Study on Steel Plate Shear Wall (SPSW) with Cutout During Seismic Excitations

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Abstract: ***Steel plate shear wall (SPSW) is rapidly gaining popularity as a very effective lateral load resisting system in highly seismic areas. This system consists of steel infill plate surrounded by boundary beams and columns. Steel plate shear wall has high initial stiffness and very effective in reducing the lateral displacement of structures. In some situations existence of cutouts are unavoidable due to architectural reasons, structural reasons and/or installed heating and cooling systems on the walls. Cutouts in the steel infill plate leads to a decrease in lateral load resisting capacity and improper functioning of the systems and also results in an intense variation in stress distribution. In this paper, the effect of variation in cutout size and cutout shape in steel plate shear wall has been studied by performing time history analysis. The effect of these variables on displacement and stress distribution was analysed and discussed.***

Keywords: Steel plate shear wall, Time history analysis, Drift limitation, Cutout , Displacement.

1. Introduction

Recently there have been large increase in number of tall building, both commercial and residential and the modern trend is towards slender and taller structures. Design of civil engineering structures is typically based on prescriptive methods of building codes. Normally, loads on these structures are low and result in elastic structural behaviour. However, under a strong seismic event, a structure may actually be subjected to forces beyond its elastic limit. Thus the effects of lateral loads are attaining greater importance and almost every civil engineer faced with the problem of providing adequate stability and strength against lateral loads. There are number of lateral load resisting system but shear wall system is commonly adopted in building. A shear wall is a structural lateral load resisting system. Seismic and wind loads are the most common lateral loads that shear walls are designed to withstand.

Steel plate shear walls (SPSW) have been identified as an attractive option for lateral load resisting systems for both new and retrofit construction. Steel plate shear wall is made from thin steel plates which in turn are bounded by the columns and beams of structural system. A Steel plate shear wall system can be idealized as a cantilevered vertical plate girder, in which the steel infill plates act as the web, the boundary columns represents the flanges and the boundary beams act as the transverse stiffeners. Similar to plate girders, the steel plate shear wall system optimizes performance by taking advantage of post-buckling property of the steel infill panels.

The steel plate shear wall behaviour is due to developing of shear buckling and subsequently forming of diagonal tension fields within the infill plate[11]. When an increasing shear load applied to the steel plate shear wall, equal tensile and compressive stress will be developed within the plate. The compressive stress can cause local buckling and as a result the web plate develops waves perpendicular to them. If we draw imaginary diagonals on the plate, the diagonal which gets loaded in compression buckles and cannot support additional load. However, the diagonal in tension continues to take more loads. This behaviour analogous to tension only bracing.

It is obvious that any opening on infill plate could disable the distribution of tension field and hence the steel plate shear wall system leads to unstable phase. Providing cutout in load-resisting part of the structures sometimes due to architectural purpose and other reasons are unavoidable. Figure 1 shows the general view of the steel plate shear wall.

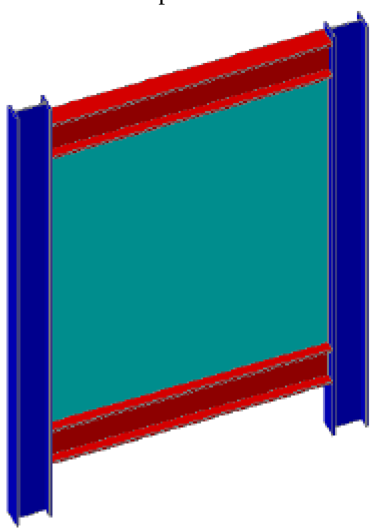

Figure 1: General view of steel plate shear wall

2. Literature Review

Steel plate shear wall (SPSW) is rapidly gaining popularity as a very effective lateral load resisting system in highly seismic areas. Even though there was a great amount of experimental works done on this topic, still it requires a detailed study.

Memarzadeh et al. (2010) conducted a study on dynamic explicit analysis of a steel plate shear wall subjected to El

Centro earthquake. Hong-Gun Park et al. (2010) reviewed the cyclic nonlinear analysis of thin infill plate. Infill steel plates were idealized with inclined tension strips. Abhishek Verma et al. (2012) carried out a study on push over analysis of unstiffened steel plate shear wall. Steel plate shear wall with relatively larger aspect ratio exhibits the greater load-carrying capacity and deformation capacity than the one with smaller aspect ratio. The ultimate load carrying capacity increases linearly with increasing the thickness of steel plate. Valizadeh et al. (2012) conducted experimental investigation on cyclic behaviour of perforated steel plate shear walls. The creation of openings decreases the initial stiffness and strength of the system. Existence of an opening at the center of the panel causes a noticeable decrease in energy absorption of the system. Erfan Alavi et al. (2013) conducted experimental study on diagonally stiffened steel plate shear walls with perforation. A circular opening with the dimension of diameter adopted was ⅓ depth of the panel at the wall center. Jian Guo Nie et al. (2013) conducted experiments on lateral resistance capacity of stiffened steel plate shear walls. The test results showed that stiffeners can be used to reinforce the openings so that the stiffness and stability of steel plate shear walls with openings can be significantly enhanced.

From the past works it was found that steel plate shear wall proved better seismic performance and any perforations on infill plate could leads the system to an unstable phase. Hence a study regarding steel plate shear wall with perforation in steel infill plates are necessary

3. Scope

Recently there has been a greater increase in the number of tall buildings, thus the effect of lateral loads like earthquake forces are attaining increasing importance. Shear wall system are the commonly adopted lateral load resisting system in tall buildings. Steel plate shear walls have became more widespread during these days and are much efficient than RC shear walls. Openings may need to be created within the steel infill plate to accommodate for architectural purposes, passing utilities, and structural reasons, hence a study regarding the seismic response of steel plate shear wall with cutout are necessary. In this paper, analysis of steel framed building with steel plate shear wall under non-linear time history analysis is studied.

4. Objectives

1) To Validate a similar problem with reference to ASCE journal [6] titled "Experimental study of diagonally stiffened steel plate shear walls" using ANSYS 14.5.
2) To analyse the single storey steel frame with and without steel infill plate.
3) To analyse the single storey steel frame with
   a) Infill plates having different shapes of cutout
   b) Infill plates having different size of cutout

5. Validation of the Model Adopted

To provide the needed experimental data for validation of the present study, the experimental data was collected from the experiment conducted by Erfan Alavi and Fariborz Nateghi in 2013 at the International Institute of Earthquake Engineering and Seismology (IIEES) structural laboratory in Iran, which was given in the journal [6]. Base shear values obtained from the push over analysis is used for validation.

Steel plate shear wall (SPSW) with 2-m width, 1.5-m height and infill plate of thickness 0.8 mm were taken. The boundary elements were made of the HEB160 used as the columns and beams. Material properties were given in table1.

Table 1: Details of Material Properties

Steel material	Elastic modulus (MPa)	Yield stress (MPa)	Poisson's ratio
HEB160	2.07 x 10^5	400	0.3
Infill steel plate	2.04 x 10^5	280	0.3

The infill plate and boundary elements of the frame were modelled using shell element of 4-node plastic 181. SHELL181 used in thin to moderately-thick shell structures. SHELL 181 is a four node element with each node has six degree of freedom: translations in x, y, and z directions, and rotations about x, y, and z axes. The meshed model for the validation was shown in figure 2.

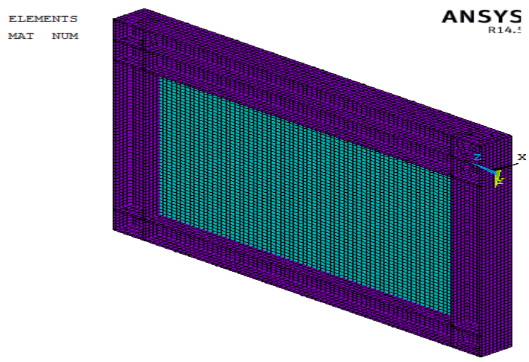

Figure 2: Steel plate shear wall for validation after meshing using ANSYS 14.5

The boundary condition provided for the single storey frame was fixed at the bottom end. The loading is provided as increment in displacement upto 70 mm horizontally at the top beam. A displacement based push over analysis was performed according to the loading given in the test setup. From the table 2 it is concluded that the results from the experiment and software are validated.

Table 2: Comparison of Results for Validation

Result	Experimental value from journal [6]	Using software ANSYS 14.5 (Present study)
Maximum base shear (kN)	765	770

6. Finite Element Analysis

The finite element model of the steel plate shear wall was modelled using the software CATIA V5 and analysis was done by using the finite element analysis software ANSYS14.5. Geometric and material properties for the present study were collected from the journal [9]. Figure 3 shows the geometric details of the steel plate shear wall and table 3 shows the material properties of the steel plate shear wall adopted.

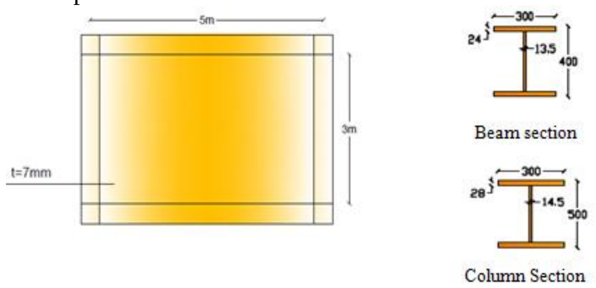

Figure 3: Geometry of the Specimen

Table 3: Material properties of the steel plate shear wall

Steel material	Elastic modulus (MPa)	Yield Strength (MPa)	Poisson's ratio
Beam, Column, Infill plate	2.1 x 10^5	240	0.3

The infill plate and boundary elements of the frame were modelled using shell element of 4-node plastic 181. The boundary condition provided for the single storey frame was fixed at the bottom end. The loading is provided as dynamically in order to produce a dynamic effect on the frame. El Centro earthquake ground-motion records in terms of acceleration time history were taken as input dynamic loading. The duration of time were taken from one to 30.84 seconds. In order to achieve the second objective a bare frame and steel plate shear wall were modelled and meshed, model was shown in figure 4 and 5 respectively.

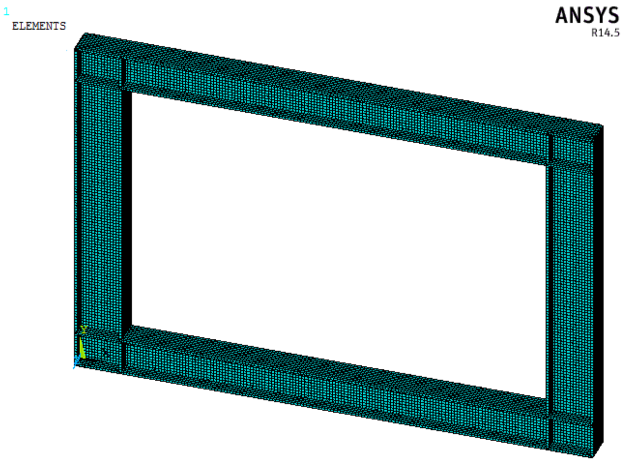

Figure 4: Bare frame

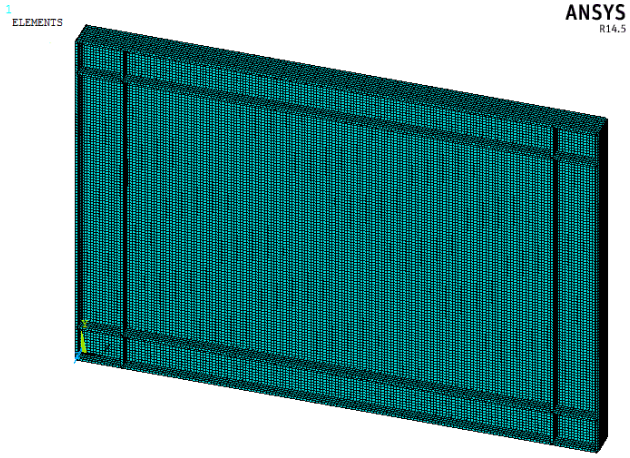

Figure 5: Steel plate shear wall

Non-linear dynamic analysis are also called Time History Analysis, is a technique for determine the dynamic response of a structure subjected any general time dependant loads. This type of analysis is used to determine the time-varying displacements and stresses. It incorporates the real time earthquake ground motions and gives the true picture of the possible deformation and collapse mechanism in a structure. It is a very tedious and complex analysis which requires enough time for solving. The acceleration time history data were collected from the website "www.vibrationdata.com" taken as the input for the dynamic loading.

7. Result and Discussions

During this study effects of steel infill plate on seismic behaviour of single storey frame were investigated. The displacement graph and von-mises stress graph was taken in to account for the study. The critical von-mises stress obtained from the time history analysis is also studied. The maximum von-mises stress in a bare frame is observed near to the base of the frame and for the steel plate shear wall it is observed at the intersection point of steel infill plate and column. Using the result of stress an engineer can say his/her design will fail, if the maximum value of stress induced is more than ultimate strength of the material. It works well for the material are ductile in nature. Displacement and von-mises stress graph obtained from the non-linear dynamic analysis were shown in figure 6-9. Table 4 shows the comparison of bare frame with steel plate shear wall.

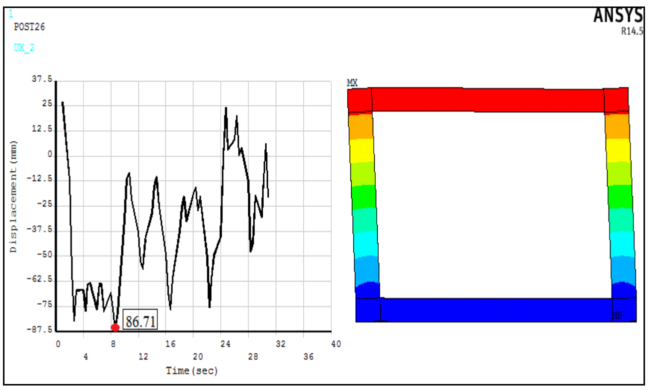

Figure 6: Displacement graph of bare frame at MX

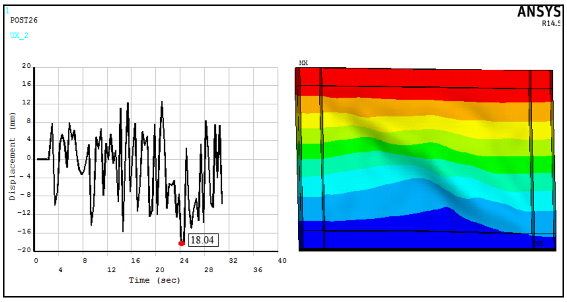

Figure 7: Displacement graph of SPSW at MX

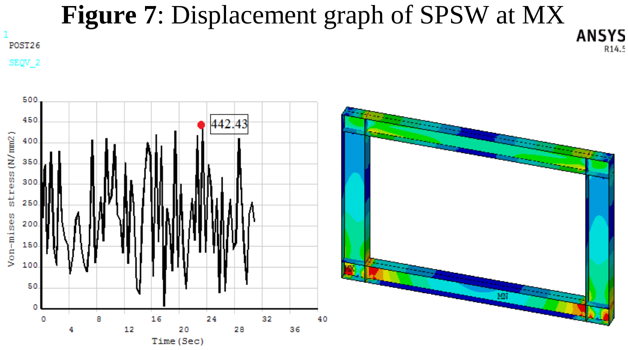

Figure 8: Von-mises stress graph of bare frame at MX

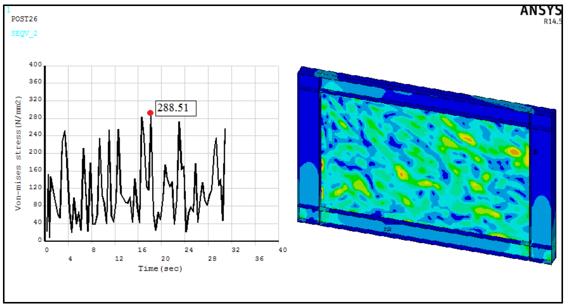

Figure 9: Von-mises stress graph of SPSW at MX

Table 4: Comparison of Bare Frame with SPSW

Parameters	Bare Frame	SPSW	Percentage reduction (%)
Maximum Displacement (mm)	**86.71**	**18.04**	79
Maximum Von-mises Stress (N/mm^2)	442.43	288.51	35

The output results from the finite element analysis shows significant reduction in displacement and von-mises stress when infill plates are attaching to the frame. The displacement and von-mises stress of bare frame were decreased about 79% and 35% respectively by the use of steel infill plate. This is due to the increased stiffness of the steel plate shear wall compared to bare frame. Hence steel plate shear wall can be used effectively as a lateral load resisting system in the seismic regions.

8. Parametric Study: Influence of cutout in SPSW

In order to access the effects of cutout on behaviour of steel plate shear wall, circular and square cutout was created in steel infill plate of steel plate shear wall. As a part of this study variety of cutout size considered in order to evaluate the relation between cutout dimension with displacement and von-mises stress of the system. Cutout sizes considered for the study are shown in table 5.

Table 5: Variations in Size of Cutout

Dimension of cutout	Diameter of the circular cutout in mm	Sides of square cutout in mm
1/6 of panel depth	500	500
1/3 of panel depth	1000	1000
1/2 of panel depth	1500	1500
2/3 of panel depth	2000	2000
5/6 of panel depth	2500	2500

The results obtained for steel plate shear wall with circular and square openings of varying sizes were shown in table 6 and 7.

Table 6: Comparison of Displacement of SPSW with Cutout

Cutout Size (mm)	Max. Displacement (mm)		Percentage reduction (%)
	Square	Circular	
500	**35.43**	**30.17**	14.84
1000	**65.06**	**61.91**	4.84
1500	**76.71**	**73.49**	4.19
2000	**86.27**	**85.41**	0.99
2500	**86.42**	**86.28**	0.16

Table 7: Comparison of von-mises stress of SPSW with cutout

Cutout Size(mm)	Max. Von-Mises Stress (N/mm^2)		Percentage reduction (%)
	Square	Circular	
500	327.68	312.76	4.55
1000	349.54	339.09	2.99
1500	381.86	357.33	6.42
2000	404.66	390.27	3.55
2500	421.36	415.19	1.46

The steel plate shear wall with circular cutouts shows comparatively less displacement than steel plate shear wall with square cutouts. Therefore steel plate shear wall with circular cutouts are more preferable than steel plate shear wall with square cutouts. The results show that maximum displacement in steel plate shear wall is increases with increase in opening size at the infill plate. The displacement of steel plate shear wall with cutout size beyond 2/3 rd of the panel depth found to be very large and which is approximately equivalent to the displacement of the bare frame and are given in red colour. The lateral load resisting capacity of steel plate shear wall reduces drastically when the cutout size in infill plate are increased beyond 2/3 rd of the panel depth and hence cutout size are not supposed to provide beyond 2/3rd of the panel depth.

The maximum von-mises stress in a steel plate shear wall with circular and square cutouts are obtained near to the cutouts in the infill plate. The steel plate shear wall with square cutouts shows more von-mises stress than circular cutouts due to the presence of corners. The results show that von-mises stress increases with increase in cutout size.

As per FEMA 310 [10], the drift ratio of the steel moment frame shall be less than 0.015. Hence maximum drift limited to 51mm. Figure 10 shows the displacement versus variation in cutout size graph of steel plate shear wall with circular cutout and figure 11 shows the displacement versus variation in cutout size graph of steel plate shear wall with square cutout.

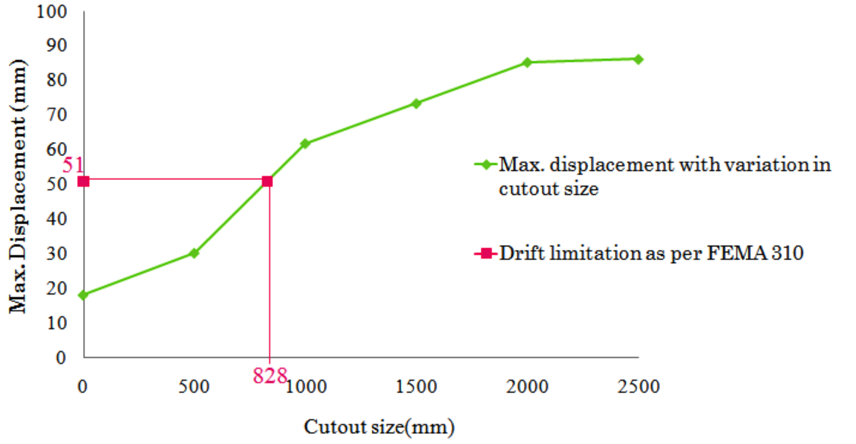

Figure 10: Displacement Vs cutout size graph of SPSW with circular cutout

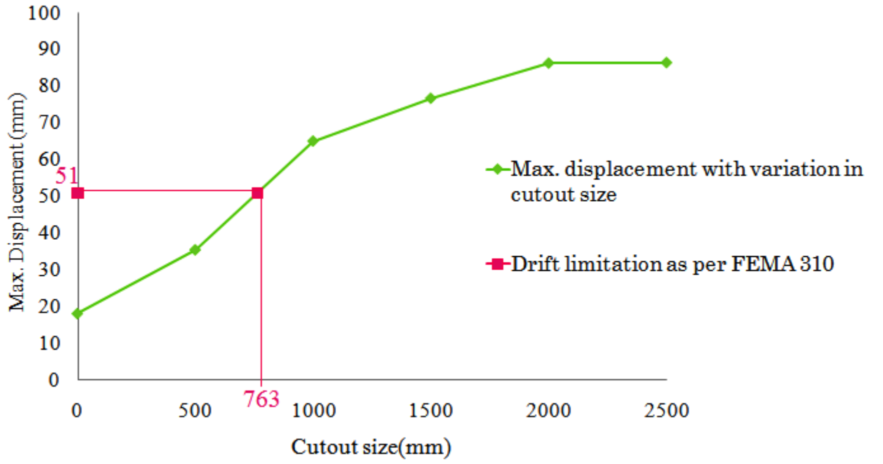

Figure 11: Displacement Vs cutout size graph of SPSW with square cutout

As per FEMA 310 [10], steel plate shear wall with circular cutout of diameter upto 828 mm are within in the safe drift limit and also steel plate shear wall with square cutout of size upto 763 mm are within in the safe limit .A cutout on infill plate beyond a limit leads the system to an unstable phase. As a remedial solution for 1000 and 1500 mm cutouts are located on infill plate of steel plate shear wall, two options can be adopted in order to overcome the difficulties, increasing thickness of infill plate and/or providing stiffeners to infill plate. In both cases system can be made withstand with the seismic requirements.

9. Conclusions

The steel plate shear wall system presented in the present study can be used as an effective lateral load resisting system in high seismic regions. A finite element model of the structure was subjected to the El Centro earthquake and was analysed using the non linear dynamic procedure. During this study a comparative analysis was performed on single storey steel frame with and without infill plate. A parametric study was conducted by considering variety of openings. This study leads to following conclusions:

- The model considered is validated with an experimental study from the journal, “Experimental Study of Diagonally Stiffened Steel Plate Shear Walls” by Erfan Alavi and Fariborz Nateghi.
- The displacement and von-mises stress of bare frame were decreased about 79% and 35% respectively by the use of steel infill plate. This is due to the increased stiffness of the steel plate shear wall compared to bare frame. Hence steel plate shear wall can be used effectively as a lateral load resisting system in the seismic regions.
- Based on the requirements of opening, variety of cutout be considered into steel infill plate and influence of these cutout on displacement and von-mises stress was studied.
- The steel plate shear wall with circular cutouts shows comparatively less displacement and von-mises stress than steel plate shear wall with square cutouts. Therefore steel plate shear wall with circular cutouts are more preferable than steel plate shear wall with square cutouts.

- The lateral load resisting capacity of steel plate shear wall reduces drastically when the cutout size in infill plate are increased beyond 2/3 rd of the panel depth and hence cutout size are not supposed to provide beyond 2/3rd of the panel depth.

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