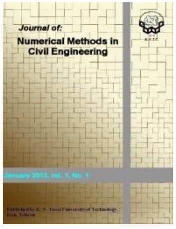

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Numerical study of the effect of the width-to-thickness ratio of incline strips on the behavior of slotted steel plate shear wall under cyclic loading

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Abstract:

This paper numerically studies the effect of the width-to-thickness ratio of inclined strips on the behavior of a novel slotted steel plate shear wall (SPSW). The slotted SPSW consists of horizontal and vertical boundary elements (BEs) and two inclined-slotted plates (ISPs) connected by high-strength steel bolts. The directions of the slots in each infill plate are opposite. Steel bolts connect the two infill plates through the created holes at the intersection of each inclined slot. This paper numerically examined four slotted steel shear walls with different width-to-thickness ratios of strips. The research showed that when the slotted steel shear walls were put under cycling loading, the inclined steel strips on one side of the wall were placed in tension; however, the strips on the other side undoubtedly were in compression. Additionally, the study showed that when the width-to-thickness ratio of strips was adequately used, the strength, stiffness, and energy absorption capabilities of slotted SPSWs were significantly increased, whereas the out-of-plane displacement was minimized by 40.00 %.

1. Introduction

Over the past few decades, steel plate shear walls (SPSWs) have been highly regarded as lateral load-resisting systems worldwide, and various research has been conducted in this area [1-8]. These systems comprise horizontal and vertical boundary elements (BEs) and infill steel plates. In addition to their high strength and considerable initial stiffness, steel shear wall systems have excellent energy dissipation capabilities, high ductility, ease of installation, and stable hysteretic behavior [9-12]. Since SPSWs are a straightforward system with no exceptional complexity, they are widely used in earthquake-prone areas for new construction and strengthening existing structures. A note should be made regarding the slenderness of infill steel plates, which may cause them to buckle at the beginning of the loading process. In order to avoid lateral buckling, the infill plate thickness should be increased; nevertheless, When the infill steel plate is forced to buckle, a tension field is formed and causes shear forces to be transferred to the horizontal boundary elements (HBEs) and vertical boundary elements (VBEs), resulting in additional moments. In these systems, when subjected to cyclic loading, the tension field will be increased in both directions, resulting in snap-through points, which may be detrimental to the system's stability. To improve SPSW seismic performance, researchers have proposed some designs for buckling restrained SPSWs [14].

In 2017, Wang et al. [15] investigated the seismic behavior of a self-buckling-restrained SPSW with inclined-slotted infill plates (ISIPs) bonded with an inner adhesive layer, as shown in Figure 1. When the self-buckling-restrained SPSW was put to cyclic loading, the tension strips on one side provided out-of-plane support for those on the other side under compression. A study compared slotted infill plates with solid infill plates (SIPs). It was found in their studies that the strips deformed consecutively from the center to the corners, which provided energy dissipation capacity at small drift ratios by avoiding the cracks that commonly form in a solid steel shear wall during continuous shear buckling.

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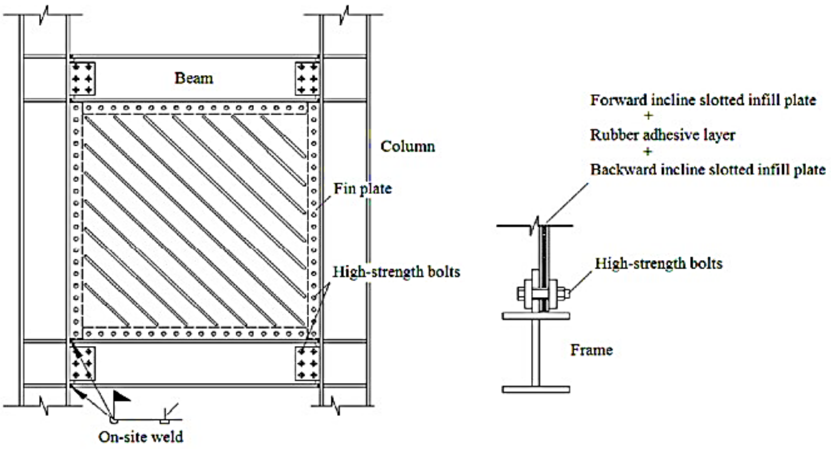
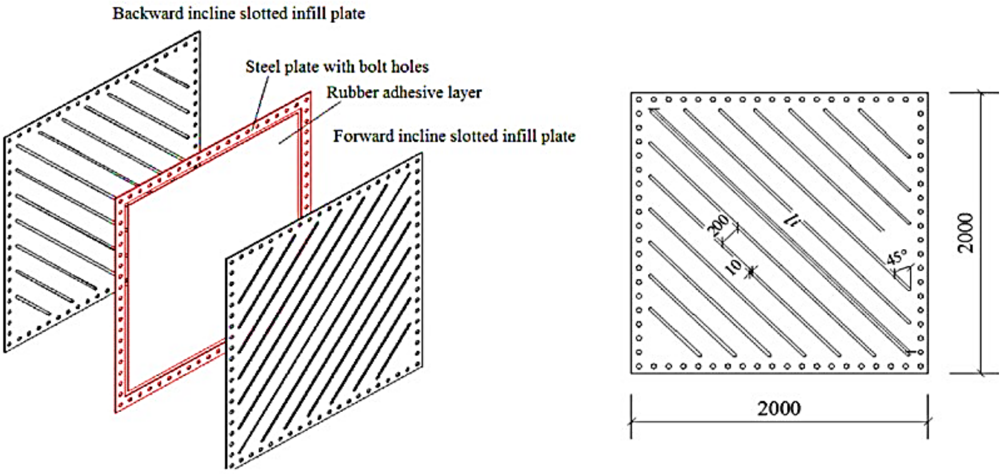


(a) Self-buckling-restrained SPSW



(b) Two incline slotted infill plates and one rubber adhesive plate

Fig. 1: Self-buckling SPSW made of two layers of ISIPs bonded with adhesive [15]

In 2019, Shuangshuang Jin et al. [16] carried out experimental research investigating the behavior of SPSW constructed from a slotted steel plate located inside two reinforced concrete panels, illustrated in Figure 2. As a result of their studies, under cyclic loading, the strips act like buckling-restrained braces, dissipating energy via elastic deformation. In addition, the slotted SPSW showed excellent stiffness and sufficient energy dissipation capacity that can widely serve in seismic-prone building structures. However, weak bonding between the steel plate and reinforced panels caused the separation of the steel plate and the concrete panel. It should be noted that the disadvantages of these buckling restrainers are their weight and the complexity of installation.

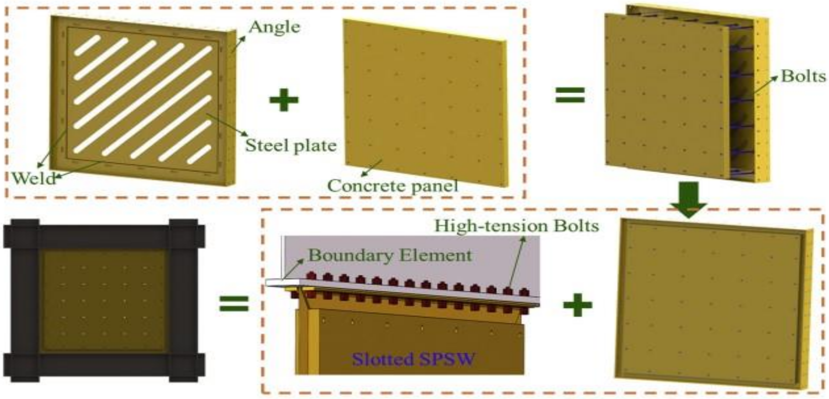
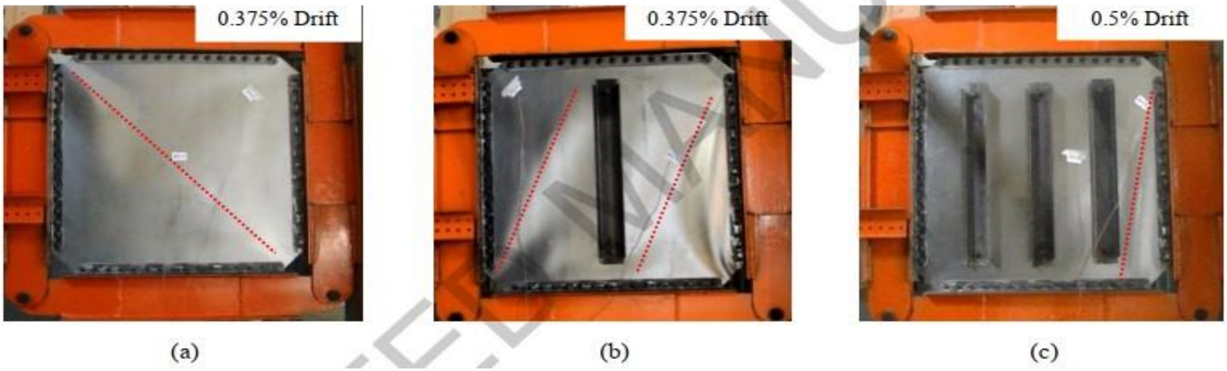


Fig. 2: Configuration of the slotted steel plate shear wall sandwiched between two precast concrete panels [16]

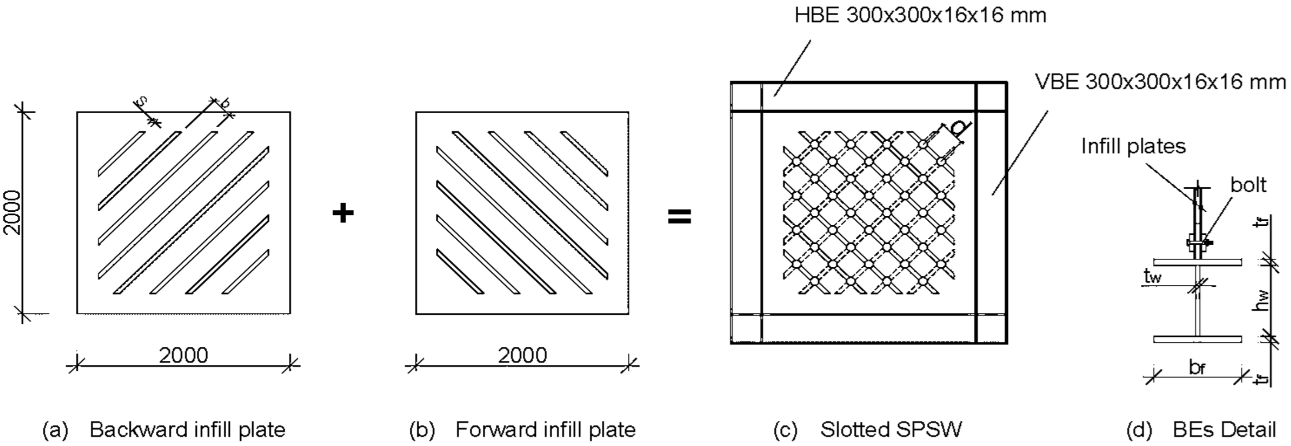
As part of the research conducted by Farzin Aminifar et al. [17] in 2020, they also investigated the performance of a new, straightforward, and cost-effective system of buckling restrainers shown in Figure 3. To prevent the SPSW system from buckling, two non-welded channels were placed on two faces of the infill plate. In their study, a series of 1/4-scaled SPSW specimens were constructed. One panel was left without restraints, and two panels with different numbers of restraints were tested. As a result of the study, the SPSW system significantly improved the energy absorption capability of the system.



(a) (b) (c)

Fig. 3: Experimental specimens tested by Farzin Aminifar et al. [17]

Since SPSWs have higher strength, stiffness, and sufficient energy-absorbing capacity than other lateral load-resistant systems, they have attracted the attention of researchers. This paper numerically investigates the influence of the width-to-thickness ratio on the performance of slotted SPSW using the finite element method (FEM). For this purpose, a similar research work studied by Wang et al., shown in Figure 1, is chosen. Firstly, the FEM is verified by simulating the slotted SPSW made of two layers of ISIPs bonded with an adhesive layer, then the adhesive layer will be removed, and steel bolts will be used to bond the two slotted steel plates. It is important to note that infill plates have slots oriented in two opposite directions. Steel bolts connect the two infill plates through the created holes at the intersection of each inclined slot. It is expected that when the slotted SPSW is applied under lateral loads, the inclined strips on one side will be put in tension, and the strips on the other side will undoubtedly be in compression. In this case, they are subjected to pure compression and tension. Strips in the same direction as the lateral loads are smooth, whereas the strips on the other side will buckle between bolt spacing. The ratio of the width to the thickness of the strips is expected to have a more significant effect on the behavior of the slotted steel shear wall. So, four different width-to-thickness ratios of 25.00, 37.50, 50.00, and 62.50 with equal steel plate thickness, illustrated in Figure 4, are numerically studied by Abaqus, finite element analysis software. In the following, the strength and stiffness of the slotted SPSWs, as well as the out-of-plane displacement and energy absorption capacity, will be evaluated.



(a) Backward infill plate (b) Forward infill plate (c) Slotted SPSW (d) BEs Detail

Fig. 4: Configuration of slotted SPSW made of two layers of ISIPs connected by steel bolts

1.1. The novelties of slotted SPSW

Compared with similar research work, the proposed slotted SPSW made of two layers of ISIPs connected with steel bolts will have the following advantages:

1. Adhesives are polymer-based materials with an average resistance to high temperatures; the slotted infill plates are immediately separated during a fire.

2. In a large deformation, the elastic characteristic of the adhesive layer will be decreased, which leads to separating each slotted plate. However, by using steel bolts, the separation of infill plates is impossible.
3. In addition, using the adhesive layer requires a heating method or pressing by advanced technology; in this case, the construction cost will increase. However, installing steel bolts is straightforward and has low consumption.

2. Theoretical analysis

First, this section explains the buckling analysis equations of the steel strips. Then, the design requirements of boundary elements are presented. The boundary elements are chosen so that the design equations are satisfied. Based on theoretical equations, the minimum width of the steel strips will also be presented.

2.1. Local buckling

As illustrated in Figure 5, a series of bolts connect the two slotted steel plates through the intersection of each incline slot. When the load is applied, the strips on one side of the wall are in tension, and the strips on the other are in compression. For this reason, the compressive strips may buckle between bolt spacing. So, based on the theory of elasticity [18], the equilibrium equation for compression strips may be written as Equation (1).

$$D_s \nabla^4 w = N_{x'} \frac{\partial^4 w}{\partial x^2 \partial y^2} \tag{1}$$

Where D_S is the flexural rigidity of one infill plate, expressed in Equation (2); Nx' is the axial compression force of steel strips, and w is the out-of-plane displacement of the infill plate.

$$D_s = N_{x'} \frac{E_s t^3}{12\left(1-\nu^2\right)} \tag{2}$$

E_s and v_s indicate the modulus of elasticity and poison's ratio, respectively; t represents the steel plate thickness. The corresponding critical elastic stress (σ_{cr}) may be obtained by Equation (3) [19].

$$\sigma_{cr} = K'_{cr} \frac{\pi^2}{d^2 t} D_s \tag{3}$$

K_{cr}' is the buckling coefficient of steel strips under compression, calculated according to Equation (4); d is the distance between steel bolts.

$$K_{cr} = \left| \begin{array}{l} 4.00 + 5.34\left(\dfrac{h}{l}\right)^2, if\ \dfrac{h}{l} \le 1.0 \\ 5.35 + 4.00\left(\dfrac{h}{l}\right)^2, if\ \dfrac{h}{l} > 1.0 \end{array} \right. \tag{4}$$

As indicated in the above equation, l and h refer to the length and height of the panel. Compression strips buckle when the lateral load is applied on slotted SPSW. Equation (5) must be satisfied to ensure that inclined strips are yielded before shear buckling to prevent them from buckling.

$$\sigma_{cr} < \sigma_y \Rightarrow \frac{d}{t} < \sqrt{\frac{K'_{cr} \pi^2 E_s}{12\left(1-\nu^2\right) f_y}} \tag{5}$$

In the above equation, σ_{cr} and f_y are the steel strip's critical and yield stress, respectively.

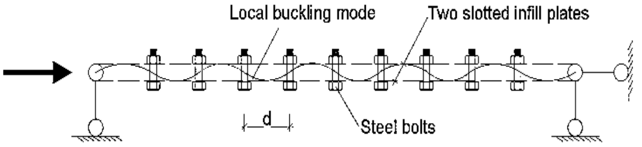


Fig. 5: Local buckling modes of the slotted SPSW

2.2. Design

In SPSWs, the formation of plastic hinges of boundary elements should be delayed after the yielding of infill plates. According to AISC341-16 [20], in the SPSW system, columns must have moments of inertia greater than $0.00307\, {}^{t_P h4}\!/_{l}$, and beams should have a moment of inertia greater or equal to $0.003\, {}^{\Delta t l^4}\!/_{h}$.

Where l is the center-to-center distance between VBEs, h is the center-to-center distance between two HBEs, and t_p is the infill plate thickness. The slotted SPSWs made from two layers of ISIPs with dimensions of $l \times h \times t_p$ of 2000 × 2000 × 4mm each, the VBEs and HBEs having $b_f \times h_f \times t_f \times t_w$ of 300 × 300 × 16 × 16 satisfied the requirements of Eqs (6), (7) and (8).

$$I_B \ge 0.003 \frac{\Delta t_p L^4}{h} \tag{6}$$

$$I_C \ge 0.00307 \frac{t_p h^4}{l} \tag{7}$$

$$\alpha = \arctan \sqrt{\frac{1 + \dfrac{t_w L_{cf}}{2A_c}}{1 + t_w h\left(\dfrac{1}{A_b} + \dfrac{h^3}{360 I_c L_{cf}}\right)}} \tag{8}$$

The infill plate's length, height, and thickness are expressed by l, h, and t_p, respectively. For the slotted SPSW system, the width and height of the section of HBEs and VBEs are expressed by b_f and h_f, respectively, and the thickness of the flange and the web are t_f and t_w.

In order to achieve a resistant slotted steel shear wall in which the plastic hinges of the strips occur before buckling, Equation (5) has been developed for four different thicknesses of slotted plates based on Q235 steel. The maximum strip widths, according to the slotted plate sizes 2000 mm x 2000 mm x 4 mm, are shown in Table 1. It should be noted that $K_{cr}' = 9.34$ was calculated by Equation (4). It is evident from this table that the widths of the strips are increased with an increase in the thickness of the infill plate.

Table 1: Maximum strip widths based on the infill plate thickness

t (mm)	1.00	2.00	3.00	4.00
b (mm)	77.45	154.90	232.35	309.78

3. Numerical analysis

The method of numerical analysis procedure of slotted SPSWs is described in this section. Firstly, the simulation of the finite element model of similar research work was conducted to validate the accuracy of this procedure. Afterward, four slotted steel shear walls with various width-to-thickness ratios of strips were modeled. In order to achieve a desired slotted shear wall, the parameters of strength, stiffness, energy absorption capacity, and out-of-plane displacement have been numerically investigated by ABACUS, finite element analysis software.

3.1. Verification

Wang et al. [15] conducted numerical studies to investigate the behaviors of steel shear walls made of two slotted plates bonded with an adhesive layer under cyclic loading. The SPSW with the dimensions shown in Table 2 is considered to verify the FEM. The modeling procedure of similar research work is similar to that of the proposed slotted shear wall, explained in section 3.2. The width-to-thickness ratio of inclined strips has been studied on Wang et al. shear wall model, with the dimensions illustrated in Table 2. It should be noted that the difference in these two research is only in the connecting type for the two slotted plates. Firstly, the FEM of similar research work was simulated by Abaqus, the finite element analysis software, then the adhesive rubber layer was removed, and steel bolts were placed at the intersection of each inclined slot to connect the two slotted plates. The comparison of the hysteretic behavior of the FEM and similar research work is shown in Figure 6. It is clear that the hysteretic curves produced by the FEM agreed well with the result of similar research work. Therefore, the FEM established in this paper can be used in this paper to investigate the parametric study of the proposed slotted SPSW

Table 2: Detailed parameters of similar research work for verification

Name	Infill plates		Boundary elements	
	$l \times h \times t_p$ (mm)	Steel type	$b_f \times h_f \times t_f \times t_w$ (mm)	Steel type
SBR-SPSW	2000 × 2000 × 4	Q235	300 × 300 × 16 × 16	Q345

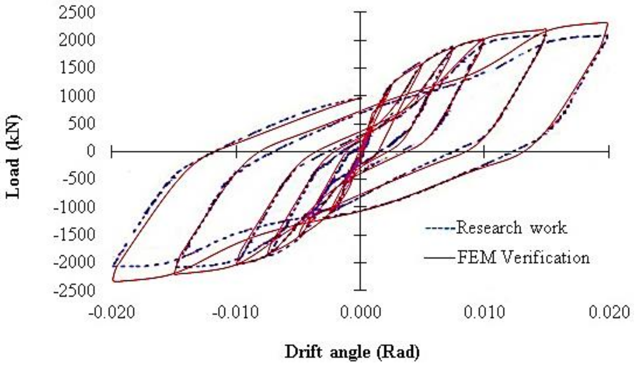


Fig. 6: Comparison of the hysteresis response of similar work and finite element method

3.2. Finite element method

ABAQUS/Explicit, a finite element analysis, was employed to evaluate the effect of the width-to-thickness ratio on slotted SPSW behavior. The slotted infill plates and boundary elements were simulated in the finite element model using the S4R element. Alternatively, bolts were simulated using solid elements of C3D8R with a mesh dimension of 50 mm x 50 mm. The edges of the infill plates were tied to the boundary elements using tie constraints. Slotted SPSWs were restrained at their top ends to prevent out-of-plane displacement, while VBEs were fixed at their bottom ends by setting the three transitional degrees of freedom. The tangential behavior with a 0.25 friction coefficient and the normal behavior with hard contact were employed between slotted infill plates and bolt surfaces.

A kinematic hardening rule based on elastic-plastic behavior was applied to explain the relationship between stress and strain in steel materials. Q345 steel was used for the boundary elements, with a yield stress of 345 MPa, an elastic modulus of 210 GPa, and a hardening stiffness of 0.01 E_0. Q235 steel with f_y of 235 MPa, E_0 of 210 GPa, and E_t of 0.01 E_0 was used for incline slotted plates. Poisson's ratio for both types of steel was 0.3. Figure 7 illustrates the displacement loading control method following the ATC-24 loading protocol [21]. The load was applied at the top of HBE in the nonlinear pushover and cyclic analyses. To study the effect of the width-to-thickness ratio of incline strips on the behavior of slotted SPSW, four finite element models of slotted SPSWs with various incline strip widths of 100mm, 150mm, 200mm, and 250mm were selected, as shown in Figure 8.

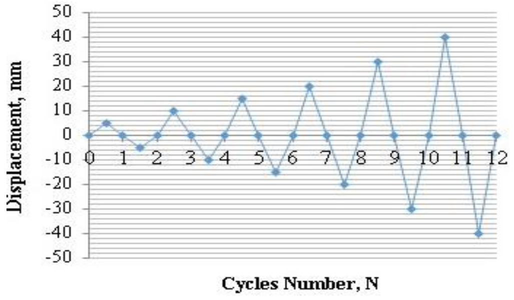
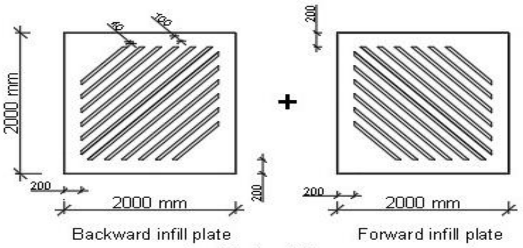


Fig. 7: Loading history [18]

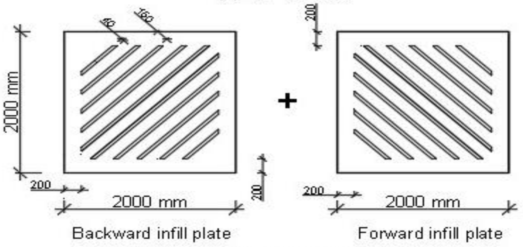
4. Comparative study

As Equation (5) shows, the strips' width and thickness significantly affect the behavior of the slotted shear wall. In addition to these critical factors, other parameters, including initial imperfections, material properties, and defects in installation, also have an essential influence on the performance of the slotted shear wall, which is not included in Equation (5). Numerical analysis of finite element method has taken into account all these factors in order to investigate the performance of the shear wall under various ratios of the width to the thickness of the strips. In this regard, parametric studies were conducted on several slotted SPSWs with different width-to-thickness ratios, illustrated in Table 3, to compare the strength, stiffness, out-of-plan displacement, and energy dissipation capacity of slotted SPSWs.

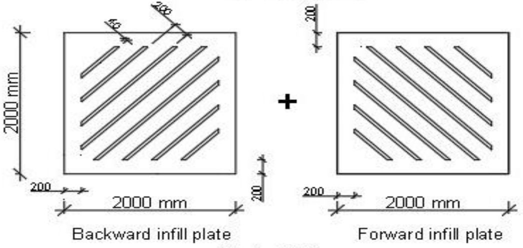
A buckling analysis was conducted on slotted SPSW with non-bonded infill plates to consider the initial deformations. As a result of the analysis, the first mode was considered the geometric imperfection.



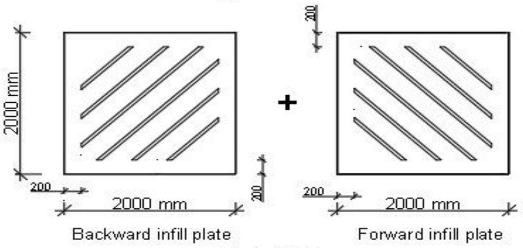
(a) b =100 mm



(b) b =150 mm



(c) b = 200 mm



(d) b = 250 mm

Fig. 8: Slotted infill plates with various incline strip widths

Table 3: Specifications of the slotted SPSWs

SPSWs	Type	Infill plate *l* x *h* x *t* (mm)	Yield point (MPa)	BEs (mm) h_b x b_f x t_f x t_w	Yield point (MPa)	Strip width (mm)	Width-to-thickness ratio
SPSW-1	Slotted	2000 x2000 x4	235	300 x 300 x 16 x 16	345	100	25.00
SPSW-2	-	-	-	-	-	150	37.50
SPSW-3	-	-	-	-	-	200	50.00
SPSW-4	-	-	-	-	-	250	62.50

4.1. Strength and stiffness of slotted SPSWs

The strength of a system shows how much force the structure can withstand without collapsing, whereas stiffness is the strength of a member against deformation. The strength of a shear wall is equal to the sum of the strength of the boundary elements and the strength of the infill plate. The greater the cross-section of the infill plate, the greater its strength. By creating slots on the infill steel plate, the strength and stiffness of steel plate shear walls are reduced, making them less useful in earthquake-prone areas. This strength and stiffness reduction is because the slots reduce the amount of steel material in the section, which decreases its capacity to resist lateral forces such as those generated in an earthquake. Additionally, the slots reduce the rigidity of the wall, which further reduces its ability to resist lateral forces. This section studied the strength and stiffness of slotted SPSWs using displacement loading control in nonlinear pushover analyses using FEM. In this regard, the top ends of the right columns of all SPSWs were displaced based on a 2 % drift ratio. As a result of the study, using the proper width-to-thickness ratio, the shear strength of slotted SPSWs with two layers of ISIPs increased to 11.79 %, as shown in Figure 9.

Additionally, it was seen that SPSW-1, SPSW-2, and SPSW-4, with width-to-thickness ratios of 25, 37.5, and 62.5, respectively, had approximately the same strength. However, SPSW-3, with width to thickness ratio of 50, has more strength than others.

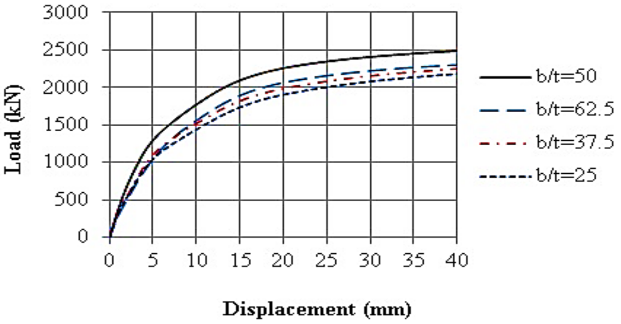


Fig. 9: Load-displacement curves of various slotted SPSWs

The stiffness-drift ratio curves for slotted SPSWs are displayed in Figure 10, showing that by proper use of width to thickness ratio of incline strips, the lateral stiffness of slotted SPSWs improved up to 12.38 percent. It is seen in Figure10 that the stiffness rapidly changed downward prior to the drift ratio of 1.00 %. It shows that the yield of incline strips began from middle tensile strips and ended with short ones at the corners. When loads were applied, only the tensile steel strips contributed to resisting the lateral loads. However, after lateral support was provided, the compressive steel strips resisted the forces gradually. After providing lateral supports to the compressive steel strips, they also contributed to resisting the lateral loads. Therefore, the difference between lateral stiffness after the drift ratio of 1.00 % is negligible. As a result of the study, the ratio of width-to-thickness for incline strips less and more than 50 does not significantly affect the performance of slotted shear walls.

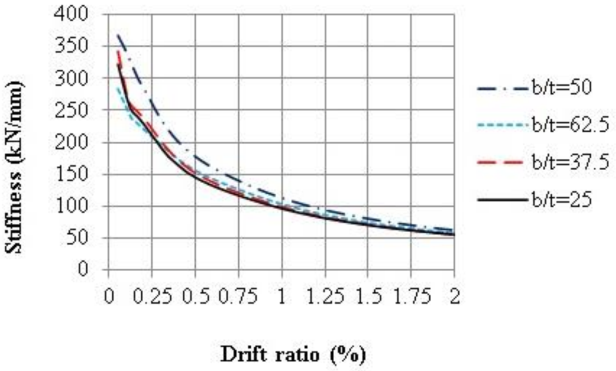


Fig. 10: Stiffness-drift ratio curves of slotted SPSWs

4.2. *Out-of-plane displacement*

In order to study the out-of-plane displacement of slotted SPSWs, four various slotted infill plates with incline strip widths of 100mm, 150mm, 200mm, and 250mm with the same infill plate thickness were selected. However, more than four different strip widths may be needed to make a generalizable claim about the out-of-plan displacement of slotted SPSWs. The comparison of out-of-plan displacement for four slotted SPSWs with various width-to-thickness ratios is shown in Figure 11. It can be observed that the width-to-thickness ratio significantly influences the out-of-plane displacement of slotted SPSWs. The details of out-of-plan displacement for both slotted infill plates are shown in Figure 12. As can be seen when the strip widths for infill plates were 250mm, the buckling of compression strips was significantly greater than that of tension strips. In addition, the slotted SPSW with a 200mm strip width has minimal out-of-plane displacement for both compression and tension strips than those of the other slotted SPSWs. As a result of the investigation in this section, the out-of-plane displacement of slotted plates was decreased by 40.00% by proper use of width to thickness ratio.

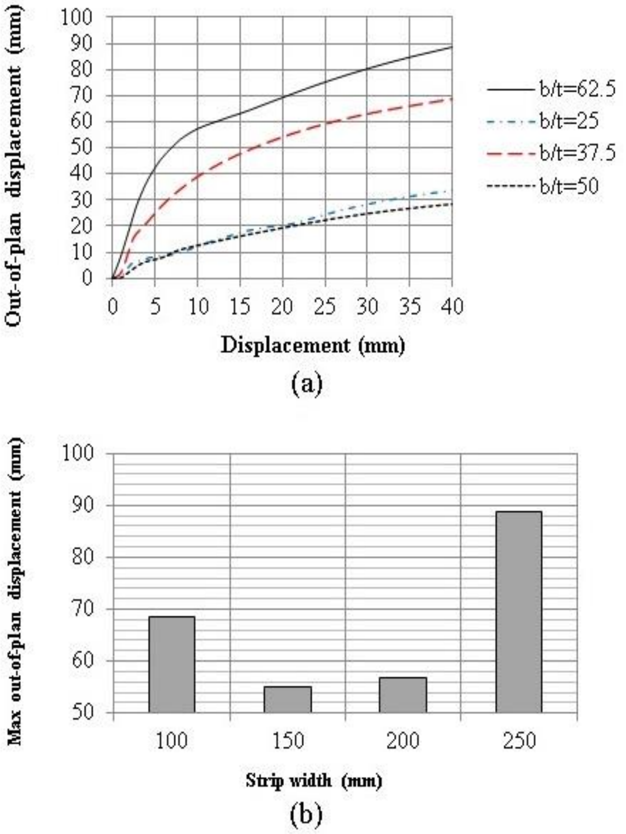
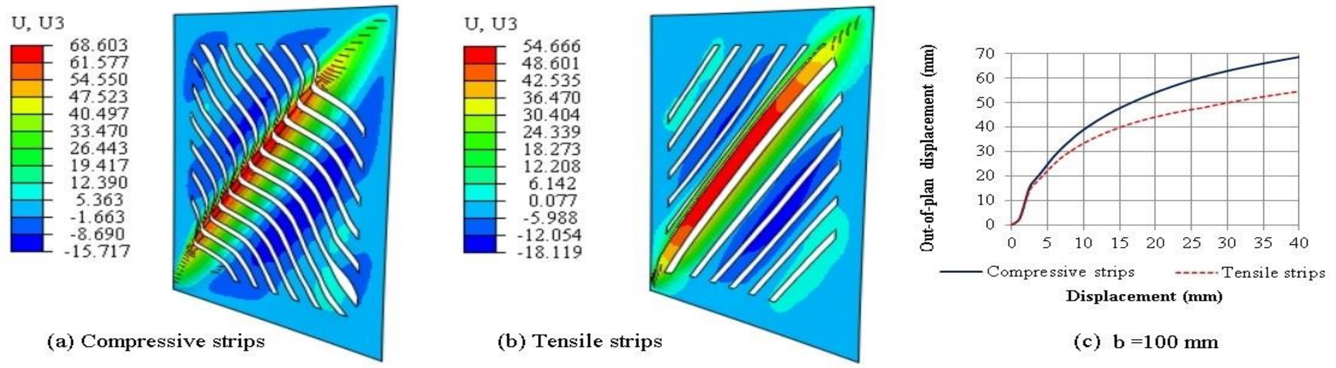


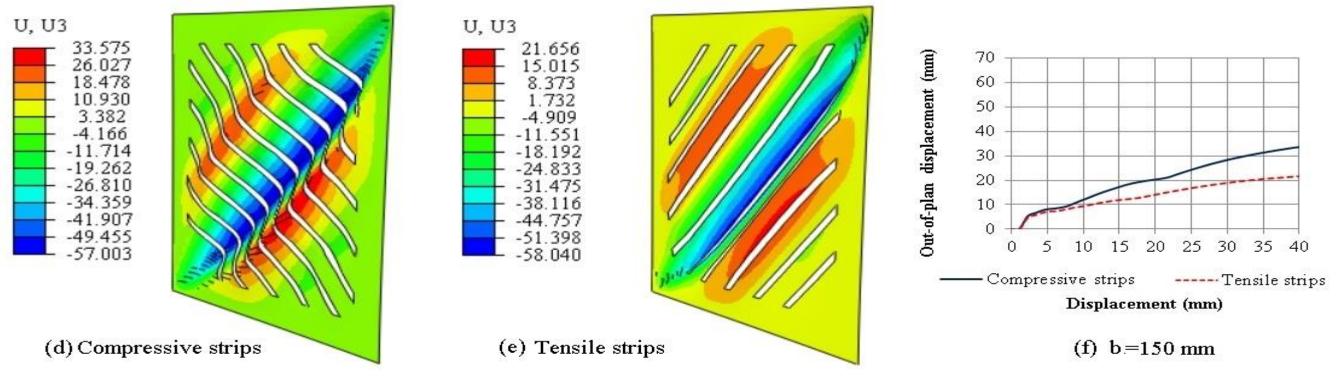
Fig. 11: Comparison of out-of-plane displacement of various slotted infill plates

4.3. *Hysteretic behavior*

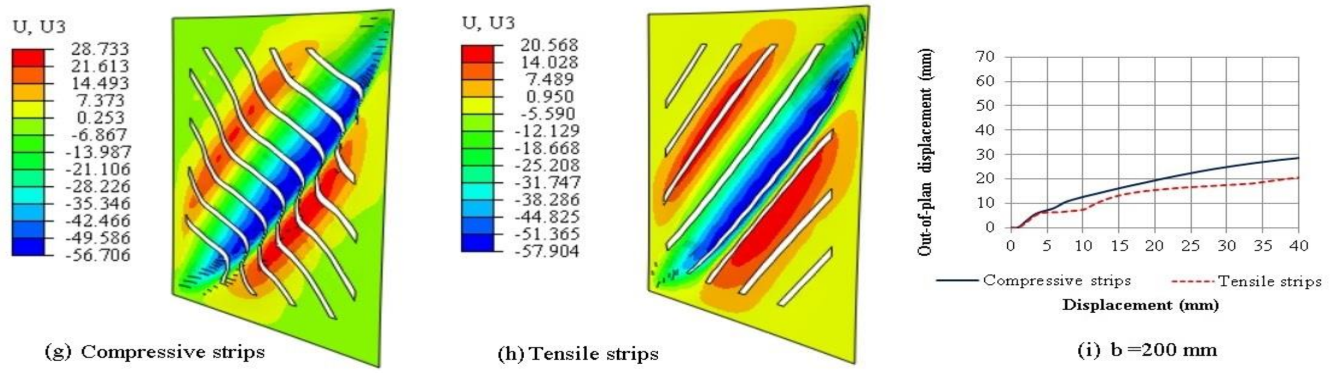
Hysteretic response refers to the nonlinear stress-strain behavior of the structure, and the hysteretic cycles show the exact picture of the response and the energy dissipated by the structural system. In addition, the hysteretic curves of a system reflect changes in strength, stiffness, energy dissipation capacity, and the number of cycles. Figure 13 illustrates the hysteretic behavior of four slotted SPSWs with different ratios of width-to-thickness for infill plates. As can be seen, the slotted SPSWs showed stable cyclic behavior without apparent pinching. It is shown that the slotted SPSWs had a consistent amount of displacement per cycle when the width-to-thickness ratio of infill plates was varied, which indicates that the slotted SPSWs can maintain a stable energy dissipation rate, allowing for consistent behavior without sudden changes in displacement. However, as shown in Figure 13(c), the slotted SPSW with 200mm strip widths has more appropriate hysteretic behavior than those of 100mm, 150mm, and 250mm.



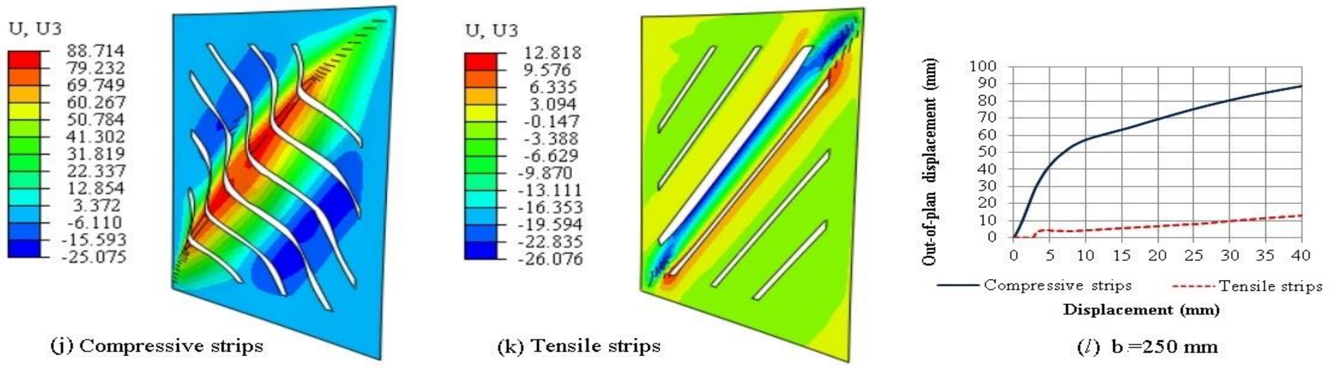
(a) Compressive strips (b) Tensile strips (c) b =100 mm



(d) Compressive strips (e) Tensile strips (f) b =150 mm

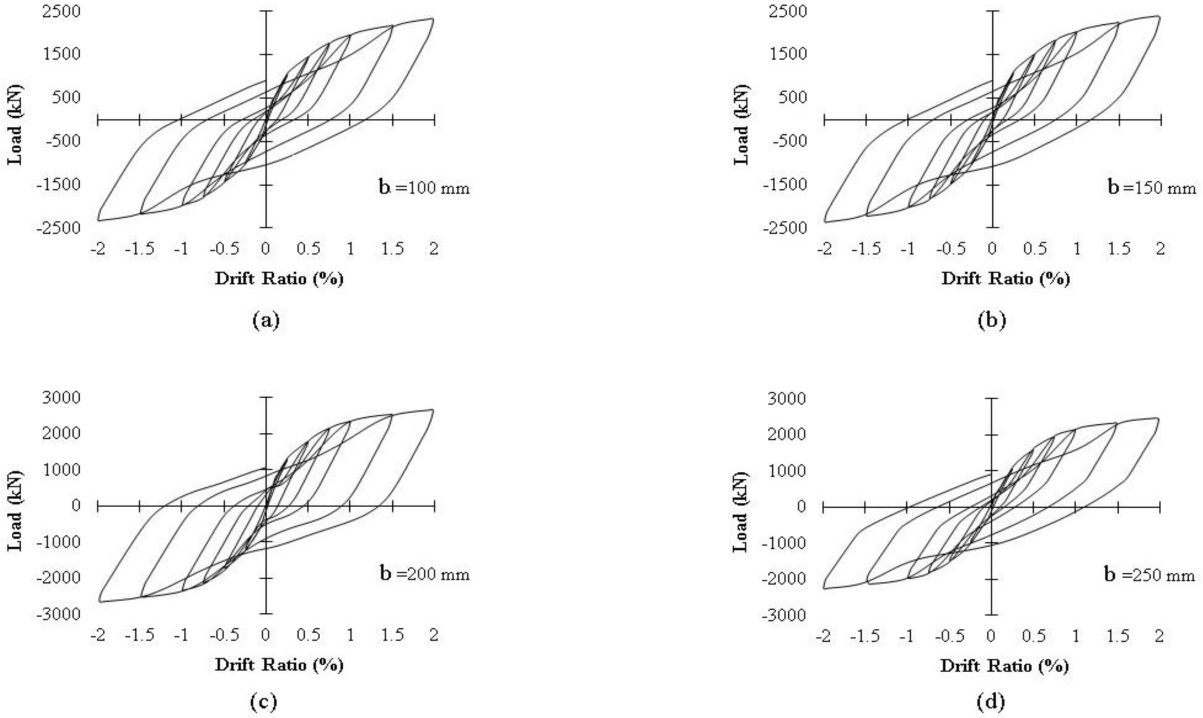


(g) Compressive strips (h) Tensile strips (i) b =200 mm



(j) Compressive strips (k) Tensile strips (*l*) b =250 mm

Fig. 12: Out-of-plane displacement of slotted SPSWs for both compressive and tensile strips



(a) (b)

(c) (d)

Fig. 13: Hysteretic behavior of slotted SPSWs with various width-to-thickness ratios under cyclic loading

Shear strength is the maximum force a structure can withstand when subjected to lateral loading, which is significant for lateral load-resisting systems, such as beams, columns, and infill plates because it determines their capacity to resist forces that act in a lateral direction. However, it is essential to note that shear strength is not the only factor determining a structure's capacity to resist lateral forces. Other factors, such as the stiffness, the amount of deflection that is permitted, and the amount of deformation that is allowed, also play a role in determining the capacity of a structure to resist lateral forces. In order to determine the shear strength of slotted shear walls, the maximum points of the hysteresis curves of four slotted shear walls were considered. As a result, their skeleton curves were drawn and shown in Figure 14. The skeleton curves of slotted SPSWs show the strength route of hysteresis curves. As shown in Figure 14, the slotted SPSW with a width-to-thickness ratio of 50 has a more significant skeleton curve than those with ratios of 25, 37.5, and 62.5.

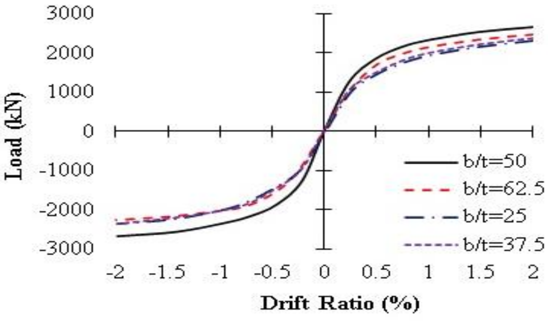


Fig. 14: Skeleton curves of slotted SPSWs with various width-to-thickness ratios

4.4. *Cumulated dissipated energy*

The energy absorption capacity curves of slotted SPSWs made of two layers of ISIPs with various width-to-thickness ratios of 25, 37.5, 50, and 62.5, with the same thickness of infill plate versus drift ratio, are illustrated in Figure 15. As can be seen, the SPSW-3 with width to thickness ratio of 50 has more energy dissipation capacity. As a result of the study, using a width-to-thickness ratio equal to 50, the cumulative dissipated energy of slotted SPSW increased by 24.08 %.

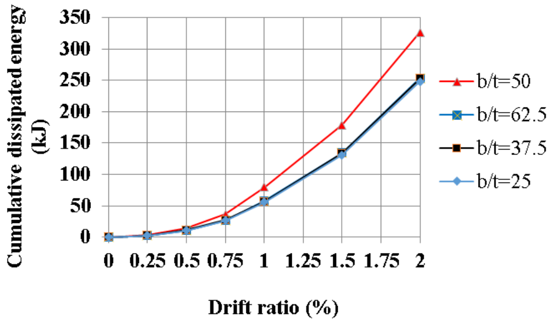


Fig. 15: Cumulative dissipated energy of slotted SPSWs based on width-to-thickness ratios

5. Conclusions

An investigation of the effect of width to thickness ratio on the behavior of inclined-slotted SPSW was carried out using numerical analysis. For this purpose, finite element models of slotted SPSWs with various width-to-thickness ratios of incline-slotted infill plates were compared. The results showed that the slotted SPSW with proper use of the width-to-thickness ratio had higher strength, stiffness, and energy dissipation capacity. The key findings are presented below.

1- When the slotted SPSWs were under lateral loads, the tensile strips provided lateral support for those under compression; as a result, both the tensile and compressive steel strips resisted lateral forces. By proper use of width to thickness ratio of incline strips, the strength, stiffness, and energy dissipation capacity of slotted SPSWs improved by 12.00%, 12.38%, and 24.08 %, respectively.

2 – Using two slotted infill plates caused the out-of-plan displacement of infill plates to be decreased. When the width-to-thickness ratio of infill plates was selected as 50, the out-of-plane displacement of compressive strips decreased by 38.00 %.

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