"Seismic Behaviour of Stiffened Steel Plate Shear Walls"

Isha Verma, S. Setia

Abstract: ***The need of seismic upgradation in building structures has gained importance in recent years. For lateral load resistance system steel plate shear wall had more advantages compared conventional lateral load resisting systems used for earthquake resistant design of structures due to robust post-buckling strength, substantial ductility, stable hysteretic characteristics and high initial stiffness. In the present paper various aspect of Steel plate shear wall (SPSW) is studied are discussed and opinions of various researchers have been considered with different approaches. Discussion of analytical, experimental and Finite elementmethods using different material composition, connectivity consideration and codal provision aspect are also discussed which may help for advance analysis and design methodologies for the engineering community. The existing design guidelines for the SPSW system in current US and Canadian codes are also discussed.The new concept of low yield point (LYP) steel having improved serviceability, structural performance, and enhanced energy absorption characteristics in design of SPSW is also studied***

Keywords: ***Steel plate shear walls (SPSW),Stiffened or unstiffened, Material non-linearity, shear strength capacity, experimental work, connectivity, codal provision, Design methodologies.***

I. INTRODUCTION

The steel plate shear wall finds its initial application since the early 1980s as a load resistance system in Japan and the United States. Initially, the SPSW was constructed of thick steel plates or rigid steel plates. These projects were based on the concept of avoiding the (elastic) instability of the steel plates. The use of thick or rigid SPSW is an unattractive option due to the higher cost compared to reinforced or prestressed concrete walls. This resulted in a gradual and general change towards the use of sheet steel cutting walls without thin reinforcement. The structure of SPSW consists of a sheet steel panel filled into the structure of the building structure which extends beams and columns, as shown in figure 1. The connections between beams, columns and steel panels resist at the moment. The moment resistance connections between beams and columns are used, while the steel panels are bolted / welded.

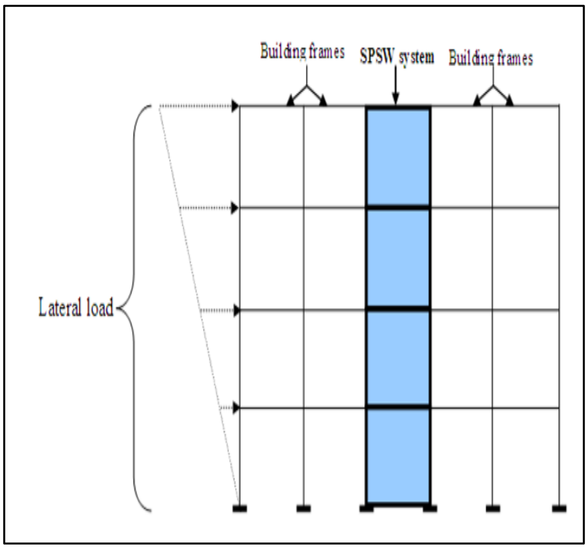

Figure 1a: SPSW system as lateral load resisting system

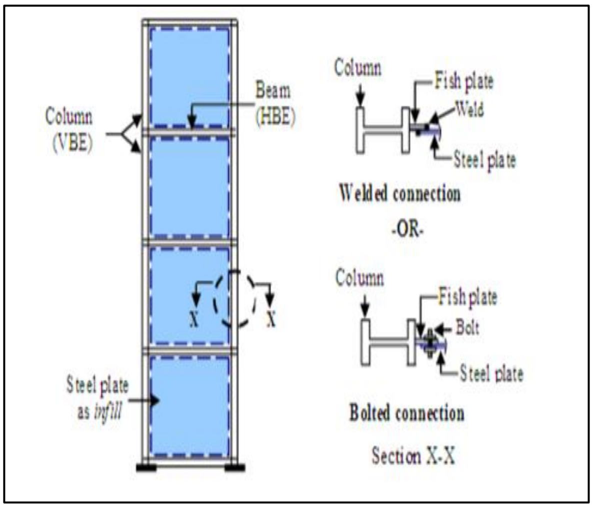

Figure 1b:Components of SPSW system

In recent years, sheet metal partition-wall systems have been used as part of the side-load resistance system in several buildings, mainly in highly seismic areas in Japan and North America. The 56-story LA Live Hotel and Residence in Los Angeles, USA UU., Is the latest example of multi-storey facilities where SPSW systems are used. Nabih Youssef Associates, the structural advisor of this project, decided to replace the heavy concrete walls with a thickness of 762 mm (30 inches) with partition walls in 1 / 4-3 / 8 inch steel sheet (6.13- 9.53 mm) of light.

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This resulted in the availability of free and valuable real estate space, reduced seismic design strengths and foundation dimensions, eliminating 35% of the structure's weight, compressed construction program and budget, and allocation for a Construction simplified and more efficient. [26]

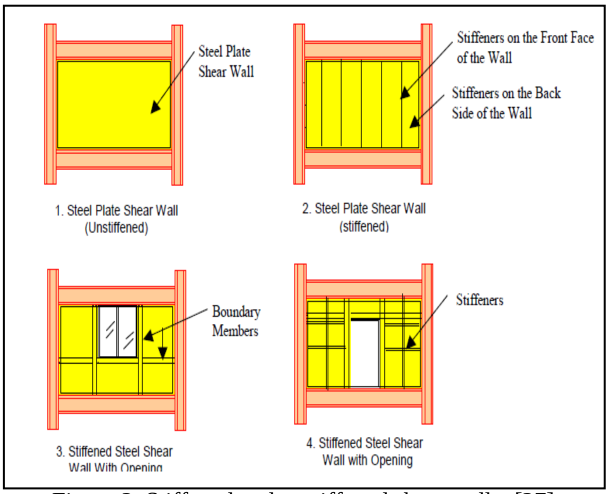


Figure 2: Stiffened and unstiffened shear walls. [27]

The categorization of SPSW is performed based on the criteria of performance, load capacity and perforations. Details are shown in Table 1.

Table1: Different categories of steel plate shear walls

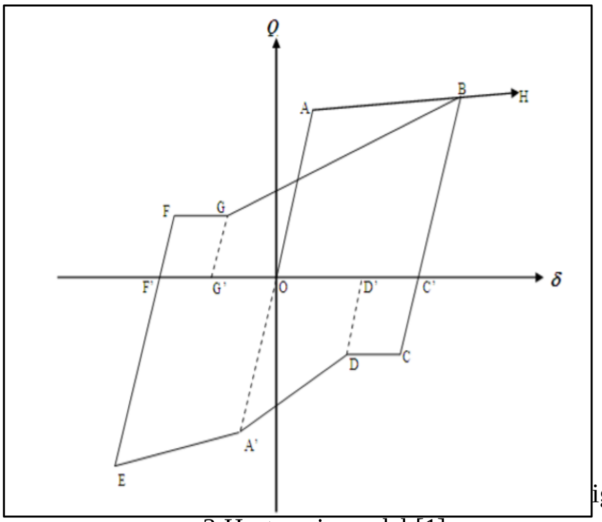
Performance Characteristic	**Features of SPW**
Type of Loading carried by SPW	Lateral Load Only / Lateral Load + Dead wall load / Gravity + Lateral Loads
Structural System	Single wall with and without infill Columns / Coupled wall with and without infill Columns
Stiffener Spacing and Size	Sub panels / Panel buckles with the stiffeners globally / Stiffeners
Web Plate Behavior	Web plate yields before critical elastic buckling occurs (thick plate) / Web plate buckles elastically, develops post-buckling tension field, then yields (thin plate)
Web Plate Perforations	With perforations / Without perforations

Many researchers carry out exhaustive research to study the static and dynamic behavior of SPSW using analytical, experimental and numerical methods that are discussed in the next section.

II. 2.Analytical Methods

Research into shear walls began in the early 1970s and covers a multitude of forms. The following section illustrates the analytical methods for predicting the behaviour of shear walls.

Mimura and Akiyama [1] studied the cyclic behaviour of steel sheet cutting panels using analytical methods. The structural behaviour of the filler plates is superimposed with the structural behaviour of the wall panel. The instability capacity of the filling plates is foreseen using the classic plate theory.



igure 3:Hysteresis model [1]

Thorburn et al. [2] studied the shear behavior of thin SPSW using the diagonal stress field theory. Its model known as the multiple stripe pattern, the orientation of the strips was parallel to the voltage range and the area assigned to each strip was equal to the strip for the plate thickness. The edge radii were rigid and connected to the columns and the limit columns were assigned to the actual rigidity. Elgaaly et al. (1998) [3] analyzed the effect of the lattice and the angle of inclination used in the model of several strips. The amount of strip that will be used will depend on the slenderness of the cutting panels and the rigidity of the profile elements. The results showed that small variations in the angle of inclination have a very low effect on the stiffness. Rezai[4] conducted sensitivity analyses to assess the effect of various structural properties on the inclination angle of tension field.CSA 2001 (Canadian Standard) [23] recommends minimum ten strips for modelling of web plate.

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This helps to approximate the distributed load on frame boundary elements.The widely used idealization for analysis of SPSW is multi-strip modelling technique.

III. 3.Plate-Frame Interaction Model

Sabouri-Ghomi et al. [5] has postulated a general modelling technique that independently investigates the structural behaviour of the plate and the steel frame. This modelling technique studies the interaction of both elements and, therefore, is known as the frame plate interaction model.

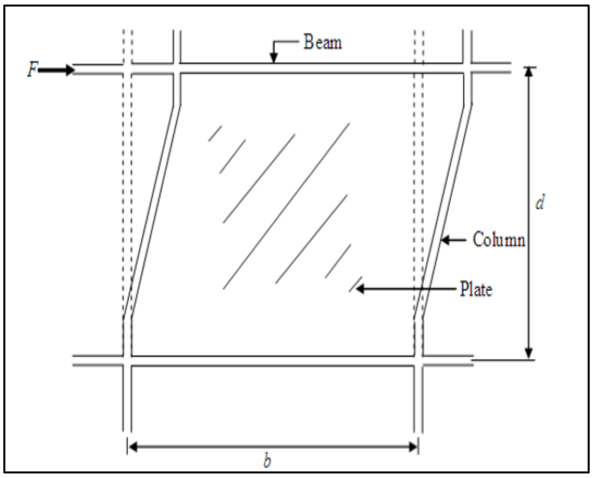

Figure 4:Plate frame interaction model as per Sabouri-Ghomi and Roberts. [5]

Kharrazi et al. [6]investigated by modification in load-deformation diagram to incumbent the overturning moment effect. This method was MPFI or modified plate frame interaction modelling technique used in design of SPSW considering different heights of the system. MPFI method was evaluated by techniques of Finite Element Method using ABAQUS software. The results have shown good agreement between MPFI method and FEM.

IV. FINITE ELEMENT MODEL

Various researchers have used Finite Element Modelling techniques to investigate post-buckling behaviour of thin steel plate shear walls. The elastic out-of-plane buckling of thin plate can be modelled explicitly using 3D finite element method. Elgaaly et al. [7] performed a nonlinear finite element analysis that includes both the geometric non-linearity and the non-linearity of the material. The results of the experiments conducted at the University of Maine were used to validate the FE model. To model the panel and the elements of the profile, three-dimensional elements with a double isoperimetric frame and beam elements of 3 isoperimetric nodes were used. The FE model consists of a 6 × 6 mesh to represent the steel plate in each story and six beam elements for each frame member. For the analysis, the NONSAP software program was used which used the Newton-Raphson algorithm for non-linear systems. The results showed the lower strength of thicker plates due to column performance. The results obtained from the analysis of the finite elements were greater in terms of capacity and rigidity than the experimental results. The finite element model cannot model deformations outside the frame of the frame members, resulting in a variation between the results. Although the prediction of elastic and post-deformation instability was close to the experimental results. Driver et al. [8]had analysed 4 storey SPSW using ABAQUS program. The model was meshed with quadratic elements (shear wall) and boundaries meshed using line elements(3-noded). The material stress-strain behaviour determined from coupon tests was used with bilinear representation in the FE simulation. Ultimate strength and initial stiffness is determined using finite element simulation techniques However, at displacements larger than the yield displacement; the simulation miscalculated the stiffness of SPSW. It was concluded that this discrepancy was due to the inability to include the second-order geometric effects. Rezai[9]has analysed buckling behaviour by defining orthotropic properties of infill panels meshed using shell elements. The orthotropic behaviour shows different elasticity in x, y and z directions. This facilitated to model different stiffness for compression diagonal as compared to tension diagonal. The infill plates are oriented to 45^0angle to horizontal.The results from finite element simulations were experimentally validated from tests at British Columbia University. Rezai et al [10] analyzed SPSW using another FE program known as LSDYNA. The filling panels are interlocked using 4-point shell elements and incorporate geometric and non-linear elements. Vertical loads and horizontal loads are applied to each floor and the loads increase up to the maximum capacity. A normal minimum load is applied to the plate surface to incorporate the imperfections of the plates. Comparison of the results of the FE model with the result of the UBC test showed varying degrees of accuracy. The results of the orthotropic analysis (FEA) have poorly calculated the elastic rigidity.

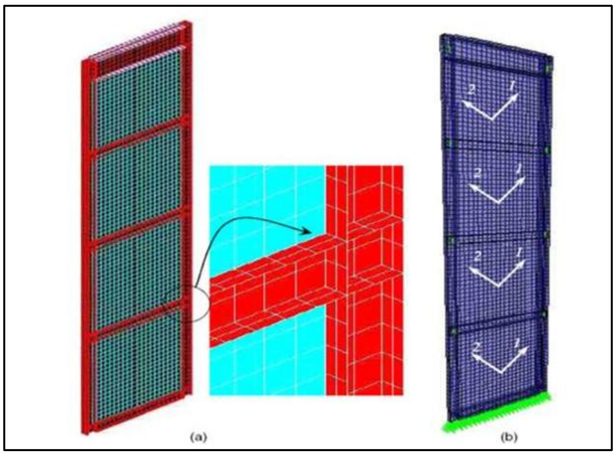

Figure 5:(a) 3-Dimensional FEM model, (b) 3-Dimensional orthotropic model of 4-story SPSW [10]

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Behbahanifard and Grondin et al [11] carried out an explicit analysis that included kinematic tempering material. The results are validated with experimental results and, subsequently, parametric studies have been conducted to identify the parameters that influence the rigidity and strength of SPSW systems. Different aspect ratios of the steel panel have been simulated under the increase in lateral forces and constant gravitational force. It has been found that changing the aspect ratio (from one to two) has a minimal effect on the elastic behavior of SPSW. The standardized cutting capacity of the panel increases for an aspect ratio of less than 1. The SPS's rigidity was strongly influenced by the initial imperfections of the filling panel. Imperfections outside the plane are negligible up to 1% of √ (Lh). The increase in gravitational loads has an inverse effect on the strength of SPSW and also on the elastic properties. Although in recent years FE simulations have promoted studies incorporating material and nonlinear geometries in the SPSW study, the results showed variations with experimental results. FE simulations provided reasonable and accurate solutions to the instability and post-buckling behavior of SPSW that were in strict agreement with the results of experimental tests. It is much more complex than other modeling schemes, such as mult modelling

V. EXPERIMENTAL TESTS

Various experimental researches have been performed on both stiffened SPSW and unstiffened SPSW and multi-storey specimen of different configurations. Comprehensive researches conducted using experimental testing method are reviewed in this section. Takahashi et al. [12] has conducted first extensive research on studying behaviour of SPSW.This research was intended to study both stiffened and unstiffened SPSW with different stiffener configuration for shear panels under inelastic cyclic loadingto determine suitability as load resisting system of heavy structuresdetermine their stability for use as a lateral load resisting system for building and tests were carried out in 2 phases. The first phase tests was conducted on 12 SPSW panels. Four to six cyclic shear loads were applied in each cycle. The important findings from this experimental research were: (a) energy dissipation in stiffened panels is higher as compared to unstiffened panels (b) both stiffened and unstiffened panels behaved in stable and ductile manner Timler and Kulak [13] conducted a survey using a multi-strip model in their test sample using experimental tests. The test was performed using different samples with subsequently reduced cross-sectional area. The expected values of the filling plates stress and the axial deformations coincide closely with the experimental values. This was also observed with the load deformation curve. The bending stiffness of the columns is influenced by the inclinationangles. .

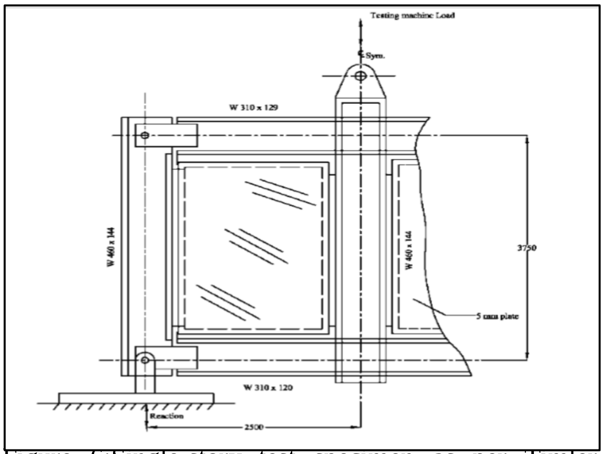

Figure 6:Single-story test specimen as per Timler and Kulak. [13]

Tromposch and Kulak [14] tested a sample of a plant and two panels, similar to those tested by Timler and Kulak [13]. The only difference was that the connections of the screwed beam were not used. The new sample had a thinner filler plate (3.25 mm). Before performing tests to simulate gravitational loads, the columns are subjected to a previous voltage as shown in Figure 6. The hysterical behavior of the sample and a multistrip model proposed by Thorburn et al are examined. [23] is verified. The prestressing bars of the column have been removed before complete. The structural component consists of concrete filled tubes or steel tubes (CFT) such as gravity columns, wide flange steel (WF) beams and columns and a steel wall panel. The failure modes for these test samples were the local instability of the wide flange column (not a gravity column) for one sample and the fracture at the joint of the upper floor radius for the other. Both samples showed high ductility before failure.

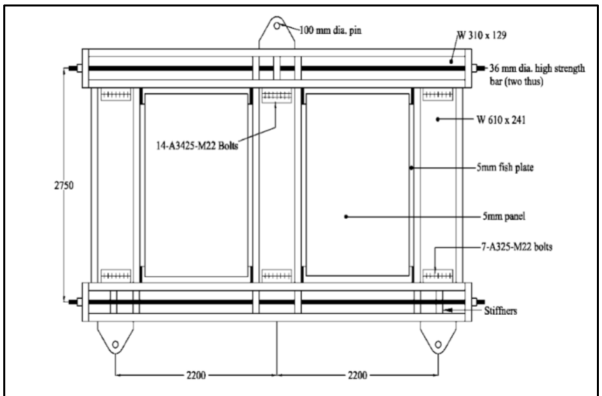

Figure 7:Test specimen as per Tromposch and Kulak. (1987)[14]

Sabouri-Ghomi and Roberts (1992)[15] has investigated small scale SPW models under semi static cyclic stacking tests. The examples were made out of single-board unstiffened plates with a firm, stick finished limit outline.

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The boards were either 300 mm × 300 mm or 300 mm × 450 mm in size and having a thickness going from 0.54 mm to 1.23 mm. Something like four complete cycles of stacking with steadily expanding pinnacle dislodging were connected to every example as such. Another technique for dynamic investigation is created which utilizes time-venturing calculation and fathoms overseeing differential condition of movement. The time-subordinate stacking is likewise expected to act discretely at each floor. To incorporate the nonlinear material conduct, an inexact elasto-plastic hysteresis demonstrate was recommended that incorporated the impact of shear clasping and yielding of basic casing. Lubell et al. (2000)[16]investigated on 2 storey steel plate shear wall and 4 storey steel plate shear wall as shown in figure 7. In every one of these examples, the bars were associated with the segments utilizing minute opposing associations. A moderately stiffer bar was utilized at the rooftop level for the example SPSW2 so as to build up a full strain field. Steel masses were set at every account of example SPSW4 to reenact gravity stacking. Semi static cyclic burden was connected according to ATC-24 (ATC 1992) prerequisites. These trials were likewise mimicked diagnostically through a progression of numerical investigations to asses the capacity of the disentangled examination system introduced in Canadian steel structure standard, CAN/CSA-S16-1 (CSA 1994)[24].

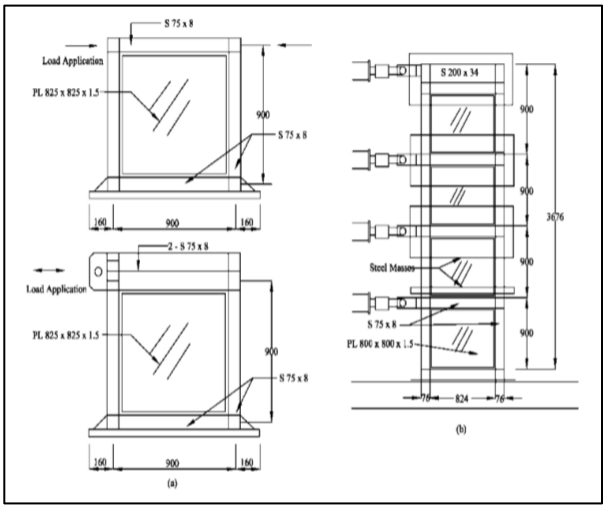

Figure 8. Test specimens of (a) Single story (b) Single story SPSW with stiffer beam (c) Four story SPSW

There was a changing level of consistency in limits anticipated by test outcomes and by investigative models. Moreover, it was discovered that the utilization of a stiffer rooftop bar in the example SPSW2 lead to critical increment in a definitive quality and strength of the SPSW framework. Astaneh-Asl and Zhao (2002)[17]has investigated cyclic behaviour of three-storey SPSW structure. Top and bottom comprised of two half stories and middle comprised two full stories. The structural component consists of concrete filled tubes or steel pipes (CFT) as gravity columns, wide flange (WF) steel beams and columns and steel wall panel. The failure modes for these test specimens were the local buckling of the wide flange column (not a gravity column) for one specimen and the fracture at the upper floor beam-column junction for the other. Both the test specimens demonstrated large ductility capacities before failure.

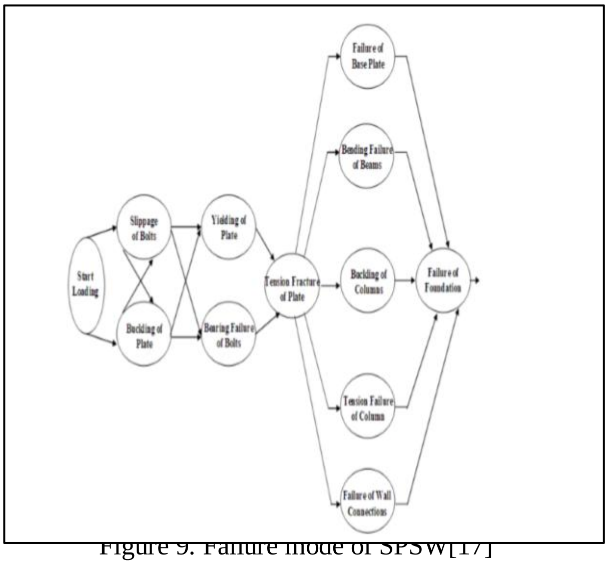

Figure 9. Failure mode of SPSW[17]

Astaneh-Asl [17] has also compiled a complete document detailing the behavior and design of SPSW. Figure 8 shows a list of possible error mechanisms. which is organized in a hierarchical order of error modes.The performance-based design method proposed by Ghosh et al. (2009) [18] is based on the inelastic work performed by the elastic plastic deformation in which the load is of a monotonic nature.

VI. 5.Performance Based Design of SPSW

The performance-based design method as proposed by Ghosh et al., (2009)[18] is based on inelastic work done by elastic plastic deformation where loading is monotonic in nature.

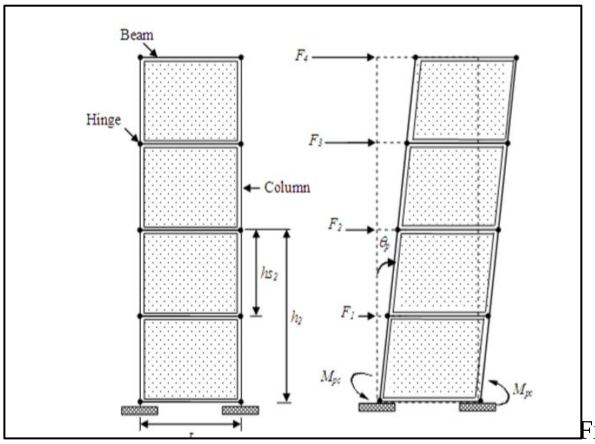

Figure 10. (a) Schematic of the SPSW with pin-connected beams, (b) Selected yield mechanism as per Ghosh et al. (2009)[18]

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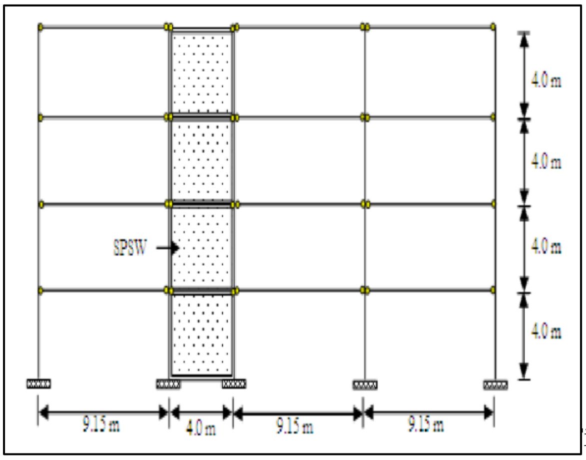
Following is a very brief overview of the design formulation presented by Ghosh et al. (2009)[18]. Another simple design of steel plate shear wall is considered in which beams and columns are pin connected while columns are fixed at base as shown in figure 9 above.



igure 11. Four storey building with pin-connected beams and one SPSW

Gupta et al. (2009) [19] with the use of standard hot moving areas accessible in the United States. UU. (AISC 2005b) have effectively linked the structural technique based on the execution proposed by Ghosh et al. (2009) [18]. The use of SPSW in India is limited to considerable flexibility structures of the fragile seismic tremor. For the use of these advanced seismic design methods, the availability of the sections must be improved

VII. DESIGN CODE PROVISIONS FOR SPSW

The sharp steel sheet walls stand out visibly from the reference points of the plan of two nations, Canada and the United States. The first to adhere to a particular agreement for the SPSW plan was the Canadian standard CAN / CSA-S16.1 in 1994 (CSA 1994) [24], although he had just referred to SPSW in an informational supplement. The 2001 version of a similar standard had fine-grained structure determinations for steel sheet cut dividers, which we examine in this segment. In the United States UU., The AISC Seismic Dispositions (AISC 2005a) [25] were the first to incorporate the rules for SPSW plan frameworks. Subsequently, AISC distributed a different structure directly for the SPSW frameworks. Canadian series of 2001, CAN / CSA-S16-01 (CSA 2001) [23] merged mandatory provisions on the structure of steel sheet cutting partitions. The fundamental estimate of the components of the SPSW framework has been prescribed to be based on the demonstration of a comparable historical support proposed by Thorburn et al. [2]. After the priming plan, any test was approved to be performed using a progressively refined multi-stripe model by Thorburn et al. [2]. For a flexible SPSW, it has been shown that the perimeter components remain flexible to oppose the total pressure range created in the filling plates. The imaginable obstruction of the Vre cutting divider hasbeen reported as

$Vre=0.5RYFYtLsin(2\alpha)$

where Ry = the proportion of normal performance is due to the performance pressure of the structure (which is 1.1 for steel A572 Grade 50). For the nonlinear weakness test, this amplification is not necessary

VIII. Recent Researches in SPSW

Zirakian and Zhang [20] have studied the instability and production of LYP sheets (low Point yield) in the system like SPSW lateral strength system. Detailed analyses are performed to determine the thickness of the limiting plate as a design criterion. The early production of the slabs determines an increase in energy absorption by the slabs, which decreases the amount of energy absorbed by the components of the system structure. Further numerical research was conducted to determine the steel hysterical rigidity, strength and performance wallboard cutting LYP [21] [22]. It has been found that the use of the LYP steel filler plate results in desirable structural behaviour and plate frame interactions.

IX. CONCLUSION

A detailed summary of the research conducted by academics covering various aspects of the SPSW system is discussed. The design philosophy of SPSW should shift from design based on elastic strength to design based on capacity to performance-based seismic design. Design methods should be developed for non-seismic loads, such as wind, gusts, fires, etc. New modeling techniques are also needed to allow the analysis and design methods of SPSW to be useful for practical purposes. It is expected that the actual use of this resistance will set up a relatively new lateral load increase considerably over the next decade, and this process can be accelerated and enhanced if obstacles, as mentioned above, are removed through effective cooperation between researchers, code writers, engineers and developers' practitioners. The SPSW project requires more research, design rules and appropriate recommendations along with standard provisions for standardization.

Future Scope

Steel plate shear wall systems have a huge potential of application in both moderately seismic and high seismic areas. The advantages offered by SPSW makes it more economical and superior in seismic performance than traditional lateral load resisting systems. Besides recent applications as discussed in the previous section, applications of SPSW have been minimum, which may have resulted due to i) conservative or over-designed SPSW with limited aspect ratios as per current code provisions, which hampers its economy, ii) cumbersome and time-consuming analysis techniques not suitable as a design tool for practicing engineers, iii) less flexural stiffness as compare to

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RC shear wall, which challenges its application in high rise buildings where wind load governs the design, iv) almost negligible out-of plane stiffness, which affect the application for structures susceptible to face impact and blast loading, and v) lack of knowledge of the behaviour of SPSW withnon-traditional configurations.

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