Evaluation of Steel Plate Shear Wall Performance with Different Sections and Arrangements of Stiffeners and its Effect on Project Management during Construction and Improvement of the Building

Ali Jafarian¹; Seyed Babak Jafarian²
¹School of Civil Engineering, Structural Engineering, Islamic Azad University, Tehran (Varamin) Branch, Tehran, Iran.
²School of Civil Engineering, Project Management and Construction, Islamic Azad University, Tehran (Safadasht) Branch, Tehran, Iran.

¹s.a.jafariyan@gmail.com, https://orcid.org/0000-0002-2086-7029
²s.babakjafarian@gmail.com, https://orcid.org/0000-0002-7803-4775

Abstract
Considering the increase in the current construction process and the future needs of Iran, the necessity to use high-rise buildings for reduction in urbanization costs and optimal use of land will be inevitable in the future. The performance of steel plate shear wall system as a modern global system, which has an effective application in high-rise buildings and also brings economic benefits compared to previous systems, is evaluated in this study. Steel Plate Shear Walls (SPSW) are a new type of system resistant to wind and earthquake lateral loads, which dates back to the 1970s. In this research, eight samples of shear wall with various stiffening arrangements and sections with ST37 and ST52 alloys are modeled. To evaluate the nonlinear dynamic analysis, the samples are subjected to the San Fernando earthquake force and are modeled and analyzed by ABAQUS software based on the finite element theory. The results of analyzing the samples indicate better performance of the system with stiffener in both vertical and horizontal directions. Also, the use of sections with ST52 alloy has improved the performance of the shear wall by approximately 40%.

Key-words: Shear Wall, Stiffeners, Nonlinear Dynamic, Different Arrangements.

1. Introduction

The seismicity of Iran and the importance of designing structures resistant to lateral forces are crucial for the future and sustainable development of Iran. The designers of the country have always been well acquainted with the gravitational forces and the way of designing for such forces and have performed it well. Historical monuments indicate the long history of Iranian builders in this field. In
recent years, given the development of cities and the progress of construction in every part of the
country, the necessity to pay attention to the issue of earthquakes and the importance of wind forces
in high-rise buildings has become a serious problem for designers, (Bathaei, B, 2020),
(Kadaei, S. 2020) In order to control the lateral forces, various types of lateral bearing systems are
used, each of which has its own characteristics (Bathaei, B, 2016) Choosing the type of a system
resistant to lateral forces depends on the loading combination, how the structure behaves, how the
gravitational loads are directed to the base and the architectural design. Furthermore, choosing the
type of a system resistant to lateral loads, in addition to the above, depends on the geometric
dimensions of the structure, regulatory restrictions, the amount of lateral force, maximum
displacement, etc. (Bathaei, B, 2018) Although steel plate shear walls have been known for many
years, no one paid attention to them seriously, but today this method is quite acceptable to owners
and builders. Steel plate shear walls have been considered, especially in the last three decades, and
are expanding rapidly. (Bathaei, B, 2016) This system has been used to build and reinforce important
buildings in the world, especially in earthquake-prone countries such as Japan and the United States.
(Bathaei, B, 2016) Steel plate shear walls used in both thin and reinforced walls are an innovative
system for resistance to wind and earthquake lateral loads. In recent decades, its thin-walled type has
attracted the attention of researchers. Given the optimal performance of this type of lateral bearing
system such as high stiffness, good ductility and high energy dissipation power, this system can be
used in the reinforcement of unsafe structures. Generally, a steel plate shear wall consists of a steel
plate surrounded by a boundary frame. Steel plate shear walls are commonly used in the design of
structures or the reinforcement of existing buildings as reinforced or unreinforced. In the first method,
the steel plate shear walls are reinforced using horizontal and vertical stiffeners such as plate beams
in such a way as to prevent out-of-plane buckling of the middle plate and ensure that it reaches the full
plastic limit. However, the construction and implementation of a large number of horizontal and
vertical stiffeners can be time consuming and cost more than an unreinforced shear wall. The use of
reinforced steel plate shear walls in the design of some structures, such as high-rise structures or
industrial structures or in situations where there are functional and operational limitations of the
structures due to out-of-plane buckling of the steel plate or in the reinforcement of existing structures,
may be preferred to unreinforced shear walls.¹

¹Alinia et al. (2012)

Steel plate shear wall is a simple system and no special complexity has been seen in its
implementation. Steel consumption can be reduced using steel plate shear wall system. Having the
accuracy in performing the work in the level of conventional accuracy in the implementation of steel structures and observing it, the factor of safety for implementation is much higher than other types of systems. Also, considering the possibility of manufacturing parts of this system in the factory and installing it on site, the speed of implementing the system is high and operating costs are reduced to some extent (Kalantari et al 2020). This system is the best alternative in terms of performance and safer in terms of strength and behavior in comparison with concrete shear walls, and it can be used not only in steel structures but also in concrete structures (Girhammar et al 2017). In terms of comparison with bracing systems and in terms of shear stiffness, this system is stiffer than the stiffest bracing systems, and due to the possibility of making openings anywhere, it has the efficiency of all bracing systems in this regard (Wang, M et al 2017) Research results show that the behavior of the system in the plastic environment as well as its energy absorption is better than bracing systems (Hosseinzadeh, L et al 2017) In this system, due to the wide range of materials and connections, the stresses are adjusted much better than in other strong systems, (Hosseinzadeh, L et al 2017) such as moment frames and various types of braces in which the materials are usually bundled and the connections are concentrated and the behavior of the system is especially more suitable in a plastic environment (Zhi, Q et al,2017).

2. History

Akbari in 2020 paper presents a new system to improve the structural behavior of unstiffened steel plate shear walls and eliminate the known defects of these efficient seismic-resistant systems. One of the significant drawbacks of unstiffened steel plate shear walls is the pinching of their hysteretic curve that happens due to the early out-of-plane buckling of the infill plate under small shear forces. Therefore, the primary purpose of this study is to reduce the amount of out-of-plane buckling using perforated plates with periodic auxetic-shaped cellular forms, which have a negative Poisson's ratio. To this aim, a parametric study is conducted on 255 finite element models of auxetic-shaped steel plate shear walls using ABAQUS software to select the most efficient configuration considering some design parameters such as the amount of out-of-plane buckling, energy dissipation and strength. Then, two full-scale specimens of the selected models are investigated experimentally under a quasi-static cyclic loading history. Finally, regarding this fact that for broader adoption of a new system, besides its structural performance, the total weight of that structural system is a determinant factor, two 5-and 10-story plane building models with unstiffened
and auxetic-shaped steel plate shear walls are designed to have the life safety performance level at the BSE-1 hazard level and they are evaluated by performing nonlinear static analyses. The results show that auxetic-shaped steel plate shear walls, while improving the seismic performance of a building, reduce its weight. (Akbari B. 2021).

Jianwei Zhang in 2020 investigate the seismic behavior of shear walls with high-strength materials, cyclical quasi-static tests on five half-scale shear walls with an aspect ratio of 1.5 were carried out, including four conventional reinforced concrete walls and one composite wall. The steel fiber-reinforced concrete shear wall with HRB 600 MPa reinforcement located completely in the boundary element and in the wall web was taken as the reference specimen. The presence of steel fibers, the strength of wall web rebar, and the presence of high-strength reinforcement diagonal bracing (X configuration) were selected as major test parameters for the other three conventional walls. The results reveal that the high-strength concrete (HSC) shear wall with high-strength steel rebar (HSSR) showed stable hysteresis performance, and all specimens had acceptable crack widths and residual deformations before a lateral drift of 1%, except for the non fiber-reinforced concrete specimen. The addition of steel fibers can reduce the crack width, limit the shear crack development, and increase the flexibility deformation, thus improving the deformation capacity of the specimens. Using HRB 600 MPa reinforcement instead of HRB 400 MPa reinforcement as wall web rebar can significantly reduce the residual deformation. The specimen with high-strength reinforcement diagonal bracing in the wall web and the composite shear wall with a built-in steel truss not only had desirable repairability after a large earthquake but also showed much higher energy consumption capacity under a strong earthquake. Finally, based on the experimental and theoretical analysis, a simple method for calculating the lateral strength was established, and the predicted results showed good agreement with the test data. (Wanga X, 2020).

Jinguang in 2020 paper proposes a novel plate-frame connection for thin SPSWs. The proposed connection, consisting of a fishplate with large holes, steel angles with standard holes, and bolts, is able to achieve a multi-stage force transfer mechanism. Two failure criteria of the proposed connection were defined, followed with shear test of the novel connection. Three SPSW structure specimens with various thicknesses of steel plate and plate-frame connections were tested. Finite element models for SPSW structure with novel connections were developed and verified by the test results. (Jinguang Y, 2021). The influence of thickness of infill steel plate on the seismic performance and connection slippage of SPSW structure was evaluated. The results show that the novel plate-frame connection is convenient to install in SPSW as the precision requirement of bolt holes in
traditional connection is mitigated. The SPSW structure with the novel connection exhibits similar seismic performance as that in the traditional bolts-connected SPSW structure. With the plastic deformation of angle steel at the latter stage (Sabouri Ghomi, S. 2015) the load bearing and energy dissipation capacities of SPSW structure are increased by 0.83% and 5.4% as compared with those of the SPSW with the traditional bolt connection, respectively. The multistage stress model and two-stage failure criterion can accurately predict the failure of the plate-frame connection.

Ahmadi, Zarrinkolae in 2021 studied the behavior of SPSWs with perforated panels. In order to conduct a parametric study, the effect of circular and elliptical openings on steel plate shear walls, as well as the order, arrangement and number of these openings on the behavior of the structure in terms of energy were evaluated (Ahmadi, 2021) Absorption level, total load carrying capacity of the system (waste curve) as well as the resulting stress distribution. ABAQUS finite element software was used to model the samples. The results of the parametric study on 17 finite element models under cyclic loading as displacement showed that in general, with increasing opening percentage, shear capacity and energy absorption level of the wall experienced a significant decrease with an average of 20% reduction in energy absorption capacity with a tenfold increase in the opening (Wang meng et al., 2015).

In 2021, labi and Naci Caglar selected L-shaped cold steel plates for numerical analysis under lateral cycle forces. A large-scale numerical model was developed using a fiber beam column element with a shear spring model to reproduce the actual behavior of composite shear walls. In addition, the OpenSees-based model was confirmed against three combined composite shear walls and demonstrated robust simulation capability. Furthermore, (labi, Naci Caglar, 2021) in order to fully explain their effect on the performance of composite shear walls, the properties of L-shaped steel plates were investigated parametrically using a numerical model in terms of thickness and yield strength. It was clear that increasing the strength and thickness of the plate would increase the lateral load capacity of the walls. It was thought that the two factors were interconnected in terms of effects, and that the arrangement of the L-shaped steel plate in the boundary region had a major role in the response of the entire composite shear wall under the applied loads. (Zhang, X, 2014).

3. Finite Element Modeling and its Validation

Data analysis was carried out using ABAQUS software. In this research, in order to evaluate the performance of steel plate shear walls with different arrangement of stiffeners, the samples are
considered to have a steel plate with a length and height of 4 and 2.80 m, respectively, and a thickness of 0.25 cm and stiffeners with a thickness of 0.8 cm and IPB240 profile are considered as beams and columns. The model is modeled once without stiffener and other times with horizontal and vertical stiffeners and simultaneously horizontal and vertical, which is made of ST37 steel once and ST52 another time.

4. Analysis Method

In this research, nonlinear dynamic analysis is used to evaluate the samples. For this purpose, the samples are affected by the San Fernando earthquake record in the X and Y directions with the following specifications.

Table 1 - San Fernando Earthquake Record Specifications

| Station     | Year | Earthquake   | Record Seq |
|-------------|------|--------------|------------|
| Lake Hughes | 1971 | San Fernando | 70         |

Figure 1 - Graph of San Fernando Earthquake Record

The material specifications of all the members of the samples are given in Table (2). Figure (2) also shows a schematic view of the gridding and a sample of shear wall. As can be seen, the samples are gridded with 15 cm meshes.

Table 2 - Material Specifications of the Samples

| Steel materials       | Modulus of elasticity (GPa) | Yield stress (MPa) | Ultimate stress (MPa) |
|-----------------------|-----------------------------|--------------------|-----------------------|
| IPB 240, ST37         | 210                         | 240                | 360                   |
| IPB 240, ST52         | 210                         | 300                | 470                   |
| Plate,at37 (THK.=2.5mm) | 210                       | 165                | 240                   |
| Plate,at52 (THK.=2.5mm) | 210                       | 200                | 300                   |
| Plate stiffner (THK.=8mm) | 210                      | 165                | 240                   |
5. Evaluation of Numerical Results using ABAQU Software

It should be noted that in reality there is no perfectly flat (ideal) steel plate. Therefore, in Abacus software, a number should be considered as imperfection in buckling analysis for distortion in the dominant mode. Figure (3) shows a view of the buckling analysis model and contour.
B) (Model with Vertical Stiffener)

C) (Model with Horizontal Stiffener)
After analyzing all the samples under the nonlinear dynamic analysis of the earthquake, the results were reported as follows.

Figure 4 below shows the distribution of the deformation of shear walls with ST37 steel due to the San Fernando earthquake.

Figure 4 - Distribution of the Deformation (cm) of Shear Wall (ST52) under the San Fernando Earthquake
A) (Model without Stiffener)
B) (Model with Horizontal Stiffener)

C) (Model with Vertical Stiffener)
As can be seen from Figure 4, the maximum displacement is in the mode without stiffener and the minimum displacement is in the mode reinforced with both horizontal and vertical stiffeners simultaneously.

Figure 5 shows how the deformation of shear walls with ST52 steel materials is distributed due to the San Fernando earthquake.

Figure 5 - Distribution of the Deformation (cm) of Shear Wall (ST52) under the San Fernando Earthquake
A) (Model without Stiffener)
B) (Model with Horizontal Stiffener)

C) (Model with Vertical Stiffener)
As can be seen in Figure 5, the maximum displacement is in the mode without stiffener and the minimum displacement is in the mode reinforced with both horizontal and vertical stiffeners simultaneously.

The results of the Von Mises stress distribution are also observed in the case where ST37 materials are used.

Figure 6 - Stress Distribution (Kg/cm²) of Shear Wall (ST37) under San Fernando Earthquake

A) (model without stiffener)
B) (Model with Horizontal Stiffener)

C) (Model with Vertical Stiffener)
As can be seen in Figure 6, in constant loading conditions and only the position of the stiffener, the stress in the mode without stiffener is the lowest value and it is the highest value in the mode reinforced with horizontal and vertical stiffeners.

Figure 7 shows the results of the Von Mises stress distribution in the case where ST52 materials are used.

Figure 7 - Stress Distribution (Kg/cm²) of shear wall (ST52) under San Fernando Earthquake

A) (Model without Stiffener)
B) (Model with Horizontal Stiffener)

C) (Model with Vertical Stiffener)
According to Figure 7, it can be seen that in constant loading conditions and only the position of the stiffener, the stress in the mode without stiffener is the lowest and it is the highest in the mode reinforced with horizontal and vertical stiffeners.

The graphs also show the results of viscous energy dissipation when ST37 materials are used.

Figure 8 - Graph of Viscous Dissipation in the Sample without Stiffener with ST37 Materials
Figure 9 - Graph of Viscous Dissipation in the Sample with Vertical Stiffener with ST37 Materials

Figure 10 - Graph of Viscous Dissipation in the Sample with Horizontal Stiffener with ST37 Materials

Figure 11 - Graph of Viscous Dissipation in the Sample with Both Vertical and Horizontal Stiffeners Simultaneously with ST37 Materials
Also, the following graphs show the results of viscous energy dissipation in the case where ST52 materials are used.

Figure 12 - Graph of Viscous Dissipation in the Sample without Stiffener with ST52 Materials

Figure 13 - Graph of Viscous Dissipation in the Sample of Vertical Stiffener with ST52 Materials

Figure 14 - Graph of Viscous Dissipation in the Sample without Stiffener with ST52 Materials
6. Conclusion and Discussion

The performance of steel plate shear walls in this research is described in detail and in the part of its effect on project management during construction and improvement of the building, the following items should be considered in the research:

1. Cost management: Given that in the research, the performance improves by 1.4 using ST52 alloy instead of ST37, but it only causes a 15% increase in cost, which should be discussed in detail in the research.

2. Quality improvement management: Considering that most of steel frame shear walls is made in the factory, all the necessary controls and welding inspections are well implemented on the steel frame shear walls, and after installation in the workshop, the welding inspections can be controlled. However, in concrete shear walls, due to the fact that all works are done in the workshop, it is not possible to track the quality of the work compared to the factory, and different parts including connections, reinforcement, framing, concrete quality control and concreting and concrete curing should be monitored and inspected in the workshop.

3. Time management: Due to the fact that the construction of steel frame shear walls is made in the factory and only installation is done in the workshop, it is not comparable to concrete shear walls in terms of time, and the implementation of connections, reinforcement, framing, concreting, and concrete curing should be done for concrete shear walls. Under these conditions, time is saved approximately by 80% during the implementation of steel plate shear walls compared to concrete walls.

4. In case of out-of-plan earthquake and damage to the steel plate shear wall or revision of the building design that leads to the strengthening of the shear wall, the steel plate shear wall can be easily replaced and can be installed without the need for concrete destruction in the shortest possible time.

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