Computational Engineering and Physical Modeling 1-1 (2018) 58-67

Contents lists available at **CEPM**

Computational Engineering and Physical Modeling

Journal homepage: www.jcepm.com

The Effect of Diagonal Stiffeners on the Behaviour of Stiffened Steel Plate Shear Wall

B. Amiri[1*], H. AghaRezaei[2], R. Esmaeilabadi[3]

1. Young Researchers Club, Roudehen Branch, Islamic Azad University, Roudehen, Iran
2. Department of Civil Engineering, Roudehen Branch, Islamic Azad University, Roudehen, Iran
3. Assistant Professor, Department of Civil Engineering, Roudehen Branch, Islamic Azad University, Roudehen, Iran

Corresponding author: *esmaeilabadi@riau.ac.ir*

https://doi.org/10.22115/CEPM.2018.112951.1007

ARTICLE INFO

Article history:
Received: 02 January 2018
Revised: 15 March 2018
Accepted: 19 March 2018

Keywords:
Steel plate shear wall;
Stiffened steel plate shear walls;
Finite element method;
Nonlinear pushover analysis.

ABSTRACT

In the current study, the nonlinear behavior of the stiffened steel plate shear wall with diagonal stiffeners is numerically studied. After nonlinear pushover analysis, the finite element modeling results are compared with un-stiffened and stiffened steel plate shear walls, with the horizontal and vertical stiffeners. First, a finite element model of steel plate shear wall is developed and validated by using Abaqus software. After assuring the behavior of the boundary elements (beams and columns) and the infill steel plate, the finite element models of the steel shear walls are developed and analyzed using nonlinear pushover method. Steel plate shear wall models are designed according to AISC 341-10 Seismic Provisions. Finally, the obtained results and the behavior of finite element models are compared with each other. The important seismic parameters (initial elastic stiffness, ultimate shear strength, and ductility) are calculated and percentage of changes are discussed. Based on the results, the performance of steel plate shear walls with diagonal stiffeners enhances as compared with unstiffened steel plate shear walls.

How to cite this article: Amiri B, AghaRezaei H, Esmaeilabadi R. The Effect of Diagonal Stiffeners on the Behaviour of Stiffened Steel Plate Shear Wall. Comput Eng Phys Model 2018;1(1):58–67. https://doi.org/10.22115/cepm.2018.112951.1007

1. Introduction

Over the past three decades, unstiffened and stiffened steel shear walls have been used to design and construct special high-rise buildings in high seismic zones. The systems have good seismic performance which provides high lateral stiffness and shear capacity. Steel plate shear wall consists of infill steel plates surrounded by beams and columns. In addition, it is possible to have an unstiffened or stiffened opening in steel plate shear walls [1–10].

The main function of the infill steel plate is to resist the lateral loads induced due to wind or earthquake. Although steel plate shear walls are made of the infill steel plate surrounded by beams and columns and act like steel girders, beams and columns should be designed to remain elastic throughout the lateral loading. In order to prevent global and local elastic buckling of the inner steel plate, horizontal or vertical steel stiffeners or concrete panels are used. The name of this system is stiffened steel shear wall [1-10].

It can be stated that steel plate shear walls are categorized into two different groups, stiffened or unstiffened. In stiffened steel shear wall, the infill steel plate buckles in compression fields and the system resists lateral load by developing tension field actions [11,12]. In stiffened steel plate shear wall, concrete panels or steel stiffeners prevent global and local buckling of the inner plate. Therefore, the inner plate carries the lateral shear loads by developing shear yielding [5-10].

In this research, the behavior of stiffened steel plate shear walls with diagonal stiffeners is studied. The obtained results and observations are compared with unstiffened steel plate shear wall. In addition, the performance of stiffened steel plate shear wall with diagonal stiffeners is compared with shear walls with horizontal and vertical stiffeners.

2. The finite element method and validation

For nonlinear pushover analysis of steel shear walls, the commercial finite element software, Abaqus, was used [13]. In the finite element model, 4-node S4R shell elements (with element size of 75 mm) were used for the inner plate, due to the fact that the inner steel plate is thin. 8-node C3D8R solid elements (with the element size of 75 mm) were selected for beams and columns in order to capture the desirable behavior [6,10,14]. In this research, two different steel materials, A36 and A572, are utilized to model steel behavior. A36 steel with the tensile yield stress of 2,480 kg/cm^2 and ultimate strength of 4850 kg/cm^2 was selected for the infill steel plate. A572 steel with the tensile yield stress of 3,450 kg/cm^2 and ultimate strength of 5230 kg/cm^2 was chosen for boundary elements (beams and columns). For finite element models, tri-linear elastic-plastic behavior model with strain hardening is considered for the steel materials [8,10]. Initial imperfection is applied to the finite element models because of initiation of elastic buckling for tension field actions. The eigenvalue buckling analysis is conducted and magnitude of h/10000 imperfection is defined based on the first mode of buckling [15]. In order to validate the finite element method, a steel plate shear wall specimen tested by Lubell et al. (2000) is developed. The observations and results of finite element model are compared with experimental data. There is a good agreement between finite element method and experiment data. Fig. 1 shows the verification and comparison of the finite element model and test results.

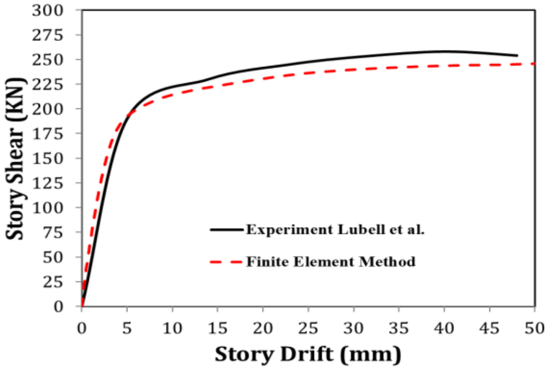

Fig. 1. Comparison of finite element results with experimental data.

3. Analysis results

For the design of steel plate shear walls, which include beams, columns and internal steel sheets, AISC 341-10 Seismic Provisions for Structural Steel is used. The length and height of code designed shear wall are 3 meters. The infill steel plate thickness is 4.76 mm. The columns and beams of steel shear wall models are W14x398 and W14x342 respectively. Table 1 gives the details stiffeners of steel plate shear wall models.

Table 1
The details stiffeners of steel plate shear wall models.

model	Size of stiffeners	Number of stiffeners	Diagonal stiffeners	Vertical stiffeners	Horizontal stiffeners	model	Size of stiffeners	Number of stiffeners	Diagonal stiffeners	Vertical stiffeners	Horizontal stiffeners
SD1	100x10mm	1	1	-	-	**SH1**	100x10mm	1	-	1	-
SD2	100x10mm	1	1	-	-	**SV1**	100x10mm	1	-	-	1
SD3	100x10mm	2	2	-	-	**SHV1**	100x10mm	2	-	1	1
SD4	100x10mm	3	3	-	-	**SH2**	100x10mm	3	-	3	-
SD5	100x10mm	3	3	-	-	**SV2**	100x10mm	3	-	-	3
SD6	100x10mm	6	6	-	-	**SHV2**	100x10mm	6	-	3	3
SD7	100x10mm	7	7	-	-	**SH3**	100x10mm	5	-	5	-
SD8	100x10mm	7	7	-	-	**SV3**	100x10mm	5	-	-	5
SD9	100x10mm	14	14	-	-	**SHV3**	100x10mm	10	-	5	5

3.1. The behavior of steel plate shear wall with a diagonal stiffener

The purpose of studying of these steel shear wall models (SD1, SD2, SD3) is to understand the effect of diagonal stiffeners on the behavior of shear wall. The diagonal stiffeners are perpendicular to the angle of the compression fields (approximately 45º). In other words, the diagonal stiffeners are perpendicular to the overall and local buckling of the infill steel plate. In comparison with unstiffened steel shear wall, in stiffened shear walls with diagonal stiffeners, global buckling of the inner plate is precluded. Hence, the system provides slightly higher shear capacity and lateral stiffness. Fig. 2 illustrates Von Mises stress distribution and “lateral shear loads-drift” curves of steel shear walls without and with a diagonal stiffener.

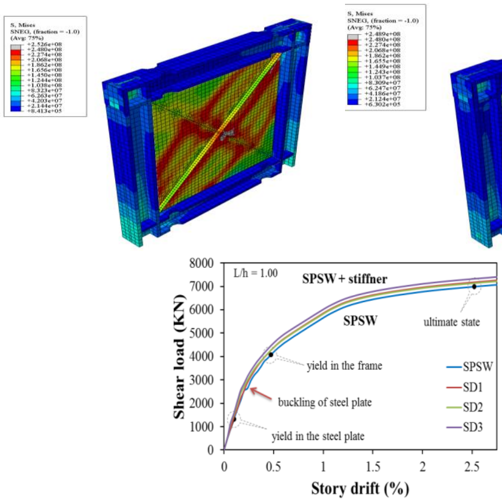

Fig. 2. Von Mises stress distribution and “lateral shear loads-drift” curves of steel plate shear wall without and with a diagonal stiffener.

3.2. The behavior of steel plate shear wall with three diagonal stiffeners

By increasing the number of diagonal stiffeners, the shear capacity of the shear wall increases considerably. The main reason is that three diagonal stiffeners prevent the global and local buckling of the infill steel plate. In other words, when the number of diagonal stiffeners is increased to three, the out-of-plane flexural capacity of inner plate increases. It should be noted that when the diagonal stiffeners are arranged along the tensile strips, they do not affect the elastic buckling of inner plate and the initial elastic stiffness of steel shear wall. Fig. 3 shows Von Mises stress distribution and “lateral shear loads-drift” curves of steel plate shear walls with three diagonal stiffeners.

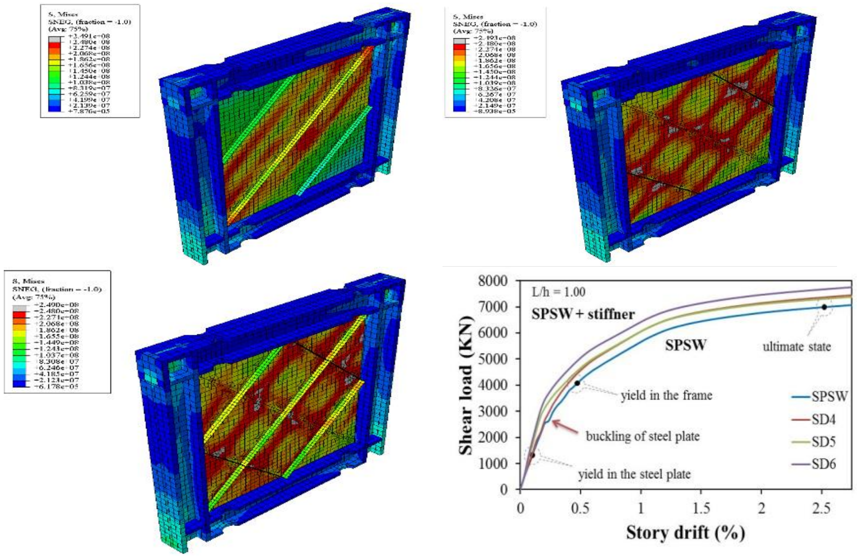

Fig. 3. Von Mises stress distribution and “lateral shear loads-drift” curves of steel shear wall by three diagonal stiffeners.

3.3. The behavior of steel plate shear wall with seven diagonal stiffeners

The finite element models of the steel shear wall with seven diagonal stiffeners are simulated and analyzed. When the distance of diagonal stiffeners approaches each other, the overall and local elastic buckling of the inner sheet is completely controlled. The system provides the most elastic stiffness and the shear capacity as compared with other finite element models. However, because the number of diagonal stiffeners is high, the yield of the infill steel plate occurs later, and the behavior of the system is completely different. Fig. 4 shows Von Mises stress distribution and "lateral shear loads-drift" curves of steel plate shear walls with seven diagonal stiffeners. As shown in Fig. 4, when the number of diagonal stiffeners is seven, the yield starts from stiffeners and afterward the infill steel plate initiates to yield. It is also quite noticeable in Fig. 4 that the initial elastic stiffness of the system increases markedly.

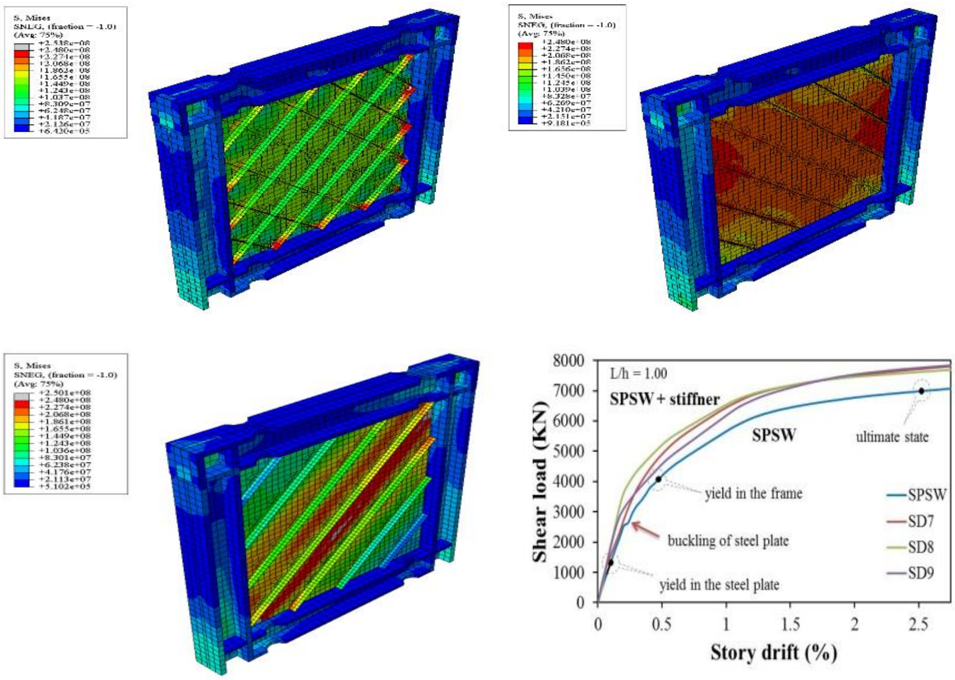

Fig. 4. Von Mises stress distribution and "lateral shear loads-drift" curves of steel shear wall by seven diagonal stiffeners.

3.4. The behavior of steel plate shear wall with horizontal and vertical stiffeners

In order to understand the effect of diagonal stiffeners, finite element models of steel shear walls with horizontal and vertical stiffeners are considered and subjected to nonlinear pushover analysis. Fig. 5 shows Von Mises stress distribution and "shear load-story drift" curves of steel plate shear walls with horizontal and vertical stiffeners. It is worth to mention that the use of horizontal and vertical stiffeners divides the infill steel plate into smaller parts; however, it does not have much impact on the system's behavior.

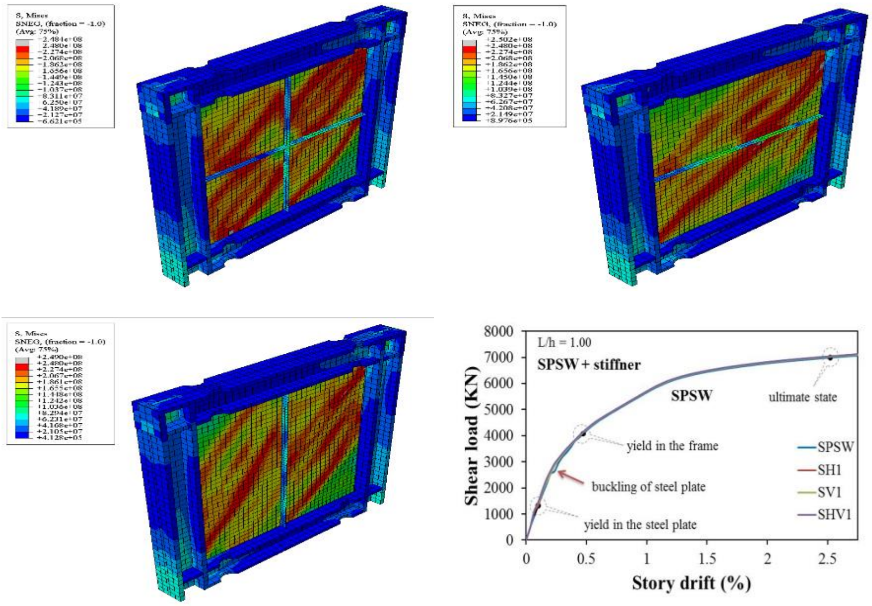

Fig. 5. Von Mises stress distribution and "lateral shear loads-drift" curves of steel shear wall by single horizontal and vertical stiffeners.

3.5. The behavior of steel shear wall with three horizontal and vertical stiffeners

In order to divide the infill steel plate into smaller parts, three horizontal and vertical stiffeners are used. Fig. 6 shows Von Mises stress distribution and "shear load-story drift" curves of steel plate shear walls with three horizontal and vertical stiffeners. As it is shown, the inner plate is divided into smaller parts. The yield is uniform on the inner plate. Although the yield in the inner plate is occurred uniformly, the shear capacity of the system does not increase significantly.

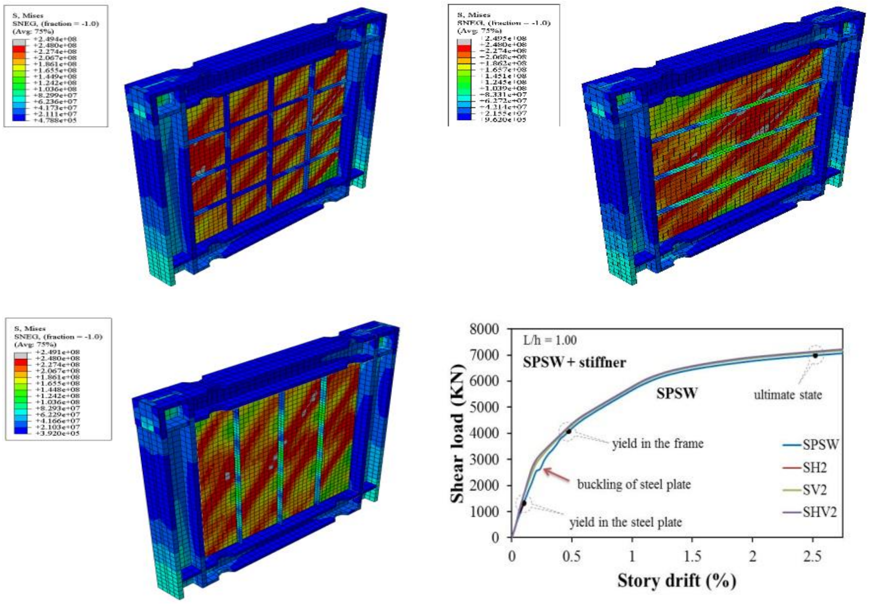

Fig. 6. Von Mises stress distribution and "lateral shear loads-drift" curves of steel shear wall by three horizontal and vertical stiffeners.

3.6. The behavior of steel shear wall with five horizontal and vertical stiffeners

The finite element models of the steel plate shear walls with five horizontal and vertical stiffeners are developed to understand the impact of more stiffeners on nonlinear behavior of the shear walls. Fig. 7 depicts Von Mises stress distribution and “lateral shear loads-drift” curves of steel plate shear walls by five horizontal and vertical stiffeners. In accordance with the figure, the infill steel plate undergoes full shear yielding and the tensile strips (tension fields) are no longer formed on the inner plate. It is perfectly observed that the overall and local elastic buckling of the inner plate is prevented and the steel plate is subjected to pure shear yielding. It is noteworthy that the initial elastic stiffness and shear absorption of shear wall increase. However, the amount of shear capacity increase is much lower than shear walls with diagonal stiffeners.

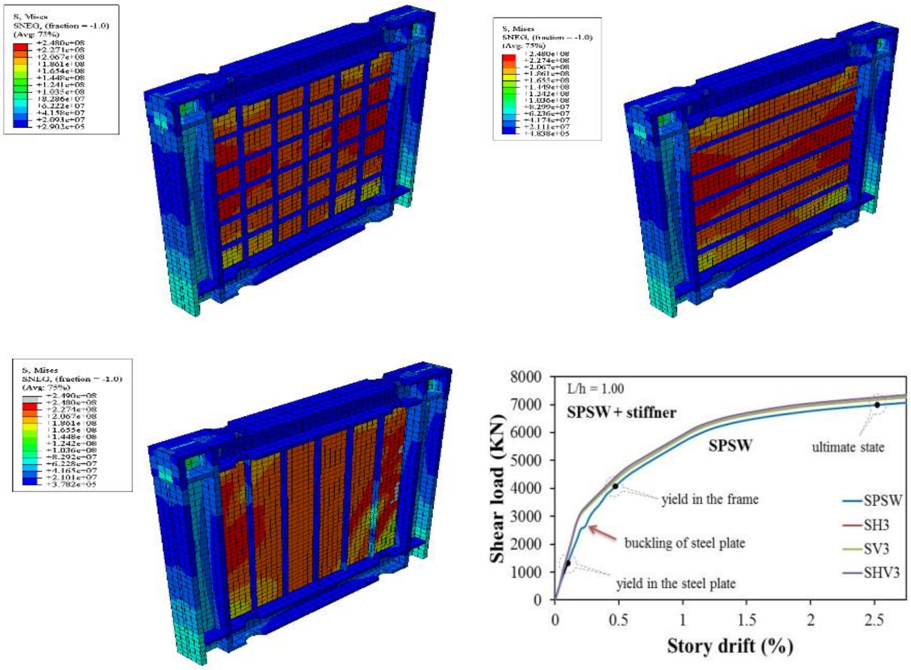

Fig. 7. Von Mises stress distribution and “shear load-story drift” curves of steel plate shear walls with five horizontal and vertical stiffeners.

4. Seismic design parameters (initial stiffness, ultimate strength, and ductility)

Initial elastic stiffness is an important factor in seismic design and displacement control of structures. Initial elastic stiffness of finite element models is calculated and compared with unstiffened steel shear walls. The initial elastic stiffness of finite element models of steel plate shear walls is given in Table 2. As it can be seen, the initial elastic stiffness of the steel plate shear plate with diagonal stiffeners is increased by 44%, which is very effective in controlling the relative displacement of high-rise buildings. Also, the use of single horizontal and vertical hardening does not have a significant effect on the initial elastic stiffness of the shear wall. But when the single diagonal stiffener is used, the initial elastic stiffness of the system increases by 12.4%.

Table 2
The initial elastic stiffness of finite element models.

Model	Stiffness (KN/mm)	Difference	Increase %	Model	Stiffness (KN/mm)	Difference	Increase %
SPSW	417.75						
SD1	419.51	1.76	0.42	**SH1**	417.78	0.03	0.01
SD2	447.05	29.3	7.01	**SV1**	421.6	3.85	0.92
SD3	469.69	51.94	12.43	**SHV1**	437.09	19.34	4.63
SD4	436.93	19.18	4.59	**SH2**	471.24	53.49	12.8
SD5	516.47	98.72	23.63	**SV2**	467.95	50.19	12.02
SD6	567.88	150.13	35.94	**SHV2**	493.38	75.63	18.1
SD7	451.41	33.66	8.06	**SH3**	507.94	90.19	21.59
SD8	514.55	96.8	23.17	**SV3**	508.12	90.37	21.63
SD9	601.61	183.86	44.01	**SHV3**	519.13	101.38	24.27

The ultimate shear capacities of steel plate shear wall models are calculated according to ASCE7. The ultimate shear strength of the finite element models of this study is represented in Table 3. According to the table, diagonal stiffeners can increase the ultimate shear capacity of steel plate shear walls up to 11% as compared with unstiffened steel plate shear wall. It is worth noting that when horizontal and vertical stiffeners are used, the ultimate shear strength of the shear wall does not increase noticeably. However, when a single diagonal stiffener is utilized, the ultimate shear strength increases by 4.8%.

Table 3
The ultimate shear capacity of finite element models.

Model	Capacity (KN)	Difference	Increase %	Model	Capacity (KN)	Difference	Increase %
SPSW	6988.33						
SD1	7178.09	189.76	2.72	**SH1**	7031.35	43.02	0.62
SD2	7137.28	148.95	2.13	**SV1**	7018.73	30.4	0.44
SD3	7324.46	336.13	4.81	**SHV1**	7040.14	51.81	0.74
SD4	7364.01	375.68	5.38	**SH2**	7105.54	117.21	1.68
SD5	7303.01	314.68	4.50	**SV2**	7092.13	103.8	1.49
SD6	7671.73	683.4	9.78	**SHV2**	7134.8	146.47	2.10
SD7	7719.79	731.46	10.47	**SH3**	7182.81	194.48	2.78
SD8	7621.66	633.33	9.06	**SV3**	7170.68	182.35	2.61
SD9	7761.66	773.33	11.07	**SHV3**	7260.97	272.64	3.9

The ductility of a structure is another important seismic parameter. The nonlinear response of steel plate shear wall is idealized to bilinear elastic-plastic behavior based on the theory of equal energy. Therefore, the ductility of finite element models is calculated according to the idealized bilinear curve. In Table 4, the ductility of finite element models of steel plate shear walls is shown. The use of diagonal stiffeners increases the ductility of shear wall by 29% as compared with unstiffened steel shear wall. This is due to that the diagonal stiffeners prevent the overall and local elastic buckling and increase the initial elastic stiffness. When the single horizontal or vertical stiffener is used, the increase of ductility is small as compared with the shear wall with a single diagonal stiffener.

Table 4
The ductility of finite element models.

Model	Ductility	Difference	Increase %	Model	Ductility	Difference	Increase %
SPSW	5.14						
SD1	5.21	0.07	1.35	**SH1**	5.15	0.01	0.15
SD2	5.37	0.23	4.48	**SV1**	5.16	0.02	0.4
SD3	5.49	0.34	6.67	**SHV1**	5.35	0.21	4.09
SD4	5.28	0.13	2.6	**SH2**	5.74	0.6	11.64
SD5	6.05	0.91	17.61	**SV2**	5.71	0.56	10.95
SD6	6.3	1.16	22.54	**SHV2**	6	0.86	16.65
SD7	5.46	0.31	6.08	**SH3**	6.14	0.99	19.32
SD8	5.8	0.66	12.84	**SV3**	6.15	1.01	19.58
SD9	6.64	1.5	29.18	**SHV3**	6.2	1.05	20.51

5. Conclusion

In this study, finite element model of stiffened and unstiffened steel plate shear wall is developed. Stiffened steel plate shear wall models have diagonal or vertical and horizontal stiffeners. The results of nonlinear pushover analysis of steel plate shear walls are compared with shear walls with the unstiffened shear wall. In accordance with the obtained results and observations, the following conclusions can be drawn:

- The nonlinear behavior of steel shear walls with and without stiffeners can be modeled using finite element method.
- The steel shear wall with stiffeners provides higher initial elastic stiffness than unstiffened steel shear wall.
- In comparison with the shear wall with horizontal and vertical stiffeners, steel plate shear wall with diagonal stiffeners provides grater elastic stiffness.
- The shear load absorption and maximum shear strength of steel shear walls with diagonal stiffeners are higher than unstiffened steel plate shear wall or with vertical or horizontal stiffeners.
- The ductility of steel plate shear wall with diagonal stiffeners is greater than shear walls with horizontal and vertical stiffeners. The reason is that diagonal stiffeners increase the initial lateral stiffness.

References

[1] Sabelli R, Bruneau M. Design guide 20: steel plate shear walls, American Institute of Steel Construction. Chicago, IL, USA 2007.

[2] Association CS. Limit states design of steel structures. Canadian Standards Association; 2001.

[3] Astaneh-Asl A. Seismic behavior and design of steel shear walls 2001.

[4] AISC A. AISC 341-10, Seismic Provisions for Structural Steel Buildings. Chicago, Am Inst Steel Constr 2010.

[5] Shafaei S, Ayazi A, Farahbod F. The effect of concrete panel thickness upon composite steel plate shear walls. J Constr Steel Res 2016;117:81–90. doi:10.1016/j.jcsr.2015.10.006.

[6] Rassouli B, Shafaei S, Ayazi A, Farahbod F. Experimental and numerical study on steel-concrete composite shear wall using light-weight concrete. J Constr Steel Res 2016;126:117–28. doi:10.1016/j.jcsr.2016.07.016.

[7] Ayazi A, Ahmadi H, Shafaei S. The effects of bolt spacing on composite shear wall behavior. World Acad Sci Eng Technol 2012;6:10–27.

[8] Shafaei S, Farahbod F, Ayazi A. Concrete Stiffened Steel Plate Shear Walls With an Unstiffened Opening. Structures 2017;12:40–53. doi:10.1016/j.istruc.2017.07.004.

[9] Sabouri-Ghomi S, Ventura CE, Kharrazi MH. Shear Analysis and Design of Ductile Steel Plate Walls. J Struct Eng 2005;131:878–89. doi:10.1061/(ASCE)0733-9445(2005)131:6(878).

[10] Soheil S, Farhang F, Amir A. The wall–frame and the steel–concrete interactions in composite shear walls. Struct Des Tall Spec Build 2018;0:e1476. doi:10.1002/tal.1476.

[11] Hosseinzadeh SAA, Tehranizadeh M. Introduction of stiffened large rectangular openings in steel plate shear walls. J Constr Steel Res 2012;77:180–92. doi:https://doi.org/10.1016/j.jcsr.2012.05.010.

[12] Berman JW, Bruneau M. Experimental investigation of light-gauge steel plate shear walls for the seismic retrofit of buildings 2003.

[13] Hibbitt, Karlsson, Sorensen. ABAQUS/Explicit: user's manual. vol. 1. Hibbitt, Karlsson and Sorenson Incorporated; 2001.

[14] SHAFAEI S, RASSOULI B, AYAZI A, FARAHBOD F. NONLINEAR BEHAVIOR OF CONCRETE STIFFENED STEEL PLATE SHEAR WALL n.d.

[15] Lubell AS, Prion HGL, Ventura CE, Rezai M. Unstiffened Steel Plate Shear Wall Performance under Cyclic Loading. J Struct Eng 2000;126:453–60. doi:10.1061/(ASCE)0733-9445(2000)126:4(453).