NONLINEAR BEHAVIOR OF CONCRETE STIFFENED STEEL PLATE SHEAR WALL

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ABSTRACT

In recent decades, Steel plate shear wall (SPSW) and concrete stiffened steel plate shear wall (CSPSW) owing to their lateral stiffness, shear capacity, and ductility are considered as proper lateral-load resisting systems. In SPSW system, infill steel plate buckles in compression field and the system carries lateral load by developing diagonal tension field; on the contrary, in CSPSW due to the introduction of reinforced concrete panel, buckling of the infill steel plate is prevented. Therefore, the CSPSW resists shear forces by pure shear yield of the infill steel plate which is markedly higher.

In this study, 16 one-story one-bay CSPSWs, with different infill steel plate thicknesses and practical aspect ratios, are designed in accordance with AISC Seismic Provision. This paper investigates nonlinear behaviour of CSPSW and its corresponding SPSW in order to grasp general behaviour and characteristic of CSPSW. Finite element code is developed by the authors and the nonlinear pushover analysis results depict that the complex behaviour of CSPSW can be predicted. In addition, CSPSW provides considerably higher shear capacity and greater initial elastic stiffness. It is worth mentioning that in CSPSW, the infill composite wall-the steel plate and the reinforced concrete panel- resists lateral load up to a drift of 1.2~1.4 and after that shear capacity of frame becomes dominant. Based on obtained results, ultimate strength and ductility of CSPSW is noticeably greater than SPSW.

INTRODUCTION

Nowadays, steel plate shear wall (SPSW) and concrete stiffened steel plate shear wall (CSPSW) are identified as proper lateral-load resistant systems which have been utilized in some countries such as United States and japan. They can be designed and used in both high-seismic and low-seismic regions (Rafael and Michel, 2006 and Astaneh-Asl, 2002). CSPSW has a composite behaviour because of introduction of the reinforced concrete panel and the composite manner is ensured by shear connectors (Astaneh-Asl, 2002). In addition, limited researches have been fulfilled on CSPSWs; hence, this field of study requires more researches, specifically numerical investigation (Zhao, 2007 and AISC 341-10).

First experimental study was conducted in 2002 by Astaneh-Asl and Zhao at university of Berkeley. Based on obtained results, CSPSW demonstrates ductile behaviour and can resist lateral load up to drift of 5%. In addition, bolts, as shear connectors, can be manipulated to ensure the composite behaviour of the infill steel plate and the prefabricated reinforced concrete panel; therefore, global buckling of the infill steel plate is precluded (Zhao, 2004).

In 2010, Arabzadeh and Ayazi tested several CSPSW specimens at Tarbiat Modares University. Specimens were seven one-story one-bay and four three-story one-bay CSPSWs with scale of 1:3 and 1:4 respectively. In accordance with one-story one-bay CSPSW results, by increasing a number of bolts, the composite behaviour and the shear capacity of the system improves. Based on three-story specimens, base columns must be designed for both shear and bending forces produced by pure shear yielding of the infill steel plate (Arabzadeh, 2011).

According to literature review and AISC 341, more investigation into CSPSW must be accomplished for comprehending its complex behaviour; therefore, this paper investigates nonlinear behaviour of CSPSWs. In order to grasp general behaviour of CSPSWs, several one-story one-bay CSPSWs with different infill steel plate thicknesses and various practical aspect ratios (L/h) are designed in according to AISC341 and nonlinear push-over analyses is conducted.

NUMERICAL METHOD OF STUDY AND VERIFICATION

Variety CSPSWs and corresponding SPSWs are considered in this research. CSPSWs with practical aspect ratios (L/h = 1, 1.5, 2, and 2.5) and different steel plate thicknesses (t_w = 3.42, 4.76, 6.35, and 7.94 mm) are designed according to AISC Seismic Provision (AISC341-10). Table 1 shows designed beams and columns-horizontal boundary elements and vertical boundary elements-sections and aspect ratio of models. The beam-to-column connection with reduced beam section (RBS) is utilized to ensure plastic behaviour of beam at specific location and decrease flexural stiffness demand to columns. RBS details are in accordance with AISC358-11 which are demonstrated in table 2. Fig 1 depicts a typical finite element model of CSPSW.

Table 1. The infill steel plate thicknesses and boundary elements sizes of CSPSWs

Model	**L (m)**	**Aspect ratio. (L/h)**	**Infill Steel plate thickness t_w (mm)**	**HBE**	**VBE**
C3-A1	3	1.00	3.42 (0.1345 in.)	W14x159	W14x211
C4-A1	3	1.00	4.76 (0.1875 in.)	W14x211	W14x311
C6-A1	3	1.00	6.35 (0.25 in.)	W14x257	W14x342
C7-A1	3	1.00	7.94 (0.3125 in.)	W14x311	W14x370
C3-A1.5	4.5	1.50	3.42 (0.1345 in.)	W14x311	W14x342
C4-A1.5	4.5	1.50	4.76 (0.1875 in.)	W14x398	W14x426
C6-A1.5	4.5	1.50	6.35 (0.25 in.)	W14x500	W14x550
C7-A1.5	4.5	1.50	7.94 (0.3125 in.)	W14x665	W14x730
C3-A2	6	2.00	3.42 (0.1345 in.)	W27x281	W14x426
C4-A2	6	2.00	4.76 (0.1875 in.)	W27x368	W14x426
C6-A2	6	2.00	6.35 (0.25 in.)	W27x539	W14x550
C7-A2	6	2.00	7.94 (0.3125 in.)	W36x395	W14x730
C3-A2.5	7.5	2.50	3.42 (0.1345 in.)	W36x395	W14x550
C4-A2.5	7.5	2.50	4.76 (0.1875 in.)	W36x487	W14x605
C6-A2.5	7.5	2.50	6.35 (0.25 in.)	W36x652	W14x730
C7-A2.5	7.5	2.50	7.94 (0.3125 in.)	W36x800	Built Up1*

*Built Up1 section depth=870mm, flange width=500mm, flange thick=160mm, web thick=100mm.

Table 2. RBS connection detail for beam sections (AISC 358-05)

Section	a (mm)	b (mm)	c (mm)	Section	a (mm)	b (mm)	c (mm)
W14x159	200	250	95	W27x281	185	485	90
W14x211	205	260	95	W27x368	190	505	90
W14x257	210	275	100	W27x539	195	540	95
W14x311	210	290	100	W36x395	215	635	105
W14x398	215	305	105	W36x487	220	650	105
W14x500	220	325	105	W36x652	225	680	110
W14x665	230	360	110	W36x800	230	705	110

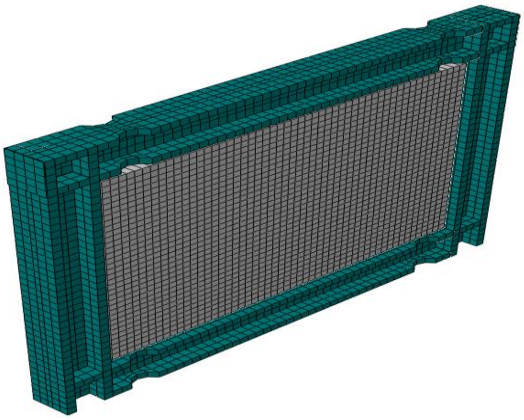

Figure 1. Typical finite element model of CSPSW

The reinforced concrete panel is designed based on ACI 318M-11 to prevent overall buckling of the infill steel plate (Astaneh-Asl, 2002); therefore, a reinforced concrete panel with thickness of 15 cm and reinforcement ratio of 1% is attached to the steel plate by bolts. Centre-to-centre distance between bolts is designed 25 cm to guarantee pure shear yield of infill steel plate based on the b/t ratio of compact webs in plate girders.

The commercial finite element software, ABAQUS, is used for nonlinear push-over analyses. In finite element analysis 4-node shell elements are utilized for infill steel plates and solid continuum 8-node elements are manipulated for beams, columns, and the concrete panel. In addition, 2-node truss element and 2-node Timo'shenko's beam are manipulated for longitudinal and transverse reinforcements and bolts respectively.

Finite element modelling and loading procedures are verified by compering obtained finite element results with two experimental results which were published (Lubell, 2000 and Astaneh-Asl, 2002). A one-story one-bay SPSW and three-story one-bay CSPSW tested by Lubell et al. and Zhao et al. respectively were modeled. İn finite element modelling verifications, material properties were the same as the test reports. Calculated Shear force-Drift curves by finite emelemt modeling is delineated and compared with back-bone curves of experiment, as shown in figure 2, which attest validation of finite element modelling.

Elasto-Plastic behaviour for Steel material and Concrete Damaged Plasticity for concrete material are considered in finite element modeling. The compressive strength of concrete is 50 MPa. Material properties are illustrated in table 3. Moreover, gravity load is not applied in push-over analyses.

Table 3. Material properties of finite element modelling

Elements	Elastic modulus (GPa)	Yield stress (MPa)	Ultimate strain (MPa)	Poisson's ratio
Infill steel plate	200	248	400	0.3
Columns and beams	200	345	490	0.3
Reinforcement	210	365	505	0.3

Bolts	210	600	710	0.3

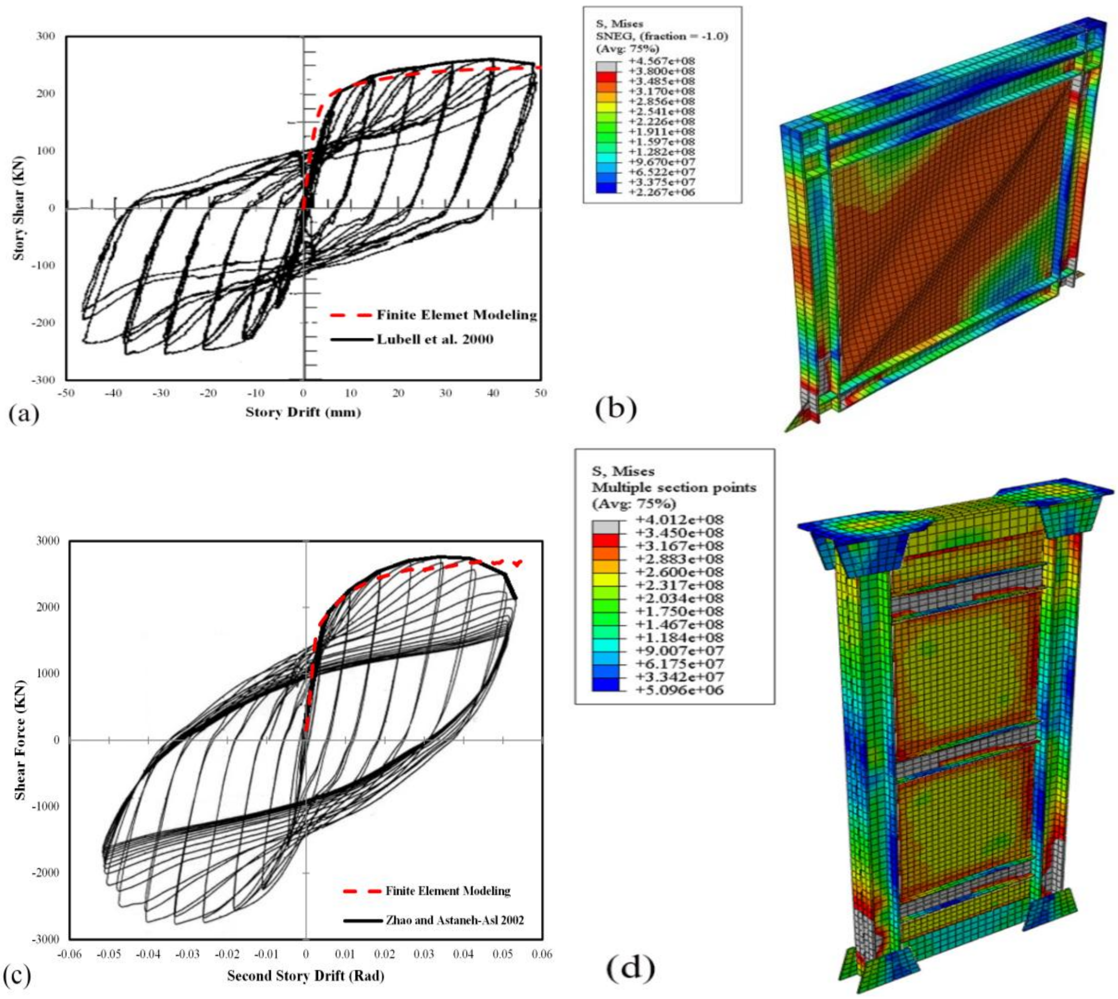

Figure 2. Verification (a) results of Lubell et al. 2000 (b) Mises stress distribution of Lubell's specimen at the displacement of 20 mm (c) results of Qiuhong Zhao and Abolhassan Astaneh-Asl. 2004 (d) Mises stress distribution of Astaneh-Asl’s specimen at the drift 0.024 rad.

DISCOUSSION RESULTS

In order to perceive general behaviour of the CSPSW, “shear force-displacement” curve of typical CSPSW and corresponding SPSW is shown in figure 3. It can be obviously seen that CSPSW provides the higher elastic stiffness and ultimate shear strength. Yield of the infill steel plate and frame, plastic hinge at bottom of columns, in both CSPSW and SPSW take place approximately in the same displacements; by contrast, resisted shear force in CSPSW is markedly greater.

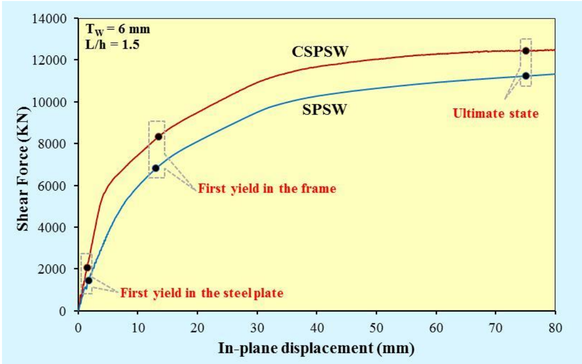

Figure 3. Typical “shear force-displacement” curve of CSPSW and corresponding SPSW

“Shear force-story drift” curves of CSPSW and corresponding SPSW with different aspect ratios are depicted in figure 4. It should be noted that by increasing aspect ratio the shear capacity of both SPSW and CSPSW will increase; however, the rise of shear capacity in CSPSW is considerably superior due to buckling prevention of the infill steel plate owing to the presence of the reinforced concrete panel.

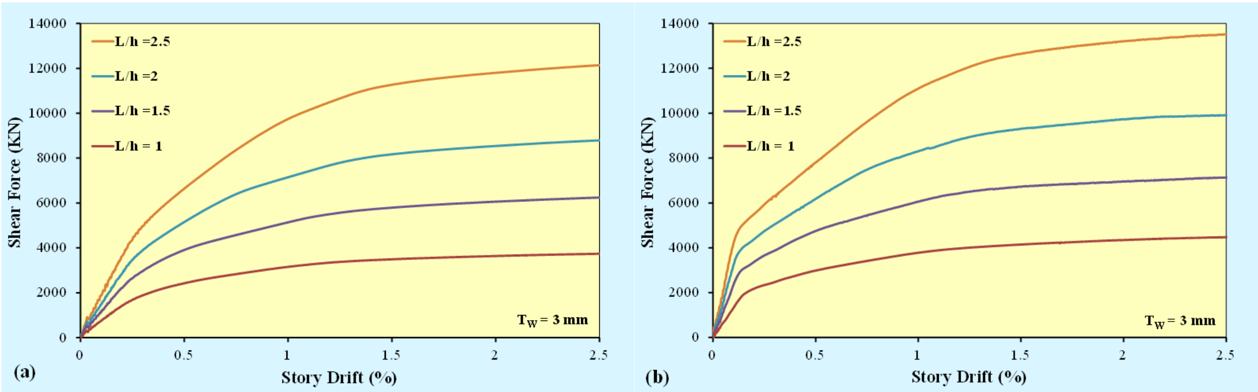

Figure 4. “Shear force-story drift” curve of CSPSW (a) and corresponding SPSW (b) with different L/h.

WALL-FARME INTERACTION

The effective method to comprehend the impact of the composite infill wall is to calculate absorbed shear force by the infill wall. Figure 5 illustrates shear force resisted by the system, the infill wall, and the bare frame. The absorbed shear force is evaluated by deducing the bare frame shear capacity from the system. In CSPSW, it is evident that the infill composite wall, the infill steel plate and the reinforced concrete panel, carries great proportion of story shear up to displacement of 35~40 mm and then the frame shear capacity becomes dominant. In SPSW, the infill steel plate resists lateral shear force up to displacement of 25~30 mm and after that the frame shear capacity overwhelms.

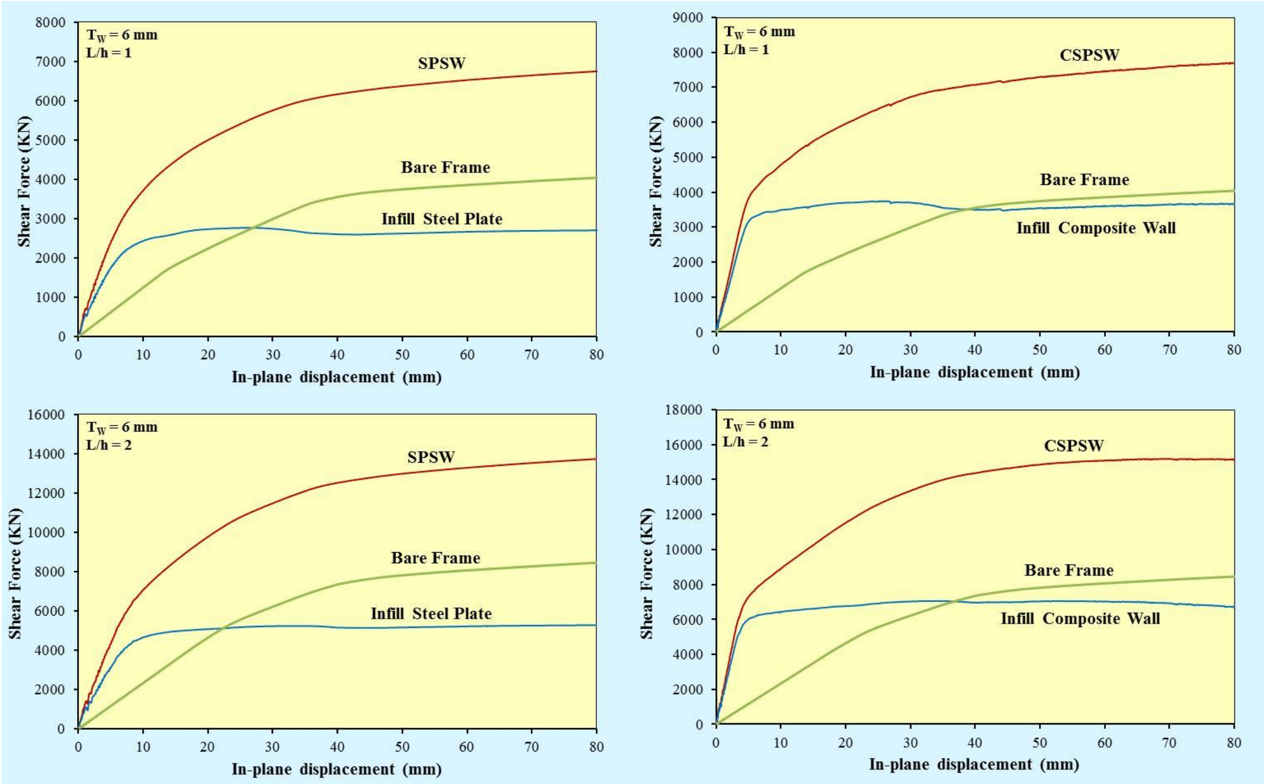

Figure 5. "Shear force-displacement" curve of the system (CSPSW and SPSW), the infill wall, and bare frame.

ULTIMATE SHEAR STRENGTH AND DUCTILITY

Table 4 shows the ultimate strength of SPSW (Ps) and ratio of CSPSW to SPSW (Pc /Ps). The results indicate that owing to composite behaviour of the infill steel plate and the reinforced concrete panel ultimate shear strength of CSPSW increases. It should be noted that while a slender steel plate is utilized, ultimate strength improvement due to the introduction of the reinforced concrete panel is markedly greater in comparison to corresponding SPSW.

Table 4. The ultimate strength of SPSW and ratio of CSPSW to SPSW

	Steel plate thickness=3mm		**Steel plate thickness=4mm**		**Steel plate thickness=6mm**		**Steel plate thickness=7mm**	
L/h	**Ps**	**Pc/Ps**	**Ps**	**Pc/Ps**	**Ps**	**Pc/Ps**	**Ps**	**Pc/Ps**
1	3739.37	1.20	5562.02	1.16	6700.79	1.14	7817.91	1.12
1.5	6244.54	1.14	8416.69	1.15	11238.1	1.11	16033.3	1.08
2	8791.71	1.13	9990.77	1.14	13635.5	1.11	18557.1	1.09
2.5	12142.6	1.11	14565.6	1.11	19157	1.11	35998.4	1.05

The ductility of SPSW and ratio of CSPSW to SPSW are illustrated in Table 5. The ductility ratio is measured based on ultimate drift to yield drift (i.e.μ=d.max/d.y). The yield drift is calculated according to concept of equal energy; put it simple, it is extracted from the idealized elastic-plastic curve. In accordance with ductility ratio results, CSPSW is a proper ductile lateral-load resisting system.

Table 5. The ductility of SPSW and ratio of CSPSW to SPSW

	Steel plate thickness=3mm		**Steel plate thickness=4mm**		**Steel plate thickness=6mm**		**Steel plate thickness=7mm**	
L/h	**μs**	**μc/μs**	**μs**	**μc/μs**	**μs**	**μc/μs**	**μs**	**μc/μs**
1	5.69	1.51	5.94	1.45	6.55	1.37	7.05	1.32
1.5	5.32	1.79	5.64	1.69	5.92	1.62	5.97	1.51
2	4.88	1.95	5.55	1.86	5.86	1.74	5.75	1.59
2.5	4.47	2.12	4.96	1.99	5.26	1.85	4.98	1.64

CONCLUSIONS

In this paper several CSPSWs and corresponding SPSWs with different infill steel plate thicknesses and aspect ratios (L/h) are numerically investigated by using finite element method which is developed by authors. Based on the obtained push-over analyses, the following conclusion can be drawn:

- Finite element method can predict complex behaviour of CSPSW.
- CSPSW provides higher initial elastic stiffness.
- The infill composite wall resists story shear force up to a drift of 1.2~1.4 (displacement of 35-40 mm) and after that shear capacity of the frame becomes dominant.
- By increasing aspect ratios, ultimate shear strength of the CSPSW increases more in comparison to the SPSW.
- Ductility ratio of CSPSW is greater than its corresponding SPSW.

REFERENCES

Arabzadeh A, Soltani M and Ayazi A (2011) Experimental investigation of composite shear walls under shear loadings. Thin-Walled Structures 49 - 842–854

Astaneh-Asl A (2002) Seismic behavior and design of composite steel shear walls. Steel TIPS Report, Structural Steel Educational Council. Moraga, California

AISC, ANSI/AISC 341-10. Seismic provisions for structural steel buildings, Chicago (IL): American Institute of Steel Construction

Building Code Requirements for Structural Concrete (ACI 318M-11), American Concrete Institute. September 2011

Lubell AS, Prion HGL, Ventura CE and Rezai M (2000) Unstiffened steel plate shear wall performance under cyclic loading, Journal Structural Engineering-ASCE;126(4):453–60

Sabelli R and Bruneau M (2006) Steel Plate Shear Walls, American Institute of steel construction, Inc. AISC steel design guide 20. pp. 1-21

Zhao Q and Astaneh-Asl A (2007) Seismic Behavior of Composite Shear Wall Systems and Application of Smart Structures Technology, Steel Structures 7 - 69-75

Zhao Q and Astaneh-Asl A (2004) Cyclic behavior of traditional and innovative compo- site shear walls, Journal of Structural Engineering, ASCE 2004; 130:271–84