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A Comprehensive Review of Recent Experimental and Numerical Investigations on the Impact of Openings in Steel Plate Shear Walls (SPSWs)

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ABSTRACT

Structural buildings such as steel and reinforced concrete frames usually include doors and windows on the front or back facades, interior to the open areas. This; should be arranged to have an excellent correspondence for the location of shear walls, which are counted as essential elements for lateral stability. As a result, these architectural elements across the building assist in creating areas that are relatively less resistant to lateral loads. This review investigates the behavior of steel plate-framed shear walls with openings when subjected to lateral force exposure by thoroughly evaluating the composition of previous studies. To assess the impact of opening size, type, and layout effects on the overall performance of the lateral force-resisting system. There are studies explore on Steel Plate Shear Walls (SPSWs), both with and without openings. This study emphasizes the effect of openings on shear capacity. It investigates the effect of adding openings to steel plate shear walls on stiffness, ductility, damping ratio, and strength of the system. Key findings from the studies show that openings in SPSWs invariably reduce their lateral stiffness and strength. The amount of deduction in the strength of a structure depends on various factors such as the size, shape, and location of the opening. Additionally, the corners of the opening may experience stress concentrations which can cause tearing and reduced ductility. As a result, it disrupts the tension field action, which is the primary mechanism for SPSW energy dissipation. Most studies reviewed only the relatively thin infill plates and particular boundary conditions, which are highly important but have a gap in thick plates. Caution should be exercised when extrapolating due to thicker infill plates or different frame configurations. Considering a broader range of parameters, further research is necessary to establish comprehensive design guidelines for SPSWs with various opening configurations.

Keywords: Opening in Steel Plate Walls; Shear Strength; Stiffness; Ductility; SPSW.

1. Introduction

1.1 General Background

Three forms of steel plates are known as steel plate shear walls, corrugated steel plates, and composite steel plates. These structural systems are widely recognized as being efficient and performing as lateral force-resisting mechanisms. The system is very ductile and has high energy dissipation capacity with correct design and construction. One of the well-known methods that resist lateral loads is corrugated steel plate. Corrugated infill steel wall plates are used within a steel edge frame in this system. The corrugated steel plate technology offers several advantages over flat steel plate shear walls (SPSWs), notably improved lateral stiffness and elastic buckling stress. It stated the concerns regarding flat wall deformations while under construction and having gravity stresses; however, the corrugated members are reducing and avoiding gravity loads when the vertical load isparallel to the rib, averting these problems encountered for traditional flat walls[1-3]. For SPSWs, fire safety requirements have a significant impact on shear strength, stiffness, and energy dissipation. It also has extremely low out-of-plane stiffness and overall buckling, the development of a recent system to remove the inadequacies that occurred in the SPSWs became crucial. Both sides of the steel plate can be covered with precast reinforced concrete.[4]. Figure 1 shows the network of the earlier work that the SPSW discussed and investigated in their studies. Most studies in this field are conducted in only a few countries: China, India, USA, and Iran. The system that appeared is known as a composite steel plate shear wall or CSPSW. Steel plates have been used with a mechanical system that incorporates mechanical connections, such as bolts or shear studs, to warrant the

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composite behavior of the system. To prevent buckling of the infill plate, using a concrete cover is considered as the best option.

The attached concrete layer protects the steel plate member from corrosion, fire, and explosions[5]. When a reinforced concrete layer is added to one side of the SPSW, it can cause the new system to behave in a manner that is like that of the stiffened SPSW system. This is happend because the reinforced concrete layer acts as a stiffener, which prevents early local and global buckling of the SPSW[6, 7]. That is why the steel plate shear yielding will occur, and it has a significant impact than the tension field effect. Therefore, it can be stated that with a thinner infill plate, the CSPSW can provide greater shear strength and lateral stiffness, and it has a more ductile behavior when compared with the SPSW system[4, 8, 9].

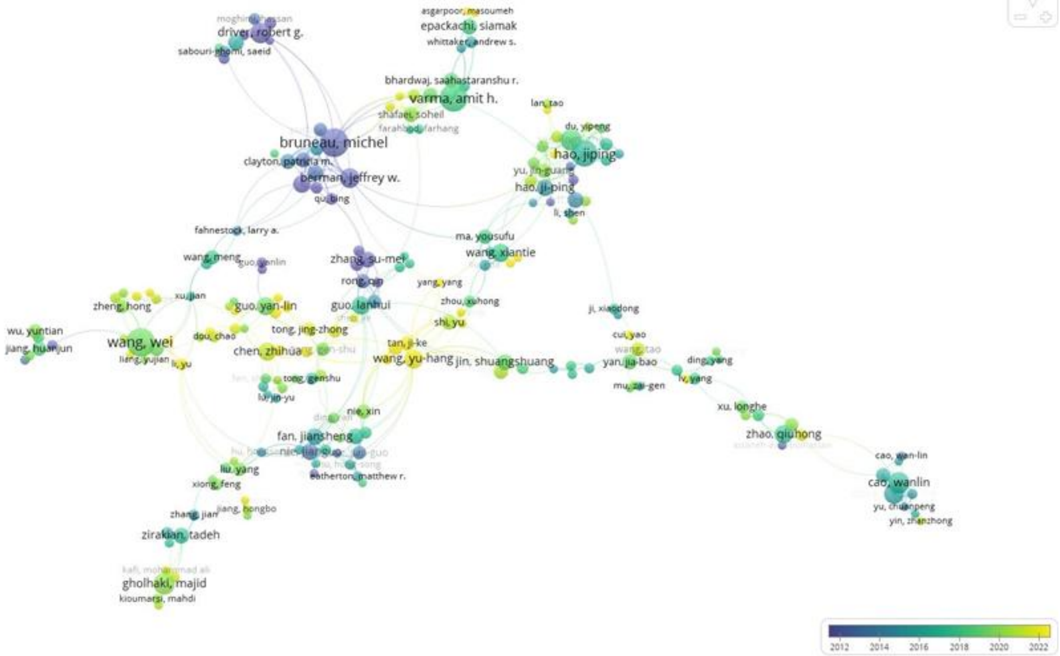


Figure 1: Shows the network of those who have studied SPSW from 2012 until 2022.

Table 1 illustrates that considerably more high-rise buildings incorporated SPSWs into their construction for thirty years to withstand lateral forces generated by wind and seismic activity. The structural members such as beams and columns could support the thin steel plates that withstand these types of shear walls. These types of plates have several advantages, including increased ductility, strength, and stiffness, compatible hysteretic characteristics, and a substantial ability to absorb plastic energy[5, 10-12]. As Compare to unstiffened SPSWs, the stiffened SPSW will have more initial stiffness, shear strength, and significant ductility[13].

Table 1: Structural buildings made of steel plate for shear walls.

No.	Project	Storey	Height (m)	Year	Location	Higlight
1	Shanghai Tower	128	587.4	2015	501 Yincheng Middle Rd, Lujiazui, Pudong, Shanghai	Shear Studs, and Vertical stifferes have been used
2	United States Federal Courthouse, Seattle	23	120	2004	Seattle, Washington-USA	It has 3 parts: a central block, a long, wedge-shaped wing, and a rectangular appendage jutting from its west side
3	Sylmar Hospital	6	24	2003	Los Angeles, CA-USA	Now it is cnverted to Olive View–UCLA Medical Cente
4	Canam-Manac Headquarters Expansion, St. George	6	24	2000	Quebec-Canada	The shear walls were fabricated in two tiers to optimize column selection and facilitate erection
5	Hyatt Regency Hotel at Reunion	50	171	1978	Dallas, TX	It has seen many innovarion
6	Shinjuku Nomura Building	55	209.9	1978	Shinjiku,Tokyo	It is in the Nishi-**Shinjuku** business district in **Shinjuku**, **Tokyo**, **Japan**
7	Kobe Office Building	35	130	1988	Kobe, Japan	Sustainedminor damage in 1995 earthquake

A vertical cantilever plate girder can be considered a shear wall frame made of steel plates, with the floor beams acting as transverse stiffeners, the columns functioning as flanges, and the steel plates acting as the web[14]. They are an economical and practical choice for both new building construction and existing structure retrofitting. A fundamental SPSW comprises of thin steel plates that can be either stiffened or unstiffened. These plates are surrounded by horizontal and vertical boundary elements (HBE and VBE), spanning several bays and floors[15].

The stiffened plates have been employed in the most steel plate shear walls constructed to date to prevent shear buckling. However, several studies[5, 9, 16, 17] have used in-depth theoretical and experimental research to investigate the static and quasi-static cyclic loading characteristics of thin, unstiffened steel plate shear walls. The experiment's findings demonstrated that thin, unstiffened steel plates had steady hysteretic features and sufficient post-buckled reserves of stiffness and strength. Simple SPSW is comprised of thin, unstiffened, or stiffened steel plates that are surrounded by horizontal and vertical boundary elements (HBE and VBE), which may span multiple stories. Experimental results demonstrated an acceptable correlation, and the theoretical method ignored the critical shear stress of a sequence of inclined tensile strips in place of the web plate[10, 18].

Due to particular constraints and architectural requirements in building constructions with SPSWs, openings must be made within the perimeter and inside the system. As a result of openings, certain defects will be produced, which decrease the system's overall capacity. Numerous experimental and numerical studies[19-21] have been implemented separately and jointly to explore the impact of various opening characteristics such as size, location, orientation, and so forth on the ductility, damping ratio, dynamic behavior, shear behavior, bending behavior, and torsional behavior of SPSWs.

1.2 Research Significance

This comprehensive review paper holds significant research value by advancing the knowledge of the performance and design to optimize the steel plate shear walls (SPSWs) containing openings. By thoroughly examining recent experimental and numerical studies on various new SPSW systems in previous studies, thin unstiffened walls, and the effects of different opening configurations, the work enables a more sophisticated understanding of SPSW dynamic behavior and limitations under seismic and wind loading. Notably, the introduction and evaluation of composite steel plate shear walls addressed important issues such as fire safety and buckling to enhance their strength, stiffness, and energy absorption. Furthermore, the compilation of results provides an essential basis for further research and engineering innovation toward effective SPSW layout solutions when architectural openings are necessitated. Maximizing seismic resilience and efficient construction via steel plate shear wall systems with critical analysis.

2. Systems and Characteristics of Steel Plate Shear Walls

Researchers have studied and utilized a various of SPSW systems, including un-stiffened, thin SPSW, stiffened SPSW, and composite SPSW, in the construction industry. Single steel plate composite shear walls (SSPCSWs), double steel plate composite shear walls (DSPCSWs), and embedded steel plate composite shear walls (ESPCSWs) are the three forms of CSPSWs[5, 22]. Unstiffened SPSW is the most straightforward configuration and consists of thin infill plates connected to the surrounding beams and columns. It relies on the post-buckling tension field action of the infill plate for energy dissipation. Unstiffened SPSW has a problem which is considered prone to early out-of-plane buckling of the infill plate. Stiffened SPSW includes horizontal and/or vertical stiffeners welded to the infill plate. The stiffeners improve the buckling resistance, increase strength, and they are responsible for the formation of the tension field. Different stiffener arrangements lead to variation in behavior. Composite SPSW incorporates concrete layers on one or both sides of the steel plate and these parts increase the stiffness and strength of the system. The composite action can enhance buckling resistance and improve fire resistance.

Additionally, Magnusson Klemencic Associates developed and used a unique SPSW technology to build a courthouse. This "dual" system is made up of a boundary moment frame that is welded within a steel shear wall that serves as the "backup" lateral load-resisting system and serves as the "Primary" lateral load-resisting system. Two steel shear wall bays are linked by the horizontal coupling beams depicted in Figure 2[8, 9, 16, 23, 24]. Moreover, different SPSW design types with various construction features are depicted in Figure 2.

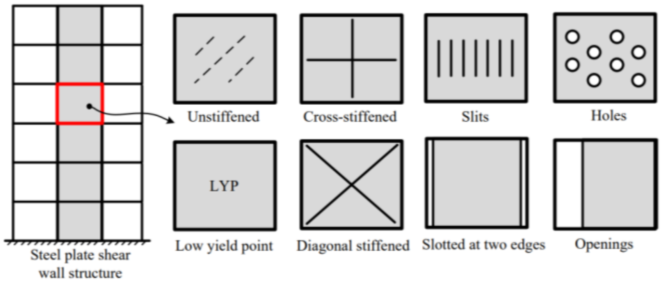


Figure 2: Different types of SPSW designs with different construction characteristics[25].

Some researchers have used inventive steel shear wall systems as can be seen from Figure 3, which consist of a coupling beam, wide flange beam and wide flange column, bolted splice, and steel shear wall. They investigated in a laboratory program the structural performance of the building core and evaluated the behavior of the connections and the whole system performance and its effect on the lateral load-resisting system[23, 26].

Various SPSW configurations have been developed and studied; for example, Unstiffened SPSWs, although they can perform well on post-buckling tension field action, they are prone to early out-of-plane buckling[5, 22]. Furthermore, stiffened walls introduce stiffeners to improve the buckling resistance and increase strength while guiding tension field formation[5, 22]. The composite SPSWs (CSPSWs) also enhance stiffness, strength, and fire resistance[5, 22]. "Dual" SPSW can combine the boundary moment frames and steel shear walls with coupling beams for optimized performance[8, 23, 24].

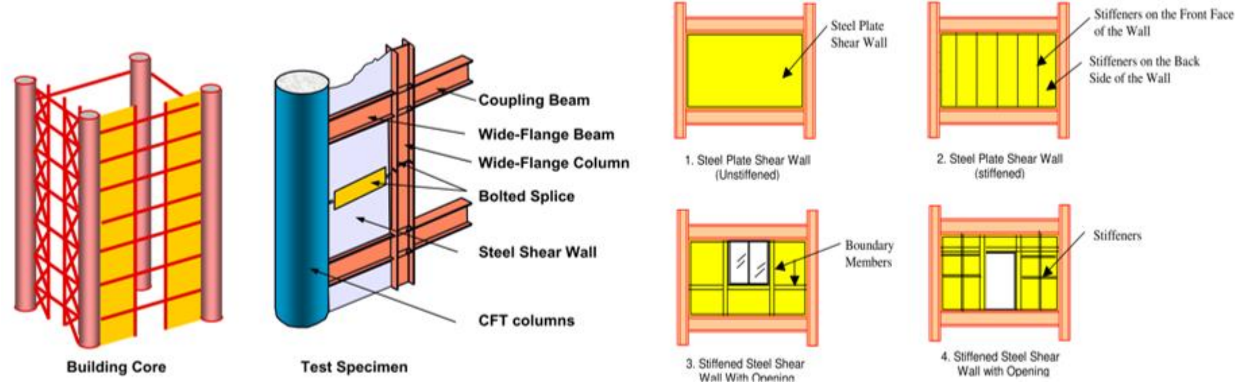


Figure 3: A steel building employs an inventive steel shear wall system[23, 26].

3. The location and types of openings in SPSW

Sometimes, due to specific architectural, mechanical, electrical, ventilation, and other requirements, diaphragms or shear walls must have varying ratios and types of perforations and openings. This is because the openings affect the system's ability to distribute lateral loads due to changes in stiffness and ductility. Numerous studies have examined the impact of openings in SPSW systems, according to a literature review. Zhao et al., 2021 carried out a comprehensive investigation into the impact of strategically placed openings on the shear strength of steel plates. By considering the effect of geometrical characteristics such as opening form, opening location, panel thickness, and material strength, their research has produced an analytical approach for forecasting the shear strength of steel panels with various openings. The capacity of shear steel plates with openings confirmed utilizing the results from the earlier studies was conducted by Hosseinzadeh & Tehranizadeh[15], Kordzangeneh et al.[27], and Zhao et al.[28]. Moreover, Roberts and Sabouri-Ghomi[8] conducted a theoretical and experimental study on the hysteretic behaviors of unstiffened steel plate shear panels with centrally located circular openings. The theoretical model that was first demonstrated has been modified to account for linear losses in the panel's strength and stiffness as a result of openings[10, 29].

Hong[30] performed both experimental and numerical experiments to inspect how the location, as well as the dimensions of the openings, affect the shear wall's structural performance under different static loads. ANSYS12.0 used for the numerical analysis of the structural elements. The results from the findings could be utilized to determine the shear strength of steel plates with holes in them. The specimens consisted of solid shear walls and shear walls with different sizes and openings positions. For analytical purposes, the specimens were exposed to two different loading scenarios: an equally distributed lateral load and an evenly distributed axial load. After applying equal magnitudes of loads to the shear walls, the researchers analyzed the patterns of cracking and stress distribution. Significant results showed that shear walls with bigger openings were less efficient regardless of the form of applied stress (axial or lateral). In particular, the wall's strength under axial load was more strongly impacted by the opening's location farther from the support than it was under lateral stress. Furthermore, the efficacy of the shear wall was inversely linked with proximity to the applied force[30].

Since the performance and design of SPSWs significantly rely on the infill steel plate, any unrequired addition to the infill panels' thicknesses may require huge and thick boundary elements, which is a noneconomic design decision. Infill panel opening is one of the solutions that have gained increasing popularity in SPSW design and construction among the many researchers who have suggested and explored[31]. According to Bypour, et al.[32], designers should determine the optimal opening layout. They should then attempt to replace the insufficient design's infill panel with an opened one with a minimum practicable thickness and a comparable level of lateral stiffness and strength, using an approximation of the stiffness reduction calculation. The ideal opening widths for different diagonal and rectangular opening layouts were examined by Naraki, et al.[33], and the results were compared to those obtained using the stiffness reduction formulas that were then available. The optimization's outcomes demonstrate that regular-spaced rectangular opening designs are more effective at lowering SPSW stiffness. In addition, the effectiveness of stiffness reduction formulas and dependable techniques for rectangular opening patterns have been evaluated [33]. Table 2 lists the influence of types and ratios of various openings on the behavior of SPSWs. As can be seen from the table the displacement related to the failure loads for the circular shape openings are approximately for the sizes that are close to each other are similar; however, the displacement of the rectangular shape openings is not close to each other, and this may be attributed to the tension field action and the response of circular opening in even in the absence of stiffeners performs better than rectangular shape openings.

Table 2: The effect of opening types and ratios on the performance of SPSWs[34-38].

Authors	Opening types	Percentage of area of opening to panel area	Failure Load	Displacement related to failure load	Thickness
[35]	No	0	3628 kg	31 mm	2 mm
	Circular	2.71	3505 kg	37 mm	
		10.91	3050 kg	43 mm	
[36]	Rectangular	21	79 KN	60 mm	2 mm
		28	720 KN		
		36	680 KN		
		45	620 KN		
		60	500 KN		
[45]	Rectangular	20 L/h=2	1142 KN	46.2 mm	4 mm
		25 L/h=2	553.71 KN		2 mm
		30 L/h=2	550.98 KN		2 mm
		35 L/h=2	765.64 KN		3 mm
		40 L/h=2	728.89 KN		3 mm
[34]	Circular	0	680 KN	45 mm	4 mm
		20	620 KN		
		35	420 KN		
[33]	Circular	0	818 KN	34.32 mm	1 mm
		20	510 KN	36.82 mm	
		35	611 KN	43.05 mm	
[37]	Rectangular	21	34 KN	20 mm	2 mm
		28	32 KN		
		36	30 KN		
		45	28 KN		
		60	23 KN		

The existing studies on SPSWs having openings have revealed the critical effect of these openings on the overall performance, stiffness, and strength. Most of the works have focused on factors such as the opening location, size, and shape, which provides beneficial insights for designers[10, 15, 27- 30]. More research is still required to fully show the very complex behavior of SPSWs with openings. The limitations of SPSWs are apparent in understanding those with thicker infill plates, multiple opening parameters, and complex shapes. The long-term behavior under sustained or cyclic loads is crucial for a robust design.

4. Shear capacity and behavior of SPSW with openings

The shear behavior or shear capacity of SPSW is one of the relatively essential properties of these systems. Due to the uneconomical nature of moment frame systems in resisting very high wind and very high seismic loads when the building heights increase, designers are forced to implement these systems so that the building's overall performance due to the large shear capacity and significant shear stiffness will be enhanced and the total cost is decreased.

Although these systems can increase the shear performance of the buildings, having perforations or openings inside the panels will have an inverse effect on their behavior. For this reason, Zhao, et al.[28] systematically studied the effect of located perforation on the shear capability of steel plate shear walls in their study. Their attention has been directed to the impact of geometric characteristics, including panel thickness, material strength, opening shape, and opening position. It has been determined that altering the location of openings in steel panels can slightly reduce their shear strength. The most significant effect will come from the opening nearest the panel's center. Steel plates should be positioned along the tension diagonal line if more than one opening is required. By contrast, they have shown that a circular opening with the same opening area has a more significant impact than a rectangular one.

Additionally, sixteen perforated panel steel plate shear walls (SPSWs) were the subject of a parametric finite element (FE) study by Zarrinkolaei, et al.[39]. The outcomes were then compared to the solid SPSW model. To determine the optimal condition for the perforated panel SPSWs based on the three criteria that indicate the structural performance, they subsequently developed several SPSW models with various opening configurations and shapes in the steel infill panel. They concluded that the shear wall's shear capacity and energy absorption generally decreased as the opening ratio of the SPSWs increased. More precisely, an increase of tenfold in the opening percentage (from 1.45% to 14.5%) resulted in an average energy absorption loss of 20%.

Kordzangeneh, et al.[27] have assessed the influence of rectangular opening size and position on the cyclic behavior of SPSWs using an experimental examination. The seven specimens were conducted through quasi-static cyclic load tests. It demonstrated that in the SPSW specimens with rectangular openings and relative opening-to-plate areas of 4.00, 6.76%, and 10.24%, respectively, the maximum shear capacity could be decreased by 28%, 33%, and 46%. Nonetheless, the cut generated in different ranges of 5%, 42%, and 48% to decrease in stiffness in these specimens. The test specimens from the study by Zhao, et al.[28] are displayed in Figure 2. (a) solid plate (SPSW0%); (b) opening at diagonal (SPSW-4.00%RD; a × b = 80 × 125); SPSW-6.76% RD; a × b = 104 × 162.5); SPSW10.24%RD; a × b = 128 × 200); (c) opening at off-diagonal (SPSW-4.00% RD; a × b = 80 × 125); SPSW-6.76% RD (a × b = 104 × 162.5); SPSW10.24%RD (a × b = 128 × 200); (d) infill plate and frame connection details[27]. Figure 4 illustrates the dimensions of the tested specimens.

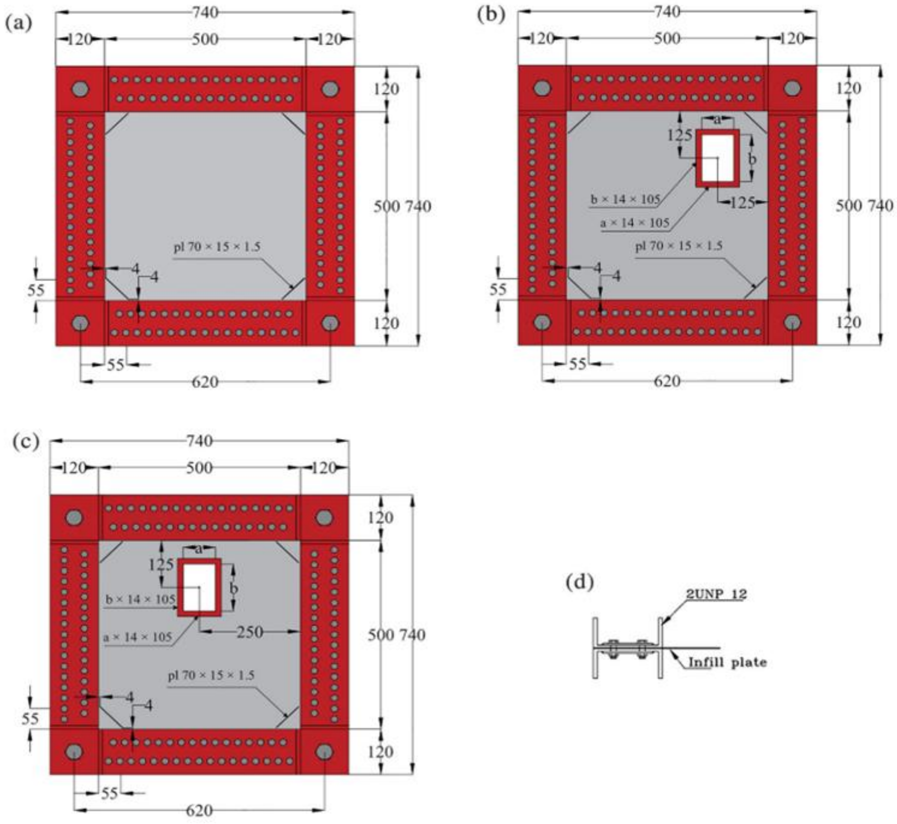


Figure 4: Dimensions of test specimens in millimeters [27].

In their research, Zarrinkolaei, et al.[39] used the finite element findings for all the opening parameters to establish a broad model of stiffness and strength. Based on all the computer models, they developed models for estimating lower initial stiffness and shear strength using nonlinear regression analysis. They have considered in their study as given below:

$$V_{uo} = \left[\frac{1}{(1 + 15x)}\right]^{0.25} V_u,$$

$$K_{io} = \left[\frac{1}{(1 + 6.5x)}\right]^{0.60} K_i,$$

where $X = A_o / A_p$ indicates the proportion of the opening's area to the solid infill plate's area, Vu and Ki represent the SPSW with a solid infill plate's ultimate strength and initial stiffness, and Vuo and Kio represent the associated SPSW with opening's ultimate strength and initial stiffness[40].

Overall, while providing valuable insights into SPSWs with openings, the existing research has limitations regarding the adequacy of parameters examined, the extent of experimental validation, capturing post-peak response, and the depth of analytical scrutiny. More comprehensive empirical testing matching with high-fidelity nonlinear simulations can further enhance the shear behavior understanding of SPSWs containing openings. Table 3 contains the key details and gaps of the earlier studies elaborated in this section regarding the shear behavior of steel plate shear walls (SPSWs) with openings.

Table 3: Explanation and gaps regarding the performance of SPSWs.

Study	Methodology	Parameters Considered	Limitations
Zhao et al. (2021)	Numerical simulation (FE models)	Opening shape, location, panel thickness, material strength	Does not capture post-buckling behavior; lacks experimental validation
Zarrinkolaei et al. (2021)	Numerical simulation (FE models) - 16 perforated SPSW cases	Opening configuration, shape; 3 criteria compared - shear capacity, energy absorption, stiffness	Lacks experimental validation of optimal identified cases to examine post-peak response
Kordzangeneh et al. (2021)	Experimental (cyclic quasi-static tests) - 7 perforated SPSW specimens	Rectangular opening size and placement	Limited parametric study; lacks numerical simulation for additional mechanics insights
Khan and Srivastava (2020)	Empirical models based on numerical dataset	Opening area ratio	Models not validated experimentally; narrow parameter range

5. The energy absorption and hysteretic properties of SPSW with different opening locations and ratios

The hysteresis curves generated by SPSW hysteretic properties are essential for predicting the system's energy dissipation. As shown in Figure 5, the area surrounding each loop calculates the energy dissipated in that loop.

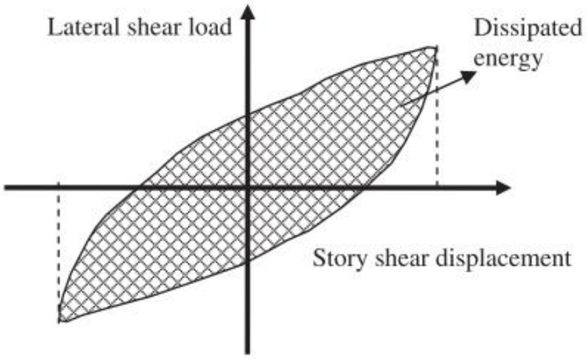
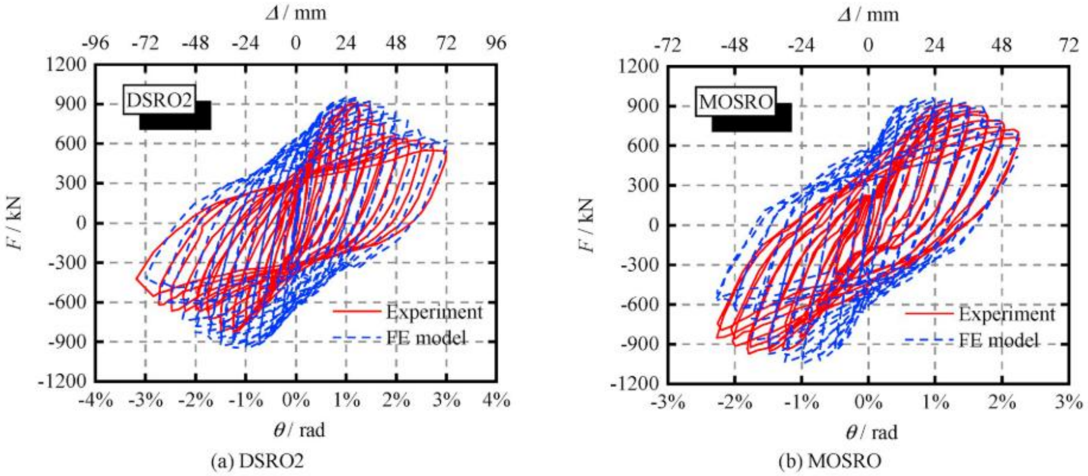


Figure 5: Energy dissipation capacity corresponds to the hysteresis curve[41].

Mu and Yang[42] employed experimental research to investigate the impacts of plate slenderness parameters and opening size in a study on the seismic behavior of SPSWs. The eight specimens scaled 1:6 with two distinct plate thicknesses and four different ratios of circular opening at the panel's center were subjected to cyclic hysteresis loading. The study found that the system's initial stiffness and strength were decreased when openings were added. The researchers predicted that this effect would be amplified by increasing the opening's diameter. They concluded that the system's energy absorption was significantly reduced by an opening in the panel's center, even while stable cyclic performance in the nonlinear range still contributed to energy dissipation during loading [43].

The effects of frame-to-plate connections and oblique channel-shaped stiffeners on the seismic behavior of SPSWs using cyclic quasi-static testing on two one-bay, two-story specimens have been studied by [41]. The experimental data confirmed the FE software simulation. Two rectangular openings on one specimen allowed for diagonal stiffening, whereas one had one rectangular entrance for multi-oblique stiffening. The experiment results showed that the channel-shaped stiffeners employ higher torsional and flexural stiffness, enhancing the constructions' elastic buckling stress, stiffness, and bearing capacity [42, 44]. The hysteresis diagrams for the theoretical and experimental results for the specimens that were the multi-oblique channel-stiffened SPSW with one rectangular opening (MOSRO) and the diagonally channel-stiffened SPSW with two rectangular openings (DSRO2) are displayed in Figure 6.



(a) DSRO2 (b) MOSRO

Figure 6: Hysteresis curve comparison between the experimental and numerical results[42].

Comparatively, Sabouri-Ghomi and Mamazizi[45] investigated how different types of opening ratios at 21%, 28%, 36%, 45%, and 60% affected the hysteretic behavior and energy absorption of steel plate shear walls that were stiffened and unstiffened. They discovered that the energy absorption ratio (%) for the stiffened and unstiffened panels was 48.3%, 64.3%, 84.7%, 117%, and 170.2% for 21%, 28%, 36%, 45%, and 60%, respectively.

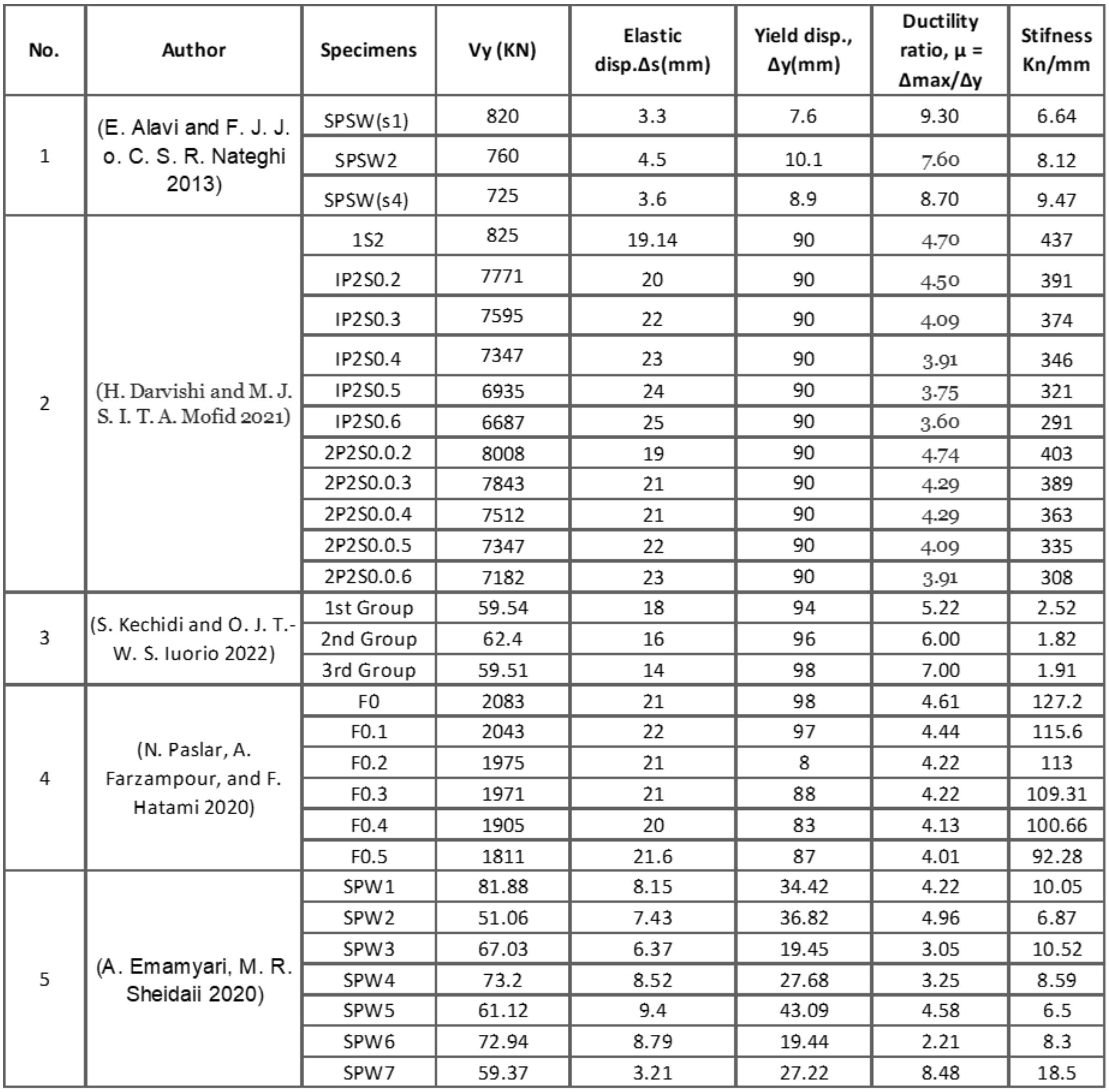
Hysteretic properties of SPSWs are essential in providing insights into the energy dissipation capabilities. A recent studies such as Valizadeh, et al.[43] show that openings can decrease the initial strength and stiffness, and larger opening diameter can amplify its strength. Even where the location at the central opening, the energy dissipation is significantly diminished under stable cyclic performance[42]. Similarly, Mu et al.[41, 43] have observed such significant adverse effects on the validity of channel-shaped stiffeners. Their investigations showed that bearing capacity, stiffness, and elastic buckling stress can be enhanced when oblique stiffeners have been used in SPSW specimens. In summary, the current research provides fragmentary perspectives into the energy dissipation capability degradation induced by SPSW openings without broader parametric and comparative examination. Quantifying this loss for various opening configurations and relating it to resilience decline levels can enable performance-based design guidelines to support unavoidable opening placement scenarios.

6. Alterations in the system strength, stiffness, ductility, and damping ratio due to the introduction of openings in steel plate shear walls

In order to precisely determine the impacts of various opening types, positions, and opening ratios on the system strength, stiffness, ductility, and damping ratio of the SPSWs, various experimental and numerical investigations were carried out[19, 32, 39, 42, 46-51]. H. Darvishi et al. used numerical analysis to examine how various perforation ratios affected the behavior of the frame and the infill steel plate. They have used several one-story and 14-story SPSWs. It has been observed that the opening ratio did not exclusively govern the ductility and strength of the shear wall test samples, and these mentioned parameters of SPSW depend as well upon the placement direction and location of the openings. According to the test findings, the perforated SPSWs' ductility ratio, ultimate strength, and initial stiffness were reduced by 29%, 28%, and 33.5%, respectively. Additionally, for those specimens with openings, the values of equivalent viscous damping ratio, normalized Cumulative Hysteresis Energy, and last cycle Hysteresis Energy are decreased by approximately 26, 28, and 10%, respectively[46].

Since an opening in the SPSWs may negatively impact the seismic behavior of SPSWs. It is suggested by[10, 14, 27, 49, 52, 53] that the openings can have the proper stiffeners around them to get over these limitations. Findings from the hysteresis curves and seven steel shear panels subjected to cyclic loading, with and without central circular openings, diameter-to-width ratios of 20% and 35%, and with diamond-shaped, horizontal, and vertical stiffeners were discussed. It is evident that specimens with diamond-shaped stiffeners functioned well for seismic prior to rupture and that the shear panel's seismic performance was suitably enhanced by the horizontal and vertical stiffeners. Table 4 tabulates the structural values for SPSW specimens with and without openings under cyclic testing.

Table 4: Structural values for SPSW specimens with and without openings from cyclic testing.



No.	Author	Specimens	Vy (KN)	Elastic disp.Δs(mm)	Yield disp., Δy(mm)	Ductility ratio, μ = Δmax/Δy	Stifness Kn/mm
1	(E. Alavi and F. J. J. o. C. S. R. Nateghi 2013)	SPSW(s1)	820	3.3	7.6	9.30	6.64
		SPSW2	760	4.5	10.1	7.60	8.12
		SPSW(s4)	725	3.6	8.9	8.70	9.47
2	(H. Darvishi and M. J. S. I. T. A. Mofid 2021)	1S2	825	19.14	90	4.70	437
		IP2S0.2	7771	20	90	4.50	391
		IP2S0.3	7595	22	90	4.09	374
		IP2S0.4	7347	23	90	3.91	346
		IP2S0.5	6935	24	90	3.75	321
		IP2S0.6	6687	25	90	3.60	291
		2P2S0.0.2	8008	19	90	4.74	403
		2P2S0.0.3	7843	21	90	4.29	389
		2P2S0.0.4	7512	21	90	4.29	363
		2P2S0.0.5	7347	22	90	4.09	335
		2P2S0.0.6	7182	23	90	3.91	308
3	(S. Kechidi and O. J. T.-W. S. Iuorio 2022)	1st Group	59.54	18	94	5.22	2.52
		2nd Group	62.4	16	96	6.00	1.82
		3rd Group	59.51	14	98	7.00	1.91
4	(N. Paslar, A. Farzampour, and F. Hatami 2020)	F0	2083	21	98	4.61	127.2
		F0.1	2043	22	97	4.44	115.6
		F0.2	1975	21	8	4.22	113
		F0.3	1971	21	88	4.22	109.31
		F0.4	1905	20	83	4.13	100.66
		F0.5	1811	21.6	87	4.01	92.28
5	(A. Emamyari, M. R. Sheidaii 2020)	SPW1	81.88	8.15	34.42	4.22	10.05
		SPW2	51.06	7.43	36.82	4.96	6.87
		SPW3	67.03	6.37	19.45	3.05	10.52
		SPW4	73.2	8.52	27.68	3.25	8.59
		SPW5	61.12	9.4	43.09	4.58	6.5
		SPW6	72.94	8.79	19.44	2.21	8.3
		SPW7	59.37	3.21	27.22	8.48	18.5

7. Parametric study - Failure mechanisms of opening in steel plate shear walls.

An analysis of failure patterns in a new Special Plate Shear Wall (SPSW) design that the featured a perforated panel with a web-reduced beam section was carried out by Fereshteh Hassani and Zia Javanbakht, 2021. The objective is to apply several geometric alterations to modify the failure mechanism of the design. By investigating the relationship between structural components in plastic strain distribution, ductility, strength, and stiffness, an optimized design with exceptional performance was developed. In this study, numerous geometric properties were added to a prototype of a finite element. The evaluations were accompanied by altering the panel and beam opening diameters. This combination demonstrated better performance and was subjected to additional experiments by modifying the frame aspect ratio and panel thickness. The model provided valuable insights into the underlying reasons for these failure mechanisms by effectively distinguishing between three typical failure modes. The modifiable elements found to attain the desired failure mechanism, such as changes to the dimensions of the horizontal border components and the sizes of the openings in the panel and beam. Remarkably, it was discovered that the tensile failure to be the main mode of panel failure where a plastic band formed across the panel to cover the vertical border parts and their connections. The model demonstrated an improvement of roughly 250% in hysteresis ductility and absorbed energy compared to its imperforate counterpart, owing to the enhanced engagement of structural components[29].

Investigators presented the findings of a thorough numerical parametric analysis that compared shear walls with and without openings made of plain and corrugated steel plates[54, 55]. The incomplete knowledge of the nonlinear, inelastic behavior of shear walls made of corrugated steel plates, specifically those with openings, has led to an examination of a numeral of structural characteristics, including plate thickness, corrugation angle, opening size, and opening location[56]. Essential factors such as the force-displacement relationship, initial stiffness, ultimate strength, and energy absorption were the focus of the comparative analysis for the SPSW specimens[57, 58]. Their study showed that using trapezoidal corrugated steel shear walls increases the initial lateral stiffness and ductility of corrugated steel shear walls by 30 to 50% compared to their corresponding solid equivalents. Interestingly, solid shear walls typically have a higher ultimate shear strength with a larger aspect ratio than corrugated steel shear walls. The study also showed that shear walls, especially those with bigger apertures, had an ultimate shear strength and initial stiffness that increased by up to 250%. It found that placing openings away from the diagonal tension field results in a 10% performance improvement under monotonic loads.

Figure 7 depicts the lateral load-displacement under monotonic loading which has been classified into three stages; initial behavior showed elastic properties for both models with and without openings. As the stress on the CSSW increases, local buckling occurs. In the SSW, global buckling modes are observed however significant local buckling is not present. Early local buckling behavior of the CSSW could delay the final strength peak and deteriorate the trend.

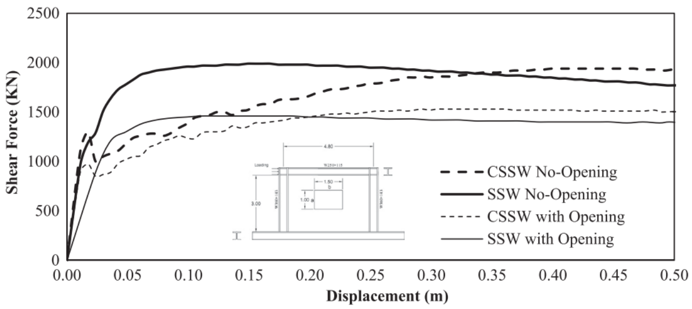


Figure 7: Curves showing the load-displacement of SSW and CSSW with and without openings corrugation angle = 90°[54]

Conclusions

From the review of the literature, the following points regarding the opening effect on the overall and system performance of SPSWs can be concluded:

- Openings significantly reduce SPSW shear strength and stiffness, with central openings causing maximum strength degradation. Circular openings also have more significant adverse impact compared to rectangular ones.
- Increasing opening size proportionally reduces initial stiffness, shear strength, energy dissipation, and seismic resilience. Smaller-sized openings with stiffeners perform better.
- Openings alter SPSW failure modes due to discontinuity-induced stress concentrations and localized damage at opening edges rather than global buckling.
- Plate slenderness, stability and out-of-plane buckling resistance should be carefully considered in SPSW design when having openings in the structural elements. Concrete encasement can assist in the composite systems.
- Overall seismic performance, ductility, damping, and hysteretic behavior are negatively affected by openings depending on size and location. Optimal design solutions are needed when openings are necessitated.

The authors would like to recommend the following points for future research and practice:

- Since the presence of openings alters the behavior of SPSWs by reducing the strength, stiffness, and energy dissipation. The designers must carefully consider the impact of opening in light of potential functional requirements that demand openings.
- To optimize the opening in SPSW's design, it is essential to have a precise analysis and design guidelines to ensure that the opening's practicality is balanced with reliability and structural safety.
- It is vital to develop the numerical modelling techniques. The modelling techniques must include the whole interaction among the boundary frame, opening and infill plate; therefore, this calculation give realistic predictions for various design configurations.
- More experimental research is required to be conducted such as; wide range of reinforcement strategies, opening configurations, bracing with different aspect ratios. This will increase the dataset and could be used to validate numerical models and optimize design recommendations.
- It is essential to direct future research toward determining the impact of opening on the global structural behavior and considering the lateral load resisting systems with potential interaction incorporating opening.

Author Contributions

Conceptualization, methodology, supervision, writing, I.M.; software, supervision, P.S.; validation, revision, P.S.; investigation, data curation, revision original draft, D.N.Q. and A.S., data collection and methodology of application, S.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

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