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Improving Cyclic Behavior of Steel Plate Shear Walls with Elliptical Perforations

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ABSTRACT: In this paper, the effect of elliptical shape openings was numerically compared to the case when circular openings were used in the steel panel shear walls. At first, the finite element model in ABAQUS was calibrated by experimental results, obtained from previous studies. Then, three steel shear panels with different sizes of elliptical openings were analyzed under cyclic loads, and the results were compared to those circular perforations. Moreover, comparisons of cyclic response parameters such as elastic stiffness, ductility ratio, and energy absorption were made. According to the results, the shape of the openings has a significant effect on the seismic behavior of the perforated shear wall. The elliptical opening with the smaller to larger diameter ratio, equal to 0.5, increased the ultimate capacity by 15%. Furthermore, the elastic stiffness, ductility ratio of the frame, and the absorbed energy were promoted by 28%, 3%, and 8%, respectively. Finally, the distance between the openings was improved. Using a ratio of about 0.17 for the center to center distance of elliptical openings to the total width of steel panel led to the best performance.

Keywords: Circular Opening, Elliptical Opening, Finite Element Analysis, Perforated Shear Wall, Steel Panel.

INTRODUCTION

The steel plate shear wall (SPSW) has been considered in buildings since the 1970s as a resistance system, against lateral forces such as earthquakes and winds, especially in high-rise structures. The system has demonstrated itself to be very well behaved in the Unites States and Japan, as well as in laboratories.

This new phenomenon, which is rapidly expanding in the world, has been used to construct new buildings and to strengthen existing structures (TahamouliRoudsari et al., 2019). The technology of designing and manufacturing steel plate shear walls has been prominent in recent years, and its design and implementation rules have been introduced into various seismic provisions such as CSA-S16 and AISC-341 (AISC-341, 2016; CSA, 2014).

The SPSW system consists of a steel shear panel as an infill to the structural frame, which consists of beams (Horizontal Boundary Element or HBE) and columns (Vertical Boundary Element or VBE). The steel shear wall is similar to a cantilever plate girder, in which the columns are as the flanges, beams as the hardeners, and steel panels as their webs (Gholizadeh and Shahrezaei, 2015).

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Boundary columns are sometimes exposed to proportionally larger story shears, which may lead to early failure of the columns. The research has recently tended to the use of light-gauge, cold-formed steel panels (Berman and Bruneau, 2005), low yield steel web plates, perforated web plates (Bhowmick et al., 2014; Shekastehband and Azaraxsh, 2019), and slit plate shear walls (He et al., 2016; Lu et al., 2018).

The research on circular perforations in shear panels similar to SPSWs started with Roberts and Sabouri Ghomi (1992). They tested unstiffened steel plate shear panels with centrally-placed circular openings. Valizadeh et al. (2012) experimentally studied the effect of opening sizes and slenderness ratio of the steel plate on seismic behavior of SPSW under cyclic loads. Bahrebar et al. (2016) considered the structural and architectural features of corrugated and perforated web SPSWs together in order to enhance the efficient lateral force-resisting system.

The effect of crack at the corner of SPSWs on the seismic behavior of the system was investigated by Broujerdian et al. (2017). Numerical results indicated that horizontal cracks were more effective than vertical ones.

Nie and Zhu (2014) studied an experimental research to investigate the seismic behavior of steel plate shear walls in the presence of the openings. The experimental results showed that the strength and stiffness specifications of the walls declined due to the existence of openings.

Tsavdaridis and D'Mello (2012) numerically optimized the elliptically-based web opening shapes in perforated beams. It was shown that perforated beams with vertical and inclined classic elliptical web openings (3:4 width to depth ratio) behaved more effectively in terms of stress distribution and local deflection, compared to perforated beams with conventional circular and hexagonal web openings.

In this study, ABAQUS/Standard solver (Hibbit, 2009) is used to study the cyclic behavior of steel plate shear walls. At first, the finite element model is verified by experimental test results in the literature. Then, sensitivity analysis is carried out on steel plate shear walls such as shapes and distances between the openings. Seismic parameters such as ductility ratio, elastic stiffness, and energy absorption are used to compare the results. At the end, both the best arrangement and the geometry of the openings are recommended.

The novelty of this research, which aimed necessary improvements in hysteresis behavior of SPSWs, is the use of elliptical-shaped openings in the shear wall web plate. The mechanical properties of the steel panel and the VBE and HBE elements are presented in the next section.

VERIFICATION OF THE FINITE ELEMENT MODEL

The behavior of the steel material is considered bilinear with hardening (5% for frame members and 2.5% for steel panel). This behavior is the same in tension and compression stresses. The density values and Poisson's coefficient of steel materials in the analysis are considered to be 7800 kg/m^3 and 0.3, respectively. Other mechanical properties of steel materials are presented in Table 1.

In this research, all components of the system are modeled using solid element (C3D8R element in ABAQUS). According to Figure 1, the cubic element C3D8R consists of an 8-node element with reduced integration. Each node has three degrees of freedom in three directions of the axes X, Y, and Z (Hibbit, 2009).

The Vian et al. (2009b) test specimen was used to validate the modeling, by Finite

Element method in ABAQUS CAE (Hibbit, 2009). Then, through performing appropriate modelling, a perforated steel shear wall with elliptical openings was compared with a wall with circular openings. Finally, the geometry and spacing of elliptical openings were discussed and improved.

Vian et al. (2009b) experimentally studied the perforated steel shear walls. The test specimens consisted of steel members with properties according to Table 1. According to the literature (Vian, 2005; Vian et al., 2009b), using Low-Yield-Strength (LYS) steel for infill plates reduces the forces acts to the boundary elements.

The details of the frame are shown in Figure 2. Cyclic loading pattern according to Figure 3 was applied to the middle of the upper beam, simulating the seismic loads applied by earthquakes.

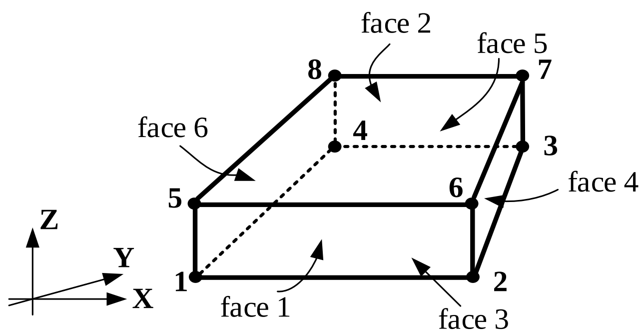


Fig. 1. Cubic element C3D8R (Hibbit, 2009)

Table 1. Properties of the tested steel materials (Vian et al., 2009b)

Experiment members	Yield strength (MPa)	Ultimate strength (MPa)	Modulus of elasticity (GPa)	Elongation (%)
Frame members	345	466	205	14
Infill plate	160	300	205	30

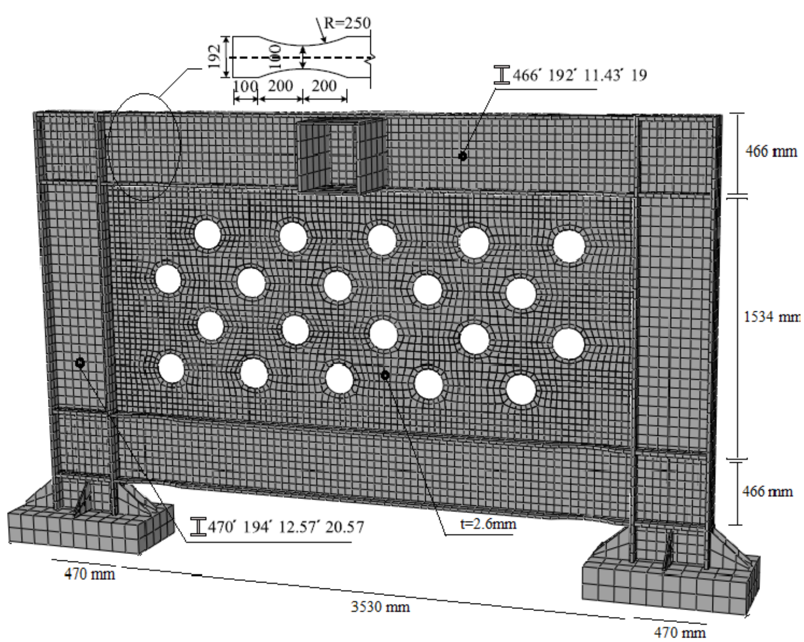


Fig. 2. The geometry of the frame tested by Vian et al. (2009b)

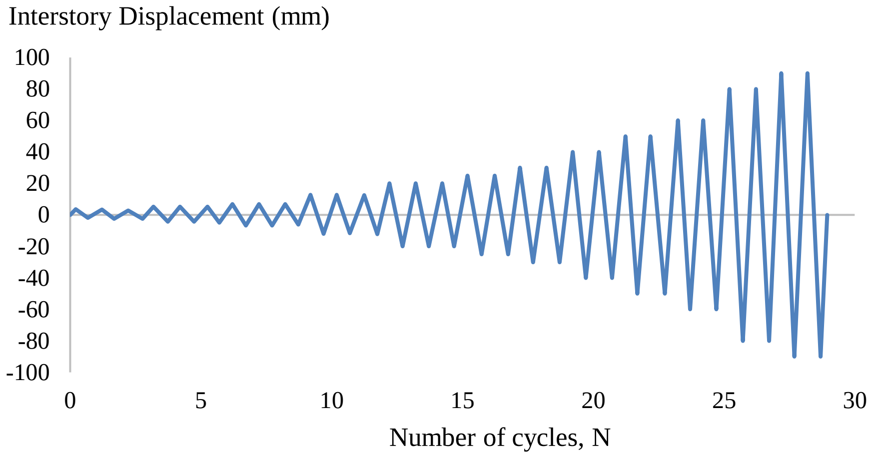


Fig. 3. Loading history (Vian et al., 2009b)

BOUNDARY CONDITIONS, INTERACTIONS AND MESH SIZE

In many cases, especially in nonlinear FE analysis, the finer mesh size leads to more accurate response, but it is time consuming. This is more important in structures with large numbers of meshes. Therefore, an optimum mesh size must be adopted at the beginning of the analysis process. In order to justify the mesh size, three models were analyzed and compared here with experimental results obtained from Vian et al. (2009b) test. According to the results presented in Table 2, the average mesh size in the steel panel, equal to 40 mm, had an acceptable accuracy.

With respect to Figure 4, the displacements of the supports in all directions are limited. The panel, beams, columns, stiffeners, and rigid loading plates are full-bound. Moreover, they are tied with each other in complete continuity.

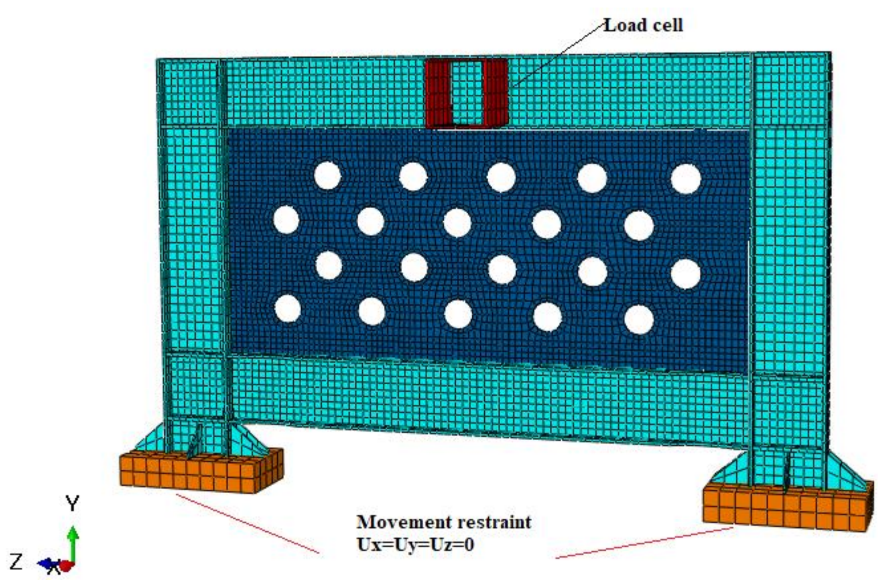


Fig. 4. The model and boundary conditions

Table 2. The effect of mesh size on FE analysis results

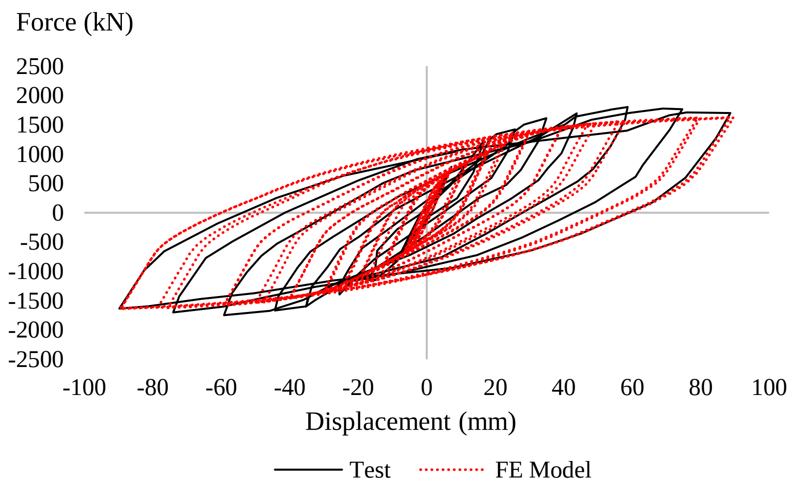
	Test	Small mesh	Normal mesh	Large mesh
Size of the component mesh	-	40 mm	60 mm	80 mm
Frame base shear (kN)	1665	1625	1741	1792
Difference with the test (%)	-	-2.4	+4.6	+7.6

COMPARISON OF THE RESULTS

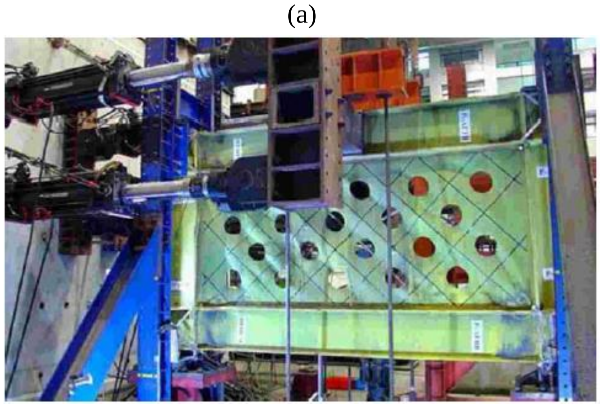
The load-displacement curve (P-Δ) and the typical failure modes, obtained from finite element modelling and the test carried out by Vian et al. (2009b), are compared in Figure 5. The Figure 5a indicates the Finite Element model, which predicts the strength and stiffness degradation of the shear wall accurately. It is remarkable in Figures 5b and 5c that the numerical method could also accurately predict the cumulative damage, deformation developing process, the local buckling of columns and the panel, and the crossed tension fields in the steel plate shear wall.

The Effect of the Opening Shape on the Behavior of Perforated SPSW

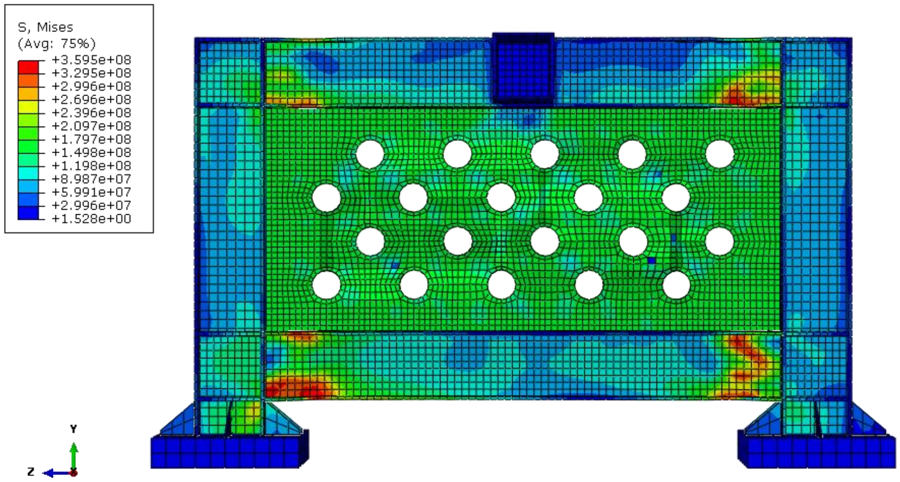
Two models of perforated SPSW, named SW-1 and ESW-2, were modeled in order to compare the wall with elliptic and circular opening shapes. Geometric characteristics of the walls are shown in Table 3. The other dimensions such as the length of both HBE and VBE and their cross sections are the same as Vian et al. (2009b) test (Figure 2).



(a)



(b)



(c)

Fig. 5. The comparison of test vs FE model: a) hysteresis curves; b) The test failure modes; c) Von Mises stress contour of FE model

Table 3. Geometric characteristics of models (SW-1 and ESW-2)

Frame ID	Thickness t (mm)	Larger diameter (mm)	Smaller diameter (mm)
SW-1	2.6	200	200
ESW-2	2.6	200	100

The models under the quasi-static cyclic loading protocol, based on the proposed seismic criteria recommended by AISC-1997 (1997, 1997), are utilized as shown in Figure 6. The FE model analysis was performed until 180 mm displacement (9% drift ratio) in order to obtain the ultimate capacity and failure modes. This lateral displacement approximately equals to twice the ultimate demand in most of seismic provisions.

By applying the cyclic loading as previously mentioned, Figure 7 shows the hysteresis load-displacement curve obtained from the SW-1 and ESW-2 modeling. The following sections deal with the comparison of seismic parameters of two models.

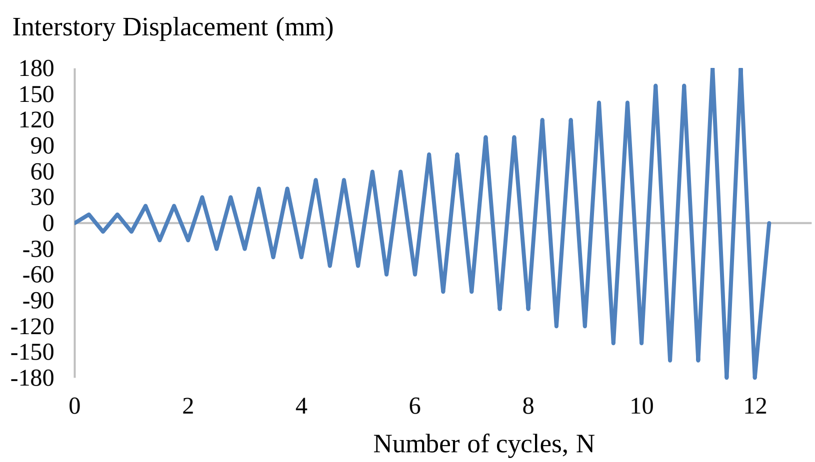


Fig. 6. Loading history based on AISC seismic provisions, 1997 (AISC, 1997)

The Von Mises stress contour of shear walls with circular-shaped (SW-1) and elliptical-shaped (ESW-2) perforations were obtained and showed in Figures 8a and 8b. The comparison of these two figures proved that elliptical openings resulted in decreasing the HBE yield stress. But according to Figure 8-b, some stress increase is observed in the columns of shear wall with elliptical openings (ESW-2) rather than SW-1 with circular ones, which is not desirable.

The equivalent plastic strain (PEEQ) of shear walls with circular-shaped (SW-1) and elliptical-shaped (ESW-2) perforations were obtained and showed in Figures 8c and 8d. The comparison of two figures showed that in ESW-2, more plastic strains were observed in vertical direction due to stress concentration. However, in SW-1, plastic strains were equally distributed in both vertical and horizontal directions. The elliptical-shaped shear wall behaved approximately similar to multi-row slit shear walls and stress concentration occurred in the top and bottom adjacent elements, as in rows of links in slit shear walls. Therefore, the steel plate shear wall could have the advantages of both kinds of steel shear walls.

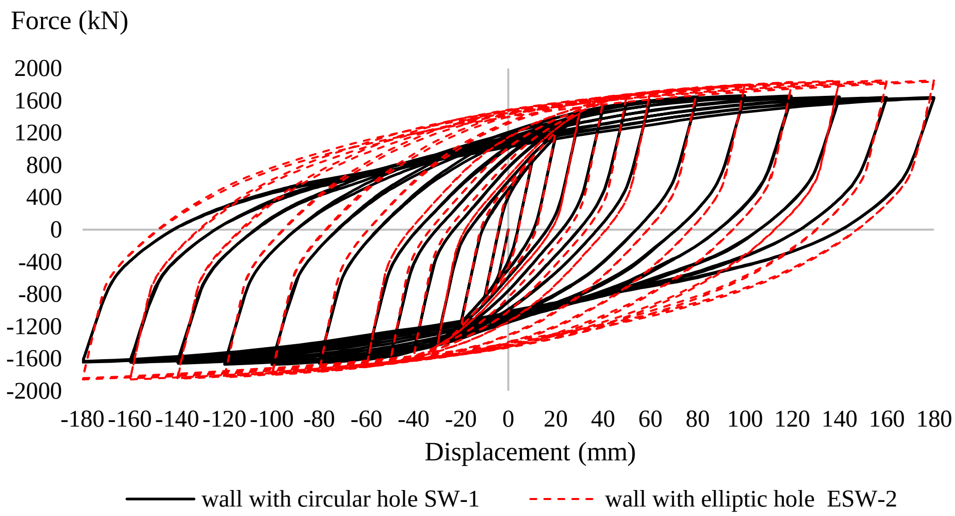
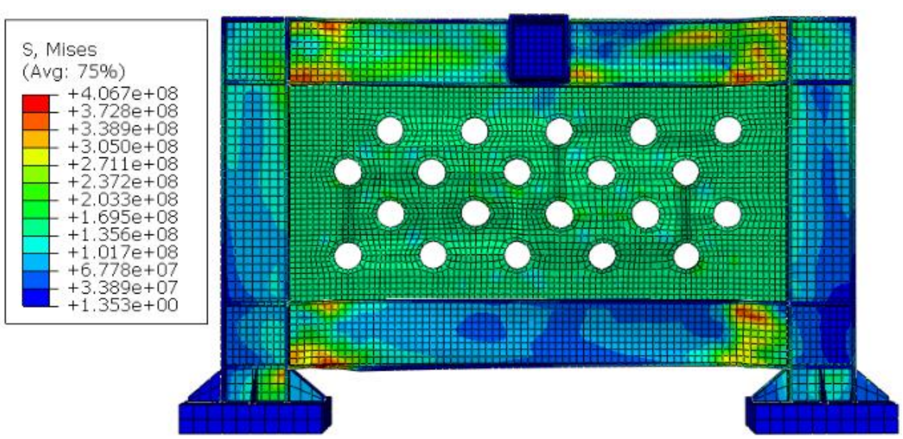
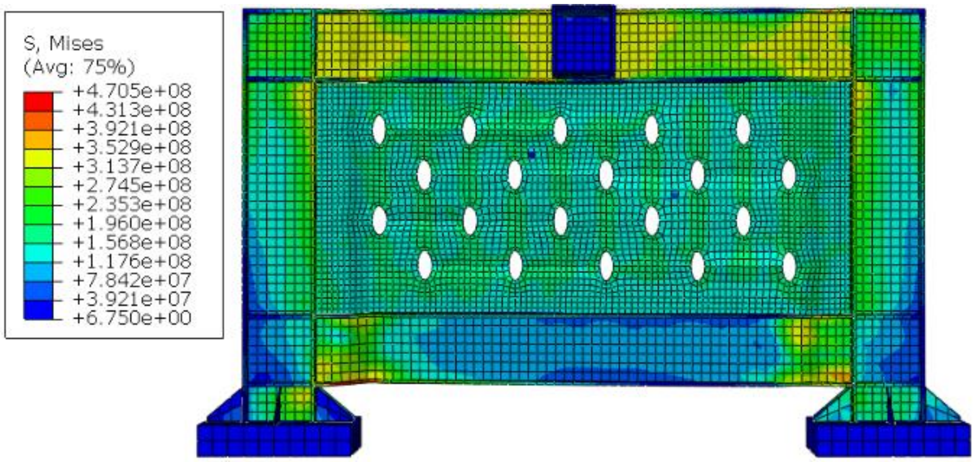


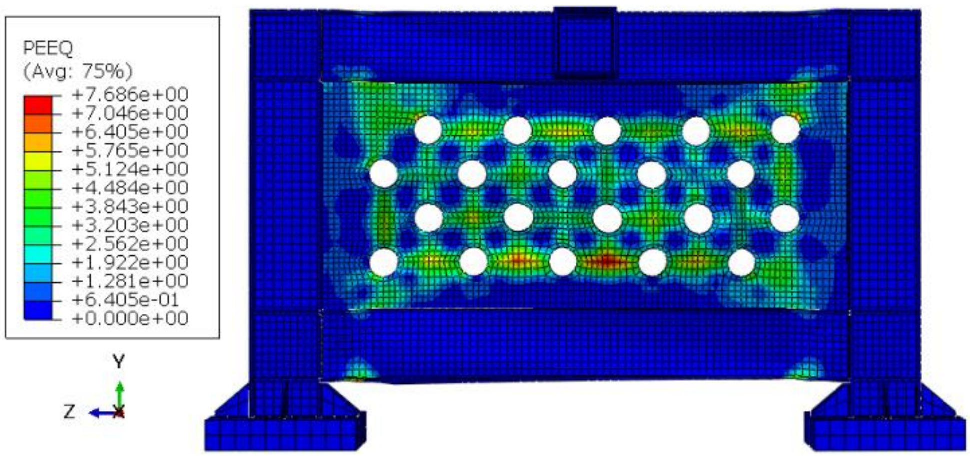
Fig. 7. Cyclic load-displacement curve of two models



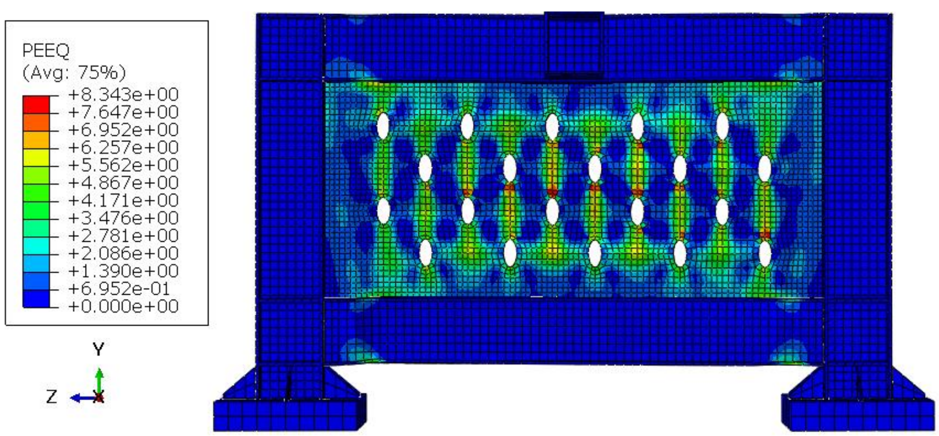
(a)



(b)



(c)



(d)

Fig. 8. a) Von Mises stress contour of (SW-1); b) Von Mises stress contour of (ESW-2); c) Equivalent plastic strain of (SW-1) and; d) Equivalent plastic strain of (ESW-2)

Energy Dissipation

In this section, the cumulative dissipated energy of the modeled frames is shown and compared. The dissipated energy can be represented by the surface between the hysteresis load-displacement cycles. Figure 9 shows the cumulative dissipated energy of two modeled frames. Within a story drift ratio of 9%, the ESW-2 frame with elliptical openings has 26% more energy dissipation than SW-1.

Comparison of the Other Seismic Parameters

To evaluate initial resistance parameters, ultimate strength, elastic stiffness, ductility ratio, and energy absorption, we need to use equivalent bilinear graph. According to Figure 10, point A, representing the yielding force (F_y), should be chosen so that the surface below the nonlinear behavior curve equals to the enclosed OABD level and the line OA intersects the nonlinear curve in 0.6 F_y (point C) (ODSS, 2009).

Seismic parameters are obtained according to the equivalent bilinear curve as follows (ODSS, 2009):

1) Primary resistance (F_y): the shear force corresponding to point A;

2) Ultimate strength (F_u): the shear force corresponding to point B;

3) Elastic stiffness (K_e): the slope of OA;

4) Energy absorption: Area under the polyline (OABD).

The seismic parameters presented in Table 4 can be obtained from bilinear envelope curves according to Figure 11.

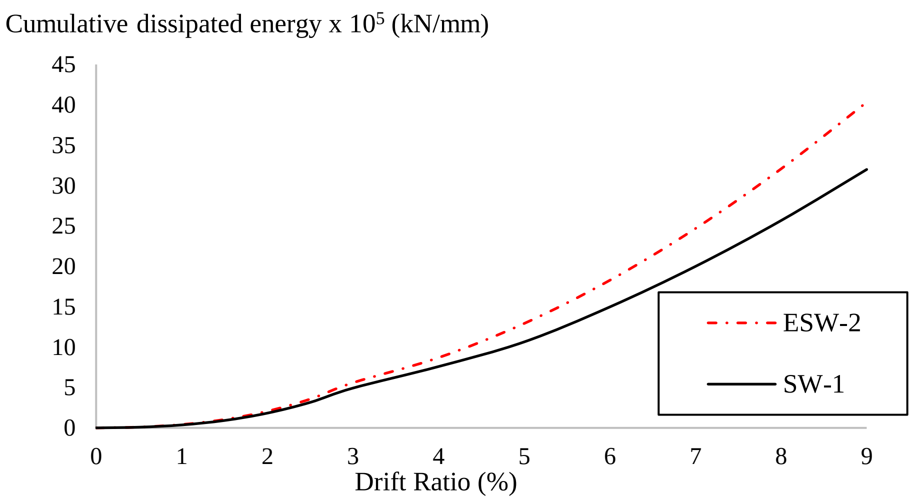


Fig. 9. Cumulative energy dissipation

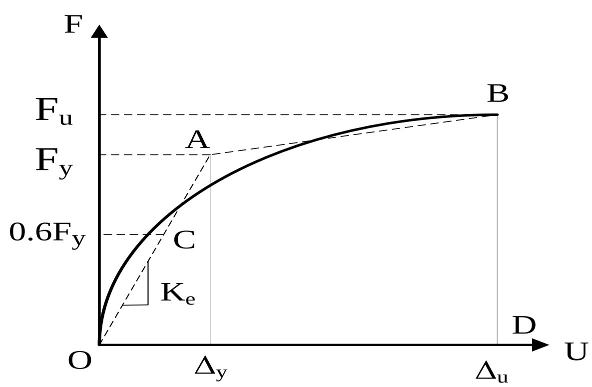


Fig. 10. Equivalent bilinear graph of capacity curve (ODSS, 2009)

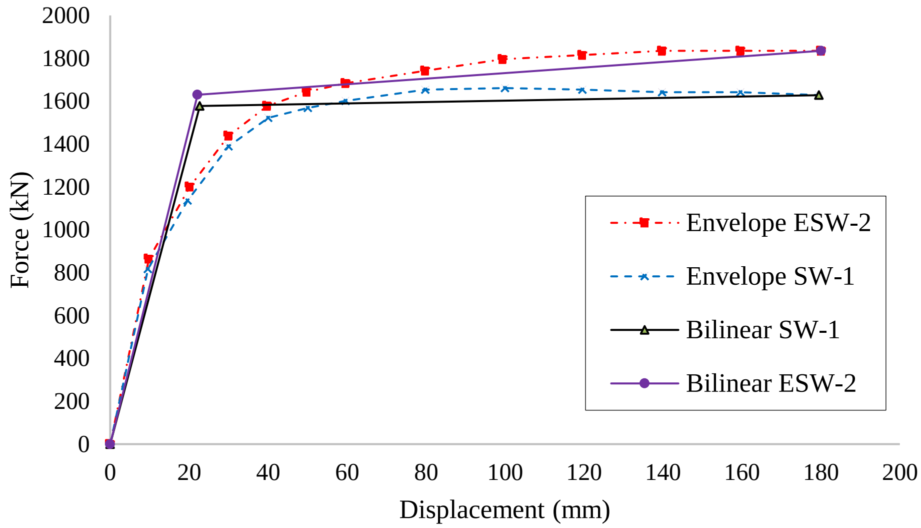


Fig. 11. The envelope and bilinear curves for two models

Table 4. Comparison of seismic parameters of the two models

Frame ID	Yielding capacity F_y (kN)	Ratio to SW-1	Ultimate capacity F_u (kN)	Ratio to SW-1	Ductility ratio ($\mu=\Delta_u/\Delta_y$)	Ratio to SW-1	Elastic stiffness (kN/mm)	Ratio to SW-1	Energy absorption (kN.mm)	Ratio to SW-1
SW-1	1577.74	-	1627.91	-	7.91	-	69.473	-	269343	-
ESW-2	1629.86	1.03	1834.98	1.13	8.13	1.027	73.583	1.06	291696	1.083

According to Table 4, yielding and ultimate capacity, ductility ratio, elastic stiffness, and energy absorption in ESW-2 increased, compared to circular perforated shear panel (SW-1). The elastic and ultimate capacity stiffness increased by about 6% and 13%, respectively. Improving the elastic stiffness in lateral resisting system leads to a lower lateral displacement. So, elliptical openings in steel shear walls in medium to high rise buildings are more efficient, compared to perforated walls with conventional circular openings.

The Geometry of Elliptical Openings

In order to improve the shear wall behavior by changing the geometry of elliptical openings, three SPSW with elliptical openings were modeled. The material properties of recent models were presented in previous sections.

According to Figure 12, the smaller diameters of the ellipsis (*b*) were 60 mm in ESW-1, 100 mm in ESW-2, and 140 mm in ESW-3. The larger diameter (*a*) for all three elliptical openings was 200 mm. The models were analyzed with a loading protocol as AISC-97 similar to Figure 6 mentioned before.

The yielding and ultimate strength of the models were compared in Figure 13. It is obvious that both the yielding and the ultimate capacity of the wall with 60 mm smaller diameter (ESW-1) increased by 6% and 15%, respectively, in comparison with a circularly-perforated wall (SW-1). However, this higher capacity has no advantages in shear walls because it could damage the boundary elements (VBEs and HBEs). Besides, the ESW-2 with a 100 mm smaller diameter had approximately the same yielding capacity as SW-1 and a better ultimate capacity.

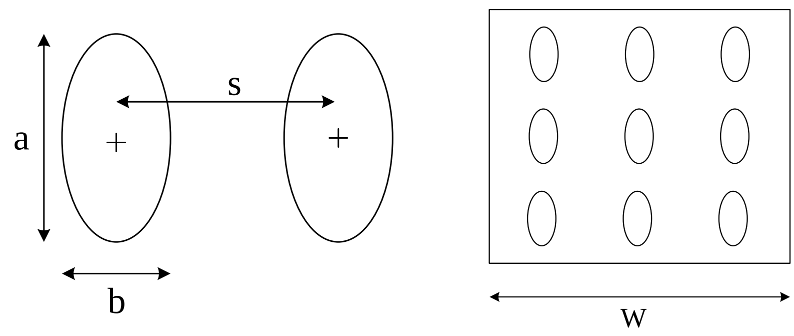


Fig. 12. Parameter definition of the geometry of elliptical openings

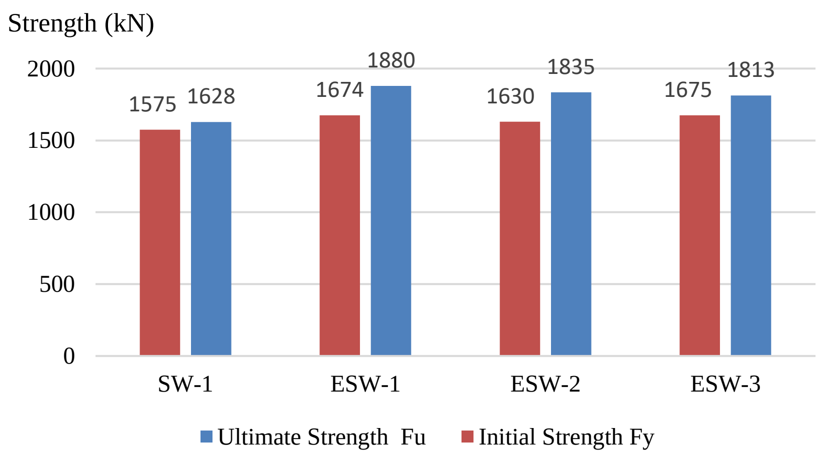


Fig. 13. Comparison of the Initial and Ultimate Strengths of the Models

Table 5 also compares the elastic stiffness, ductility ratio, and energy absorption of models. Based on the results, the elliptical opening with the smaller diameter (horizontal) of 100 mm showed the best performance. The ESW-2 increased the ductility ratio, elastic stiffness, and absorbed energy by 2.7%, 6%, and 8.3%, respectively. Besides, the ESW-1 had a better performance and ESW-3 had a weaker performance compared with SW-1 with circular openings. This reveals that increasing the horizontal diameter of elliptical openings had a negative effect on seismic parameters of steel panel shear walls. Therefore, a ratio of 0.5 between smaller to larger diameters of elliptical openings is proposed in this study.

Discussion about the Distance of Elliptical Openings

The distances between ellipsis center to center were 600 mm in previous models, similar to Vian et al. (2009b) test. In order to improve the horizontal distance of openings (*S* in Figure 12), three models with different center to center distances were analyzed. The models were named ESW-A with 370 mm, ESW-B with 800 mm, and ESW-2 (analyzed before) with 600 mm. The smaller diameters of all three SPSWs were 100 mm, while the larger ones were 200 mm. As the steel panel had a horizontal width of 3530 mm (*W* in Figure 12), the ratios of opening distance to total width of the steel panel (*S/W* ratio) for three models were about 0.1 for ESW-A, 0.17 for ESW-2, and 0.22 for ESW-B.

Table 5. The comparison of Seismic Parameters

Model ID		Ductility ratio ($\mu=\Delta_u/\Delta_y$)	Ratio to SW-1	Elastic stiffness (kN/mm)	Ratio to SW-1	Energy absorption (kN.mm)	Ratio to SW-1
ESW-1	b = 60 mm*	8.1	1.025	75.4	1.085	279881	1.039
ESW-2	b = 100 mm	8.13	1.027	88.765	1.06	291697	1.083
ESW-3	b = 140 mm	6.48	0.819	60.35	0.868	265253	0.91

* The letter (b) is the smaller diameter of ellipsis; the larger diameter was 200 mm in all three models.

The yielding and ultimate capacity of steel shear panels were presented in Figure 14. The ESW-2 and ESW-A panels had similar capacities, whereas the ESW-B had more yielding and ultimate capacities. As mentioned before, increasing the yielding capacity had negative effects on boundary elements, especially on VBEs.

For more comprehensive investigation of opening distances, Table 6 presents seismic parameters, obtained from bilinear equivalent curves, according to the Iranian provision (ODSS, 2009). Increasing the distance to 800 mm decreased both the ductility ratio and elastic stiffness and increased the energy absorption. In addition, although decreasing the distance to 370 mm had no significant effects on ductility ratio and energy absorption, it decreased the initial stiffness. Since the inter-story drift ratio is an important factor of structural design, increasing the shear wall stiffness can improve the design of medium to high rise buildings. As a result, in this study, a value of about 0.17 for the opening distance to total width ratio of the panels improved the capacity, ductility ratio, and energy absorption. This ratio, equal to 0.1, didn't significantly change the seismic parameters rather than SW-1 with circular openings.

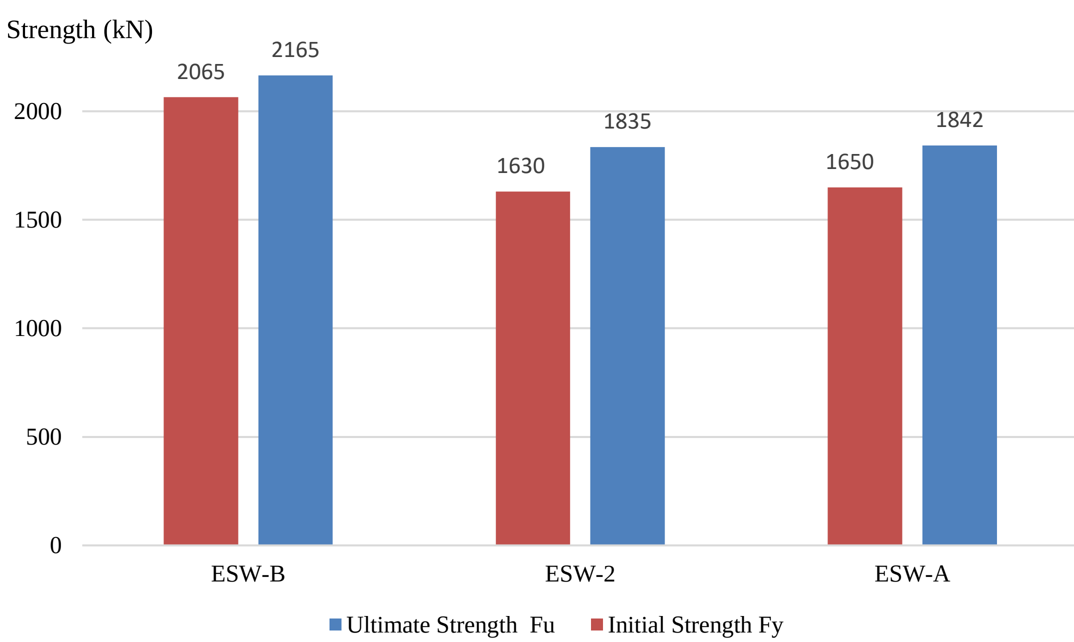


Fig. 14. Comparison of the initial and ultimate strengths of the models

Table 6. Comparison of seismic parameters

Model ID	**(S/W) Ratio**	**Ductility ratio ($\mu=\Delta_u/\Delta_y$)**	**Ratio to ESW-2**	**Elastic stiffness (kN/mm)**	**Ratio to ESW-2**	**Energy absorption (kN.mm)**	**Ratio to ESW-2**
ESW-2*	0.17	8.13	-	88.765	-	291697	-
ESW-A	0.10	8.4	1.03	77.11	0.87	294522	1.01
ESW-B	0.22	6.61	0.81	75.94	0.85	350709	1.2

* The smaller diameter is 100 mm and the larger dimeter is 200 mm in all three models.

CONCLUSIONS

In this research, after verifying the numerical model with experimental results, the elliptical-shaped openings were examined on steel plate shear walls. Three different types of perforated shear walls with elliptical openings were investigated to improve the geometry of the opening shape, based on the seismic parameters such as elastic stiffness, ductility ratio, energy absorption, and ultimate strength. The following results were obtained:

- According to the results, the shape of the holes has a significant effect on the behavior of the perforated shear walls.
- Comparing to SW-1 with circular openings, the shape of the elliptical opening, with the smaller diameter of 60 mm, increases the initial and final Strengths by 6% and 15%, respectively.
- The ESW-2 with the smaller and larger diameters of 100 mm and 200 mm, respectively, had approximately the same yielding capacity and better ultimate capacity than SW-1. The elastic stiffness, ductility ratio and absorbed energy of ESW-2 model increased by 6% ، 3% and 8%, respectively, compared to SW-1.
- Some stress increase is observed in columns of shear wall with elliptical opening (ESW-2) rather than SW-1 with circular openings, which is not desirable.
- Based on the results, a ratio of 0.5 between the smaller to the larger diameters of elliptical openings in this study leads to a better performance in perforated steel shear walls.
- Finally, the results showed that varying the horizontal distance of openings changes the elastic stiffness of SPSWs. Therefore, in this study, a value of about 0.17 for the opening distance to total width ratio of the panels (S/W) improved the capacity, ductility ratio, and energy absorption. The (S/W) ratio, equal to 0.1, didn't significantly change the seismic parameters rather than SW-1 with circular openings.

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