

Optimization of concrete/steel thickness ratio in composite steel plate shear walls (CSSWs)

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Abstract

Composite shear walls made of a thin steel plate with reinforced a concrete cover, which is attached to one or both sides of the steel plate, are the third generation of lateral load resisting shear walls. In addition to increasing resistance, ductility and energy absorption, these walls are very economical and are used in constructing tall buildings, resistance of buildings and tanks. In the present research the effect of various thicknesses of steel plate on the behavior of composite shear walls in different shear connectors has been studied. For this purpose, several different models, including moment frames, steel shear walls and composite shear walls, have been analyzed through numerical and experimental models. In composite shear walls, the number of layers of reinforced concrete cover, the distance between the shear connectors and the thickness ratio of steel plate to the thickness of concrete cover are considered as variables. Increasing the thickness ratio of the steel plate to the concrete layer up to optimum leads to reduction in the out-of plane deflection rate of the steel plate and has no effect on the performance of the composite shear wall. In addition, using two layers of concrete cover on both sides of the steel plate decreases the secondary moment.

Keywords: steel shear wall, composite shear wall, post-buckling, shear connector, concrete cover, steel plate thickness.



1 Introduction

Using shear walls in different forms of reinforced concrete, steel or the combination of both as a lateral loads resisting system is the common way in structures. Reinforced concrete shear walls have been used for about 30 years, but during the past three decades a comprehensive study on steel shear walls was carried out leading to the application of this innovative system in both new structures and the reinforcement of existing structures. A shear wall with central steel plate core is similar to the vertical plate girder that is used as a lateral load resisting system in medium and high-rise buildings. The system includes separated panels with every panel internally containing two boundary beams and columns. Resistance was also created by the diagonal tension field occurring at the steel plate in combination with the flexural action of the frame. The provision in the Canadian code of design for structural steel buildings confirmed this system and provided the necessary guidance for analysis and design.

Although this modern system has the same capabilities as the other lateral load resisting systems, such as moment frames, concentrically braced frames and eccentrically braced frames, it is better than other systems in the amount of steel used and it is also easier and faster to construct, as well as having a cleaner finished level. The researches shows that this system was more economical in about 50% of cases, considering the amount of used steel to the steel moment frames, this ratio is also about 15% for concentrically braced frames. Compared with reinforced shear walls, these systems have lower weight thus decreasing the earthquake force and consequently foundation dimensions.

Steel shear walls are stiffer compared to different bracing systems, such as X-shapes, and also with respect to the possibility of making openings in each point of the wall it is much more efficient than all other bracing systems. Furthermore, the plastic behavior of this system and the amount of energy absorption is better than other bracing systems. In this system the stress distribution was smoothed out due to greater incorporation, especially in comparison with the bracing system, which causes the suitable homogeneous behavior at the plastic ambient. One of the problems related to the system is out-of plane buckling steel plate, which causes diagonal lines on the steel plate. A smoother distribution of the lines increases the system shear wall capacity. It is possible to use this capability in two ways:

- Using steel grid as a stiffener which is connected to the steel plate, (SSW).
- Using pre-cast concrete or cast I place, which is connected to the steel plate by shear connectors, (CSSW).

Composite shear wall, (CSSW), consisting of a steel plate, is usually used with a concrete cover on both sides. Of course, the cover is located on one side of the steel plate and connects the concrete to the steel plate with shear connectors, such as studs and so on. Composite shear walls are also classified into two types of composite shear walls without gaps and composite shear walls with gaps. Using this system increases the strength and ductility and also decreases the building weight. It also has perfect behavior under seismic loads. In both steel and composite shear wall systems, there is different post-buckling



phenomenon. In steel shear walls buckling is generic and applies from resistance of the limited area of the steel plate, while in composite shear walls buckling is converted from generic to the local condition so that the whole steel plate resistance is used.

2 Previous studies

During the past twenty years, a substantial percentage of studies in North America and Japan concentrated on the behavior of these walls under their cyclic loading and analytical models. However, there are valuable results of researches about shear walls available to access and many major constructions were built based on the information from this system about the limitations of seismic designing at current seismic code.

2.1 Research in Canada

Researchers at the University of Alberta (Kulak [4] and Driver et al. [1–3]) have conducted monotonic and cyclic tests of un-stiffened steel plate shear walls. The test results indicate a ductile behavior and significant over-strength. Based on their analytical research, Thorburn et al. [5] proposed an equation for the angle of inclination of the tension field. The test indicated that the proposed equation is sufficiently accurate. Driver et al. [1–3] reported the results of cyclic testing of a four-story steel shear wall specimen. The specimen was a 1/2-scale representation of a dual system with a steel plate shear wall welded to a special moment-resisting frame. The cyclical response of the first floor steel shear wall panel indicates failure mode to local buckling of the column that had occurred during cycle 20, causing large deformation amplitudes at locally buckled areas of the column flange. Researchers at the University of British Columbia have completed a series of cyclic and shaking table tests of steel plate shear walls (Lubell et al. [6], Rezai et al. [7, 8]). In these studies, cyclic shear loads were applied to two single story specimens. The boundary frames in the specimens were moment frames resulting in a “dual” structural system. The two specimens differed only in the base gusset plate details and the top beam. For the second specimen, a stronger base connection and top beam were used. The single story specimens experienced significant inelastic deformations up to ductility of about six. The over-strength was about 1.5. The researchers concluded that the two one story specimens demonstrated that the infill steel plates significantly reduced demand on the moment-resisting frame by producing redundant diagonal story braces that alleviated the rotation demand on the beam-to-column connections.

2.2 Research in Japan

Takanashi et al. [9] and Mimura and Akiyama [10] have conducted some of the earliest tests of steel shear walls. Takanashi et al. conducted cyclic tests of 12 one-story and two 2-story specimens. The 12 one-story specimens had 2.1m width and 0.9m height. They used steel plates with about 2.3mm, 3.2mm and



4.5mm thickness. Compared to typical building dimensions, the specimens could be considered to be 1/4-scale of prototype walls. With the exception of one specimen, all specimens had vertical or vertical/horizontal stiffeners welded on one or both sides of steel plate. The boundary frames were very stiff pin-connected frames. The specimens were loaded along their diagonals to create almost pure shear in the panels. The behavior of specimens was very ductile and drift angles in some cases exceeded 0.10 radians. The shear strengths of the specimens were well predicted by von Mises yield criterion given for pure shear as $V_y = A(F_y/\sqrt{3})$.

2.3 Research in the United Kingdom

Sabouri-Ghomi and Roberts [17] and Roberts [19] have reported results of 16 tests of steel shear panels diagonally loaded. The specimens in these tests consisted of steel plates placed within a 4-hinged frame and connected to it using bolts. Some panels had perforations. The tests indicated that all panels possessed adequate ductility and sustained four large inelastic cycles. Typical hysteresis loops presented in Sabouri-Ghomi and Roberts [17] shows specimens reaching a ductility of more than seven without any decrease in strength. The researchers concluded that the strength and stiffness linearly decreases with the increase in the perforation dimensions.

2.4 Research in the United States

Astaneh-Asl et al. [25] also separated evaluations on the behavior of steel and composite shear walls. In these studies, cyclic loads were applied to 3-story specimens. The specimens were 1/10 scale. The goal was to determine suggestions of seismic designing in the field [24, 25].

2.5 Research in Iran

Alinia et al (2004-2006) numerically evaluated on behavior thin steel shear walls. The results indicated that twisting stiffness of boundary members as ambient frame has great effect on increasing buckling elastic load, but this twisting stiff on post-buckling strength of steel plate was not effective. And increasing steel plate stiffness with stiffener or increasing thickness of plate has low effect on increasing the final strength of steel [26-28].

The results of investigations carried out by Hatami and Sabouri (2005) indicates that the kind of beam to column connection has no critical effect on behavior of plates [29].

Many different experiments were carried out by Hatami and Rahai (2008) on behavior of composite shear walls made of concrete and steel or concrete and carbon polymer fibers in research Center of Structure and Earthquake of Amirkabir Industrial University that their results are about to be published [30].

3 Description of different parts of the composite shear wall system for its performance

Steel plate is a main element in composite shear wall. Preferably, this plate is selected of steel with low yield point. For example St37 steel plate is preferred for high strength steel plate. Because St37 steel plate due to its low yield point is preferred to encourage yielding of steel plate.

The reinforced concrete cover on one side or both sides of a steel plate carries some of the story shear by developing compression diagonal field and increased strength and stiffens. Of course main role of the reinforced concrete cover is to prevent out-of plan buckling of steel plate prior to reaching yielding. Shear connectors are used to concrete is to prevent buckling of steel plate. In some case shear studs not only are subjected to shear but also to a considerable tension due to local buckling of the steel plate. For cast-in-place concrete, welded shear studs are usually used, for pre-cast concrete walls bolts can be used.

4 Models properties and investigated parameters

In table 1 the properties of constructed models presented for thickness of concrete cover and shear connectors arrangement and thickness of steel plate.

Table 1: Denomination of models (rate per mm).

No	Model	Thickness of Concrete Layer	Studs Number	Thickness of Steel Plate
1	MRF	-	-	-
2	SSW	-	-	2
3	CSW-5-3*3 (3)	50	9	2
4	CSW-5-3*8 (3)	50	24	2
5	CSW-5-3*3 (5)	50	9	5
6	CSW-5-3*8 (5)	50	24	5
7	CSW-5-3*3 (10)	50	9	10
8	CSW-5-3*8 (10)	50	24	10

5 Geometrical properties of models

The length of frame span that is center distance to center of both sides column is 2000mm and height is also frame 1000-2000mm which is center distance to center of top and bottom beams. Columns and beams sections were also double IPE2000 that were reinforced with two plates (150*12) on the flanges.

Steel plate inscribed inside the boundary beams and columns, it is 1776*776 long and 1776*1776mm wide, and the thickness of these plates are also considered 3, 5 and 10mm. The thickness of concrete cover is 50 and 100mm. there is a 30mm gap between the concrete cover and the boundary elements, 716*1716, 1716*1716mm length and width. In order to connect the concrete

cover with 50mm thickness to steel plate using 7mm diameter and 100mm length bolts and for connecting the concrete cover with 100mm thickness using bolt with 10mm diameter and 120mm length. To reinforce concrete cover thickness 50mm using 6.5mm diameter bars with center distance to center 65mm and for concrete cover 100mm using 8mm diameter bars with center distance to center 85mm.

6 Mechanical properties of material

Characteristics of steel that is used in all models St37 with yield point 240MPa and ultimate stress 370MPa and the behavior of steel bilinear elastoplastic curve is applied for modeling. The concrete has also compression strength of 28 day's cylindrical core sample 45Mpa and its tension strength is equivalent to 3MPa.

7 Modeling theories

To analyze model, the following theories were considered:

- Specimens at their lower level fixed on all directions.
- The behavior of used steel such as steel plate, beams, columns and bars inside the concrete considered bilinear.

Meshing of models was also selected so that connecting the flange to web at columns and beams profile and steel plate to the boundary elements in specimens were rigid connections. Mesh dimensions was also maximum 50*50mm. Using elements on the study, includes Solid 65 for modeling reinforced concrete and considering its crack and Shell 143 for steel plate and beams and columns and Beam188 for shear connectors.

8 Loading

Applied load on models:

A. Static loading: 1. Static loading up to 600KN & 2. Static loading so that it leads to destroy the model

B. Harmonic loading-frequency 1/60HZ and amplitude value 600KN

At harmonic loading the cyclic loading was gyred and the rate of frequency of harmonic loading is 1/60HZ and the rate of amplitude value of the force is 600KN that lasted for 540Sec.

9 Comparing the results for the numerical and experimental models

To construct validity of analyzed model of composite shear wall specimen (1000*2000mm) on which the thickness of steel plate and concrete cover is 3 and 50mm respectively, and height overall ratio to the span is 1/2. Applied under harmonic loading and its deformation-load diagram drawn and compared to the analyzed results of similar numerical model (Figure 2). This experimental model is shown in Figure 1.





Figure 1: Experimental comparative model.

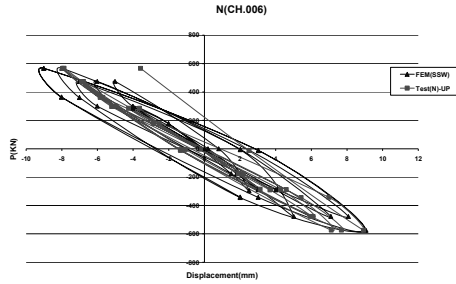


Figure 2: Comparing results of deformation-load in the numerical and experimental model for SSW.

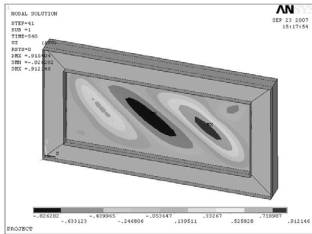


Figure 3: Out-of plane deflection of steel shear wall (SSW).

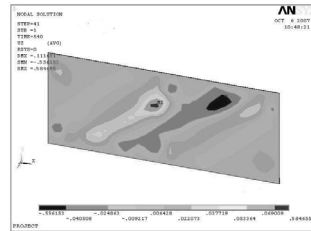


Figure 4: Out-of plane deflection of steel shear wall (CSW-5-3*3).

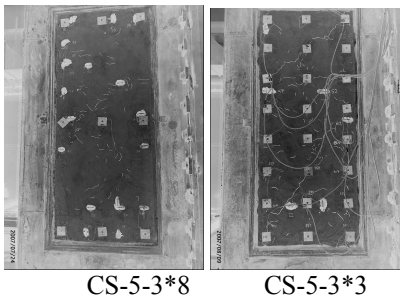


Figure 5: Comparing ultimate cracks at testing specimens.

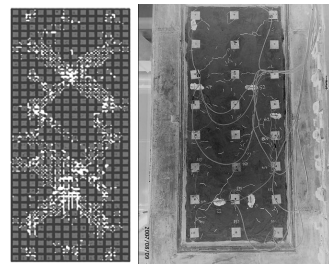


Figure 6: Comparing cracks of experimental with numerical models (CS-5-3*8).

It can be observed that the discrepancy of area under hysteresis curve for numerical and experimental is less than 8%.

10 Software output results in harmonic loading

At the last harmonic loading step, at step 41 where the time of loading is 540Sec after beginning the results of software output and experimental study graphically presented in figure 3–6 to see and compare out-of plane deflection of steel and composite shear wall and also formation of cracks in different experimental and numerical specimens.

11 Comparing the results of numerical models analysis

11.1 Effect of various distances between shear connectors

As is clear from tables 2 and 3, when the number of shear connectors increases (decreasing distance between shear connectors), the rate of lateral displacement decreased 25-30% and the rate of stiffness increased 30-35%.

11.2 Effect of various concrete cover to steel plate thickness ratios

In figure 7, the effect of various concrete to steel thickness ratio (invariable concrete thickness) is studied. This study includes in-plane and so, out-of plane deflection, steel stress, concrete stress and bolts stress.

As it can be observed in table 4 the increasing thickness of steel plate from 3mm to 5mm, the rate of in-plane and out-of plane displacement decreases so that this reduction is about 35-40%, but when the thickness of steel plate

Table 2: Increasing stiffness ratio and decreasing lateral displacement for models at harmonic loading.

Model	FRAME (MRF)	SSW	CSW-5-3-3	CSW-5-3-8
Increasing of Stiffness ratio	1	2.43	3.03	3.7
Decreasing of Lateral Displacement ratio	1	0.41	0.33	0.27

Table 3: Various ratio out-of plane displacements for models at harmonic loading.

Model	SSW	CSW-5-3-3	CSW-5-3-8
Decreasing of out of Plane Displacement ratio	1	0.63	0.37



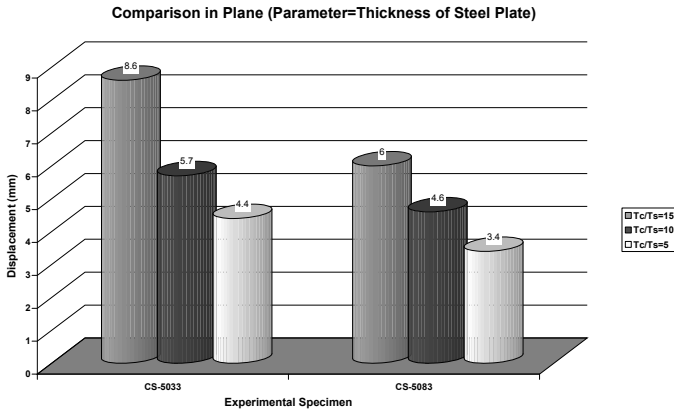


Figure 7: In-plane deflection for various thicknesses of steel plate.

Table 4: Various ratios of case study parameters and the effect of various concrete cover to steel plate thickness ratios in model 50-3-3.

Model	Max. Stress (Steel)	Max. Stress (Concrete)	Out of Plane Disp.	In Plane Lateral Disp.
50-3*3 (3)	1	1	1	1
50-3*3 (5)	0.59	0.89	0.6	0.66
50-3*3 (10)	0.42	0.68	0.49	0.51

Table 5: Various ratios of decrease in case study parameters for using two concrete layers on the sides.

Response / Model	In Plane Lateral Disp.	Out of Plane Disp.	Max. Stress (Steel Plate)	Max. Stress (Con. Layer)	Max. Stress (Shear Studs)
50-3*8	1	1	1	1	1
2*50-3*8	0.96	0.78	0.97	0.93	0.97
100-3*8	0.83	0.68	0.95	0.67	0.88

increases from 5mm to 10mm, there is no substantial in-plane decreasing and out-of plane displacement was about 10-15%. Therefore it is concluded that to minimize a specific out-of plane value of thickness displacement and increment of the thickness has no effect on decreasing displacement.

As is shown in table 5 the rate of in-plane lateral displacement to the one concrete layer on one side of steel plate decreased just 4% due to use of two concrete layer on both sides. This is not substantial. So, the rate of various out-of plane displacements decreased about 22%. Hence, when there is just one concrete layer on one side of steel plate, P-Δ (secondary moment) considered and

add with the rate of out-of plane displacement caused by buckling phenomenon while effect of $P-\Delta$ decreased using two concrete layer on both sides of steel plate and the rate of out-of plane displacement is due to plate buckling. Existence of a concrete layer on one side of steel plate having thickness equivalent twice thickness of every concrete on both sides decreased the rate of displacement and stresses.

12 Summary and conclusion

1. In case of using double concrete layers on both sides of steel plate, there are no substantial variations in the rate of in-plane lateral displacement. The composite shear wall has more capability in energy absorbing, extending the stress on more points of steel plate and ductility to the steel shear wall.
2. Increasing thickness ratio of reinforced concrete cover to the steel plate, increased stiffness and ductility of composite shear wall. Stiffness and ductility increased in field of panel size and geometry and further more it has no substantial effect.
3. Various distance between shear connectors, cause various ductility and energy absorption in composite shear wall. (for example by changing the distance of shear connectors between 440 to 195mm (decrease 56%) stress distribution between shear connectors when it is doubled the stress of steel plate will decrease about 21% and the stress of concrete plate will increase about 33%. That indicate transformation a part of steel plate stress to the reinforced concrete layer increased and cause the increasing the rate of energy absorbing of composite shear wall.
4. Variations in the thickness of reinforced concrete cover to the steel plate at composite shear wall up to a specific value can increase ductility, stiffness and energy absorbing. With respect to the analysis, this ratio obtained for composite shear wall as 1:1 and 1:3 scales equivalent 7.74 and 16.4 respectively, with respect to the thickness of 7mm and 3.5mm of steel plate, in both cases the optimum thickness of reinforced concrete cover determined about 50mm at monotonic and cyclic loading.
5. Distance between shear connectors on composite shear wall up to a specific value can improve system behavior

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