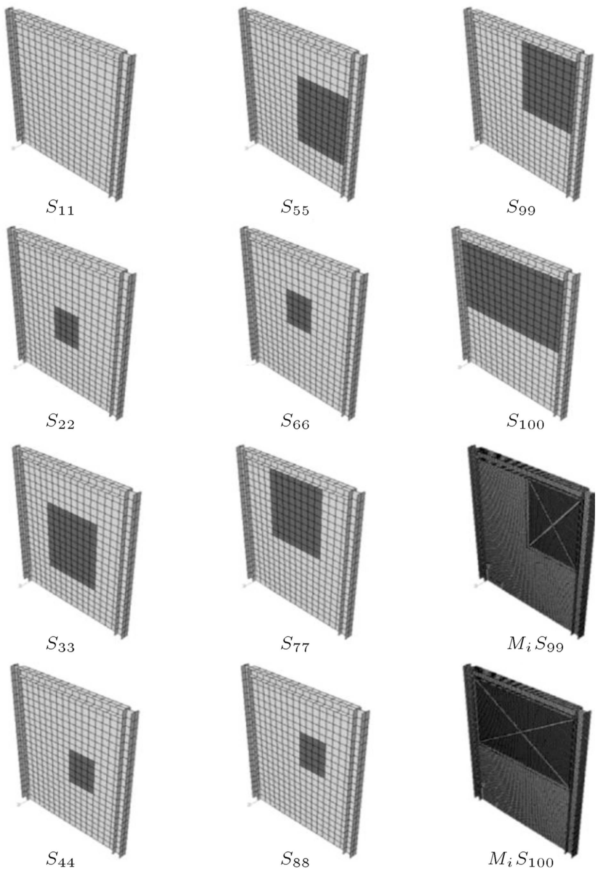


Figure 3. Finite element models with width-height ratio 3/4.

ratio of 4/3 is higher than the second one. Therefore, with attention to the ultimate strength of the SPSW including aluminum shear panel, it is more economical that the SPSW with the EAE be applied to the wider bay of the structure frames.

3.2. Effect of dimension of the EAE

To investigate the effect of dimensions of the EAE in each position, the finite element models with three different dimensions of the EAE were analyzed: the first one 1.0×0.75 or 0.75×1.0 m^2, the second one 2.0×1.5 or 1.5×2.0 m^2, and the third one 4.0×1.5 or 3.0×2.0 m^2. To compare the effect of dimension, all of the models were analyzed without the surrounding frame and bracing for the EAE. Totally, 20 models with the EAE were analyzed which were presented in Figures 2 and 3. The results indicate that the models with similar dimension of the EAE (i.e., 1.0×0.75 m^2 or 0.75×1.0 m^2) have higher shear buckling strength and the ultimate strength, as shown in Figure 6.

3.3. Effect of position of the EAE

To investigate the position of the EAE without the surrounding frame and bracing, 16 models were analyzed. The results are described in Figure 7 for dimensions of 1.0×0.75 m^2 or 0.75×1.0 m^2. This figure

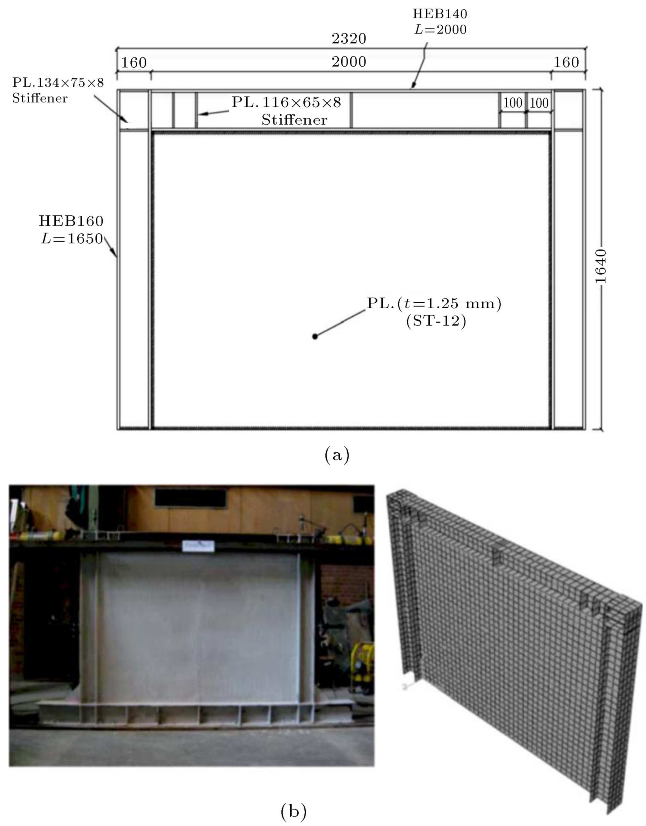


Figure 4. Flat SPSW: (a) Dimensions, beam section, and column sections; and (b) test setup and its finite element model.

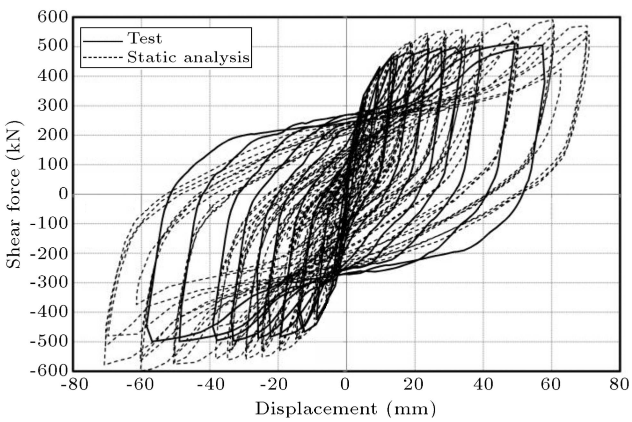


Figure 5. Verification of finite element analysis of the SPSW with experimental finding.

indicates that the positions of the EAE, only including the aluminum shear panel, have negligible effect on the lateral strength of the system.

It should be noted that the obtained results can be applied fairly for the SPSW with larger dimension of the EAE (i.e. 2.0×1.5 m^2 or 1.5×2.0 m^2). These results can be inferred from Figure 6. In fact, this figure describes that only the shear buckling and the ultimate strength of the SPSWs, together with the EAE connected to the beam and column (i.e. models

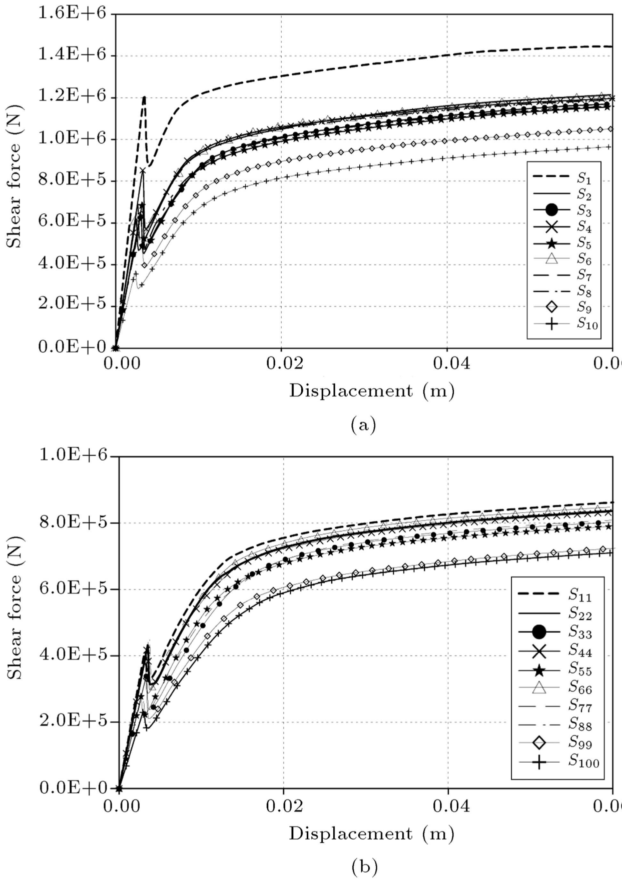


Figure 6. Shear force-displacement diagrams of the analyzed models: (a) Width-height ratio 4/3 and (b) width-height ratio 3/4.

S_9 and S_{99}), show a greater reduction rather than the rest of the models with the similar dimensions.

4. Comparison and discussion

To specify the optimum SPSW, together with the EAE, it is required to consider the extent of increase in stiffness, strength, and energy dissipated by the lateral resisting system. For this purpose, shear force-displacement diagram of the best model, i.e., S_2 and its dependent SPSW under monotonic loading, are shown in Figure 8. The comparison between this figure with Figures 6(a) and 7(a) indicates that although S_2 has the highest strength among all the models containing the EAE, its buckling and the ultimate strength are lower than that of the dependent SPSW. Therefore, it is required that the EAE be modified. To improve the behavior, a surrounding steel frame is primarily subjoined to the EAE, and then steel bracings are added to the system as they are displayed in Figures 2 and 3. Section dimensions of the surrounding frame and bracings subjoined to the EAE are demonstrated in Figure 9. The shear force-displacement diagrams of S_2 as the optimum model and its modified models under monotonic loading are indicated in Figure 10. As this figure shows, the strength of the modified models not only does not increase compared to the dependent SPSW, but actually their strength decreases compared to the S_2 model. Therefore, this model and their modified models are not confirmed as the optimum SPSW together with the EAE.

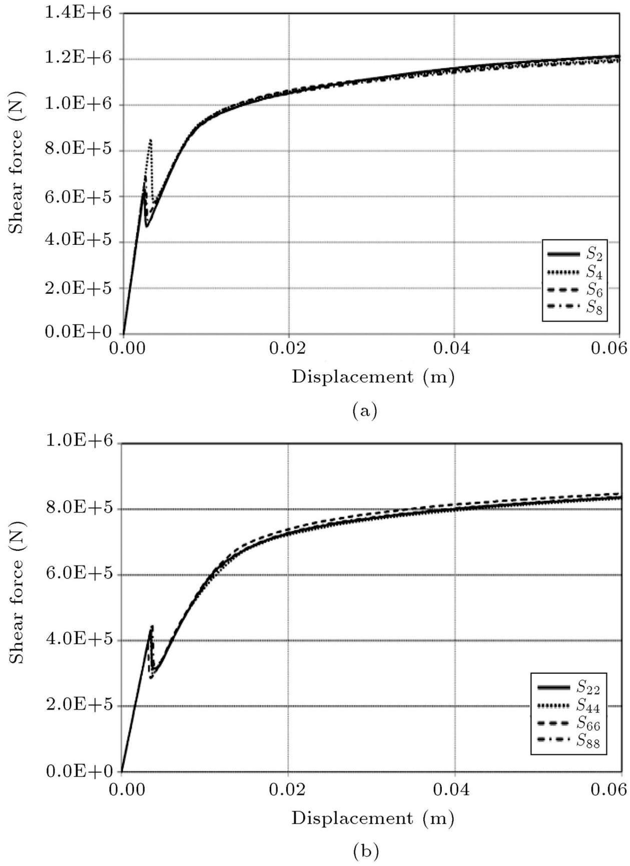


Figure 7. Effect of position of the EAE (1.0×0.75 m^2) in the SPSW: (a) Width-height ratio 4/3 and (b) width-height ratio 3/4.

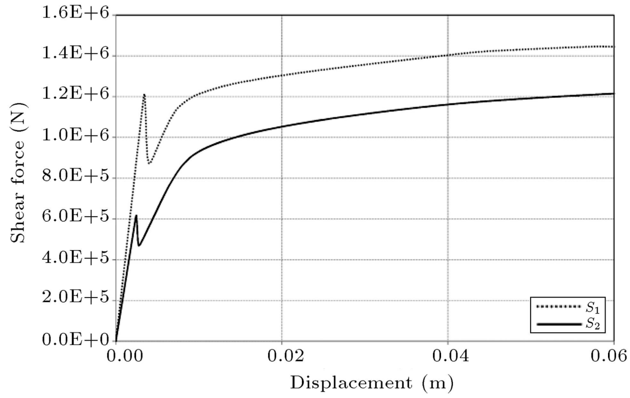


Figure 8. Shear force-displacement diagram of S_1 and S_2 under monotonic loading.

It is noteworthy that by analyzing and comparing the shear force-displacement diagrams of all models,

S_9 and S_{99} are selected as convenient models that although their lateral strengths are not the highest (among similar models), their condition becomes absolutely different when they are being modified. Their modified systems, i.e. M_iS_9 and M_iS_{99}, are illustrated in Figures 2 and 3. Their shear force-displacement diagrams are compared to the dependent SPSW system in Figure 11. This figure describes that the strength of the SPSW increases with subjoining surrounding frame and bracing to the EAE. The existing difference among the modified models is in thickness of the box utilized for the surrounding frame subjoined to the EAE as well as the bracing which is shown by 'i' subscript. In fact, 'i' indicates the thickness of the box in millimeter. Thus, it can be inferred that for the SPSW with the full EAE in dimension 1.0×0.75 m^2 or (0.75×1.0) and

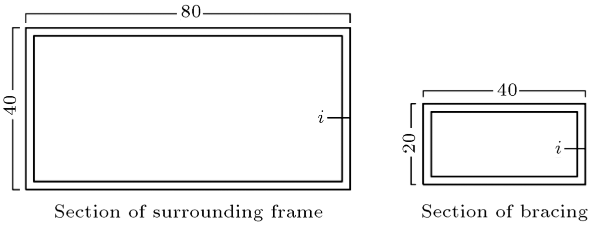


Figure 9. Section dimensions of the surrounding frame and bracing subjoined to the EAE (unit: mm).

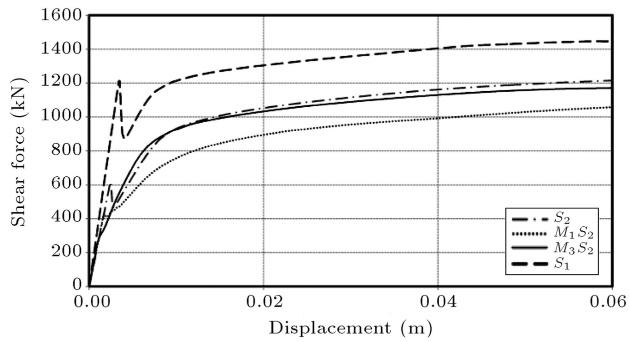


Figure 10. Shear force-displacement diagram of the best model and modified models under monotonic loading.

adjacent to the beam and column, the optimum lateral strength is obtained.

After choosing M_3S_9 and M_3S_{99} as the optimum models in the ultimate strength, their stiffness is fairly compared with the dependent SPSW. Their results are described in Figure 12, revealing that by modifying the EAE, its initial stiffness does fairly increase. Further, the selected models as the optimum system, i.e. M_3S_9 and M_3S_{99}, are analyzed under lateral cyclic loading. Hysteretic loops of these models are described in Figure 13. This figure indicates that the hysteretic

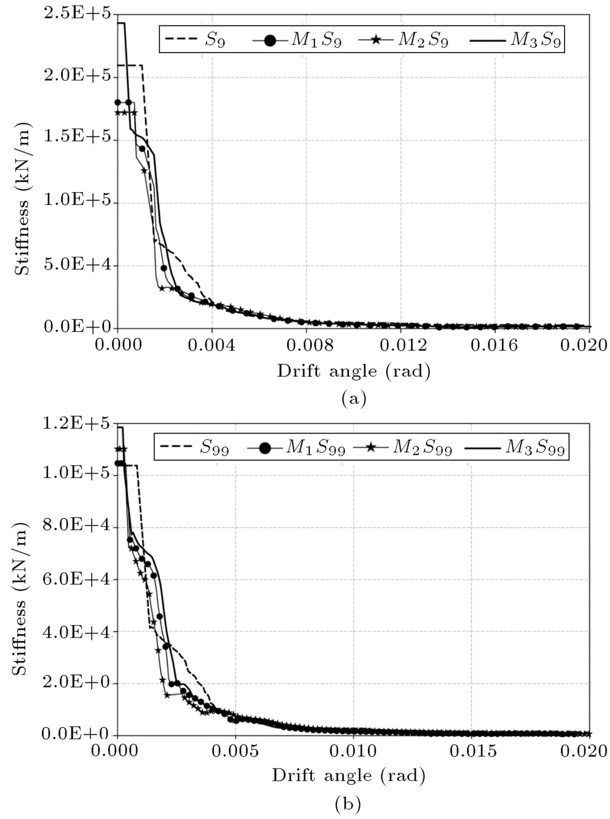


Figure 12. Stiffness of optimum models: (a) S_9 and (b) S_{99}.

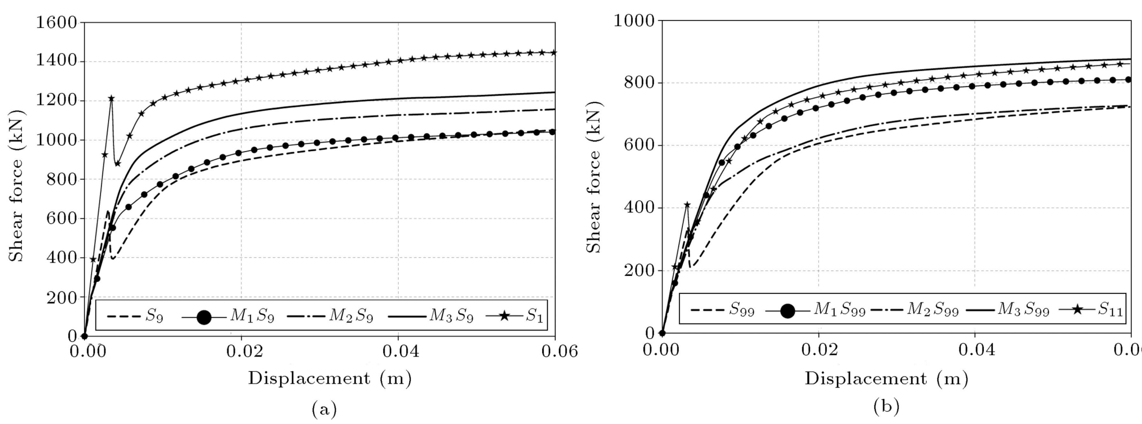


Figure 11. Shear force-displacement diagram of S_9, S_{99} and modified models under monotonic loading: (a) S_9 and (b) S_{99}.

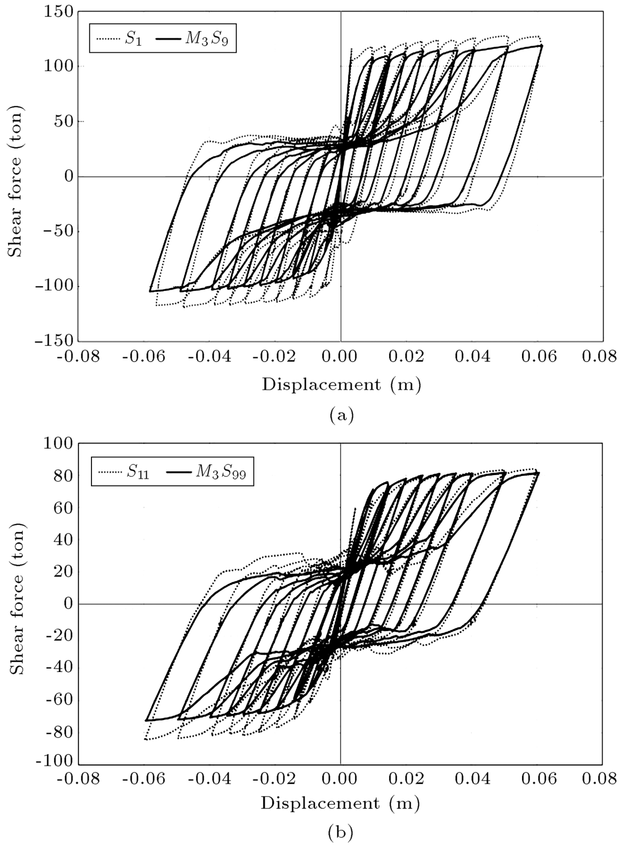


Figure 13. Hysteretic loops of the optimized models and dependent SPSW: (a) M_3S_9 and (b) M_3S_{99}.

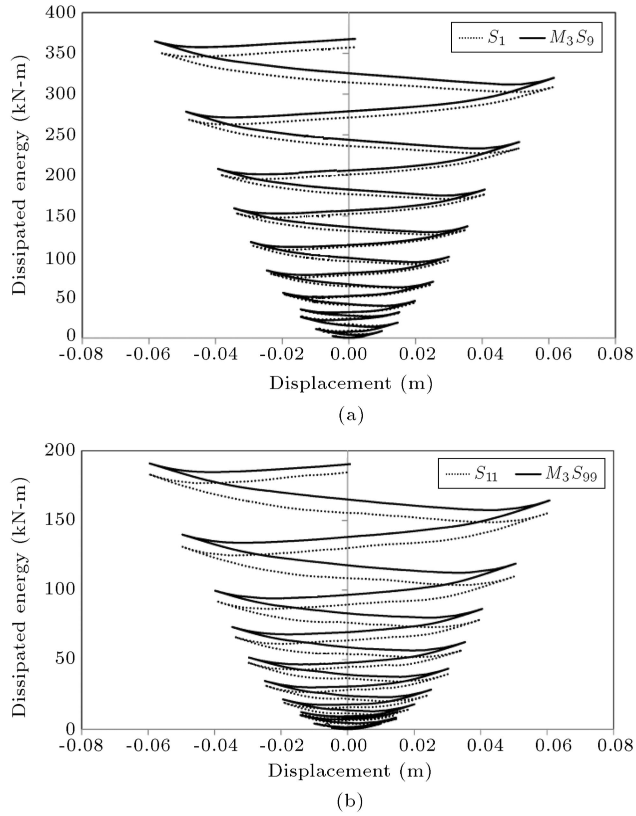


Figure 14. Cumulated energy of the optimized models and dependent SPSW: (a) M_3S_9 and (b) M_3S_{99}.

loops of the optimum models are fairly similar to their dependent SPSW models in strength as well as amount of pinching in the hysteretic loops. As it is determined from Figure 14, the amount of cumulated energy dissipated by M_3S_9 is negligible and M_3S_{99} is nearly 10% higher compared to the dependent SPSWs.

5. Conclusion

As described, by adding the full EAE including aluminum plate, its surrounding frame, and bracings to the SPSW, the buckling strength and ultimate strength of the SPSW can increase or decrease. The ultimate shear strength of the SPSW by adding the full EAE can increase compared to the SPSW if the full EAE is adjacent to the surrounding frame, i.e. next to the both of the beam and column of the SPSW. However, the position of the full EAE in other parts of the shear panel, which is not adjacent to the boundary frames of the SPSW, not only does not increase the ultimate shear strength of the system, but actually decreases compared to its dependent SPSW. Furthermore, by increasing the dimension of the EAE, the buckling and the ultimate shear strength of the SPSW decrease as well.

Furthermore, by adding the full EAE adjacent to the surrounding frames, the dissipated energy of the created system increases compared to the dependent SPSW. This increase is considerable for models with width-height ratio of 3/4. As another result, although the amount of strength does not considerably increase by changing position of the EAE, it decreases by increasing the dimension of the EAE.

References

1. Astaneh-Asl, A., *Steel Tips. Seismic Behavior and Design of Steel Shear Walls*, Canada: Structural Steel Education Council (2001).

2. Zhang, S., Kumar, P. and Rutherford, S.E. "Ultimate shear strength of plates and stiffened panels", *Ships and Offshore Structures*, **3**(2), pp. 105-112 (2008).

3. Roberts, T.M. and Sabouri-Ghomi, S. "Hysteretic characteristics of unstiffened plate shear panels", *Thin Walled Structures*, **12**, pp. 145-162 (1991).

4. Astaneh-Asl, A. "Steel plate shear walls", *Proceedings, U.S.-Japan Workshop on Seismic Fracture Issues in Steel Structures*, San Francisco (2000).

5. Paik, J.K. "Ultimate strength of perforated steel plates under combined biaxial compression and edge shear loading", *Thin Walled Structures*, **46**, pp. 207-213 (2008).

6. Kang, T.H.K., Martin, R.D., Park, H.G., Wilkerson, R. and Youssef, N. "Tall building with steel plate shear walls subject to load reversal", *The Structural Design of Tall and Special Buildings*, **22**(6), pp. 500-520 (2013).

7. Timler, P.A. and Kulak, G.L. "Experimental study of steel plate shear walls", Structural Engineering, Report no. 114, Canada: University of Alberta (1983).

8. Roberts, T.M. "Seismic resistance of steel plate shear walls", *Engineering Structures*, **17**(5), pp. 344-51 (1995).

9. Driver, R.G., Kulak, G.L., Kennedy, D.J.L. and Elwi, A.E. "Cyclic test of four-story steel plate shear wall", *Journal of Structural Engineering ASCE*, **124**(2), pp. 112-20 (1998).

10. Sabouri-Ghomi, S., Ventura, C.E. and Kharrazi, M.H.K. "Shear analysis and design of ductile steel plate walls", *Journal of Structural Engineering ASCE*, **131**(6), pp. 878-89 (2005).

11. Chen, S. and Jhang, C. "Cyclic behavior of low yield point steel shear walls", *Thin-Walled Structures*, **44**, pp. 730-738 (2006).

12. Nateghi, F. and Alavi, E. "Non-linear behavior and shear strength of diagonally stiffened steel plate shear walls", *International Journal of Engineering (IJE)*, **22**, pp. 343-356 (2009).

13. Keh-Chyuan, T., Chao-Hsien, L., Chih-Han, L., Ching-Yi, T. and Yi-Jer, Y. "Cyclic tests of four two-story narrow steel plate shear walls - Part 1: Analytical studies and specimen design", *Earthquake Engineering & Structural Dynamics*, **39**(7), pp. 775-799 (2010).

14. Chao-Hsien, L., Keh-Chyuan, T., Chih-Han, L. and Pei-Ching, C. "Cyclic tests of four two-story narrow steel plate shear walls - Part 2: Experimental results and design implications", *Earthquake Engineering & Structural Dynamics*, **39**(7), pp. 801-826 (2010).

15. Berman, J.W. "Seismic behavior of code designed steel plate shear walls", *Engineering Structures*, **33**(1), pp. 230-44 (2011).

16. 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**, pp. 155-167 (2013).

17. Alavi, E. and Nateghi, F. "Experimental study of diagonally stiffened steel plate shear walls", *Journal of Structural Engineering*, **139**(11), pp. 1795-1811 (2013).

18. Rezai, M., Ventura, C.E., Prion, H.G.L. and Lubbell, A.S. "Unstiffened steel plate shear walls: Shake table testing", In: *Proceedings, Sixth US National Conf. on Earthquake Engineering* (1998).

19. Rezai, M., Ventura, C.E. and Prion, H.G.L. "Numerical investigation of thin unstiffened steel plate shear walls", In: *Proceedings, 12th World Conf. on Earthquake Engineering* (2000).

20. Takahashi, Y., Takemoto, Y., Takeda, T. and Takagi, M. "Experimental study on thin steel shear walls and particular bracings under alternative horizontal load", *Preliminary Rep., IABSE Symp. on Resistance and Ultimate Deformability of Struct. Acted on by Well-Defined Reported Loads*, International Association for Bridge and Structural Engineering, Lisbon, Portugal, pp. 185-191 (1973).

21. Mimoura, H. and Akiyama, H. "Load-deflection relation of earthquake-resistant steel shear walls with a developed diagonal tension field", *Trans AIJ*, **260** (1977).

22. Tsai, C.T. and Palazotto, A.N. "The application of the Riks technique to shell snapping", *Original Research Article, Mathematical and Computer Modeling*, **14**, pp. 868-872 (1990).

23. Emami, F., Mofid, M. and Vafai, A. "Experimental study on cyclic behavior of trapezoidally corrugated steel shear walls", *Engineering Structures*, **48**, pp. 750-762 (2013).

24. Emami, F. and Mofid, M. "On the hysteretic behavior of trapezoidally corrugated steel shear walls", *The Structural Design of Tall and Special Buildings*, **23**(2), pp. 94-104 (2014).

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