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# NONLINEAR BEHAVIOR OF DIAGONALLY STIFFENED STEEL PLATE SHEAR WALLS

E. Alavi[1] and F. Nateghi[2]

## ABSTRACT

The recent investigations on stiffened steel plate shear walls have shown that stiffening of a thin steel plate with the conventional horizontal and vertical stiffeners improves its non-linear behavior. However, application of the conventional stiffeners, which have been usually used for precluding occurrence of the shear elastic buckling in the infill plate, is very time consuming and causes high-fabrication cost. Hence, in this study, stiffening of the infill steel plate with diagonal stiffeners is proposed, and non-linear behavior of the new system has been investigated. Several finite element models of un-stiffened and diagonally stiffened steel plate shear walls have been generated, and the analytical method has been validated with available experimental results in the literature. The results show that the diagonal stiffeners have increased the elastic and the ultimate shear capacities of the system, and the hysteretic behavior of the diagonally stiffened steel shear walls have been improved in comparison with the un-stiffened steel shear walls. Furthermore, the pinching phenomenon is observed in the hysteresis loops of the un-stiffened steel shear walls, especially if beam-to-column connections of boundary elements have been simple connections, while this phenomenon has not been occurred in the hysteretic behavior of diagonally stiffened steel shear walls.

**Keywords:** **s**teel plate shear wall, diagonal stiffener, nonlinear, hysteretic, beam-to-column connection

## Introduction

During the last three decades many researches have been carried out on steel plate shear

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walls, SPSWs, and consequently they have been classified as reliable seismic load resisting systems in the high risk zones. SPSWs have been used in structural design and retrofitting of existing buildings with different configurations and philosophies, stiffened and un-stiffened. The first approach utilizes heavily stiffened steel plate shear walls with horizontal and vertical stiffeners to ensure that the infill steel plate reaches its full plastic strength prior to the elastic out-of-plane buckling, and stiffening of the steel plate improves its strength and prevents tension field from developing in the plate. Takahashi et al. (1973) studied the stiffened SPSWs with usual light and heavy stiffeners, their experimental results showed that this system has high capability of earthquake input-energy dissipation and stable hysteresis loop with spindle shape instead of S shape; it has also high lateral stiffness, which limits its elastic shear displacement. However, construction of the numerous horizontal and vertical stiffeners is very time consuming and causes high-fabrication cost. The second approach is to use un-stiffened thin SPSWs, which relies on post-buckling strength of infill steel plate due to tension field action development in the steel plate after the elastic out-of-plane buckling and dissipation of seismic energy through the cyclic yielding of the infill in tension. Hence, nonlinear behavior exhibits at relatively small story drifts and the significant pinching in the hysteresis loops appears especially when the boundary elements are not relatively so strong , pinching phenomenon occurs due to reduction in stiffness and capacities of the infill steel plate upon load reversal until the tension field action can develop in the opposite direction, however, a well-designed un-stiffened SPSW can reach ultimate wall capacity and sustains it through high-ductility demands. Many recent research programs have been performed on this system, and some simplified analytical strip models and provisions have been consequently suggested and implemented in the codes and standards such as CSA S16-01, AISC-341-05 for analysis and design of the un-stiffened SPSW. Other approaches such as using slits in SPSWs (Toko Hitaka and Chiaki Matsui 2003), composite shear walls (Zhao and Astaneh-Asl 2004), etc. have been also studied for improving seismic behavior of SPSW system.

This paper introduces diagonally stiffened steel plate shear wall as an alternative new type system, and intends to incorporate efficiencies of the stiffening approach into seismic behavior of un-stiffened thin steel plate shear wall with using minimum number of stiffeners by increasing elastic shear buckling stress limit of the steel plate and shear strength capacity of the shear wall, and by reducing overall buckling of the infill steel plate effects and consequently improving of the non-linear behavior of the system. Besides, this system causes lower fabrication cost in comparison with the common stiffened SPSWs and facilitates erection and construction procedures. In some situations, for instance, in tall buildings or whenever operation of a system is sensitive to out-of-plane buckling and large deformation of infill plate or in retrofitting of existing buildings and industries, etc., stiffened SPSWs might be preferred to un-stiffened SPSWs by design engineers. Stiffening of a shear panel by diagonal stiffeners is not generally a new method, and this idea is previously elaborated in stiffening of the panel zones for instance in the rigid connections of gable frames. Moreover, Yonezawa et al. (1978) studied plate girders with weds diagonally stiffened between vertical stiffeners, their experimental and theoretical investigations resulted good performance of the diagonal stiffeners in stiffening of the plate girders webs and concluded that the diagonal stiffeners allows tension field action to develop in the steel plate (despite to the heavily stiffened webs).

In this study, several numerical models of one-story un-stiffened and diagonally stiffened SPSWs are generated for evaluating the role of diagonal stiffeners in the nonlinear behavior and shear load capacity of SPSWs. Push-over curves and hysteresis loops of the models are obtained and compared with the un-stiffened SPSWs. Besides, effects of the beam-to-column connection type have been investigated on the hysteretic behavior of steel shear walls.

## Analytical Method

The modeling is conducted using the general-purpose nonlinear finite element program ANSYS, which is properly suited for solution of highly nonlinear engineering problems like SPSWs. Numerical models have been validated with available experimental data in the literature, and those models with not having the experimental data with the codes provisions. If the loading on the structure is considered perfectly in-plane, the buckling will not analytically develop unless the out-of-plane deflections are applied to initiate the buckling, hence, to prevail to this problem in the analysis of SPSWs several methods are suggested by researchers in the literature. Driver et al. (1998) incorporated initial imperfections in the finite element analysis of their test specimen based on the first buckling mode of the infill plate. Behbahanifard et al. (2003) developed a finite element model based on the nonlinear dynamic explicit formulation for numerical study of the specimen and a kinematic hardening model to simulate Bauschinger effect, they applied an initial imperfections corresponding to the buckling mode of the shear wall with maximum amplitude of 10 mm in the analysis. Consequently, in this research, kinematic hardening plasticity model has been utilized with multi-linear kinematic hardening material model for the mild steel materials. Bauschinger effect is also included in the multi-linear kinematic hardening model and finite element geometrically nonlinear analysis by means of large deflection transient analysis has been executed in order to incorporate the nonlinear buckling and post-buckling effects into the results. The implicit solution method based on Newmark's algorithm is utilized, and 4-node plastic shell with six degrees of freedom at each node, shell 181, is employed for 3D-modelling of the shear walls, appropriate time-stepping by the trial and error method is used to overcome to the convergence problems.

### Numerical method validation

The analytical method has been validated with using the available experimental results in the literature; therefore the SPSW2 specimen from Lubell's work, Fig. 1, is selected and modeled in accordance with the existing information (Lubell 1997, 2000).

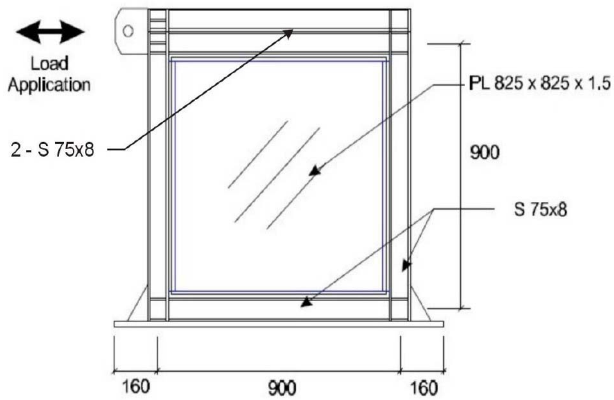



Figure 1. SPSW2 experimental model ( Lubell 1997)

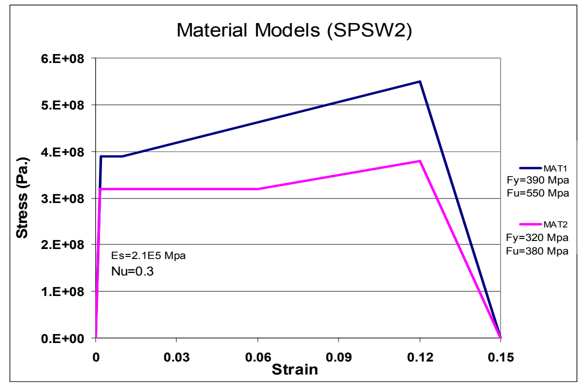
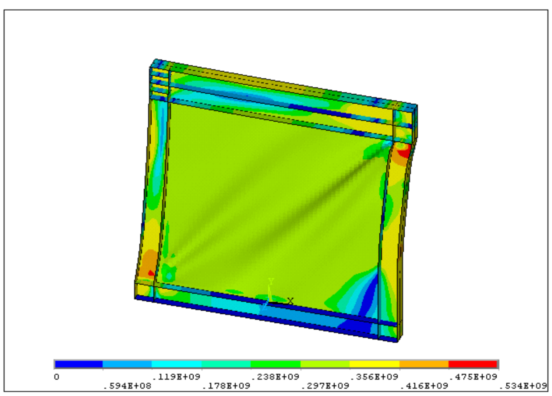



Figure 2. SPSW2 material models a) MAT1 for boundary elements, b) MAT2 for infill plate



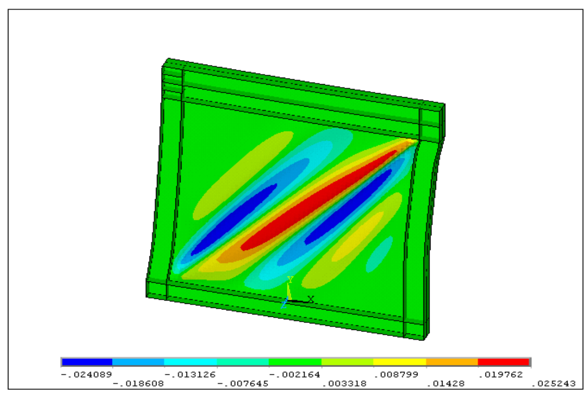


Figure 3. SPSW2 FEM models a) Von-Mises Stresses (Pa.), b) Out-of-plane deflection (meter)

Steel materials of the boundary elements (S 75x8) and the infill steel plate (1.5 mm) have been different in this specimen, Fig. 2 shows the stress-strain curves of the steel materials used in the numerical analysis. The nonlinear results such as stresses based on Von-Mises yield criterion and out-of-plane deformation at the last sub-step are presented in Fig. 3. It is observed that the infill steel plate is completely yielded and the columns have reached near the failure limits at their connections to the beams. The load-displacement curves from non-linear finite element analysis, FEM, and the experimental results are compared in Fig.4. This figure also contains other experimental results of samples SPSW1 and SPSW4 from Lubell's works, shown in dash-lines, which are not reviewed herein. It can be inferred that the analytical model have been successful to estimate the actual shear capacity of the system with good approximate precision (less than 5% deviation), (Nateghi and Alavi 2008). Then, the verified analytical method has been extended and used for the other SPSWs samples. The differences between the analytical and experimental results might have several reasons, for instance, effects of the initial imperfections and the remained residual stresses in the fabricated structural elements due to welding or hot-rolling, etc., hence, this comparison between the results is made for assurance about the used analytical method capability on estimation of the actual situation.

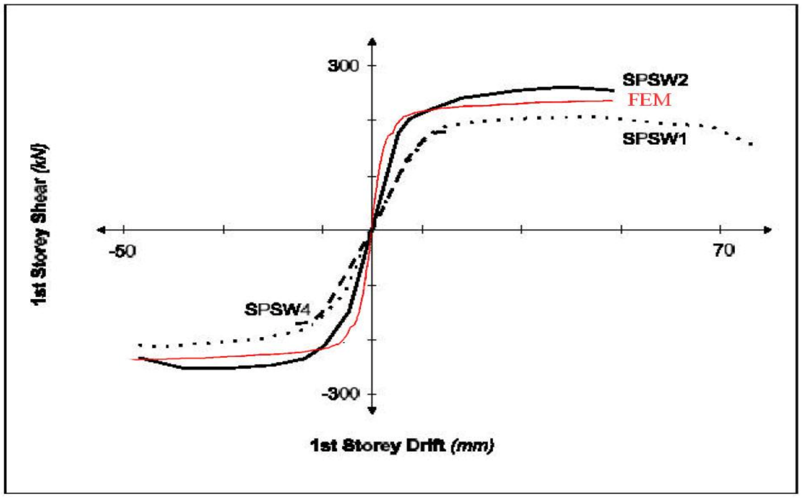



Figure 4. Envelope curves for SPSW1, SPSW2, SPSW4 (Lubell 1997) & Analytical model of SPSW2 (FEM)

**Pushover Analysis of Diagonally Stiffened SPSW2**

Then after verification of the analytical method, the specimen SPSW2 has been stiffened by two-sided diagonal stiffeners with various sizes. Push-over analysis has been executed and ultimate shear capacities of the new stiffened systems are calculated. Fig.5 and Fig.6 show FEM results of the diagonally stiffened SPSW2 at the last loading step. It can be observed that the infill plate is yielded, and with reduction of the width to thickness ratio of the diagonal stiffeners, their local buckling has been reduced. Furthermore, the diagonal stiffeners have been able to deduct the buckling lengths of the plate in comparison with the un-stiffened model. The force-displacement curves are drawn in Fig.7. This figure also conducts that the drifts of all systems have reached near 4%, which is a good range for the ductile systems. Besides, it is found that the shear strengths of the diagonally stiffened SPSWs have become from 18% to 60% greater and the stiffness has been nearly from 15% to 30% more than the un-stiffened steel shear wall outcomes. The increment rate relates also to the diagonal stiffeners dimensions.

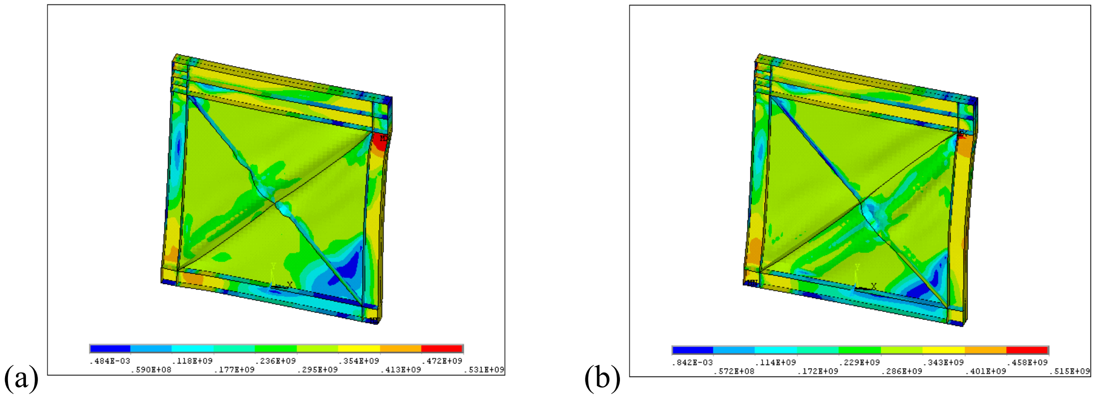


Figure 5. Diagonally Stiffened SPSW2 Von-Mises Stresses (Pa.) a) Stiffeners 2*2PL29.5mm*2mm, b) Stiffeners 2*2PL29.5mm*4mm

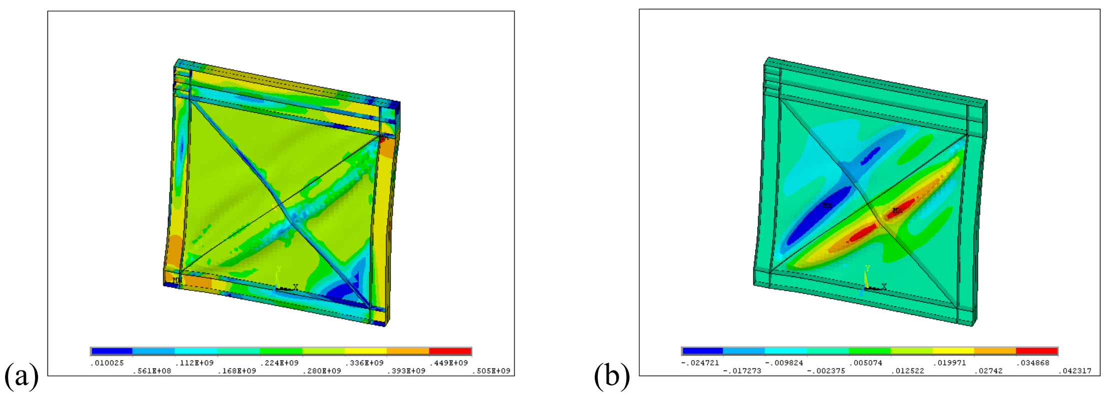


Figure 6. Diagonally Stiffened SPSW2 with 2*2PL29.5mm*6mm a) Von-Mises Stresses (Pa.), b) Out-of-plane deflection (meter)

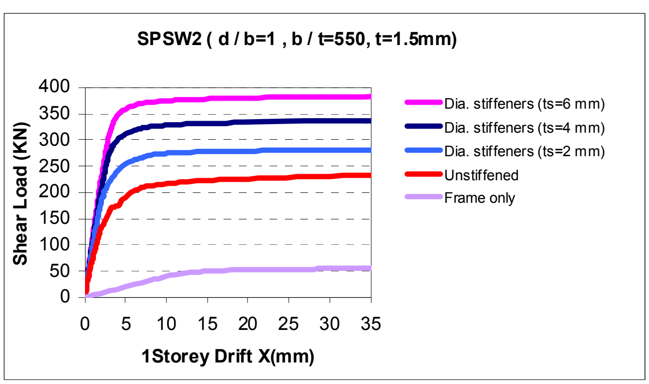
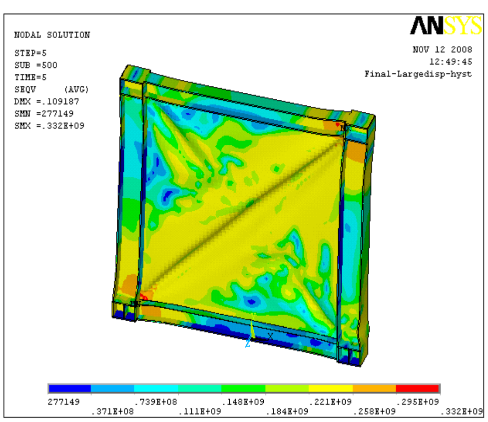



Figure 7. FEM Force-Displacement curves for Frame only, un-stiffened and stiffened SPSW2 with various diagonal stiffeners

### Hysteretic Behavior of Un-stiffened and Diagonally Stiffened SPSWs

For further investigation numbers of full scale models of one-story un-stiffened and diagonally stiffened are generated for cyclic non-linear analysis, SPSW(A,B,C,D) 3m*3m samples, the boundary elements are such designed to meet the requirements of steel plate shear walls in compliance with AISC-360-05 provisions as compact sections. Hence, the columns flanges and the webs are taken PL.300mm*15 mm and PL. 300mm*8 mm, respectively. The beams flanges and the webs are PL.200mm*15mm and PL 200mm*8mm, respectively. The continuity plates and base plates are made of PL. 15mm (thick.). The infill plate thickness is taken 3mm, and all plate connections to each other are assumed to be continuous at shell element contact surfaces nodes. The beam-to-column connections in SPSW (A, C, D) are designed rigid type, however, in SPSW (B) defined simple type, whereat only the beams webs are connected to the columns flanges to simulate the actual conditions of the simple connections. The diagonal stiffeners dimensions and configurations have been different in the samples, wherein SPSW(C) the diagonal stiffeners are directly connected to the beam-to-column joints, while in SPSW(D) the diagonal stiffeners in combination with the edge stiffeners have been used, in order to reduce the axial forces on the stiffeners and increase their involvement in controlling of the out of plane deflections of the infill plate, besides, the edge stiffeners will also reduce the stresses in the edges of the shear plates. The steel materials are assumed mild steel equivalent to A36 with the yield stress limit of 240 MPa, and the ultimate tensile strength of 360 MPa. All specimens have tolerated about 3.3% drift, this drift has been reached within several cyclic loading steps, the hysteresis curves and Von-Mises stresses of SPSW (A), a sample with rigid beam-to-column connections, are presented in Fig. 8, and the results of SPSW (B), a sample with simple beam-to column connections, in Fig. 9.



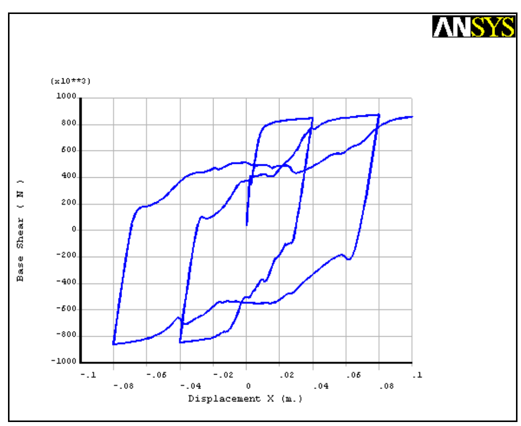




Figure 8. Von-Mises Stresses (Pa.) and hysteresis loops of un-stiffened SPSW (A) with rigid beam-to-column connections

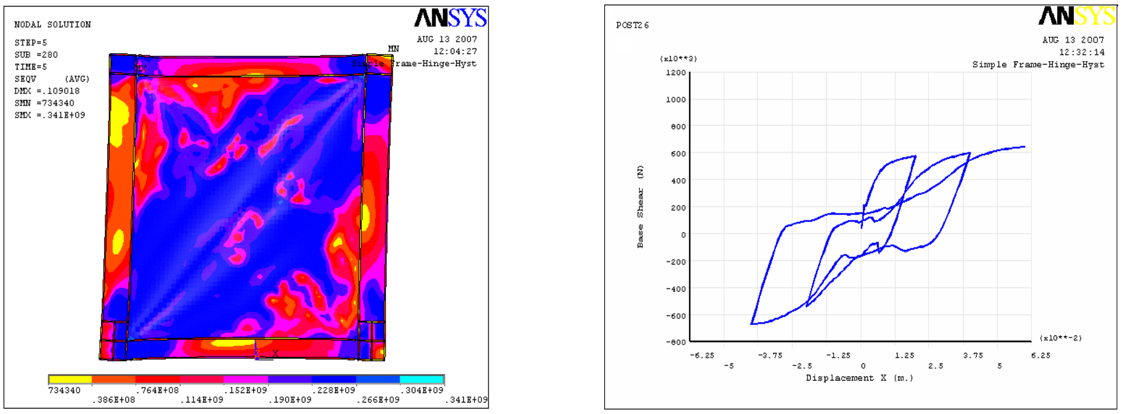



Figure 9. Von-Mises Stresses (Pa.) and hysteresis loops of un-stiffened SPSW (B) with simple beam-to-column connections

With comparison of the results, it can be derived that the steel shear walls with simple beam-to-column connections not only have less shear strength capacities than the steel shear walls with rigid beam-to-column connections, but also the pinching phenomenon has further effects on the hysteresis loops of the un-stiffened SPSWs. Therefore, the steel shear walls with rigid beam-to-column connections can dissipate more energy of the earthquakes than SPSWs with the simple type connections. However, both systems still have pinching in their hysteresis loops, and it is expected that by the diagonally stiffening of the panel, the hysteresis loops improve and change from S shape to the spindle shape. In that regard, the analyses are continued with the diagonally stiffened steel shear walls and the results are presented in Figs. 10, 11.

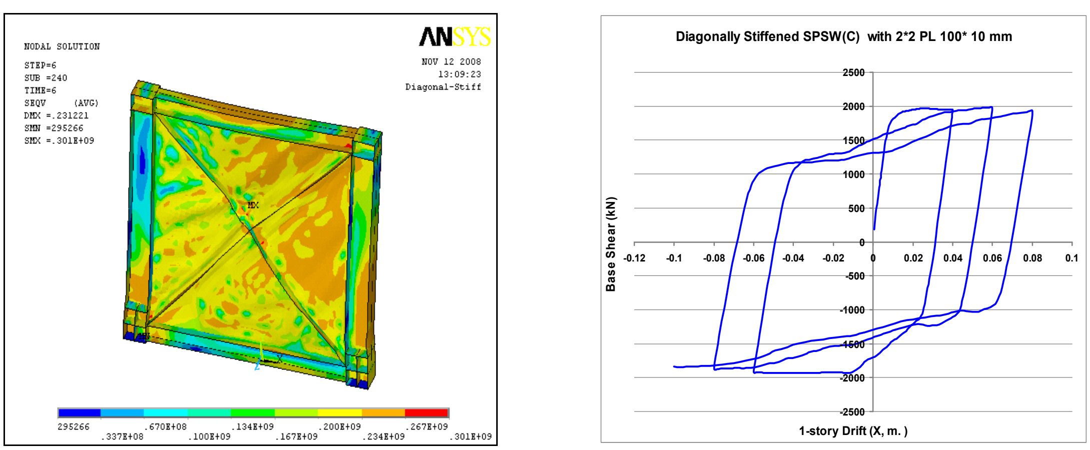



Figure 10. Von-Mises Stresses (Pa.) and hysteresis loops of diagonally stiffened SPSW (C) with 2*2PL100*10 mm, and rigid beam-to-column connections

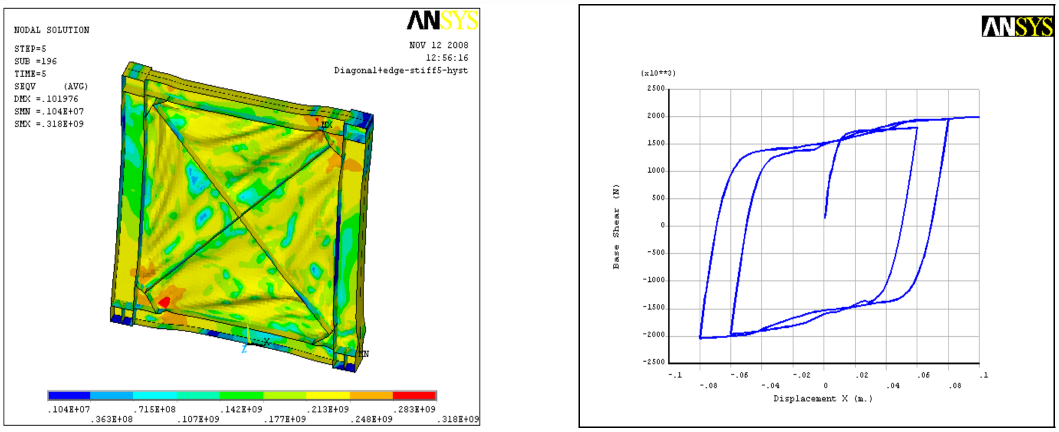



Figure 11. Von-Mises Stresses (Pa.) and hysteresis loops of diagonally stiffened SPSW (D) with 2*2PL100*20 mm and edge stiffeners, and rigid beam-to-column connections

It can be observed that diagonally stiffened steel shear walls have had more shear capacities than un-stiffened walls and hysteresis loops of the diagonally stiffened samples especially in SPSW (D), which has been also stiffened with edge stiffeners, are improved in comparison with the un-stiffened shear walls.

Theoretical formulas for estimation of the shear strength capacities of diagonally stiffened SPSWs have been also developed by the authors, (Alavi and Nateghi 2009).

## Conclusions

The main results can be summarized as follows:

1- There are good agreements between the analytical and experimental results.
2- Diagonal stiffeners have increased the shear strengths of steel shear walls.
3- Buckling lengths of the infill plates have been reduced around half by using of diagonal stiffeners, which results in increment of the elastic shear strength of the infill plate and reduction of the out-of-plane deformation.
4- Pinching phenomenon has appeared in the hysteresis loops of un-stiffened SPSWs, especially when the beam-to-column connections were the simple type.
5- Contributions of the diagonal stiffeners in bearing of the loads have been increased by reducing of their width to thickness ratios and increasing of their cross-sectional areas.
6- The diagonal stiffeners have improved the hysteretic non-linear behavior of steel shear walls, and the pinching phenomenon has not happened in the hysteresis loops.
7- Combination of the edge stiffeners with the diagonal stiffeners results in reduction of the edge stresses and improvement of the non-linear behavior of the system.

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