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Research Article

THE IMPACT OF X-SHAPED STIFFENERS ON CYCLIC BEHAVIOR OF STEEL PLATE SHEAR WALLS WITH OPENINGS

***Seyed Abbas Mousavinejad[1] and Mehdi Torabi[2]**
[1]Department of Civil Engineering, Science and Research Branch,
Islamic Azad University, Fars, Iran
[2]Department of Civil Engineering, Shiraz Branch, Islamic Azad University, Shiraz, Iran
**Author for Correspondence*

ABSTRACT

In the last three decades, steel plate shear walls (SPSWs) have been considered for the use as resistant structures against lateral forces of wind and earthquakes in buildings, especially in high-raised buildings. This new system which is growing rapidly in the world is being used for the construction of new buildings and retrofitting existing buildings, especially in earthquake-prone countries like America and Japan. This system is very simple in implementation with no certain complexity in it. Due to its simplicity, the possibility of its industrial manufacture, and its capability for in-site installation, it enjoys a high implementation speed which greatly reduces the implementation costs. SPSWs are a good replacement for reinforced concrete shear walls as the former are implemented cleaner and faster and more reliable in terms of strength than the latter and can be used not only in steel structures but also in the concrete structures. In fact, compared to other systems, in steel shear wall systems due to the expansion of materials and fittings, tensions are better modified against lateral loads such as frames and a variety of bracings in which materials are usually in the form of grouped focused connectors. These systems behave like a steel plate beam that is placed vertically. Columns act as the wings of the beam while the horizontal beams act core stiffeners. Prior to accepting the idea of SPSWs, the use of plate buckling resistance and reinforcing walls with heavy stiffeners to prevent buckling of the plate was very common. However, as the idea of SPSWs gained popularity, reinforced walls were replaced by unreinforced walls. In addition, the idea of using such structures received great attentions in recent years mainly for the purpose of seismic rehabilitation of existing buildings. Similarly, the use of stiffeners is of special importance for structures where walls with openings are used. Accordingly, the behavior of SPSWs with openings and that of X-shaped diagonal stiffeners proposal is explored in this study. Predicting the behavior of the models under study was done based on static nonlinear analysis of additional loads including nonlinear and geometric loads as well as pseudo-static loadings of the materials under ATC-24 Regulations. To this end, two sets of specimens with a 3000 × 5000 mm aperture and a height of 3000 mm were modeled. The squared-shaped opening with a ratio of 10 and 20% of the area of the filler plate was positioned in the center of the panel. Besides, the impacts of X-shaped stiffeners with two-way openings, diamond-shaped stiffeners, and X-shaped stiffeners were compared. The initial design of the boundary elements and the thickness of the filler plate were determined based on the AISC-341. A 3-D model was used by the finite element ABAQUS software to model the specimens. In this modeling, the beam-to-column and the steel plate-to frame connections were designed in a tangled form. The results show that to increase the initial stiffness, the diamond-shaped stiffener shows a better performance compared to the two other stiffeners. In addition, to increase the strength of 3000 x 3000 mm specimens, X-shaped stiffeners with openings show a more desirable performance. For 3000 x 5000 mm specimens, X-shaped stiffeners with two-way openings have a superior performance. It was also noted that diamond-shaped stiffeners create the largest increase in energy absorption in 3000 x 3000 mm specimens. Besides, X-shaped stiffeners with two-way openings come up with a greater performance with specimens with dimensions of 3000 x 5000 mm. However, the application of X-shaped stiffeners was found to be neither desirable nor cost-effective concerning the increased initial stiffness and strength.

Keywords: *Steel Plate Shear Walls, Openings, Stiffeners, Load-Lateral Displacement Diagram, Final Load, Initial Stiffness, Energy Absorption*

INTRODUCTION

Because of large loss of life and great property damages caused each year by earthquake and the wind, researchers have been trying to come up with a good structural system with a minimum of such damages. Today, different kinds of structural systems resisting lateral loads such as rigid frames, inside-filled frames, bracing systems, and shear steel and concrete walls have been designed. In the last three decades, a considerable attention was paid to the application of steel plate shear walls (SPSWs) introduced by the AISC Regulations as the lateral load resisting system in buildings. An SPSW is like a steel plate beam that is placed vertically and is extended across height of the building. A relatively thin steel plate attached to the beams and columns behave the same as the beam point. Columns and horizontal beams act as wings and stiffeners the vertical plate beam. Although the plate beam theory seems suitable for designing an appropriate SPSW structures, a key difference is related to the relatively high bending strength and the relatively high stiffness of the beams and columns that make up the boundary elements of the wall with regard to plate beams. It seems that these elements have a significant effect on the overall behavior of the building. SPSWs as an innovative system resistant to lateral loads of the wind and earthquake act as a converging bracing but outperform the other systems. The system is made of a set of separate panels, each enclosed by two columns from inside. Besides, a steel plate is attached to the peripheral elements. Peripheral forces are transferred horizontally by apertures on the floor to beams and columns inside the wall. The steel frame surrounding each panel may have simple or bending beam-to-column connections. Besides, the plate may be connected to the peripheral frame by means of screws or welding. Evidence from research shows that the use of SPSWs results in a 50% reduction in the steel consumption compared to bending frames. The stiffness of SPSW structures is even higher than the cross-bracing structures as the hardest type of bracing. In addition, the lateral displacement of the SPSWs is lower than the convergent steel bracings, so they are used more frequently in high construction structures. However, it has been known for a long time that the buckling resistance of reinforced panels is much less than the buckling resistance in reinforced panels. It should be noted that the plate buckling does not mean the destruction and collapse of the structure or its failure. If the plate has enough boundary support (as is the case for SPSWs), its buckling forces are several times bigger than its theoretical buckling forces. In the buckling point, the resistance load mechanism changes from inside-plate shear into the diagonal tensile field. When the plate thickness is small and thus it is called thin, the buckling occurs at very low loads and thus the panel strength is controlled by the operations of the tensile field. In addition, if the peripheral beams and columns are harder, the buckling resistance of the SPSW is much greater than that of a wall with flexible beams and columns. The buckling resistance of the plates has been accepted for several years in different regulations such as LRFD (1994) for designing plate beam points. It is generally recommended that stiffeners with a high thickness are not used because the high resistance of these structures will result in buckling of the columns and consequently in the destruction of the entire structure. In addition, the destruction of unreinforced structures is controlled by the formation of a diagonal tensile field. However, in either case, the existence of the plate compensate for poor connections among beams and columns.

MATERIALS AND METHODS

Methodology

Today, different approaches such as laboratory, analytical, and numerical methods are used to explore the behavior of engineering systems. Accordingly, the present study uses the finite element method for evaluating and analyzing the behavior of SPSWs. The finite element method as a numerical technique is being increasingly used for a number of reasons such as low cost, high speed, great precision, the possibility of thorough examination of different conditions of a system, and its possibility of being used at all places and times. To assess the precision of the method, different criteria are used. The use of laboratory studies and to compare the obtained results with those from the finite element method is a way to test the reliability of this method. As such, the present study, in addition to the SPSW modeling using the finite element method, uses the available consistent results for its validation. The final element method as a numerical technique can be used to solve many engineering problems. In this method, the entire geometric model is decomposed into a number of finer elements. Each element contains some nodes to which input values (loading and boundary conditions) and output values are allocated. The ability to modeling using the minimum simplifications, the ability to provide reliable results, reducing high costs of operational experiments, and the high speed of solving the problems are among features that have made the method be astonishingly developed in industrial and scientific centers. Of the general software related to the finite element method, valid software such as ABAQUS, NASTRAN, LUSAS, ANSYS have wonderful capabilities. To analyze and explore the behavior of various systems, ABAQUS is used in this study. The ability of creating very simple and at the same time powerful modeling and meshing, the ability for performing different analytical calculations, the existence of powerful nodes, and quick and total access to the outputs are among reasons for why the software was chosen in this study.

Literature Review

Rezai (1999) exposed a four-story SPSW with a scale of 1:4 to the shaking table test. This study was the first test of a dynamic type that was conducted on a SPSW sample.

All beam-to-column connections were of the bending type. To include the gravity loads, plates weighting 1700 kg were placed at each floor level. The sample under study was tested using vibrating movements with different histories and intensities.

Bending behavior was observed for the upper floor and the shear behavior was seen for the lower floor. Results from the force-displacement curve results indicated that the energy absorption in the SPSW sample occurred mostly in the first floor.

Besides, upper-floor movements such as the rotation of rigid bodies revolved around the first floor. It was concluded also that the bending strains generated in the middle horizontal boundary elements were relatively small and thus negligible.

Behbehani *et al.,* (2003) conducted cyclic experiments by imposing quasi-static loads along with simulation of the gravity loads on the three upper floors of a four-story SPSW structure. The experiment had been earlier conducted by Driver *et al.,* (1997).

Veladi *et al.,* studied the behavior of reinforced and unreinforced shear walls using analytical laboratory experiments.

The results suggested that unreinforced shear walls at the plastic stage show deformations that are much beyond what was previously predicted and they absorb a lot of energy. Chen and Hong (2006) examined the cyclic behavior of a SPSW with middle plates and low yielding.

They conducted a number of experiments on the SPSW and explored the effect of the ratio of the plate width to thickness, continuity, and a variety of connectors of the SPSW frame on the behavior of the boundary elements.

All samples had a good energy absorption capacity (Chen and Jhang, 2006; Hibbitt and Sorenson, 2003) analyzed models of the three SPSW samples with three floors and an opening at a scale of 1:3 constructed earlier by Coaks *et al.,* in the same year (Caccese *et al.,* 1993; Elgaaly *et al.,* 1993.

They used the finite element method to test the samples. Me'marzadeh *et al.,* (2009) examined the behavior of main tensions in the tensile field of an SPSW unstiffened with a thin-point plate as well as its nonlinear dynamic behavior and its deformation properties in two separate studies (Memarzadeh, 2009).

The results from the main stress behavior reflected the effects of bending and twisting rigidity of the boundary elements on the plate’s shear buckling.

Changes in values of torsional and bending rigidity of the boundary elements do not change the orientation angle of the main tensions located at the plate buckling mode (Memarzadeh, 2009).

RESULTS AND DISCUSSION

Results

Table 1: The geometrical data of the first series samples with the panel size of 3000 × 3000 (All sizes in mm)

Panel specifications	
Frame with no filler plate	
Steel shear walls without openings	
Steel shear wall with a central opening	10% opening ratio
Steel shear walls with openings in the panel center and X-shaped stiffeners on either side of openings	
Steel shear walls with openings in the panel center and diamond-shaped stiffeners	
Steel plate shear walls with openings in the panel center and X-shaped stiffeners	
Steel shear wall with a central opening	20% opening ratio
Steel shear walls with openings in the panel center and X-shaped stiffeners on either side of openings	
Steel shear walls with openings in the panel center and diamond-shaped stiffeners	
Steel plate shear walls with openings in the panel center and X-shaped stiffeners	

Table 2: The results of analyzing first series samples

Samples	Initial stiffness (KN/m)	The initial stiffness compared with SPW33	Ultimate strength (kN)	The ultimate strength compared with SPW33	Total energy absorbed (KJ)	Ratio of absorbed energy to SPW33
FRAME1	68.27	0.13	2411.39	0.54	3756.50	0.52
SPW33	496.96	1.00	4480.24	1.00	7235.70	1.00
SPW33OP10NS	382.32	0.77	3725.82	0.83	5380.70	0.74
SPW33OP10XXST	432.67	0.87	4883.94	1.09	8895.43	1.22
SPW33OP10DST	488.61	0.98	5097.09	1.14	9226.61	1.28
SPW33OP10XST	395.91	0.80	4152.62	0.92	7155.60	0.98
SPW33OP20NS	293.98	0.59	3289.39	0.73	4920.10	0.68
SPW33OP20XXST	325.93	0.65	4348.93	0.97	7301.73	1.00
SPW33OP20DST	419.05	0.84	4655.02	1.04	8411.72	1.16
SPW33OP20XST	304.28	0.61	3738.67	0.83	6416.00	0.88

Table 3: Characteristics of boundary elements of the panels

Column cross-section	Beam cross-section		Sample size
	Lower beams	Upper beams	
W14 × 193	W18 × 106	W18 × 106	3000 * 3000
W14 × 193	W24 × 335	W24 × 335	3000 * 5000

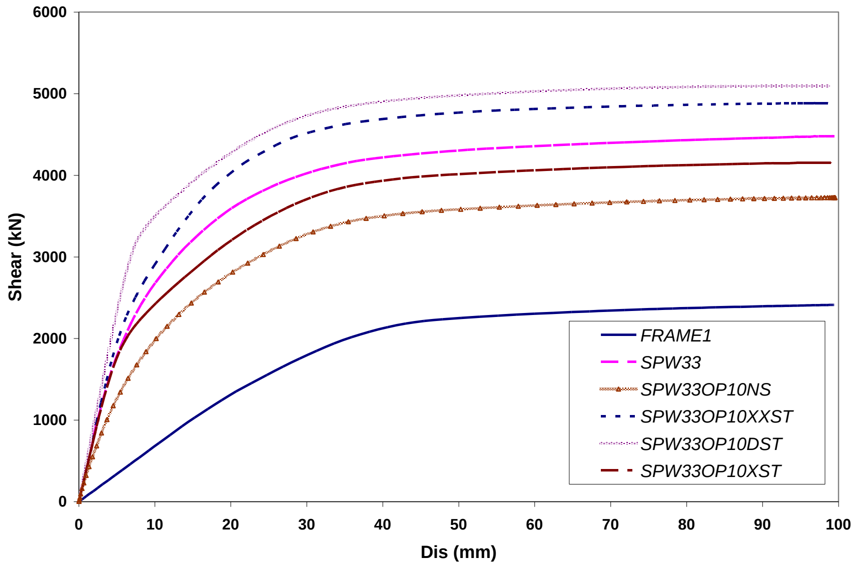

Figure 1: Comparison of the results from the first series samples with an opening ratio of 10%

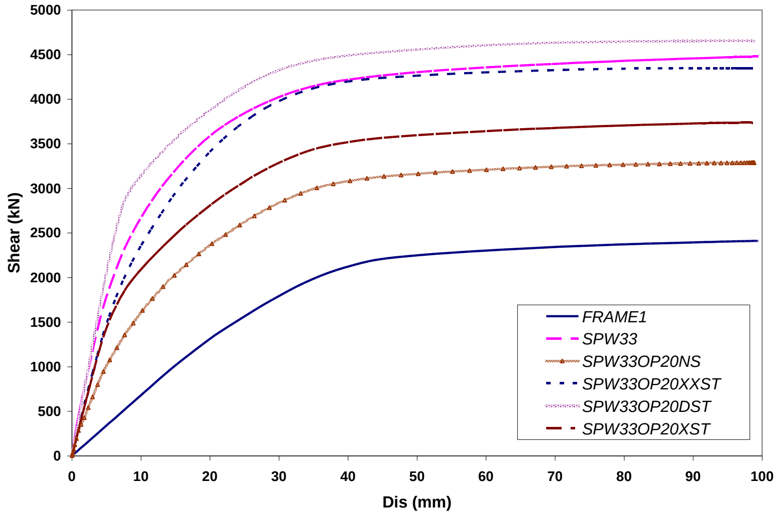

Figure 2: Comparison of the results from the first series samples with an area ratio of 20%

Conclusion

The presence of openings reduces the samples' initial stiffness, strength and energy absorption. Such reductions become more considerable as the size of the openings increases. The use of openings becomes in times inevitable for architectural reasons or due to the passage of installation systems. Therefore, the application of stiffeners will improve the SPSW behavior. In this study, panels with unstiffened openings and openings specified in regulations are modeled and compared. Then, diamond-shaped, cross-shaped, and X-shaped stiffeners with two-way openings are compared. As the findings indicate, the use of stiffeners improves the behavior and enhances the seismic parameters. The impact of stiffeners on the initial harness is a maximum of 25% for SPW33OP20DST and 20% for the sample with openings and the sample without stiffener. The impact of stiffeners on improving the ultimate strength of the samples is a maximum of about 37% for SPW33OP10XXS. The results also show that the most susceptible seismic parameter by installation of the regulated stiffeners is the energy absorption of the samples so that SPW35OP10XXST shows a 68% increase in the energy absorption.

Further Results

1. The presence of openings reduces the seismic parameters of the initial stiffness, ultimate strength, and energy absorption in the sample. As the panel aperture increases, the impact of the opening on seismic parameters fades away.
2. An increase in the opening size would result in a decrease in initial stiffness, ultimate strength, and energy absorption.
3. The presence of a 10% opening in the center of the 3000 × 3000 panel reduces the initial stiffness, ultimate strength, and energy absorption by 23%, 17%, and 26%, respectively. The same figures for a 20% opening are 41%, 27%, and 32%, respectively.
4. The presence of a 10% opening in the center of the 5000 × 3000 panel reduces the initial stiffness, ultimate strength, and energy absorption by 22%, 18%, and 15%, respectively. The same figures for a 20% opening are 37%, 26%, and 26%, respectively.
5. The use of large openings has the greatest impact on reducing the initial stiffness which is due to the installation of the opening in the panel center as a result of non-optimal development of the diagonal tensile filed.
6. With the installation of X-shaped stiffeners on either side of openings in 3000 × 3000 samples, the ultimate strength for 10% and 20% openings would increase by 26% and 24% in comparison with samples with no stiffener. The same figures for 5000 × 3000 sample with10% and 20% openings are 37% and 35%, respectively.
7. It seems that better performance of X-shaped stiffeners on either side of the openings in samples with larger apertures is due to the lower horizontal angles of the stiffeners and their bracing-like function.

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