Parametric analysis of steel plated shear structures

M. Ghassemieh, N. Heidari

School of Civil Engineering, University of Tehran, Tehran 11155–4563, Iran
© Central South University Press and Springer-Verlag Berlin Heidelberg 2014

Abstract: Due to outstanding ductility and high strength, the steel plate shear wall (SPSW) is recognized as a good lateral system for building structures; particularly as it interacts with earthquake resistant design. This study aims to reveal the dynamic and cyclic behavior of steel plated shear wall. Finite element method of analysis was implemented in order to simulate the behavior of such a wall structure. To determine the dynamic behavior of un-stiffened plate shear wall, two different analytical models were implemented. The post buckling strength of steel plate subjected to lateral loading was also examined. The post buckling strength of steel plate subjected to lateral loading was also examined. The strength and ductility of the system obtained from the analysis were compared with those of a steel shear wall tests reported before. The pertinent parameters of the shear wall system such as plate thickness, column and beam stiffness and the plate aspect ratio were recognized and their effects were recorded. The effect of stiffeners on the behavior of the SPSW was also investigated.

Key words: steel shear wall; pushover analysis; energy dissipation; ductility; post buckling behavior; Strut element

1 Introduction

From the early 1970’s until today, steel shear walls have been used as the primary lateral force resisting system in some significant buildings around the world. To assist understanding the behavior of this system, there have been research programs in US, Canada, Japan and UK. The behavior of steel plate shear walls (SPSW) appears to be similar to the behavior of the plate girder in which the beam acts as stiffener of the girder and column acts as flange of the girder, although columns appear to be much stiffer than plate girder flanges. The steel plate in the wall system is designed to withstand seismic loads or wind forces. All lateral shear forces in the panel are resisted by the plate, utilizing tension field action. When this new lateral system was introduced, in order to prevent the buckling of the plate, the steel plate wall was stiffened with stiffeners. However, as BASLER [1] demonstrated, for plate girders, the post-buckling tension field action of SPSW can provide considerable strength, stiffness and ductility. After conducting experiments on the steel shear wall system by the researchers, today this lateral system is used by thin plates without stiffeners. When the plate is loaded in shear, the diagonal compression zone buckles while the other diagonal zone yields in tension, and the buckled zone transforms back into diagonal tension zone during the unloading and reloading. Although some part of the plate buckles, the overall SPSW system remains stable during the cyclic loading and therefore it is not required to provide the plate stiffeners for stability. For this reason, some experiments have been carried out without stiffeners [2].

Although a variety of SPSW has been studied and investigated, the un-stiffened plate panel concept initiated by TIMBER and KULAK [3] and DRIVER et al [4] at the University of Alberta in the early 1980s was slowly accepted in the steel industry. Since then, the use of this system along with the research program in this area has most commonly been used in North America. The stiffened SPSW system has been practiced more in Japan. Some of the buildings in Japan that use the SPSW as their lateral force system have undergone significant seismic ground motion and all of them survived with minor damage. Today, this system has been recognized in NBCC of Canada [5] and AISC of US [6]. The concept of utilizing the post-buckling strength of SPSW was developed by THORBURN et al [7] and verified by TIMLER and KULAK [3]. TIMLER [8] evaluated the ductility and hysteretic behavior of such SPSW designed with un-stiffened infill plates and confirmed their great energy dissipation capabilities. TIMLER and KULAK [3] were pioneers in conducting cyclic tests on the steel shear wall without the stiffeners. They reported that the post buckling behaviors of the plates were ideal and they recommended the ductility for such a system. They also
proposed a diagonal tension field strut model to predict the cyclic behavior of the plate system. Afterward, several studies have been conducted to examine SPSW seismic behavior [9–16]. CACCESE et al [9] evaluated the seismic behavior of un-stiffened thin steel plate shear walls under cyclic loadings. They concluded that the nonlinear behavior of the system starts with yielding of the plate and the strength of the system was controlled by the plastic hinge in the columns. They recommended that the steel plate wall must yield before column buckling. DRIVER et al [10] tested a four-story building with unstiffened shear plate steel walls. From their test results, they reported high ductility ratio of 6 for the steel wall system.

Using the shell elements, they also proposed a simplified nonlinear finite element model which did not agree well with the test results. LUBELL et al [11] examined the performance of thin steel plate shear walls for medium- and high-rise buildings subjected to cyclic loadings. Large scale three-story un-stiffened SPSW was tested under the combination of constant gravity load and cyclic lateral loads in a quasi static condition by BEHBABHANIFARD et al [12]. The specimen showed high initial stiffness, excellent ductility and stable hysteretic loops. VIAN and BRUNEAU [13] examined a single-story and single-bay SPSW frames in which the infill panel was designed to act as a “fuse” to yield and dissipate seismic input energy while protecting the surrounding framing. BERMAN and BRUNEAU [14] proposed new linear procedure for capacity design of vertical boundary elements in steel plate shear walls using fundamental plastic collapse mechanism of SPSWs. A modified strip model for analysis of steel plate shear walls was introduced by SHISHKIN et al [15] to capture the accurate behavior of yielding and eventual deterioration of the wall. BERMAN [16] investigated the seismic performance of SPSWs designed according to the provisions. A series of walls were designed and their behavior was evaluated using nonlinear response history analysis for different ground motions. It is found that designs meeting current code specifications satisfy maximum interstory drift requirements.

Apart from the finite element modeling of the SPSW system or similar systems, some of the boundary element type methods or other mesh reduction techniques become very attractive in being applied to such system. State of the art dynamic methods have been presented by GU et al [17] and ZHANG et al [18].

In this work, an analysis of SPSW system subjected to lateral loading was conducted. Emphasis was placed on the structural behavior which was recognized via finite element analysis. One of the finite element models suggested to represent SPSW was the strip or strut model developed by DRIVER et al [10]. This model is generally recognized for providing reliable assessments of ductility and ultimate strength. The shell model was used as a basis to investigate the feasibility of pertinent parameters affecting the SPSW system. Parameters that significantly affect the structural behavior and force transfer mechanism of SPSW, such as plate thickness, plate aspect ratio and stiffeners, are also noted. The strut model was used to investigate column and beam stiffness effects on the behavior of steel plate shear wall.

2 Finite element modeling SPSW using shell elements

For modeling the steel shear wall, a test specimen from the work by DRIVER et al [10] which was a four-story frame with steel shear wall is chosen. The specimen consisted of 3.35 to 4.65 mm steel plate with the Canadian W310×60 and W530×82 steel section for the beam and W310×118 for columns (Fig. 1). According to the test program, all the connections are moment resisting connections. For analyzing the finite element model, ABAQUS, a general computer program, is used [19]. For beam, columns and infill plates, shell element S4 is selected in which both elements contain the plasticity effect and large deformation capabilities. Since during the test no out-of-plane buckling was reported in the columns and beam, the out-of-plane degrees of freedom of the beam and column nodes are restrained. The loading protocol for the test is synchronized in accordance with the test loading protocol as given by ATC-24 [19]. Both material and geometric nonlinearities are considered in the analysis. To start the nonlinear analysis, an initial out-of-plane displacement is imposed in the middle of the steel plate in order to initiate the first governing buckling mode of the plate more rapidly. In the deformed shape of the model given in Fig. 2, tension fields are formed. The diagram of the story shear versus the story drift is given in Fig. 3. Comparison between experimental and analytical pushover curves reveals that
the shell model predicts the behavior of the SPSW close to the test result. The time required to analyze the model is 15 min on the Core2quad (2.7 GHz/8 GB RAM). This indicates that structural analysis of such a model is time consuming and thus impractical for a simple four-story frame with one bay. Therefore, in order to expedite the analysis, a simple tension field strut model proposed by TIMLER and KULAK [3] is employed for further studying the behavior of SPSW system. In this modeling, shell would be replaced by some struts to simulate tension field action of the plate. Also, from failure mode observed from the deformed shape of the model and what was observed from the DRIVER’s test [10], it is understood that the failure mode of the wall was due to column failure at the bottom level. Thus, for studying parameters which play important roles in behavior of the shear wall and reducing column’s influence, a stiffer column is used.

3 Finite element modeling SPSW using tension field strut elements

The steel plate is modeled by the diagonal tension field struts as shown in Fig. 4(a). These strut elements yield in tension and buckle in compression. The plate at each story is treated as a single pin ended brace known as the equivalent story brace model which runs along the diagonal of the bay (as shown in Fig. 4(b)). The thickness of the plate is calculated using the equivalent diagonal brace strut model and based on the elastic strain energy of such system as follows:

\[
t = \frac{2A \sin \theta \sin 2\theta}{L \sin^2 2\alpha}
\]

(1)

Also, the angle of these tension field struts with respect to the column line is given by TIMLER and KULAK [3] as follows:

\[
\tan^4 \alpha = \frac{2}{L} + \frac{1}{A_c} + \frac{2h_s}{A_b} \frac{h_s^3}{180I_c L^2}
\]

(2)

where \( t \) is the steel plate shear wall thickness, \( A \) is the brace strut cross sectional area, \( \theta \) is the angle between the vertical axis and the equivalent brace struct, \( L \) is the steel plate panel length, \( \alpha \) is the angle of the tension field strut element measured from the vertical axis, \( A_c \) is the column cross section area, \( h_s \) is the steel plate panel height, \( A_b \) is the beam cross section area, and \( I_c \) is the column moment of inertia.

In the above equations for providing the least moment of inertia for the columns in the SPSW and in order to prevent the premature buckling in the compression area of the system, the inertia of the column is given as

\[
I_c = \frac{0.00307 t h_s^4}{L}
\]

(3)
Once the above requirements are met, then the SPSW is ready to be modeled with the single diagonal strut or a number of diagonal struts in angle with respect to vertical or horizontal axis (see Figs. 4(a) and 4(b)). It appears that the angle of the struts obtained from the above equation for most steel shear wall thicknesses and practical beam and column sections is commonly within 30°-50° with respect to the column line. Figure 4(c) presents the model built using these diagonal tension field strut elements with the angle of 43° with vertical line. In the model, the steel plate has been divided into 20 strips, and because of push-over analysis 20 diagonal tension field struts in one direction are required. The accuracy of the result depends on the number of strips, and thus by using more strips in the model, higher accuracy is obtained. The area of each strut in each direction is equal to the strip cross section which is the strip width times the plate thickness. In fact, by this method, the tensile and compression behavior of the plate is separated and the diagonal tension field struts are placed in one layer. For modeling the struts, element type B31 of the ABAQUS computer program is used in the analysis. The struts at the end are connected to the columns or beam. Material nonlinearity as well as geometrical nonlinearity of the frame with the diagonal tension field struts simulating the SPSW is considered in the analysis. Figure 5 shows the comparison of the results obtained from the strut model and shell model in the form of diagram of story shear force versus story displacement. The predicted result signifies the accuracy of the simplified finite element model of the steel wall system. The time required to analyze the strut model is 2 min on the Intel Core2Quad (2.7 GHz/8 GB Ram) computer, which indicates that the strut model takes about 90% less computational time for the example problem presented in this work.

4 Discussion

4.1 Effect of plate thickness on behavior of SPSW

Studying the effect of the plate thickness in the overall behavior of the steel shear wall, the shell model is implemented for analyzing different SPSWs. By changing the thickness of all 4 plates from 5 to 15 mm, the effect of plate thickness and differences in their behavior are observed. For a certain geometry and wall thickness, lateral load is applied to the SPSW so that the
elements with the initial imperfections buckle. Then the subsequent loading steps are applied for further analysis. Figure 6 shows the effect of the steel plate thickness on the overall behavior of the system. The results show that the dynamic characteristics of the shear wall improve as the plate thickness increases. Figure 7 shows the effect of plate thickness on strength and stiffness of the lateral system. By increasing the plate thickness, the ultimate strength and stiffness of the system also increase, showing an enhancement in the overall behavior. The SPSW systems are usually more flexible than the concrete shear walls, therefore, when using SPSW in buildings, flexural displacement must be controlled. Figure 7 indicates that the stiffness and strength are increased almost linearly by increasing the steel plate thickness and hence the stability capacity of SPSW is improved. It is shown that by changing the plate thickness from 5 to 15 mm, the ultimate strength of the shear wall increases from 1500 to 9000 kN and flexural stiffness of the system increases from 215 to 360 GPa.

4.2 Effect of column and beam stiffness on behavior of SPSW

Column and beam stiffness are the parameters that may affect the lateral behavior of the SPSW system. The effect of the column stiffness on the overall behavior of the shear wall is evaluated by changing the size of columns in the strut model during pushover analysis, as presented in Fig. 8. It can be observed that the increase in column stiffness can lead to increase in ultimate strength and stiffness of the system. It should be noted that column must have the required strength so that it does not yield before the tension field takes place on the diagonal of the plate. Figure 9 shows that increasing beam stiffness does not have significant effect on the SPSW overall behavior.

4.3 Effect of plate aspect ratio on behavior of SPSW

The aspect ratio of the SPSW system, which is the ratio of the panel length to the panel height, is an important feature in the design and location of the wall. In order to investigate the effect of the aspect ratio on the overall behavior of the wall system, the volume (thickness multiplied by area) of the steel plate used as well as story’s height are held constant and only the
length and thickness of the infill plates vary. Figure 10 shows the deformed shape of the models for various aspect ratios, $W$. The computer shell model is chosen in order to study this effect since the shear deformation as well as the bending deformation of the plate is required. Figure 11 indicates that the effect of aspect ratio on the behavior of SPSW is insignificant. In other words, it shows that if the amount of steel placed in infill plates remains constant, then aspect ratio has negligible effect on the behavior of the wall. In that case, it is suggested to use SPSW in longer spans to avoid having big-size columns.

4.4 Effect of stiffeners on behavior of SPSW

The vertical and horizontal stiffeners used in the steel shear walls make the stiffness as well as the energy

![Fig. 9 Effect of beam dimension on SPSW behavior](image1)

![Fig. 10 Deformation of steel shear walls for different aspect ratios: (a) $W=1.80$; (b) $W=2.75$; (c) $W=3.20$; (d) $W=3.60$; (e) $W=4.10$; (f) $W=4.50)](image2)
dissipation increase. The effect of the stiffeners must be compared with increasing the steel plate wall thickness. To identify this effect, a model with very fine elements is required. The undeformed as well as the deformed shapes of the stiffened shear plate are shown in Fig. 12. The vertical stiffeners are used in both sides of the wall plate. As expected, by utilizing the vertical stiffeners, the buckling of the plate is prevented. Figure 13 compares the pushover curves of stiffened and un-stiffened SPSW. It can be concluded that initial stiffness and final strength increase slightly by adding stiffeners. Although the stiffeners improve the behavior in some sense, fabrication of such stiffeners for the SPSW system is cost ineffective and may cause initial defects in the connections (i.e. welds and/or bolts) and increase the steel weight. Due to the fabrication difficulties of SPSW with stiffeners, it is recommended to use the un-stiffened plate with thicker plate instead. In other words, increasing the SPSW thickness is more effective than employing the stiffeners for the SPSW.

5 Conclusions

1) The performance of the steel plate shear walls is evaluated when being subjected to lateral loadings. Using the shell elements model as well as diagonal tension strut model, the behavior of such system is obtained. It is concluded that the strut model takes about 90% less computational time than shell elements model.

2) The effects of key parameters on the overall behavior of the SPSW system are also identified. The most effective parameter on the performance and behavior of the SPSW system is plate thickness of the shear wall. It is indicated that by increasing the plate thickness from 5 mm to 15 mm, the strength and stiffness of the shear wall increase from 1500 kN to 9000 kN and $2.15 \times 10^{11}$ Pa to $3.6 \times 10^{11}$ Pa, respectively.

3) Increasing column stiffness would lead to an increase in ultimate strength and stiffness of SPSW while increasing beam stiffness does not have significant effect on the shear wall overall behavior. In SPSW, the columns must be designed to remain to be elastic before SPSW, yielding to allow SPSW plates to fully contribute in energy dissipation. Besides, it is observed that the behavior of steel plate shear walls has negligible dependency on its aspect ratio. Adding stiffeners improves the shear wall behavior in some sense, however, fabrication of such stiffeners for the SPSW system may cause initial defects in the connections and increase the overall cost.
References


(Edition by FANG Jing-hua)