A Study on Steel Plate Shear Wall

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Abstract. The main objective of this research study was to evaluate the parameters of stiffened and unstiffened steel plate shear wall under seismic loads. The scope of effort included simulating five unstiffened steel plate shear wall with varying thickness, three singly stiffened steel plate shear wall, and three doubly stiffened steel plate shear wall. The validation and simulation was done using software package ANSYS v16 using loads derived from ETABS. Overall, Unstiffened steel plate shear walls produced high in-plane and out of plane displacements which decreased with increase in thickness of plate; than singly stiffened followed by doubly stiffened steel plate shear walls. With introduction of stiffener in steel plate shear wall, the in-plane displacement values reduced by about 1%, and about 3% when doubly stiffened on the other hand the out of plane came down by 50% when stiffened singly and also when doubly stiffened. It was noteworthy that stiffener does not play any significant effect on any parameter except for out of plane displacement.

1. Introduction
Since past three decades it’s demonstrated by experimental and analytical methods that the steel plate shear wall forms an effective and economic lateral load resisting system to act against both wind and earthquake loads. It consists of infill steel plate with one bay length and one storey height. These infill plates are placed at all storey or selected storey. These infill plates are connected to beam column boundary which can be of rigid or shear connection. When properly designed, a steel plate shear wall will have inherent redundancy, good energy absorption capacity, superior ductility, high initial stiffness and stable hysteresis loops; hence they are used in high-risk seismic regions. Steel plate shear wall can also be used to upgrade old buildings.

It has been shown earlier that steel plate can prove be cost effective. Being much lighter in weight, it reduces seismic forces and foundation costs. Also, it reduces time duration of construction. The existing philosophy for design of steel plate shear wall systems uses either a thick plate or heavily stiffened thin plate to prevent shear buckling of infill plate.

The later reduces the economic attractiveness of the system. However, in 1930 in aerospace engineering, Wagner (1931) showed that shear buckling of a thin plate that if adequately supported along its edges does not constitute failure. At the point of buckling the load carrying mechanism of the plate changes from in-plane shear to an inclined tension field to resist the panel shear. This concept has been used for many years in shear design of plate girders (Basler,1961) but it was first
applied to design of steel plate shear walls in the early 1980’s through a series of analytical and experimental research. Thorburn (1983) predicted the strength and stiffness characteristics analytically; Timler and Kulak (1983) experimentally confirmed it. The steel plate shear wall without stiffener has been investigated for the effect of simple versus rigid connections (Cassese et al., 1993), for time dependent response (Sabouri-Ghomi and Roberts, 1992; Rezai, 1999), the effects of openings in infill (Roberts and Sabouri-Ghomi, 1992; Vian and Bruneau, 2004), the use of light gauge and low yield (Vian and Bruneau, 2004; Berman and Bruneau, 2005). Numerical investigations have been carried out in above papers. Elgaaly et al. (1993) and Driver et al. (1997) also conducted numerical investigations. The first to conduct extensive research programme was Takahashi et al. (1973) who showed that the heavily unstiffened steel plate shear wall perform better in shear over unstiffened models under cyclic loads. But it is not economical. When a thin panel of steel is used, at very low loads buckling occurs due to the least resisting dimension of the plate and therefore by the tension field action the loads are dominantly resisted. On the other hand as the plate thickness is increased, the buckling load also increases and the post buckling is no more considerable. Stiffening therefore becomes necessary for steel plate shear wall. However, exact suitability of the type of steel plate shear wall for a particular project is difficult to suggest. Hence this study is aimed at deciding the thickness of infill plate for a 10 storey building with specific type of stiffener either single or double diagonal. The unstiffened models have very high out of plane buckling for thinner plates. It reduces with increase in thickness of infill plate. With introduction of stiffener in steel plate shear wall, the in-plane displacement values reduced by about 1%, and about 3% when doubly stiffened on the other hand the out of plane came down by 50% when single diagonally stiffened and also when double diagonally stiffened.

2. Objective and Scope

The objective of this work includes deriving a comparison between stiffened and un-stiffened steel plate shear walls. Five thicknesses of un-stiffened were used, with three single diagonally and double diagonally stiffened cases. The parameters compared are maximum storey displacements and out of plane deflections for five thicknesses of steel plate shear wall unstiffened and also for steel plate shear wall stiffened both by single diagonal and double diagonal. The above comparisons have been done for steel plate shear wall modelled up to 10 storeys and analysed under seismic loads. Finite Element Software ANSYSv16 is used to model and analyse steel plate shear wall, both stiffened and unstiffened. To check the validity, the plate buckling analysis is carried out on a plate with different boundary conditions. The results of this analysis are compared with values in literature. A regular plan symmetrical building consisting of four shear walls on all sides of the periphery is modelled using ETABS. Auto seismic forces are taken from the building model and applied to the one bay model of steel plate shear walls modelled in ANSYS.

3. Finite element modelling of Steel Plate Shear Wall

Understanding the structural behavior of steel plate shear wall and caring out a comparative investigation, geometric, and material nonlinear finite-element analyses based on the commercial FE package ANSYS® User’s Manual (2005) have been undertaken under transient loading. In this paper, the effect of thickness and type of stiffener on the parameters of steel plate shear wall have been studied

3.1. Characteristics of finite-element modeling

For modeling of various components of steel plate shear wall, ANSYS® User’s manual (2005) elements and capabilities are as follows. The column and beam was modeled using beam element BEAM188. This element is a linear 2 noded; in 3D with 6 degrees of freedom at each node and includes stress stiffness terms. It supports Elasticity and isotropic hardening plasticity models. SHELL181 was used to model infill steel plate which is well suited for analyzing thin to moderately-
thick shell structures. The element is four noded with 6 degrees of freedom and is well suited for linear, large rotation, and large stain nonlinear applications. The stiffener was modeled using LINK180 which is a uniaxial tension-compression element with 3 degrees of freedom at each node.

3.2. Material characteristics
For linear isotropic material properties the elastic modulus was taken as $E_x = 2E5\text{MPa}$ Poisson’s ratio was taken as $\nu = 0.3$. Under inelastic, rate independent, isotropic hardening plasticity, Bilinear Mises plasticity yield stress was taken as 250MPa with tangent modulus of 20% as illustrated in Figure 1.

![Figure 1: Notation for sectional dimension of I section](image)

**Figure 2:** Stress Strain Curve of Steel

3.3. Components of Shear wall and Modelling
For the beam and column in steel plate shear wall, I section of specific size was arrived using trial and error method. The plate thicknesses used were 3mm, 5mm, 8mm, 12mm, and 16mm. To investigate the effects of stiffener a stiffener with size 196mm x 8mm was used in single diagonal and double diagonal fashion with plate thicknesses of 3mm, 5mm, and 8mm.

| Specimen | Sectional Dimensions |
|----------|----------------------|
|          | Section Type | Area $\text{mm}^2$ | $W_1$ mm | $W_2$ mm | $W_3$ mm | $t_1$ mm | $t_2$ mm | $t_3$ mm |
| Column   | I            | 36200            | 500     | 500     | 750     | 25       | 25       | 16       |
| Beam     | I            | 28000            | 400     | 400     | 550     | 25       | 25       | 16       |

A single shear wall with steel infill plate was modeled up to 10 storey with 4m as base storey height and 3.2m typical storey height. The infill plate was modeled with shell element and the contacts were moment resistant contacts. A stiffener was added to the same model diagonally and double diagonally. The models were meshed and further the mesh was refined to capture the local buckling of the plate as illustrated Figure 3. The models are categorized into three groups namely unstiffened (US), single diagonally stiffened (SS), double diagonally stiffened (DS).
3.4. Validation of finite element model

A case of simply supported plate is considered to verify the accuracy and validity of finite element modelling of steel plate shear wall. Plate buckling analyses was carried out on a plate with uniaxial compression. 4 node element Shell181 was used for modelling of the plates. All translations were restrained and uniaxial compression load of 1kN was applied on two opposite sides. A plate of size 1000x1000x10mm was used. Figure 4 illustrates that theoretical behaviour which was simulated using ANSYS v16 finite element modal analysis, followed closely the behaviour available in standard literature. From Eigen buckling analysis the buckling load obtained was 720.876 N/mm. The desired value of critical buckling coefficient as per literature is 4 and the value obtained from software being 3.99 the percentage error was calculated as 0.25%. Consequently, it was found that the finite element model is reliable enough to be simulated for analyses of steel plate shear wall under seismic loading.

4. Results and Discussions from Analysis of Steel Plate Shear Wall in ANSYS

4.1. In Plane Displacement
The steel plate shear wall behaves as a vertical cantilever; it has fixity at the base. And at full height of the structure it has free end. Therefore observed, minimum displacement is observed towards the fixed
end of the steel plate shear wall and maximum displacement is at free end of the shear wall, the values of which are tabulated in Table 2. A typical illustration of which is depicted in Figure 5.

Figure 5: Illustrates a typical deflection pattern projected by steel plate shear wall

Maximum storey displacement is obtained from the nodal displacement solution of the plate in the direction of application of load, which is x direction in this case. The results for maximum storey displacement are represented in the form graphs of storey number v/s maximum storey displacement. Refer Graph 1. It was observed that the lateral displacement increased with increase in height of the structure. It was also found that the storey displacement is maximum for 3mm plate and it goes on decreasing when plate thickness is increased from 3mm and above.

Table 2: Showing Maximum in Plane Displacement for 10th Storey

| Model Name | 3 US | 3 SS | 3 DS | 5 US | 5 SS | 5 DS | 8 US | 8 SS | 8 DS | 12US | 16US |
|------------|------|------|------|------|------|------|------|------|------|------|------|
| Max UX     | 100.92 | 100.58 | 98.64 | 91.73 | 90.89 | 89.80 | 85.98 | 83.15 | 81.95 | 81.55 | 75.12 |
The parabolic pattern projected by deflected steel plate shear wall, the maximum deflection at free end and zero deflection at fixed end can be compared to a vertical cantilever. The introduction of single or double diagonal stiffener on steel plate shear wall does not have significant impact on this parameter. It can be reckoned that stiffener has no effect on linear displacement. It was observed that the maximum displacement for 3 US observed at the top storey is 100.924mm, the same was 91.7348mm for 5 US. For 8US it was observed to be 85.9874mm, for 12 US it was observed to be 81.55mm, & 75.126mm for 16 US.

**Graph 1:** Showing storey v/s deflection of steel plate shear wall in mm

**Graph 2:** Showing percentage decrease in displacement on increase of thickness.
The percentage decrease in in-plane displacement with increase in thickness of plate from 3 to 5mm is 9.1%, from 5 to 8mm was found to be 6.68%, from 8 to 12mm was found to be 5.159% and from 12 to 16mm was 7.877%. Refer

Graph 2.

Graph 3: Showing percentage decrease in lateral displacement for 3mm plate

Graph 4: Showing percentage decrease in lateral displacement for 5mm plate

Graph 5: Showing percentage decrease in lateral displacement for 8mm plate
The result of introducing a diagonal stiffener to the plate was negligible in case of in plane displacement. The reduction in percentage for in-plane displacement when a diagonal stiffener was introduced for 3mm plate i.e. 3 SS, it was 0.33% compared to 3US, when double stiffened i.e. for 3 DS it was 2.256% compared to 3SS. Refer Graph 3. For 5 SS compared to 5US it was observed to be 0.92% and 1.193% for 5DS compared to 5SS as depicted in Graph 4. For 8SS compared to 8 US it was observed as 3.29% and 1.4368% for 8 DS with 8SS as shown in Graph 5.  
It can be easily deduced that single diagonal stiffener does not play a major role in curbing in-plane displacement, whereas the double diagonal stiffener is slightly better compared to single diagonal stiffener. It can be noted that the single diagonal stiffener introduced is effective for 8 mm plate.

4.2. Out of Plane Deflection

Out of plane deflection leads to buckling of plate. The stress plot in Figure 6 gives an idea of critical sections in the steel plate. The out of plane deflections causes the development of tension field action in the plate which if not maintained within the permissible limits causes plate buckling. Hence, this is considered important in the design of steel structures.

![Figure 6: Showing out of plane deflection for 8mm singly stiffened plate.](image-url)
Referring to the results in Graph 6, the out of plane displacement goes on reducing with the increase in plate thickness. The, 3 US deflection was found to be 3.85mm in z-direction with critical section being in the 1st storey and slight buckling in 2nd storey. The out of plane displacement for 5 US were found to be 2.22mm with critical region at first storey similar to 3 US. But unlike 3 US the bucking takes place at bottom of plate. For 8 US the maximum value is 0.23mm in positive z-direction. The critical section was observed at 9th and 1st storey. Refer

Figure 7 and Figure 8: Showing critical region for out of plane deflection for 8mm plate at 9th storey.
Figure 8. For 12 US and 16 US plate shear wall there was no critical section and maximum deflection was found to be a meager of 0.074mm and 0.07mm respectively.

Graph 6: Maximum out of plane deflection for varying plate thicknesses

Graph 7: Showing % decrease in out plane deflection with thickness

When the plate was single diagonally stiffened in case of 3 SS the reduction in out of plane displacement was found to be 62.2% when compared to 3US and when compared to 5 US the reduction in deflection in 5 SS was found to be 65.3%. When 8 US was Single Diagonally stiffened i.e. 8 SS the same was observed to be 10.77%. This indicated that with increase in plate thickness the effect of stiffener reduces. The stiffener is effective in reduction of out of plane buckling when thickness is less. When the 3 US was double diagonally Stiffened i.e. 3 DS, it's out of plane buckling reduces by 17.8%, when compared to 3 SS. Refer Graph 8. The same was observed 78.96% for 5 DS compared to 5 SS. For 8 DS it was observed to be 53.17% compared to 8 SS. Refer
Graph 10. For 12mm and 16mm plate was neither double stiffened nor Single Diagonally Stiffened because its significance is very less, considering its less value of deflection. It’s observed that the double stiffener was very less significant when plate thickness is 3mm but very effective for 5mm and 8mm plate. Hence the double stiffener is efficient in reducing out of plane deflection for higher plate thickness.

Graph 8: Showing % decrease in out of plane deflection for 3mm plate

Graph 9: Showing % decrease in out of plane deflection for 5mm plate
Graph 10: Showing % decrease in out of plane deflection for 8mm plate

5. Conclusions

i. According to the Codal provisions IS 1893: 2002 for plate girder the minimum thickness that can be used for design of shear wall analogous to plate girder is 16mm. And the maximum allowable displacement for any building is given by h/250 where h is the height. Therefore the calculated maximum lateral displacement is 131.2mm and clearly all the five plate (i.e 3mm to 16mm) thicknesses have maximum displacement within the limits.

ii. The single diagonal stiffener does not play a major role in curbing in-plane displacement, whereas the double diagonal stiffener is slightly better compared to single diagonal stiffener. It can be noted that the single diagonal stiffener introduced is effective for 8 mm plate. It is observed that when 8mm plate was double diagonally stiffened, it’s in plane displacement was almost equal to 12mm plate.

iii. It can be reckoned that out of plane deflection goes on decreasing with the increase in plate thickness. From the observations it can be inferred that 8US is more effective when associated all other five thicknesses.

iv. For 3mm plate single and double diagonal stiffener had the same effect. For 5mm plate both single and double diagonal stiffeners both were effective. Whereas for 8mm plate double diagonal stiffener was more effective. The stiffeners proved very effective in arresting out of plane deflection but its use is not advisable for 12US and 16US where deflection is negligible.

Hence in conclusion, for a ten storey building a steel plate above 8mm thickness can be suggested. If lesser plate thicknesses are to be used, it is advised to stiffen the same by use of double diagonal of suitable size.

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