Steel Plate Shear Wall - A Lateral Load Resisting System

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Abstract - *The evolution of tall buildings demand excellent lateral load resisting systems. In tall buildings, the wind loads and earthquake loads are very important and need to be considered in the design. Steel plate shear wall is a lateral load resisting system, having columns and beam as horizontal and vertical boundary element respectively, and a steel in-fill plates. Steel plate shear walls was emerged in early 1970's, from there many researches were conducted on the same. In the beginning these were mainly used in Japan and United States so most of the early researches were concentrated on these parts. This paper is prepared to provide a summary on the past researches conducted on steel plate shear walls.*

***Key Words*: Tall building, Lateral load-resisting system, Steel Plate Shear Wall, in-fill plate, Horizontal boundary element, Vertical Boundary element**

1.INTRODUCTION

Now in tall buildings, earthquake and wind load have been a great concern for designers, due to urban development and construction. In order to restrain the lateral forces, various systems having specific features are used. Proper selection of these lateral force resisting systems is very important and it depends on many factors like loading composition, structure behaviour, gravity load, economy, architectural design, etc. Structures must be designed in such a way that in addition to the gravity force, it must withstand the lateral forces also. For this specific elements like tensile bracing, moment resisting frames, concrete shear walls, are required. The steel shear wall system is one of such system having some unique advantages and features. It has excellent energy dissipation capacity, initial stiffness, load carrying capacity, etc. which is very important in high seismic areas.

Since 1970, steel shear wall systems was one of important choice among various alternatives. It was used in several modern and important buildings. In Japan, these were mainly used for new buildings. These were used for seismic rehabilitation of existing buildings in the United States. The steel plate shear wall system comprises panels, two columns border, and beams. The components of steel plate shear wall are marked in Fig. 1.1. The columns and beams in SPSW are called as vertical boundary elements (VBE) and horizontal boundary elements (HBE) respectively. The vertical steel plate known as web plate, is connected to the columns and beams, which may be stiffened or unstiffened, based on the design philosophies. In stiffened the strength is more but the cost is high, so unstiffened is used, which utilize the post-buckling strength of plate.

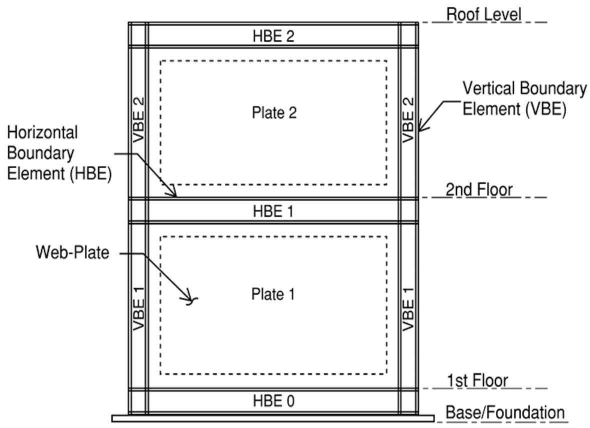

Fig -1: Components of SPSW

Design recommendations for SPSW systems are now introduced in the AISC Seismic Provisions for Structural Steel Building (Steel Design Guide 20-Steel Plate Shear Walls). These provisions are developed based on many past experimental as well as numerical studies. The following section describes some of such important studies related to steel plate shear walls.

2. LITERATURE REVIEW

The first extensive research program on the behaviour of steel plate shear wall panels was conducted by Takahashi et *al. (*1973) in Japan. The study was on various configurations of stiffened shear panels, to determine their suitability for use as a lateral load-resisting system. The researches demonstrated that the stiffened panels dissipated significantly more energy than did the unstiffened panel, but the cost is high, although both types generally behaved in a stable and ductile manner.

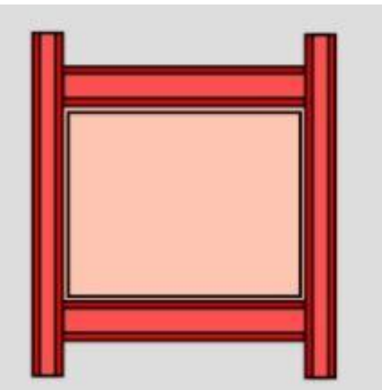

Fig – 2: Un-stiffened SPSW

Fig - 3: Stiffened SPSW

In 1983, Thorbum *et al.* conducted studies on un-stiffened steel plate shear walls and identified the post-buckling behavior. Then a model was developed based on the theory of pure diagonal tension, called strip model. In this model, the tension zone was modeled as a series of tensile only bars, oriented at same inclination as the tension stress in the web. This model helps to study the transfer of forces and resulting stress distribution in the web plate. Various parametric studies were also conducted to determine the influence of various factors like column stiffness, web thickness and panel dimensions, on the stiffness and strength characteristics of SPSW. The results show that the load carrying capacity of SPSW can be increased either by increasing the web thickness or by increasing the column stiffness.

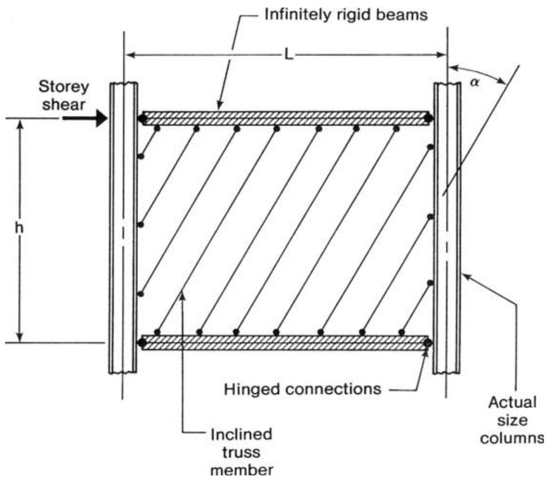

Fig – 4: Strip model (Thorburn et al.1983)

Robert *et al.* (1998) conducted a series of quasi-static cyclic tests on un-stiffened steel plate shear panels to determine the hysteresis behavior of SPSW, and get a stable S-shaped hysteresis loop. A largr-scale, four-story, single bay steel plate shear wall specimen with unstiffened panels was tested using controlled cyclic loading to determine its behavior under an idealized severe earthquake event. The test specimen proved to be very stiff, along with excellent ductility and energy dissipation characteristics, and exhibited stable behavior at very large deformations and for many cycles of loading. A theoretical model was prepared for predicting the hysteresis characteristics, and compared with the experimental. The experiments performed by providing openings shows that the strength and stiffness of panels decreased approximately linearly with increase in the size of opening.

The effects of openings in SPSW were later studied by Deylami *et al.* (2000). Introduction relatively big opening reduce the shear and energy absorption capacity of the plate. More than 50 different models were evaluated by non-linear finite element analysis program. Moreover, the effect of some important geometrical parameters such as plate thickness, opening aspect ratio and opening percentage were also studied. The study determined that the optimum aspect ratio for opening and shown that the optimum aspect ratio for opening depends mostly on the plate thickness rather than the percentage of the opening. They developed a more accurate method for computing the ultimate shear capacity of steel plate shear wall containing rectangular large opening.

Berman *et al.* (2004) determine the feasibility of light-gauge SPSW for use in the seismic retrofit of buildings. The study was conducted on both flat and corrugated plates with epoxy connection and welded connection to the frame. The study identifies the use of light-gauge steel plate shear walls as a viable seismic retrofit option for buildings. The incorporation of light-gauge steel provides substantial ductility and stiffness. From the experimental results, they concluded that corrugated profile infills offers good buckling strength but other advantages are limited.

Sabouri-Ghomi *et al.* (2005) presented Plate Frame Interaction Model (PFI)of the Ductile Steel Plate Wall (DSPW). This model describes the interaction of various components and also the system's overall hysteretic characteristics. Vian *et al.* (2009) conducted an experimental investigation of specially detailed ductile perforated steel plate shear walls. The special perforated panel SPSW specimen with multiple regularly spaced holes exhibited ductile behavior during testing and is a viable alternative to a solid panel SPSW, to allow utility access through the panel without the need for stiffeners around the perforations. The tested specimens also had low yield strength steel infill panels.

Choi *et al.* (2009) performed an experimental study to investigate the structural capacity of steel plate walls with various infill plate designs. Five three-story steel plate shear walls were tested. The parameters for this test were the connection method between the boundary frame and the infill plate, length of the welded connection, and opening in the infill plate. They proposed a method to predict the strength and energy dissipation capacity of the steel plate wall specimens with various infill plate designs. The SPSW with infill plates connected only to the beams exhibited an excellent deformation capacity equivalent to that of the solid wall with fully connected infill plates but load-carrying capacity and energy dissipation capacity decreased. The coupled wall that was stiffened only with the end plates at the wall opening also exhibited a good deformation capacity, equivalent to the deformation capacity of the solid wall. Modification of strip model was done by Shishkin *et al.* (2009) to an accurate representation of yielding and eventual deterioration of the wall.

Kurata *et al.* (2012) proposed a new configuration for SPSWs, where a plate with surrounding boundary elements is installed at the middle of the bay, separate from existing columns. The system incorporates stiffening of vertical boundary elements by tension-rods to ensure stable energy dissipation through the yielding of the thin steel plate while limiting the dimension of the boundary elements.

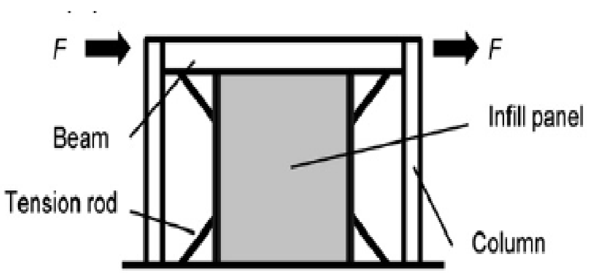

Fig - 5: Mid-span SPSW (Kurata *et al.* 2012)

Alavi *et al.* (2013) presented a special combination of diagonal stiffeners with a central perforation. The seismic behavior of the new system is experimentally investigated and compared to the solid infill plate models. Test results show that the ductility ratio of the specially perforated specimen is about 14% greater than the un-stiffened specimen. The cyclic tests showed that the specimens have had stable hysteretic loops and behaved as appropriate energy dissipative systems.

Fig - 6: Special perforated diagonally stiffened specimen (Alavi *et al.* 2013)

Farzampour *et al* (2015) compared the performance of corrugated steel plate and simple steel plate shear walls, with and without openings. Parameters studied are plate thickness, angle of corrugation, opening size, and opening placement. Behaviors of interest for comparison are initial stiffness, ultimate strength, energy absorption, force-displacement relationship. From the study, it was found that initial lateral stiffness, energy absorption and ductility, increases by trapezoidal corrugated steel shear walls but it reduces ultimate strength. The energy absorption capacity is approximately 25% higher for corrugated SPSW than the corresponding SPSW. This indicates the suitability of corrugated SPSW with an opening under cyclic loadings in regard to different size of the openings.

Guo *et al.* (2015) studied performance dependency on the connections flexibility of the joints and suggested to use semi-rigid connections on the boundary frame with the SPSW system in engineering.

Zirakian *et al.* (2015) assessed the structural behavior as well as plate-frame interaction (PFI) characteristics of un-stiffened low yield point SPSW. Low-yield stress steel plate shear wall systems improves the buckling stability, energy absorption capacity, and serviceability, in which material yielding of infill plates may occur either before or after or even at the same time as geometrical buckling.

Steel plate shear walls consist of a rigidly connected girder and two columns to form a moment resisting frame with a steel plate infill. The moment resisting frame coupled with the steel plate shear wall increases both redundancy and ductile behavior of the system. A detailed finite element analysis has been conducted by Farzampour *et al.* (2015), on 135 simple (unstiffened) steel plate shear walls and 405 corrugated steel plate shear walls (CSSW) with and without openings. The result shows that ultimate shear strength of SPSW is higher than that of CSSW with a negligible margin. The initial stiffness and ductility of corrugated shear walls without an opening are generally higher than those of un-stiffened shear walls, especially in lower thicknesses. The energy absorption capacity is approximately 25% higher for CSSW than the corresponding SSW.

Bahrebar *el al.* (2016) conducted numerical study on SPSWs with trapezoidally-corrugated and centrally-perforated infill plate, to investigate the cyclic behavior and energy absorption capacity. Introduction and increasing of size of the web opening reduced the contribution of the infill plate to the overall performance of the system and to increase the overall system demand on the boundary frame members.

Corrugated steel to significantly increase the strength of the cold-formed steel shear walls but the ductility of the wall was not suitable for seismic applications. One possible solution to improve the ductility involves creating openings in the corrugated sheet. Yu *et al.* (2016) investigated light-gauged cold-formed steel shear wall using corrugated steel sheets with circular holes. The presence of uniformly spaced circular holes in corrugated sheathing changed the failure mode and improved the ductility of the tested shear walls.

Ge *et al.* (2017) developed buckling-restrained SPSW and conducted shake-table test to study the seismic performance. The results showed that the seismic behavior was adequate for survival in large seismic excitations.

To prevent brittle failure of beam-column connection, the beam section is weakened with different methods. The methods included the reduction of the beam section with circular and elliptical web openings, vertical slots in the web and also the reduction of the beam flange. The nonlinear finite element analysis performed by Asla *et al.* (2017) shown that the model with slots in the beam web has the best performance in terms of ductility, energy absorption, stiffness and shear strength than the other proposed models.

Nassernia *et al.* (2017) examined the theoretical and experimental aspects of specific types of tensile-braced mid-span steel plate shear walls and the effects of circular opening on the system. The mid-span implemented to avoid the need for strengthening the surrounding primary columns. The existence of openings in the system leads to higher ductility, but reduced the stiffness, energy absorption capacity and lateral loading capacity of the system.

3. CONCLUSIONS

Even though SPSW systems have been emerged since 1970s, their usage was limited, as the primary lateral force resisting system in buildings for more than three decades, due to the many reason. But, now their good performance in major earthquakes and experiments, and their recent inclusion in codes and standards indicates that SPSW has a good future.

By reviewing the above papers, it is clear that this system can be used for high rise building as a lateral force resisting system. Lots of valuable research works have been performed on SPSW worldwide to evaluate the static and dynamic behavior of SPSW for the past three decades, and many innovations like use of corrugated in-fills, low-yield point steel plate, mid-span SPSW, reduced boundary element, etc were made to improve its performance. Still we can expect many future developments in this system, so the SPSW as a "emerging lateral-load resisting system".

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